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Neuromuscular capacity of knee muscles and explosive performance and injury risk in soccer players

Qingshan Zhang

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**Influence des capacités neuromusculaire
des muscles du genou sur les performances
explosives et le risque de blessure chez les
footballeurs**

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English thesis title

**Influence of the neuromuscular capacities
of the knee muscles on explosive
performance and the risk of injury in
soccer players**

Persistence is more important than brilliance.

坚持远比才华重要。

*This thesis is dedicated to Aurélie, my wife, Kaylen, my son, Mélina,
my daughter.*

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Abstracts

Français Version

L'objectif principal de cette thèse était de déterminer l'influence des capacités neuromusculaires des ischio-jambiers et des quadriceps sur les performances explosives et le risque de blessures aux membres inférieurs chez les joueuses et joueurs de football. La première étude de cette thèse a examiné la relation entre la capacité de force isocinétique des muscles du genou et la performance de décélération chez les joueuses de football professionnelles. Les résultats ont révélé l'importance de la force excentrique des extenseurs du genou contribuant à la production de force de freinage pendant le test de décélération linéaire. La deuxième étude de cette thèse s'est intéressée à l'influence de la direction de saut sur la stabilité posturale dynamique lors d'une réception unipodale et l'importance de la co-activation ischio-jambiers/quadriceps dans la capacité de stabilisation des appuis unipodaux. La principale constatation est que la jambe dominante a montré une meilleure stabilité posturale dynamique lors de l'atterrissage en saut, associée à une co-activation H / Q plus élevée dans les premières millisecondes de la phase de contact. La troisième étude de cette thèse explore l'influence de la fatigue générée par des contractions isocinétiques maximales sur la capacité de force rapide des ischio-jambiers et des quadriceps chez le footballeur. Les résultats ont montré que les ratios fonctionnels et conventionnels mesurés lors des essais de pré-saison ne sont pas sensibles à la fatigue. En revanche, le rapport de force rapide ischio-jambiers / quadriceps est plus affecté par la fatigue. En résumé, ce travail a démontré que l'évaluation des capacités de force explosive et de fatigabilité des muscles extenseurs et fléchisseurs du genou sur ergomètre isocinétique demeure un sujet central pour l'amélioration de la performance explosive et la diminution du risque de blessure chez la footballeuse et le footballeur. De plus, les résultats de ce travail montrent l'intérêt d'associer systématiquement l'analyse du signal EMG à l'évaluation des capacités de force isocinétique, de performance en sprint et de stabilité des appuis chez la footballeuse et le footballeur.

Mots clés: décélération, stabilité, isocinétisme, H/Q ratio, RTD, co-activation, fatigue.

English Version

The main objective of this thesis was to determine the influence of hamstring and quadriceps neuromuscular capacities on explosive performance and the risk of lower limb injuries in soccer players. The first study of this thesis examined the relationship between the isokinetic force capacity of the knee muscles and the deceleration performance in professional female soccer players. The results revealed the importance of the eccentric force of the knee extensors contributing to the production of braking force during the linear deceleration test. The second study of this thesis was interested in the influence of the direction of jump on the dynamic postural stability during an unipodal landing and the importance of the hamstring / quadriceps co-activation in the stabilization capacity of the legs unipodal supports. The main finding is that the dominant leg showed better dynamic postural stability during the jump landing, associated with higher H / Q co-activation in the first milliseconds of the contact phase. The third study of this thesis explores the influence of fatigue generated by maximal isokinetic contractions on the capacity for rapid strength of the hamstrings and quadriceps in footballers. The results showed that the functional and conventional ratios measured during the preseason testing are not sensitive to fatigue. In contrast, the rapid hamstring / quadriceps torque ratio is more affected by fatigue. In summary, this work has shown that the evaluation of the explosive strength and fatigability capacities of the extensor and flexor muscles of the knee on an isokinetic ergometer remains a central subject for the improvement of explosive performance and the reduction of the risk of injury in the soccer player and footballer. In addition, the results of this work show the value of systematically associating the analysis of the EMG signal with the evaluation of the isokinetic force capacities, sprint performance and stability of the supports in male and female soccer players.

Keywords: deceleration, stability, isokinetic, H/Q ratio, RTD, co-activation, fatigue.

Publications and conference proceedings

Articles

Qingshan Zhang, Robin Trama, Alexandre Fouré, Christophe A Hautier. The immediate effects of self-myofascial release on flexibility, jump performance, and dynamic balance ability. *Journal of human kinetics*, volume 75/2020, 139-148. DOI: 10.2478/hukin-2020-0043.

Qingshan Zhang, Félicie Pommerell, Adam Owen, Robin Trama, Cyril Martin, Christophe A Hautier. Running pattern and force-velocity sprinting profiles in elite training young soccer players: A Cross-Sectional Study. *European Journal of Sport Science*. DOI: 10.1080/17461391.2020.1866078.

Qingshan Zhang, Morel Baptiste, Christophe A Hautier. Influence of fatigue on the rapid hamstring/quadriceps force capacity in soccer players. *Frontiers in Physiology*. DOI: 10.3389/fphys.2021.627674.

Qingshan Zhang, Aurélie Léam, Alexandre Fouré, Del Wong, Christophe A Hautier. Relationships between rapid hamstring-to-quadriceps ratio and deceleration ability in a semi-elite female soccer player (in revision in JSCR).

Qingshan Zhang, Christophe A Hautier. Influence of rapid Hamstring-to-Quadriceps strength and Co-Activation Ratio on Dynamic Postural Stability during Different Landing Maneuvers in the Female Athletes (submitted to EJSS).

Stanislas Krug, Alexandre Polizzi, **Qingshan Zhang**, Christophe A Hautier, Cyril Martin. Influence of aerial and terrestrial running patterns on the activity profile of young elite soccer players in-game situations (In preparation).

China's Urgent Need for Sports Science Scientization: Young Sports Scholars' Consensus. Li Yongming, Han Jia, **Zhang Qingshan**, et al. *Journal of Shanghai University of Sport*, 44(2):39-52, 2020.DOI: 10.16099/j.sus.2020.02.005.

Congress

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Qingshan Zhang, Félicie Pommerell., Christophe Hautier. Relationship between running patterns and force-velocity sprinting profiles in highly training young soccer players: A Cross-Sectional Study. 24th scientific day of the EDISS Oct 2019, Villeurbanne, France (Communication orale).

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List of Abbreviations

ACL	anterior cruciate ligament
ANOVA	analysis of variance
BF.	biceps femoris
COD.	change-of-direction
COM.	center of mass
DL	dominant leg
GRF	ground reaction force
H/Q ratio	hamstring to quadriceps strength ratio
HSIs	hamstring strain injuries
ICC	Intraclass correlation coefficient
IMVC	isometric maximum voluntary contraction
KE	knee extensor
KF	knee flexor
MTU	muscle-tendon-unit
ms	millisecond
NDL	non-dominant leg
PT	peak torque
RER	rate of EMG rise

RF	rectus femoris
ROM	range of motion
RTD H/Q ratio	rate of torque development hamstring to quadriceps ratio
RTD	rate of torque development
sEMG	surface electromyographic
SM	semitendinosus
SPM	statistical parameter maps
VL	vastus lateralis

CHAPTER 1 General Introduction

1.1 Introduction

During the past decade, numerous investigations have widely detailed the physical demands of soccer players during a competitive match (Mallo and Navarro 2008, Gray and Jenkins 2010, Kelly and Williams 2020). Understanding the physical demand for soccer players during the competitive match-play is essential in understanding the match-play performance and occurrence of injury (Hawkins and Fuller 1999, Orchard and Seward 2002, Woods, Hawkins et al. 2002, Junge and Dvorak 2004, Junge, Dvorak et al. 2004, Price, Hawkins et al. 2004, Wong and Hong 2005, Ekstrand, Hägglund et al. 2011). Soccer is a team sport that combines the high-intensity intermittent activities with short recuperation and long duration, characterized by short sprints at high intensity, rapid acceleration or deceleration, and change of direction, jumping during the competitive match (Vigne, Gaudino et al. 2010). Based on the movement pattern's general motion analysis during the competitive match, the soccer players cover approximately 9~13 km within high intensity sprinting cover 2520~2745m including 1000-1400 unpredictable changes in locomotor activity, which occur every 3~6 s (O'Donoghue 2002, Mohr, Krstrup et al. 2003, Rampinini, Coutts et al. 2007, Bradley, Sheldon et al. 2009, Vigne, Gaudino et al. 2010).

The performance in soccer is a consequence of multiple factors, including individual physical capacity, strategy, skill, mental character, etc. (Dellal, Wong et al. 2010, Haugen, Tønnessen et al. 2014). But the individual physical capacity is becoming of central importance in modern soccer due to the improved quality of physical capacity of every soccer players. Thus, it is widely accepted that soccer players should focus on improving both aerobic and anaerobic performance, as well as enhancing the ability to perform repeated high-intensity movement and to recover rapidly; thereby, requiring different combinations of speed and strength of muscular contraction (Bangsbo, Mohr et al. 2006, Krstrup, Mohr et al. 2006, Bradley, Sheldon et al. 2009, Chaouachi, Manzi et al. 2010, Gray and Jenkins 2010, Nédélec, McCall et al. 2012).

The lower limb neuromuscular capacities are considered as fundamental components of soccer performance and are commonly assessed in soccer players at different moments of a competitive season (Cometti, Maffiuletti et al. 2001, Gissis, Papadopoulos et al. 2006, Lehance, Binet et al. 2009, Fousekis, Tsepis et al. 2010). Numerous studies reported that the knee muscles (hamstring,

quadriceps) strength was significantly related to athlete performance including the sprinting, acceleration, and change of direction performance (Swinton, Lloyd et al. 2014, Spiteri, Newton et al. 2015, Wang, Hoffman et al. 2016, Jones, Thomas et al. 2017, Edouard, Mendiguchia et al. 2018, Ishoi, Aagaard et al. 2019, Harper, Jordan et al. 2021), whereas just few studies examined the influence of lower limb strength on deceleration performance (Harper, Morin et al. 2020, Harper, Jordan et al. 2021). However, if extensive literature has been published about the acceleration phase or the sprinting velocity and neuromuscular capacities of knee muscles, very few studies focused on deceleration performance and its kinetics and kinematics determinants. To our knowledge, only one previous study has investigated the potential relationship between the knee muscle's strength capacities and the maximal linear deceleration performance to date (Harper, Jordan et al. 2021). However, previous investigations suffers some limitations since the deceleration performance was evaluated during decelerations from relatively low-sprinting velocities (Jones, Thomas et al. 2017), which didn't represent the real deceleration magnitude observed during a competitive match-play. In fact, the deceleration mostly starts after high velocity sprinting (Mara, Thompson et al. 2017, Harper, Carling et al. 2019), which require the athlete to maintain the dynamic body stability to efficiently decrease the magnitude of the body momentum (Myer, Ford et al. 2005, Reid, Birmingham et al. 2007, Hewit, Cronin et al. 2011). Therefore, it has been suggested to assess the dynamic stability performance (e.g., dynamic postural stability index) during the functional movement, such as jump landing in a laboratory setting (Myer, Ford et al. 2005, Reid, Birmingham et al. 2007, Collings, Gorman et al. 2019).

Meanwhile, it is well known that there is high risk of suffering musculoskeletal injury in soccer players (Orchard and Seward 2002, Woods, Hawkins et al. 2002, Junge and Dvorak 2004, Woods, Hawkins et al. 2004, Emery, Meeuwisse et al. 2005, Hägglund, Waldén et al. 2005, Wong and Hong 2005, Hägglund, Walden et al. 2006, Ekstrand, Hägglund et al. 2011, Dalton, Kerr et al. 2015). Besides, the most common injuries are hamstring strain injuries (HSIs) and anterior cruciate ligament (ACL) injuries in soccer players (Orchard and Seward 2002, Ekstrand, Hägglund et al. 2011, Elliott, Zarins et al. 2011, van Beijsterveldt, van de Port et al. 2013, Dalton, Kerr et al. 2015, Ekstrand, Waldén et al. 2016, Walden, Hägglund et al. 2016). To date, both hamstring and quadriceps neuromuscular performance and the hamstring-to-quadriceps strength ratio (H/Q ratio) have commonly been considered as important parameters related to HSIs and ACL injuries

(Knapik, Bauman et al. 1991, Bennell, Wajswelner et al. 1998, Yeung, Suen et al. 2009, Freckleton and Pizzari 2013, van Dyk, Bahr et al. 2016). However, no consensus indicated a strong and significant relationship between H/Q ratio and HSIs or ACL injuries (Grace, Sweetser et al. 1984, Yamamoto 1993, Bennell, Wajswelner et al. 1998, Myer, Ford et al. 2009) probably due to the fact that the traditional H/Q ratio could not reflect the co-contraction between the hamstring and quadriceps (Zebis, Andersen et al. 2011). Interestingly, HSIs and ACL injuries, tend to occur more often in the later stage of competitive match indicating fatigue as a potential contributing factor to these injuries (Hawkins, Hulse et al. 2001, Ekstrand, Hägglund et al. 2011). It has been hypothesized that fatigue associated with the match play induces a decrease in neuromuscular performance that could be linked to a higher risk of HSIs and ACL injury (Opar, Williams et al. 2012). However, based on the current scientific literature, the effect of neuromuscular fatigue on H/Q ratio and HSIs and ACL injury risk was not clear to until now.

Consequently, the main work of this thesis was to explore the influence of hamstring neuromuscular performance and activation on the sprint deceleration performance and the stability during landing maneuvers. The influence of fatigue on the hamstring neuromuscular performance and consequently on the H:Q ratio has been investigated. The practical applications of this work were to improve the evaluation of Hamstrings performance and to better understand its role in performance and injury in soccer players.

CHAPTER 2 Literature Review

2.1 Acceleration and deceleration in soccer

2.1.1 Introduction

Previous studies have been reported that the level of high-intensity activity was associated with the final outcome of a competitive match in soccer (Bloomfield, Polman et al. 2007, Di Salvo, Gregson et al. 2009, Buchheit, Mendez-villanueva et al. 2010). Short sprint running, acceleration, and deceleration are three substantial types of the most high-intensity activity during the competitive match in soccer players (Stølen, Chamari et al. 2005, Burgess, Naughton et al. 2006, Bradley, Sheldon et al. 2009, Vigne, Gaudino et al. 2010, Andrzejewski, Chmura et al. 2012, Akenhead, Hayes et al. 2013, Andrzejewski, Chmura et al. 2013, Buchheit, Al Haddad et al. 2014, Sarmiento, Marcelino et al. 2014, Wehbe, Hartwig et al. 2014, Russell, Sparkes et al. 2015, de Hoyo, Cohen et al. 2016, Russell, Sparkes et al. 2016, Tierney, Young et al. 2016, Newans, Bellinger et al. 2019). However, these three actions require distinctive and disparate internal physical and mechanical characteristics (Andrews, McLeod et al. 1977, Hewit, Cronin et al. 2011, Morin, Edouard et al. 2011, Buchheit, Samozino et al. 2014, Morin, Slawinski et al. 2015).

2.1.2 Acceleration and deceleration demand during competitive match

To date, the professional soccer players perform more than 40 high-intensity sprints, during which the velocity reached approximately $6 \sim 8 \text{ m}\cdot\text{s}^{-1}$ with an average duration between 2s and 4s, while the majority of sprint distance are shorter than 20m, and almost half of sprinting are less than 10m (Stølen, Chamari et al. 2005, Burgess, Naughton et al. 2006, Bradley, Sheldon et al. 2009, Vigne, Gaudino et al. 2010, Andrzejewski, Chmura et al. 2012, Andrzejewski, Chmura et al. 2013, Sarmiento, Marcelino et al. 2014, Newans, Bellinger et al. 2019). Besides, several recent studies have been quantifying the acceleration actions during competitive match play, and found the professional soccer players perform approximately 26 high acceleration efforts ($> 3\text{m}\cdot\text{s}^{-2}$) in professional soccer matches (Bradley, Sheldon et al. 2009, Akenhead, Hayes et al. 2013, Buchheit, Al Haddad et al. 2014, Wehbe, Hartwig et al. 2014, Russell, Sparkes et al. 2015, de Hoyo, Cohen et al. 2016, Russell, Sparkes et al. 2016, Tierney, Young et al. 2016, Newans, Bellinger et al. 2019). More importantly, the short sprint running also form interdependent relationships with acceleration performance since the ability to accelerate rapidly the center of mass (COM) is the primary parameter that determines the short sprint performance (Morin, Edouard et al. 2011,

Morin, Bourdin et al. 2012); Thus, short sprint performance and acceleration capacity are considered as the prerequisite for successful performance in soccer, which could assist the soccer players in overtaking the ball in the game-deciding situation (Bradley, Sheldon et al. 2009), or to attack and defense, respectively (Chaouachi, Manzi et al. 2012). Furthermore, the other high-intensity activity in parallel to acceleration is deceleration; The soccer players perform approximately 46 high-intensity decelerations ($< -3\text{m. s}^{-2}$) per match, which are up to 1.7 times more frequent comparing to high-intensity acceleration (Chaouachi, Manzi et al. 2012, Akenhead, Hayes et al. 2013, Buchheit, Al Haddad et al. 2014, Wehbe, Hartwig et al. 2014, Russell, Sparkes et al. 2015, de Hoyo, Cohen et al. 2016, de Hoyo, Cohen et al. 2016, Russell, Sparkes et al. 2016, Tierney, Young et al. 2016). A recent meta-analysis about deceleration demands in elite team sport illustrates the prevalence of high-intensity decelerations in soccer match-play performance (Harper, Carling et al. 2019).

As a consequence, acceleration and deceleration performances may provide further insight into the characteristics of soccer's performance (Bradley, Sheldon et al. 2009, Newans, Bellinger et al. 2019).

2.1.3 Influence of fatigue on acceleration and deceleration performance

As aforementioned earlier, soccer involves many high-intensity intermittent activities (e.g., sprinting, acceleration, deceleration, changes of direction) with short recuperation, which lead to neuromuscular fatigue during the competitive match (Mohr, Krstrup et al. 2005, Rampinini, Bosio et al. 2011, Brownstein, Dent et al. 2017, Silva, Rumpf et al. 2018) . This fatigue could significantly reduce the soccer player's physical performance (e.g., lower limb strength, sprint performance) and subsequently reduces the amount of high-intensity movement, including sprinting, acceleration, and deceleration were lower into the second half compared to the first half due to fatigue (Akenhead, Hayes et al. 2013, Russell, Sparkes et al. 2016). Akenhead et al., (2013) indicated that the distance covered at high acceleration decreased in the second half ($> 3\text{m.s}^{-2}$, 91m vs. 88m) as well as the deceleration ($< -3\text{m.s}^{-2}$, 84 vs. 78) (Akenhead, Hayes et al. 2013). Besides, Russell et al., (2016) profiled the markers of acceleration and deceleration capacity during professional soccer match-play. Their results found that both the acceleration and deceleration performance reduced with a total number of high-intensity of accelerations that significantly

decreased in the last 15 minutes of the competitive match ($> 3\text{m}\cdot\text{s}^{-2}$, 14 vs. 12) and like decelerations ($< -3\text{m}\cdot\text{s}^{-2}$, 24 vs. 19) (Russell, Sparkes et al. 2016). More recently, Newans et al., (2019) used a global positioning system to quantify the acceleration and deceleration quantity and quality of soccer players during match play by linear mixed models. The results indicated the acceleration and deceleration metrics displayed negative logarithmic curves within each half (Akenhead, Hayes et al. 2013). In summary, the fatigue related to the competitive match significantly impairs the performance of acceleration and deceleration.

2.1.4 Assessment of acceleration and deceleration performance

2.1.4.1 Introduction

Both acceleration and deceleration performance could be considered as the ability to rapidly move the Center of Mass of the body (COM). Acceleration is considered as a positive acceleration of the COM in the forward direction to increase the velocity, whereas the deceleration is a negative acceleration orientated in the backward direction to reduce the velocity. Thereby, both short sprint running and acceleration need the athlete to produce the higher propulsive force (i.e., preponderance in concentric work) to forward the COM (Morin, Edouard et al. 2011, Buchheit, Samozino et al. 2014, Morin, Slawinski et al. 2015), whereas the deceleration needs the athlete to apply as much braking force (i.e., preponderance in eccentric work) to decrease the COM velocity (Andrews, McLeod et al. 1977, Hewit, Cronin et al. 2011). Global positioning system (GPS) devices are most commonly used to quantify the occurrence and characteristics of higher intensity accelerations and decelerations during competitive match (Spilker Jr, Axelrad et al. 1996, Stevens, de Ruiten et al. 2014). Typically, acceleration performance in soccer is assessed using single (Nikolaidis, Knechtle et al. 2016) or repeated sprints of short duration (Buchheit, Mendez-villanueva et al. 2010), while the deceleration is assessed as the time to stop and distance to stop after a short distance sprint running in the field (10m, 15m, 20m) (Ashton and Jones 2019, Harper, Jordan et al. 2021).

2.1.4.2 Assessment of acceleration performance

Generally, short sprint running performance development as measured by sprint times over certain distances as the split time such as 5m, 10m, 15m, 20m which could be used to demonstrate the acceleration performance (e.g., photocell timing) in soccer player; namely, the players are asked to cover this distance as fast as possible (Nikolaidis, Knechtle et al. 2016). In 2016, Samozino et al., (2016) proposed a novel method to assess the mechanics variable during the sprint running in the field sport including soccer called “Force-Velocity relationship profile”. This simple method could compute sprint acceleration kinetics from the running time-velocity curve in the basic of macroscopic model, which has been validated for measuring mechanical effectiveness based on an inverse dynamic approach (Samozino, Rabita et al. 2016, Morin, Samozino et al. 2019) (Figure 2-1).

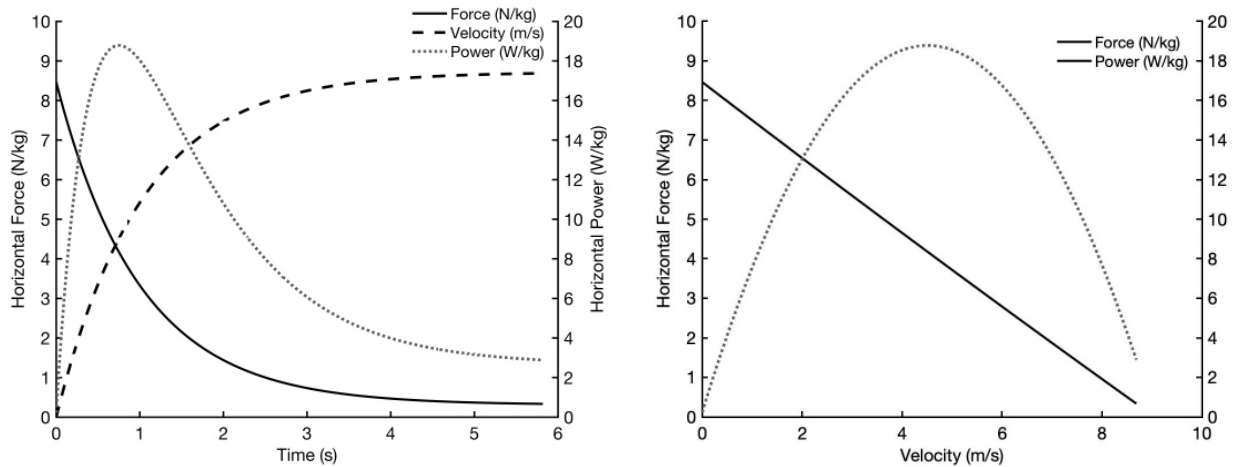


Figure 1: Example of Force-Velocity profile during sprint running. A) force-power curve with the time increasing, B) force-power curve with the velocity increasing.

The main sprint mechanical Force-Velocity profile include maximal acceleration (Acc), maximal theoretical force (F_0), maximal theoretical velocity (V_0), maximal power (P_{max}), decrease in the ratio of horizontal-to-resultant force (D_{RF}), the slope of the linear Force-Velocity relationship (F - V slope) and maximal ratio of horizontal-to-resultant force (RF_{max}) (Samozino, Rabita et al. 2016).

Based on this method, the sprint velocity-time curve ($v(t)$) was fitted by a mono-exponential function using least-squares regression:

$$V_{(t)} = V_{max} * \left(1 - e^{-\frac{t}{\gamma}}\right)$$

with τ the acceleration time constant. The horizontal acceleration of the centre of mass can be expressed as a function of time, after derivation of velocity over time:

$$a_{(t)} = \left(\frac{V_{max}}{\gamma}\right) * e^{-\frac{t}{\gamma}}$$

Net horizontal force (F_h) was then modelled over time:

$$F_{(t)} = m \cdot a_{(t)} + F_{air(t)}$$

with F_{air} as the aerodynamic friction force to overcome during sprint running computed from sprint velocity and an estimated body frontal area and drag coefficient. From the horizontal-force and sprint-velocity values, individual force-velocity relationships were determined with least-squares linear regressions. F_0 and V_0 were then identified from the force-velocity relationship as the x- and y-intercepts, respectively. Maximum horizontal power output was determined as $(F_0 * V_0/4)$. Maximum velocity (V_0) was identified as the maximal velocity obtained during the 40-m sprint. The ratio of force was calculated as the ratio of the horizontal component of the ground reaction force to the total ground-reaction force. RF_{peak} corresponded to the maximal value of the ratio of force. Besides, the linear decrease in the ratio of force with velocity was calculated as an index of the ability to maintain the ratio of force throughout the acceleration phase (D_{RF}). The power-force-velocity-profiling approach is based on force-velocity (F-V) and power-velocity relationships characterizing the maximal mechanical capabilities of the lower limbs' neuromuscular system. The definition and the practical interpretation of the main mechanical variables of interest are presented in Table 1 (Morin and Samozino 2016).

Horizontal		
<i>HZT-F0</i> (N/kg)	Theoretical maximal horizontal force production as extrapolated from the linear sprint F–V relationship; y-intercept of the linear F–V relationship.	Maximal force output (per unit body mass) in the horizontal direction. Corresponds to the initial push of the athlete onto the ground during sprint acceleration. The higher the value, the higher the sprint-specific horizontal force production.
<i>HZT-V0</i> (m/s)	Theoretical maximal running velocity as extrapolated from the linear sprint F–V relationship; x-intercept of the linear F–V relationship.	Sprint-running maximal velocity capability of the athlete. Slightly higher than the actual maximal velocity. The theoretical maximal running velocity the athlete would be able to reach should mechanical resistances (ie, internal and external) against movement be null. It also represents the capability to produce horizontal force at very high running velocities.
<i>HZT-Pmax</i> (W/kg)	Maximal mechanical power output in the horizontal direction, computed as $P_{max} = F0 \times V0/4$, or as the apex of the P–V 2nd-degree polynomial relationship.	Maximal power-output capability of the athlete in the horizontal direction (per unit body mass) during sprint acceleration.
<i>RF</i> (%)	Ratio of force, computed as the ratio of the step-averaged horizontal component of the ground-reaction force to the corresponding resultant force.	Direct measurement of the proportion of the total force production that is directed in the forward direction of motion, ie, the mechanical effectiveness of force application of the athlete. The higher the value, the more important the part of the total force output directed forward.
<i>RFmax</i> (%)	Maximal value of <i>RF</i> , computed as maximal value of <i>RF</i> for sprint times >0.3 s.	Theoretically maximal effectiveness of force application. Direct measurement of the proportion of the total force production that is directed in the forward direction of motion at sprint start.
<i>D_{RF}</i>	Rate of decrease in <i>RF</i> with increasing speed during sprint acceleration, computed as the slope of the linear <i>RF</i> –V relationship.	Describes the athlete’s capability to limit the inevitable decrease in mechanical effectiveness with increasing speed, ie, an index of the ability to maintain a net horizontal force production despite increasing running velocity. The more negative the slope, the faster the loss of effectiveness of force application during acceleration, and vice versa.

Table 1: Definition and practical interpretation of main variables of F-V profile adapted from (Morin and Samozino 2016).

2.1.4.3 Assessment of deceleration performance

Despite the linear deceleration performance plays an important role to determine the agility or COD performance, until recently there has been limited attention in the literature to evaluate this physical quality. During the linear deceleration, the athlete needs to stop as rapidly as possible in the shortest time and distance after the beginning of the deceleration. Therefore, the linear deceleration performance was usually evaluated using distance-to-stop (DTS) and time-to-stop (TTS) after different sprint running durations (e.g., 5m, 10m, 15m, 20m) (Ashton and Jones 2019). These two variables were usually measured with high-frequency cameras or a radar gun (Ashton and Jones 2019, Harper, Jordan et al. 2021). Furthermore, the deceleration could be considered as the negative acceleration after the sprint; thus, the deceleration performance could also evaluate the ability to produce breaking forces to reduce the running velocity, which could be express by the kinematic and kinetic variables. Harper et al., (2020) proposed a new method to calculate the

kinetic and kinematic variables during the linear deceleration testing using the time-curve recorded with a radar gun. This method could calculate the kinetic and kinematic parameters using the Newton's second law.

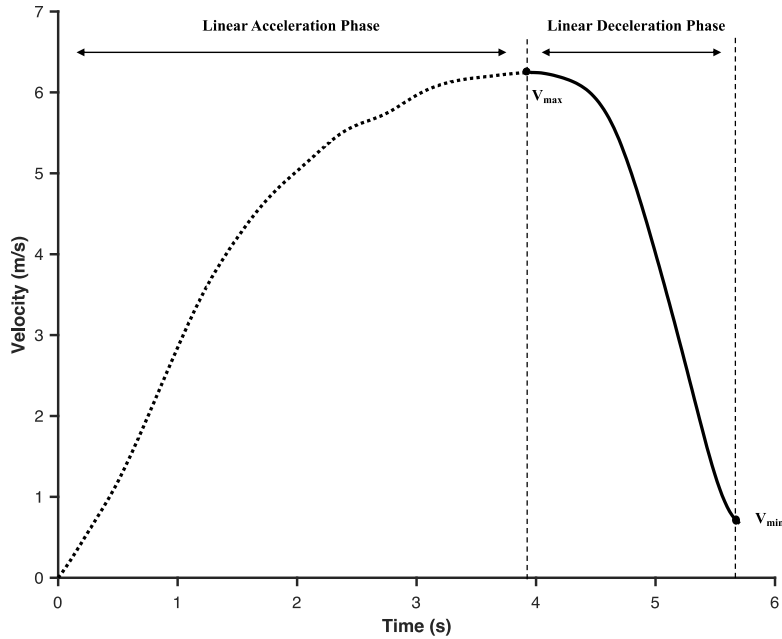


Figure 2: Example of velocity-time profile showing the acceleration and the deceleration phase. V_{max} : maximum velocity defining start of deceleration phase. V_{min} : lowest velocity defining end of deceleration phase.

In this novel method, the kinetic variable including the horizontal braking force (F_H), power (P_H), and impulse (I_H) was calculated from the start to the end of the maximal sprint deceleration using the equation below (Harper, Morin et al. 2020). The instantaneous horizontal acceleration (a_H) was calculated by the gradient of the time-velocity curve as:

$$a_H(t) = \frac{\partial v}{\partial t}$$

And, the net horizontal force $F_H(t)$ during the deceleration period was then modeled over time:

$$F_H(t) = m \cdot a_H(t) + F_{aero}$$

Where: $a_H(t)$ is the acceleration at time t and m is the body mass. In addition, ∂t is the variation in time, and ∂v is the variation in velocity. F_{aero} is the air friction, which was calculated with the equation F_{aero} as the aerodynamic friction force to overcome during sprint running computed from sprint velocity and an estimated body frontal area and drag coefficient (Arsac and Locatelli 2002).

$$F_{aero}(t) = (0.2025 * Height^{0.725} * Mass^{0.425}) * 0.266$$

Besides, the horizontal power ($P_H(t)$) was calculated with the following equation:

$$P_H(t) = F_H(t) * V_H(t)$$

Instantaneous horizontal impulse ($I_H(t)$) was calculated between each data point during the deceleration phase using the change in the momentum.

$$I_H(t) = \partial v * mass$$

The average horizontal braking force (F_{ave}), braking power (P_{ave}), and braking impulse (I_{ave}) calculated using the average of all instantaneous F_H , P_H , and I_H , during the entire deceleration phase. Furthermore, the maximum braking force (F_{max}), power (P_{max}), and impulse (I_{max}) were obtained as the highest value of all instantaneous F_H , P_H , and I_H value during the entire deceleration phase. Therefore, this method added the more kinetic and kinematic variable to estimate the deceleration performance.

2.1.5 Conclusion

As shown above, the physical demands of soccer include numerous and high acceleration and deceleration efforts during the competitive match, inducing the development of methods to accurately evaluate these capacities and to develop performance. In addition, the frequency of high-intensity acceleration and deceleration tends to reduce from the first to the second half indicating the development of fatigue during the match; thereby, specific testing procedure and training programs should be designed to accurately evaluate soccer player strength and weakness and to orientate physical preparation in order to maximize the acceleration and deceleration

capacity of players throughout the entire duration of a soccer match (Russell, Sparkes et al. 2015, Russell, Sparkes et al. 2016).

2.2 Hamstring and quadriceps muscles strength assessment

2.2.1 Introduction

The muscular strength has been defined as the ability to produce force on an external object or resistance (Siff 2008). Greater muscular strength allows an individual to improve his or her performance across a wide range of both general and sport specific skills while simultaneously reducing the risk of injury (Sugiura, Saito et al. 2008, Lee, Reid et al. 2009). Numerous previous studies measured and reported the strength of the knee muscle groups (i.e., hamstring, quadriceps) in association with the athlete's performance in jumping (Tillin, Pain et al. 2013), sprinting (Morin, Gimenez et al. 2015, Ishoi, Aagaard et al. 2019), decelerating (Harper, Jordan et al. 2021) or changing of direction (Jones, Thomas et al. 2017), etc. These findings indicated the crucial role of the hamstring and quadriceps strength in predicting athlete performance. Therefore, a frequent assessment of muscle strength should be performed to evaluate potential muscle strength deficit (e.g., explosive power, maximum strength) and/or hamstring to quadriceps strength imbalance. Such an evaluation could permit the coach to design specific strength training programs to improve the athlete's performance and prevent injury. Many tools and methods could be used to evaluate knee muscle strength but the isokinetic dynamometry has been demonstrated to be one of the most reliable and accurate to discriminate between athletes of different performance abilities (Brown 2000).

2.2.2 Quadriceps and Hamstring anatomy

The hamstring and quadricep muscles are the major muscle groups of thighs which are integrally involved in the kinetic chain of the lower limb. They are two opposing muscle groups always activated together as a co-activation of agonist and antagonist actors to produce coordinated lower limb movement during the physical activity (i.e., jumping, running, walking). The quadriceps muscle at the anterior muscles loge of the thigh consists of four muscles: rectus femoris (RF), vastus intermedius (VI), vastus lateralis (VL), vastus medialis (VM) (see figure 3A) which are involved in knee extension and hip flexion.

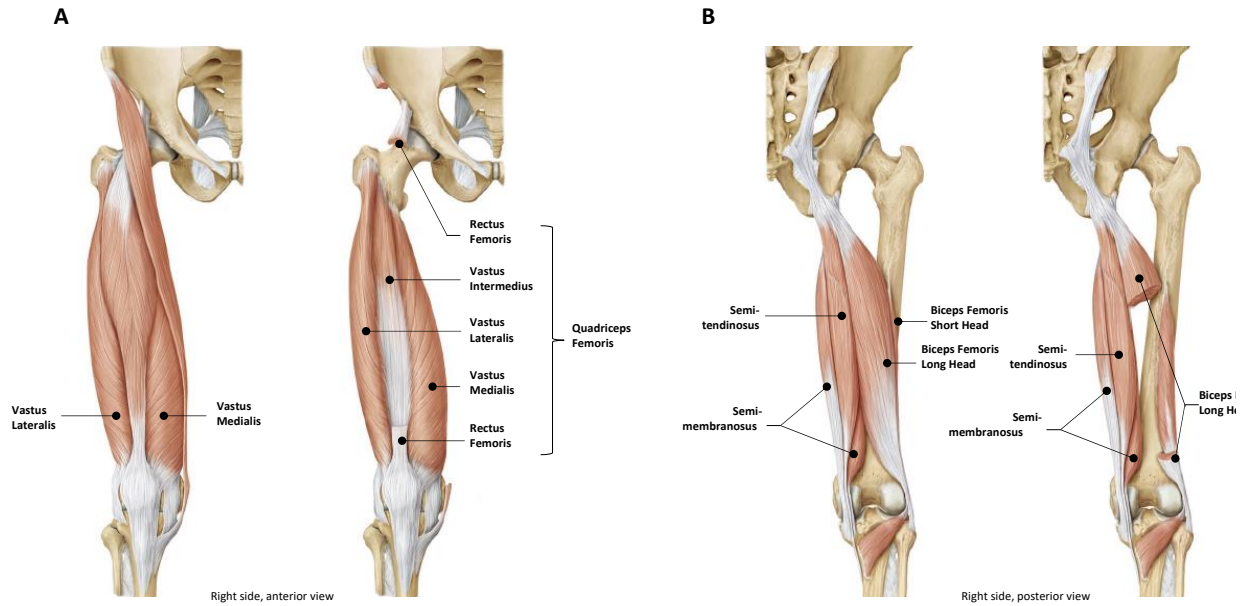


Figure 3: Anatomy of quadriceps (A) and hamstring muscles (B) (adapted from P477) (Schünke, Ross et al. 2006).

The complex hamstring muscles, located at the posterior lobe of the thigh consists of three muscles: biceps femoris (BF), semimembranosus (SM), and the semitendinosus (ST) (see figure 3B). The main functions of the hamstrings are the knee flexion, the hip extension, and the internal (SM and ST) or external knee rotations (BF) (Thorborg, Opar et al. 2020).

2.2.3 Fundamental of muscle strength

The muscle strength is dependent on the combination of the morphology of the muscle and the tendon and neural factors, including muscle volume, type of muscle fiber, cross-sectional area, musculotendinous stiffness, muscle pennation angle, motor unit recruitment, neuromuscular inhibition, motor unit synchronization, firing frequency, contraction velocity, etc. (Suchomel, Nimphius et al. 2018). Besides, given the mechanism of contraction model in skeletal muscles, the Force-Length-Velocity relationship's curve (Figure 8) is frequently used to describe the force production characteristic. Force-Length-Velocity relationship indicated that the muscle force production can be influenced by the shortening or lengthening velocity of the muscle, with the relationship respectively shown in the concentric and eccentric zones of the graph in Figure 8 (F_M - V_M relationship). This force-velocity relationship was first described for concentric tension

development in muscle by Hill in 1938 (Hill 1938). Simply, the maximum force at zero velocity and maximum contraction velocity at a minimal load vary with the size and type of muscle. In parallel, the Force-Length relationship indicated the muscular force production dependent on the muscle's length (Gordon, Huxley et al. 1966). The muscle force production is at its peak when the muscle is slightly stretched, whereas muscle tension development capability is less following muscle shortening or lengthening (Abbott and Aubert 1952, Herzog and Leonard 2000). For now, two main standardized methods were used to assess the muscle strength with high reliability: isometric maximum voluntary contraction (MVIC) in static mode (Meldrum, Cahalane et al. 2007) and isokinetic testing in dynamic mode (Osternig 1986). These two main methods are not the unique method used for measurement of muscle strength in athlete since iso-load dynamic contractions usually used in resistance training associated with a measurement of movement velocity may also provide interesting indications (Rahmani, Samozino et al. 2018, Lu, Boyas et al. 2019).

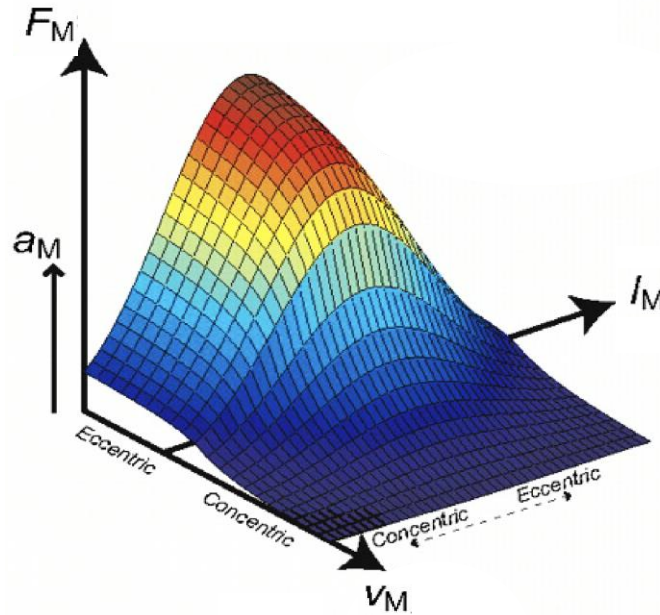


Figure 4: 3D Force-Length-Velocity relationship of muscle. F_M = muscular force; L_M = muscular length; V_M = muscular contraction velocity. Adapted from (Crossley, Dorn et al. 2012)

2.2.4 Assessment of hamstring and quadriceps strength

Currently, there are two parameters that can describe the force production capability of a muscle group like the hamstring and quadriceps muscle during a mono-articular exercise, which were typically classed into maximal voluntary force and explosive force. Typically, the maximal voluntary force corresponded to the peak force or moment produced by the muscle during static or isokinetic testing whereas the explosive force is generally evaluated by the rate of force and torque development at the beginning of a contraction.

2.2.4.1 Maximal voluntary force (MVF)

2.2.4.1.1 Non-angle specific isokinetic torque

The isokinetic testing (i.e., isokinetic dynamometry) is considered as the ‘Gold Standard’ for testing multiple parameters of muscular capacity, including peak torque, angle of peak torque, time to peak torque, etc. (Osternig 1986, Lord, Aitkens et al. 1992, Aagaard, Simonsen et al. 1995). Isokinetic testing is performed on isokinetic dynamometers (Figure 5), which permits to measure the muscle torque (Nm) in different contraction regimens (i.e., concentric contraction, eccentric

contraction) and constant angular velocities through joint range of motion (Edouard and Degache 2016). Isokinetic testing of the knee flexors and extensors has been becoming a preferred method of clinical and research assessment of dynamic muscle function, which plays a critical part in the comprehensive evaluation and rehabilitation of athletes (Sangnier and Tourny-Chollet 2007, Sangnier and Tourny-Chollet 2008). The most frequently measured parameters with an isokinetic apparatus are peak torque (PT) and angle of peak torque at different angular velocities (Baltzopoulos and Brodie 1989). Given the significant correlation between body weight and muscle strength, maximal force is often normalized to body weight in $\text{Nm}\cdot\text{kg}^{-1}$ (Harbo, Brincks et al. 2012).

The standard isokinetic tests for knee extensor (extension) and flexor (flexion) muscles measures at angular velocity from $0^\circ\cdot\text{s}^{-1}$ up to $500^\circ\cdot\text{s}^{-1}$ (Baltzopoulos and Brodie 1989). Traditional angular velocities used for the isokinetic test are classified into lower angular velocity ($30^\circ\cdot\text{s}^{-1}$, $60^\circ\cdot\text{s}^{-1}$), moderate velocity ($90^\circ\cdot\text{s}^{-1}$, $120^\circ\cdot\text{s}^{-1}$, $180^\circ\cdot\text{s}^{-1}$), and rapid angular velocity ($240^\circ\cdot\text{s}^{-1}$, $300^\circ\cdot\text{s}^{-1}$) (Baroni, Ruas et al. 2020). Furthermore, to date, no consensus existed in the ‘optimal’ angular velocity for isokinetic testing. Thus, it is suggested that using the angular velocity with good reproducibility and reliability such as $60 \sim 240^\circ\cdot\text{s}^{-1}$ in concentric, $30 \sim 90^\circ\cdot\text{s}^{-1}$ in eccentric is a good way to perform reliable evaluations. During the isokinetic test, the warm-up phase permits to the subjects to familiarized with the movement and to increase gradually the contraction intensity up to their submaximal and maximum effort at the angular velocities that will be used. The common isokinetic test for each muscle group should incorporate 3 to 10 repetitions at each velocity of contraction (3 for lower angular velocity, 5 for moderate angular velocity, 10 for rapid angular

velocity) (Pinto, Blazeovich et al. 2018) with a rest period time at least 15s and 60s between the contraction sets, respectively (Pincivero, Lephart et al. 1997, Parcell, Sawyer et al. 2002, Celes,



Figure 5: *Contrex isokinetic dynamometer. Con-Trex® (Con-Trex MJ; CMV, Dübendorf, Switzerland) and PC in the right side.*

Brown et al. 2010). Besides, repeated isokinetic endurance tests (e.g., continuous reciprocal knee flexion and extension) are usually used to generate the hamstring and quadriceps fatigue, which was usually consisted within 25 ~ 50 contractions inducing a reduction of force ranging between 10% and 60% (Sangnier and Tourny-Chollet 2007, Sangnier and Tourny-Chollet 2008, Kellis, Zafeiridis et al. 2011, Schwartz, Bottaro et al. 2014, Alhammoud, Morel et al. 2018, Pinto, Blazeovich et al. 2018). This kind of evaluation makes it possible to evaluate the muscle endurance (Sangnier and Tourny-Chollet 2007, Sangnier and Tourny-Chollet 2008), hamstring-to-quadriceps co-activation (Kellis and Baltzopoulos 1996, Kellis 1999, Hassani, Patikas et al. 2006), H/Q ratio modifications associated with a potential increased risk factor of musculoskeletal injury.

2.2.4.1.2 Angle specific isokinetic torque

Basically, the isokinetic testing induces maximum torque production over a large knee joint angle range. As the angle-specific moment curves represent the moment produced throughout the range of motion (ROM), indicating the torque production is distinct according to the contraction manner and also muscular length (Figure 9). Therefore, the torque-angle relationship could better evaluate the muscle function because it provides more information about the muscle properties and the functional performance of the muscle group, in different positions which can correspond to different sport specific tasks. The optimal angle is the joint angle corresponding to the maximum muscle strength. Typically, the torque production increased before reaching the optimum angle (i.e., the joint angle with the peak torque) and decreases when the joint angle is more than the optimum angle (Edouard and Degache 2016).

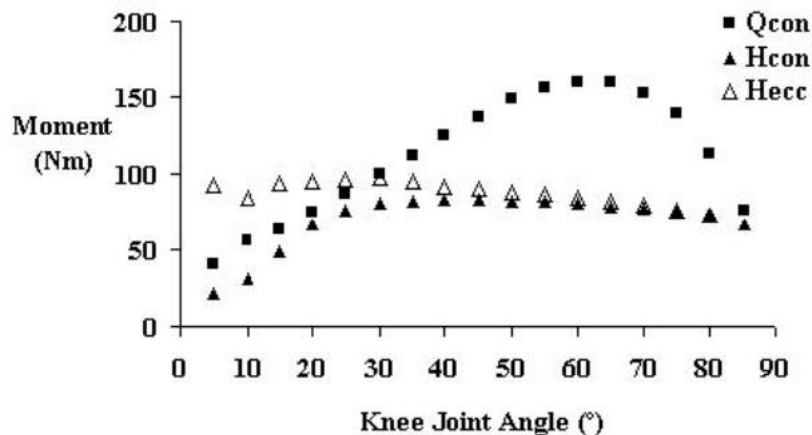


Figure 6: Moment of force of the concentric quadriceps (Q_{con}), eccentric hamstrings (H_{ecc}) and concentric hamstrings (H_{con}) as a function of knee joint angle. Moments are representative of 60o.s^{-1} in a seated position. 0° represents full knee extension. Adapted from (Coombs and Garbutt 2002).

Coombs et Garbutt (2002) presents this manner in the figure 9 which indicated the torque production of quadriceps and hamstring at $60^\circ.\text{s}^{-1}$ throughout a 90° range of motion of knee (Coombs and Garbutt 2002) in agreement with the previous studies (Kannus and Beynnon 1993,

Aagaard, Simonsen et al. 2000). The shift of the torque-angle relationship toward longer muscle length have been related to the muscle strain injury risk due to the fact that the sarcomeres are operating near the plateau of their length-tension curves during a greater part of the joint range of motion; thus it seems possible that shifting the optimum length of the knee extensors or flexors to longer muscle lengths could reduce the future muscle strain occurrence (Brockett, Morgan et al. 2004, Brughelli, Mendiguchia et al. 2010, Wan, Qu et al. 2017, Wan, Li et al. 2021). Whatever, measuring the capacity of the subject to produce joint moment at different angles with and without fatigue seems important to better understand performance and injury risk in soccer players.

2.2.4.1.3 Maximal isometric force test

The isometric maximum voluntary contraction (IMVC) test is a fundamental method with high reliability and is used to evaluate maximal muscle force in several studies. It has been extensively quantified to characterize in vivo skeletal muscle function in a variety of subject populations and conditions in the past 15 years (Meldrum, Cahalane et al. 2007). The widespread use of this variable has resulted from its relatively easy (and valid) evaluation in both laboratory and clinical

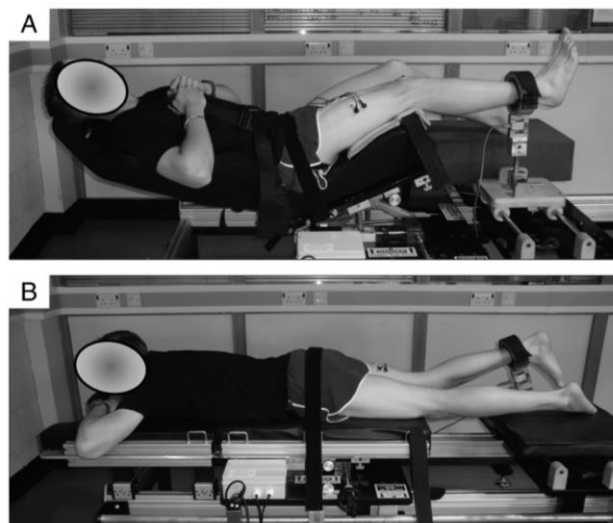


Figure 7: MVIC test of knee extensor (quadriceps) and flexor (hamstring) Load cell. Adapted from (Hannah, Minshull et al. 2014).

settings as well as to its good sensitivity to detect acute and chronic changes in neuromuscular function (Wilson and Murphy 1996, Maffiuletti, Aagaard et al. 2016).

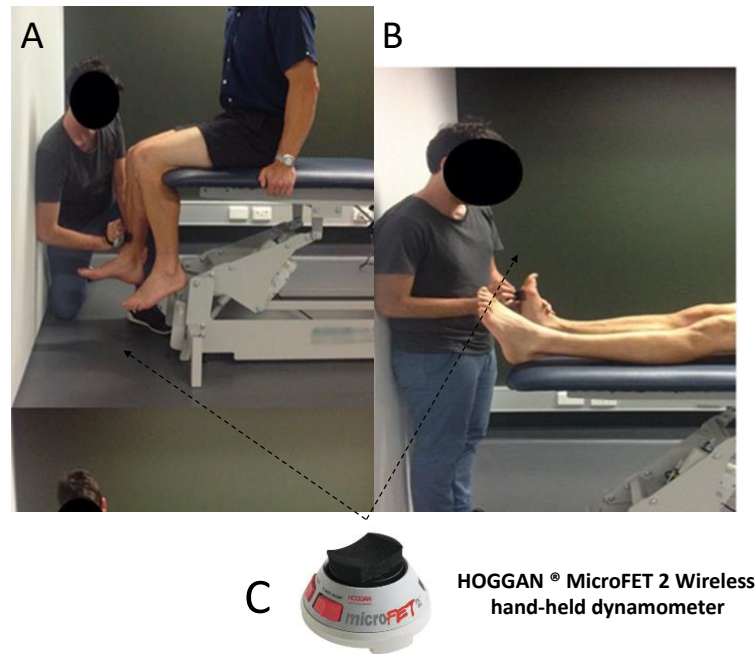


Figure 8: Testing position for knee extensor(quadriceps) and flexor (hamstring) force assessment with hand-held dynamometer. Adapted from (Mentiplay, Perraton et al. 2015).

IMVC testing is assessed at zero angular velocity with the target muscle fixed in a static position (i.e., muscle length is kept constant), which is relatively simple to administer, poses minimal injury risk and presents high reliability. In addition, IMVC test is also influenced by the knee joint angle like the torque-angle relationship of isokinetic test (Alegre, Ferri-Morales et al. 2014). Typically, IMVC testing measured using strain gauge tensiometers (Figure 6), hand-held dynamometry (Figure 7) are the most common measurement methods in the clinic and research setting, which have good reliability and validity for knee muscle force measurement in sitting posture or prone/supine posture (Bohannon 2005, Mentiplay, Perraton et al. 2015, Reurink, Goudswaard et al. 2016, Hirano, Katoh et al. 2020). Besides, IMVC of knee extensor and flexor are generally achieved at 60° and 30° knee flexion angle, respectively (Williams and Stutzman 1959) and the choice of the joint angle is of fundamental importance. IMVC provides interval data, typically in

units of kilogram or Newtons of force which could be also normalized by the body weight or length of the external lever arm (Thorborg, Bandholm et al. 2013).

Moreover, IMVC is a commonly suggested as the standard reference method (peak muscular activation) to normalize surface electromyography (sEMG) signal in the studies analyzing muscular contraction pattern such as muscular activation, muscular coordination, muscular fatigue, etc. (Soderberg 1992, Burden, Trew et al. 2003, Sinclair, Brooks et al. 2012, Sinclair, Taylor et al. 2015). In spite of the limitations, such as the maximal muscular electric activity is not always achieved during the IMVC, it is the most widely employed normalizing method suggested by the SENIAM and kinesiology's guideline (Hermens, Merletti et al. 1996, Hermens, Freriks et al. 2000).

2.2.4.2 Muscular explosive capacity

Meanwhile, an important aspect of explosive muscular function and capacity is the ability to produce muscle force or torque as quickly as possible from a low or resting level, which could be measured as rate of torque development (RTD) (Aagaard, Simonsen et al. 2002, Maffiuletti, Aagaard et al. 2016). Conventional RTD was calculated from linear slope of the force/torque-time curve (i.e., $\Delta\text{force}(\text{torque}) / \Delta\text{time}$) at the different time intervals (i.e., 0-50ms, 0-100ms, 0-200ms) or overlapping (i.e., 50-100ms, 100-150ms, 150-200ms) during IMVC testing after the onset of torque (Maffiuletti, Aagaard et al. 2016) (Figure 4), and divided into the early phase RTD (<100ms) and last phase RTD (> 200ms). Given previous studies have shown that the RTD depends predominantly on the increase of muscle activation at the onset of the contraction; thus, RTD is thought to reflect motor unit firing rate as a motor control summation strategy during the rapid initiation of a IMVC action (Aagaard, Simonsen et al. 2002, Andersen and Aagaard 2006, Maffiuletti, Aagaard et al. 2016). Besides, the RTD is a more critical parameter compared to maximal muscle force in determining the explosive performance due to the fact that many movement (e.g. jumping, sprint running) allow for a short period of less than 200ms to develop force (see section 2.3.3.2) (Ishoi, Aagaard et al. 2019); thus, the assessment of early phase RTD is warranted in athlete. (see paper Greco 2013 pour add more detail). More recently, numerous studies proposed to measure RTD during isokinetic contractions and proposed significant results about fatigue influence or differences between subjects (Alhammoud, Morel et al. 2018) Despite the fact that this method suffers some limitations such as the isokinetic dynamometers are often

more compliant at the beginning of the contraction and noisier than strain gauges which may induce a lower measurement precision for RTD calculation (Maffiuletti, Aagaard et al. 2016), but it is sometimes used because it makes it possible to obtain additional results during standardize isokinetic test.

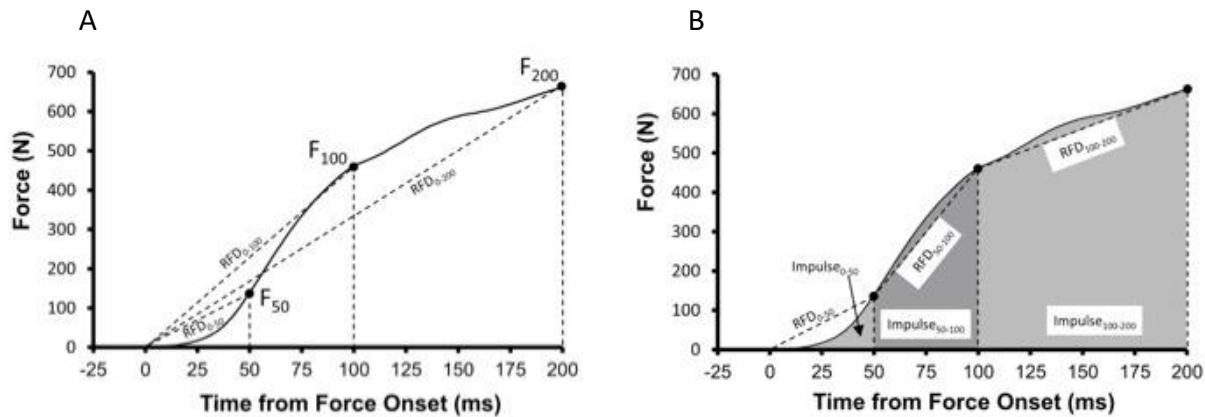


Figure 9: Common measurements of the rising force–time curve. A: Force at specific time points (F_{50} , F_{100} , etc.) and overlapping RFD measurements all starting from force onset (RFD_{0-50} , RFD_{0-100} , etc.). B: An identical force trace showing measurements of sequential. Adapted from (Maffiuletti, Aagaard et al. 2016).

2.2.5 Assessment of hamstring to quadriceps strength imbalance

2.2.5.1 Introduction

According to numerous previous studies, the quadriceps strength is usually stronger than hamstring strength, indicating a strength imbalance between them. This strength imbalance has traditionally been used to describe the potential for knee joint stability during the movement (Aagaard, Simonsen et al. 1997, Aagaard, Simonsen et al. 1998) and it has been widely studied by sport medicine clinicians (Wright, Ball et al. 2009). It has been suggested that the H/Q ratio could provide a valuable predictive parameter for injury prevention (i.e., ACL injury, HSIs) in some of most popular team sport such as soccer, basketball, and volleyball (Sangnier and Tourny-Chollet 2008). This imbalance parameter was typically determined as the hamstring-to-quadriceps torque ratio (H/Q ratio), which is traditionally calculated as knee flexors peak torque divided by knee extensors peak torque during a maximal voluntary contraction (MVC) of either static (isometric) or dynamic character (isokinetic) (Hislop and Perrine 1967, Baltzopoulos and Brodie 1989).

Isokinetic torque ratios of the knee flexor and knee extensor muscles, and their implication in muscle strength imbalance, have been investigated for more than three decades. Assessment of the H/Q ratio via isokinetic testing is the most used method in both laboratory and clinic to identify the muscle balance between knee flexor and extensor.

2.2.5.2 Maximal voluntary hamstring-to-quadriceps Force ratio (MVF H/Q ratio)

In general, three type of MVF H/Q ratios were used including conventional H/Q ratio and functional H/Q ratio, and isometric H/Q ratio. Both modes of H/Q ratio could be considered as a non-angle specific H/Q ratio due to the calculation mode which included the peak torques ignoring the joint angle at which this torque has been measured. More recently angle-specific H/Q ratio have been proposed dividing the peak torque of hamstring by the peak torque of quadriceps for each knee joint angle to take into account the potential influence of the joint angle on the muscle strength balance.

2.2.5.2.1 Non-angle specific H/Q ratio

The isometric and conventional H/Q ratio was the basic variable to determine the strength imbalance between knee flexor and extensor muscles, which was calculated by dividing the concentric peak torque of knee flexor by the concentric peak torque of knee extensor (H_{con}/Q_{con} ratio) in isometric and concentric regimen at the same velocity, respectively (Aagaard, Simonsen et al. 1995). Although these two modes of H/Q ratio could provide a significant value in describing the maximal strength difference between the hamstring and quadriceps, it is argued that this conventional H/Q ratio could not reflect the reciprocal functional activity of antagonistic muscles, where a forceful concentric contraction of the agonist is associated with a forceful eccentric contraction of the antagonist. In fact, it is impossible to produce or observe a human dynamic movement in which the two muscle groups contract simultaneously in a concentric manner; namely, the agonist and antagonist muscles always contract in the opposite manner. For example, the knee extensors contract in a concentric way while the knee flexors contract in an eccentric way during any knee extension movement. If assessing muscle balance is crucially important, the conventional H/Q ratio paid less attention since it is irrespective of the real functional movement and it provides a limited principal amount of parameter. Considering the conventional results,

Bruno et al., (2020) indicated that the conventional H/Q mean scores of professional soccer players were close to 0.6 at low angular velocity (e.g., $30^{\circ} \cdot s^{-1}$, $60^{\circ} \cdot s^{-1}$), and approximate 0.7 ~ 0.8 at fast angular velocity (e.g., $240^{\circ} \cdot s^{-1}$, $300^{\circ} \cdot s^{-1}$) (Baroni, Ruas et al. 2020).

Meanwhile, a functional H/Q ratio was proposed and calculated by dividing the knee flexor's eccentric peak torque to the extensor's concentric peak torque (H_{ecc}/Q_{con}). This ratio was also considered as the 'dynamic control ratio', which is more adapted to reflect the real movement condition (Dvir, Eger et al. 1989) compared to the conventional H/Q ratio. For example, during the fast and forceful knee extension movement such as the swing phase during the high-speed sprinting and kicking, the hamstring and quadriceps muscles do not simultaneously contract in the same manner; namely, the extensors contract concentrically whereas the flexors contract eccentrically to control the tibial movement. Therefore, the functional H/Q ratio is considered to better describe the agonist and antagonist muscle contraction relationship, which could potentially indicate an enhanced capacity of the hamstring muscle to stabilize the knee joint (Aagaard, Simonsen et al. 1997). Moreover, the high-speed sprinting and kicking were considered as the susceptible moment to induce hamstring strain injuries (HSIs), so a higher functional H/Q ratio is often suggested to screen HSIs injury risk (Coombs and Garbutt 2002, Small, McNaughton et al. 2009, Schache, Dorn et al. 2012, Yu, Liu et al. 2017). Baroni et al. (2020) summarized that the H/Q functional ratio mean scores of professional male soccer players were close to 80% at $60^{\circ} \cdot s^{-1}$ ($79 \pm 19\%$), around 100–130% at intermediate to fast angular velocities ($120^{\circ} \cdot s^{-1} = 127 \pm 42\%$; $180^{\circ} \cdot s^{-1} = 96 \pm 19\%$; $240^{\circ} \cdot s^{-1} = 109 \pm 22\%$; $300^{\circ} \cdot s^{-1} = 123 \pm 18\%$), and near or above 130% when angular testing velocities were mixed (eccentric hamstring, concentric quadriceps; $30/240^{\circ} \cdot s^{-1} = 132 \pm 26\%$; $60/180^{\circ} \cdot s^{-1} = 129 \pm 20\%$; $60/240^{\circ} \cdot s^{-1} = 153 \pm 30\%$) (Baroni, Ruas et al. 2020).

2.2.5.2.2 Angle-specific H/Q ratio

As mentioned above, the isometric, conventional, and functional H/Q ratios are calculated with the peak torques, but it is often overlooked that these muscles reach their maximal torque at different joint angles inducing that these ratios ignore the continuous changes in joint angle during movement (Coombs and Garbutt 2002, Eustace, Page et al. 2020). In addition, the hamstring and quadriceps peak torques occurred frequently at different knee joint angles and the H/Q ratio would also change when calculated at different knee joint angles. The angle-specific conventional H/Q

ratio was calculated by dividing hamstring concentric torque by quadriceps concentric torque at the same knee joint angle across the analyzed range of motion (Alhammoud, Morel et al. 2019). Aagaard et al. (1998) studied the conventional H/Q ratio, and examined their relationship to knee joint angle (Aagaard, Simonsen et al. 1998). They found the conventional H/Q ratio increased (0.5, 0.7, 0.8) when the knee flexion angle decreased (50°, 40°, 30°) (0° = full extension). Furthermore, Evangelidis et al. (2015) found the similar results that the conventional H/Q ratio enhances with the knee joint extension position increased from 105° to 165° (180° = full extension) (Evangelidis, Pain et al. 2015) in line with Aagaard et al. (1998). They investigated the angle-specific H/Q ratio in soccer players. More recently, Alhammoud et al., (2018) analyzed the angle-specific H/Q throughout the knee's range of motion using statistical parametric mapping (SPM) analysis in elite alpine skiers. Their results indicated that H_{con}/Q_{con} ratio increased (~0.7 to ~0.9) when the knee joint angle increased from 30° to 90° (Alhammoud, Morel et al. 2019).

Meanwhile, the angle-specific functional H/Q ratio was proposed and calculated by dividing hamstring eccentric torque by quadriceps concentric torque at the same knee joint angle across the analyzed range of motion (Alhammoud, Morel et al. 2019). Aagaard et al. (1998) indicated that the functional H/Q ratio increased (1.0, 1.1, 1.4) with extended knee joint position (50°, 40°, 30°) (0° = full extension), indicating a significant knee joint angle on functional H/Q ratio (Aagaard, Simonsen et al. 1998). Besides, Evangelidis et al. (2015) found that the angle-specific functional H/Q ratio increased when the knee angle increased (~1 to ~2.5) within the knee joint extension position from 105° to 165° (180° = full extension) in soccer players (Evangelidis, Pain et al. 2015). De site Croix et al. (2017) also indicated the angle-specific functional H/Q ratio increased at more extended knee position ranged from ~0.8 to ~1.0 (De Ste Croix, ElNagar et al. 2017). These findings indicated that the angle-specific conventional and functional H/Q ratio increased when the hamstring lengthen (e.g., more extended knee position). More specifically, the angle-specific functional H/Q ratio seems to increase much more than the angle-specific conventional H/Q ratio; thus, this suggested that the hamstring eccentric co-contracting has a dynamic role in maintaining the stability of the knee joint during the forceful knee extension. Despite the fact that some previous studies suggested that the functional H/Q ratio of 1.0 ensures the eccentric hamstring force is capable to fully brake the action of the concentric contraction of the quadriceps during the

knee extension, there is no meaning if the H/Q ratio calculated by the peak torque ignores the impact of the knee joint angle on force production.

2.2.5.3 Explosive hamstring-to-quadriceps force ratio (RTD H/Q ratio)

Although the MVF H/Q ratios were widely studied in recent years, it can't fully describe the knee joint stability capability as mentioned above. Typically, the peak torque is reached in approximately 500-ms from onset of contraction during the MVF test including isokinetic or MVIC test. In contrast, during the explosive movements such as sprinting, hopping, jump landing, and cutting maneuvers, the athlete needs to maintain the knee joint stability at the ground strike phase to reduce the risk of ACL injury. During these particular movements, the athlete needs to rapidly reach a given antagonist vs. agonist joint moment at the ground contact time to stabilize the knee joint (Krosshaug, Nakamae et al. 2007). Furthermore, during the initial ground contact phase, less than 50-ms are often available to stabilize the knee joint, which need the hamstring and quadriceps to co-contract rapidly in this short period; Thus, the peak torque of hamstring and quadriceps could not be reached during this short period. This could explain why the traditional H/Q ratios could not predict the knee joint stability during the explosive movement. It seems that the ability to produce rapidly the force is as important as the peak torque for performance and injury prevention.

As aforementioned, RTD appeared to be a major indicator of the ability to rapidly produce the force, therefore the ratio of RTD between the hamstring and quadriceps (RTD H/Q ratio) was recently proposed by Zebis et al., (2011) to reflect the capacity of rapidly contract the hamstring and/or quadriceps muscles (Zebis, Andersen et al. 2011). This ratio could be better used to estimate the potential for dynamic knee joint stabilization during the rapid ground contact phase (e.g., jump landing, cutting). More specific, it could be speculated that the initial phase (less than 50 milliseconds) of the RFD H/Q time curve may be better used to identify athlete with a potentially higher risk for knee injury which generally occurred at the initial ground strike phase (Olsen, Myklebust et al. 2004, Krosshaug, Nakamae et al. 2007). Furthermore, the RTD H/Q ratio present different value compared to the traditional H/Q ratio. Zebis et al. (2011) found the RTD H/Q ratio reduced during the initial phase of contraction (up to 50-ms from onset) compared to the MVC H/Q ratio. Moreover, Greco et al. (2012) didn't find any significant correlation between the

traditional H/Q ratio and early phase (< 50ms) RTD H/Q ratio, and the RTD H/Q ratio displayed a lower value compared to the traditional H/Q ratio in professional soccer player (Greco, Da Silva et al. 2012). These findings tended to indicate that the early phase RTD H/Q (< 50-ms) might be useful in identifying players at a potentially risk for ACL injury.

2.2.6 Influence of fatigue on hamstring and quadriceps strength and H/Q ratio

Neuromuscular fatigue has been classically defined as an exercise-induced reduction in muscle or muscle group capacity to generate maximal force (Gibson and Edwards 1985, Gandevia 2001). Although a large number of previous studies have been widely investigated the influence of neuromuscular fatigue induced by simulated fatigue protocol and real competitive match on hamstring and quadriceps strength in soccer, a large discrepancy seems to exist regarding the game-induced effect on lower limb strength players (Greig 2008, Small, McNaughton et al. 2009, Thorlund, Aagaard et al. 2009, Rampinini, Bosio et al. 2011, Grazioli, Lopez et al. 2019). For example, Rampinini et al., (2011) indicated that the IMVC of knee extensor (-11%, $p < 0.001$) immediately declined after a 90-min game (Rampinini, Bosio et al. 2011). In line with their findings, Wollin et al., (2017) investigated the effect of competitive football match on IMVC of hamstring in 15 male international young football players, and they revealed that the IMVC of hamstring immediately reduced of 25% after match (2.43 ± 0.32 vs. 2.00 ± 0.39 , $p < 0.01$) (Wollin, Thorborg et al. 2017). Thorlund et al., (2009) also observed a ~11% IMVC decline in knee extensor and a ~7% decline in flexor torque, in elite young soccer players (Thorlund, Aagaard et al. 2009). In contrast, Grazioli et al., (2019) investigated the influence of match-induced fatigue on knee muscle strength, which indicated non-significant changes of IMVC in knee extensor and flexor (Grazioli, Lopez et al. 2019).

Meanwhile, numerous current evidences indicated that both simulated general fatigue and real competitive match significantly decrease isokinetic strength of quadriceps and hamstring (Greig 2008, Small, McNaughton et al. 2009, Small, McNaughton et al. 2010, Matthews, Heron et al. 2017). Greig investigated the influence of 90-min soccer-specific fatigue on isokinetic torque of knee flexors and extensors in male professional soccer players. They found that the concentric knee extensor and flexor peak torque were maintained irrespective of angular velocity throughout the entire protocol. However, the peak eccentric knee flexor torque was significantly reduced

before and after fatigue (167 ± 35 N.m vs. 127 ± 25 N.m) (Greig 2008). In line with Greig, Small et al. (2010) and (Cohen, Zhao et al. 2015) found that the eccentric strength of hamstring decreased significantly after a multidirectional soccer-specific fatigue, whereas no significant changes in concentric hamstring or quadriceps torques were observed (Small, McNaughton et al. 2010, Cohen, Zhao et al. 2015). More recently, Matthews et al., (2017) also found that the eccentric hamstring torque reduced after the 55-min soccer-specific fatiguing exercise in male soccer players (Matthews, Heron et al. 2017). In addition, Sangnier and Tourny-Chollet (2007) assessed the decline in isokinetic peak torque of the knee flexors and extensors after an isokinetic protocol including 50 repeated isokinetic contractions. They found that knee flexors torque reduction was significantly greater than that of the knee extensors after 15 repetitions for the dominant leg and after 40 repetitions for non-dominant leg, respectively (Sangnier and Tourny-Chollet 2007). Thus, the current findings above clearly indicated that the hamstring strength decrement seems to be more pronounced compared to the quadriceps muscle. A major explanation for this might be that the hamstring muscles may contain a higher proportion of type II muscle fibers, characterized by a lower resistance compared to type I muscle fibers that are predominant in the quadriceps (Garrett, Califf et al. 1984).

Taking that the decline of the hamstring strength after fatigue seems to be higher compared to the quadriceps; the H/Q ratio should be reduced after fatigue. Based on the current finds, the functional H/Q ratio reduced approximately between 8% and 15.4% (Small, McNaughton et al. 2010, Delextrat, Baker et al. 2013), while the conventional H/Q ratio reduced approximately between 10% and 27% after fatigue (Rahnama, Reilly et al. 2003, Sangnier and Tourny-Chollet 2007, Delextrat, Gregory et al. 2010). Given the influence of muscle length (i.e., joint angle) on the muscle force output, Cohen et al. (2015) evaluated the effect of simulated soccer fatigue the functional H/Q ratio at specific joint angles in semi-professional soccer players (Cohen, Zhao et al. 2015). Their results reported that the hamstring torque declined at 60° , 50° , and 10° knee joint angles however, there was a significant 21.8% decrease in functional H/Q ratio at 10° of knee flexion, but not at any other angle. Their results are in agreement with those obtained by El-Ashker et al. (2019) who investigated the effect of fatigue exercise on the functional H/Q ratio at several angular velocities and joint angles (El-Ashker, Allardyce et al. 2019). They found that the functional H/Q significantly declined after fatigue irrespective of joint angle and angular velocity,

and the reductions of functional H/Q ratio were most pronounced in more extended knee joint angle (e.g., 15°), thereby, longer hamstring length. Therefore, these findings tended to confirm that the hamstring strength is more affected by fatigue at longer length.

Furthermore, explosive movements are often decisive in the situation leading to scoring in a competitive match; thus, soccer play requires maintaining the ability to generate explosive muscle force all over the match. Previous studies demonstrated that the explosive capacity of hamstring and quadriceps muscles to generate torque as quickly as possible (RTD) were also affected by the fatigue (Thorlund, Aagaard et al. 2009). Thorlund et al. (2009) examined the influence of soccer match fatigue on the rapid force characteristics in young elite soccer players. They found that late RTD (0 ~ 200 ms) decreased ~9% for the knee flexors while there was a tendency towards reduced (7 ~ 8%) RTD for knee extensors between 0 ~ 50ms and 0 ~ 200ms (Thorlund, Aagaard et al. 2009). In line with this study, Torlund, Grazioli et al. (2019) investigated the match-induced fatigue on knee flexors and extensors RTD and IMVC. They found a right shift in the knee flexors torque-time curve with a decrease in RTD_{50ms} (~16%) and RTD_{200ms} (~11%), while the knee extensors RTD didn't like change (Grazioli, Lopez et al. 2019). the explosive capacity was more influenced that peak torques after the competitive match (Grazioli, Lopez et al. 2019). considering that the RTD of hamstring and quadriceps reduced after fatigue, the RTD H/Q can be an indicator of knee joint stability performance but it is not widely documented up to now (Greco, Da Silva et al. 2012, Grazioli, Lopez et al. 2019). Only two studies have attempted to investigate the influence of fatigue on RTD H/Q, but no consistent results occurred. Greco et al. (2013) reported that the RTD H/Q ratio at 0~50ms and 0~100ms didn't change after fatigue induced by an exhaustive soccer-specific exercise (Greco, da Silva et al. 2013). In contrast to Greco et al. (2013), Grazioli et al. (2019) found that the early RTD H/Q at 0~50ms decreased by ~24%, while the late RTD H/Q at 200ms and MVC H/Q remained unchanged (Grazioli, Lopez et al. 2019). The results suggest that the muscular explosive capacity is more sensibility to the fatigue results in altering the rapid H/Q ratio compared to the traditional H/Q.

2.3 Influence of hamstring and quadriceps strength on acceleration and deceleration performance

2.3.1.1 Introduction

Successful sprint performance is achieved through the generation of large torque by muscles crossing the hip, knee and ankle joints (Miyake, Suga et al. 2017). Numerous investigations have explored the multiple kinetic and kinematic variable measured by short sprint performance such as ground contact time, stride frequency, stride length, lower limb stiffness, which could determine sprint running performance; as a matter of fact, most biomechanical parameters are interdependent upon analysis of sprint running performance (Haugen, McGhie et al. 2019). For now, the common consensus is that the ground reaction force (GRF) could strongly account for sprint performance. The GRF has been divided into vertical GRF and horizontal GRF based on the direction of force vector during the sprint running, and both are associated with the sprint performance (Buchheit, Samozino et al. 2014, Morin, Slawinski et al. 2015, Nagahara, Mizutani et al. 2018). Thus, the capacity to rapidly absorb the braking force and produce horizontal force is considered as one of the main determining factor for sprint performance (Hunter, Marshall et al. 2005).

In particular, numerous investigations have clearly shown that the horizontal GRF was the key mechanical feature of short sprint performance (Hunter, Marshall et al. 2005, Morin, Edouard et al. 2011, Morin, Bourdin et al. 2012). The better sprint performance requires to rapidly generate the highest horizontal force to pull the body in the horizontal direction. Although mechanics of sprint running have received considerable attention in the scientific literature over the years, only few studies focused on the deceleration mechanism. When considering deceleration performance, the lower limb strength has been given limited attention.

As aforementioned, the deceleration could be viewed as the negative-acceleration activity which require the athlete to decrease the body's momentum by applying as much braking force over minimal time to allow a complete stop with or without a change in direction (Barth, Freeman et al. 2001, Hewit, Cronin et al. 2011). Comparing to the acceleration, the objective of deceleration is to absorb negative work by lower limb to reduce the velocity. Kovacs et al., (2015) has been suggested that 4 major physical qualities exert a significant influence on deceleration ability,

namely, dynamic balance, eccentric strength, power, and reactive strength (Kovacs, Roetert et al. 2008). That is to see, three components are related to strength performance, which indicating the important role of the lower limb strength for deceleration performance. This section will show the relationships between hamstring, and quadriceps strength and acceleration and deceleration performance.

2.3.2 Influence of hamstring and quadriceps strength on acceleration performance

2.3.2.1 Fundamental of sprinting biomechanics

The sprint running can be considered as a cycle of two phases of movement including the stance and swing phase, which has been measured at approximately 40%, and 60% of gait cycle, respectively (Mero, Komi et al. 1992, Novacheck 1998) (Figure 7). The gait cycle begins when the foot meets the ground and ends when the same foot meets the ground again. The stance phase is marked by the foot's initial contact with the ground (foot strike), mid stance through toe-off and takeoff. The swing phase begins with the float as the toe off, which morphs into the forward swing or swing reversal, and finishes with the landing or absorption (Howard, Conway et al. 2018). From initial-stance to mid-stance phase, the quadriceps contract eccentrically to attenuate the GRF within store elastic energy to be used later for propulsion moment. After that, both hamstring and quadriceps contract in a concentric manner in the terminal stance phase to produce the propulsive force in a close-kinetic chain. From the initial- to mid-swing phase, the quadriceps work in concentric to rapidly swing the leg forwards. In the swing phase, the hamstring become highly active, especially in the terminal phase of knee extension as they work eccentrically, but in an open-kinetic chain fashion to decelerate the forward swinging tibia and fibula and control extension of the knee joint. Thus, hamstring contraction is used to control the rapid knee extension caused by contraction of the relatively stronger quadriceps femoris group. Hamstring contraction increases to finally decelerate the tibia to position the leg for the next stance phase. The main function of the hamstring muscle group during the final swing phase of gait has been described as eccentrically decelerating the lower leg. Muscle contraction during the final swing phase of gait serves to prepare for impact absorption, stiffen joints and decrease joint loading.

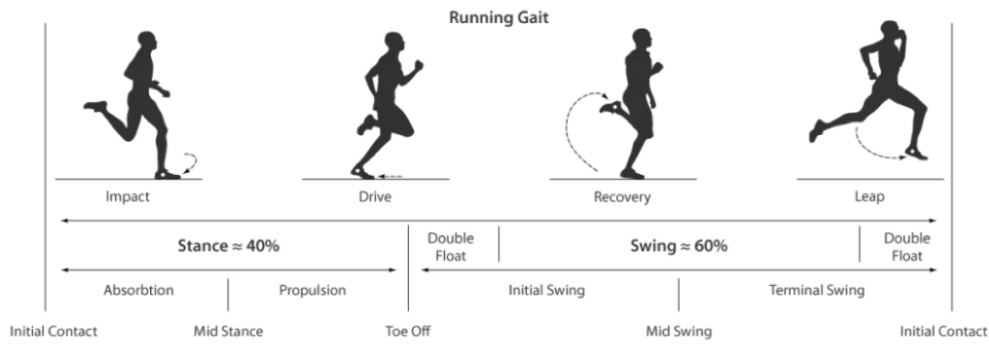


Figure 10: Running gait cycle.

According to the analysis of muscular activity through sEMG during sprint running, the hamstring and quadriceps activities depend on the different phase of gait cycle. The quadriceps is activated in the stance phase and mid-swing phase, whereas the hamstring is active in the stance phase and the terminal swing phase. Besides, the muscular activation increases when the sprint velocity increased. For example, Higashirara et al., (2010) reported that increasing the sprinting velocity from 85% to 95% significantly increased the activation of the hamstring muscles during the last swing phase, while lower extremity kinetics did not change significantly (Higashihara, Ono et al. 2010). Besides, the stance phase is the only ground contact moment that allows the lower limb to produce the propulsive force.

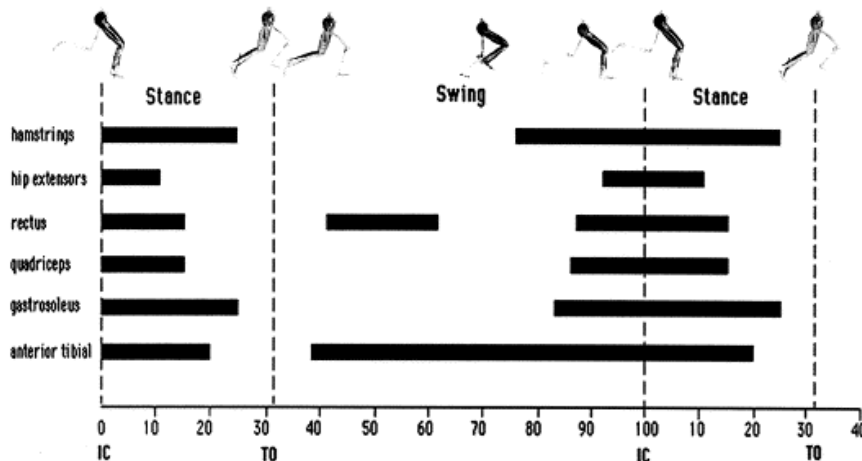


Figure 11: Muscular activation of lower limb muscle during running gait cycle, IC = initial contact. TO = toe off; Adapted from (Novacheck 1998).

As mentioned above, the higher sprinting performance needs the soccer player to rapidly accelerate during the stance phase (propulsive phase) which need high external magnitudes of propulsion. The quadriceps and hamstring muscle groups are the two majors muscle groups during sprint running, which could be investigated by the surface electromyography (sEMG). In 1998, Novachech (1998) reported that the quadriceps and hamstring were activated at a high intensity level across the different phases during the gait cycle (Novacheck 1998). During the early stance phase (braking), the quadriceps work in eccentric to absorb the ground reaction force, whereby the hamstring work in concentric as co-activate to stiffen the knee. And then the hamstring continues acting as the hip extensor in a closed-kinetic chain manner, to produce hip torque to push off the body forward during the propulsive phase (mid to terminal stance phase).

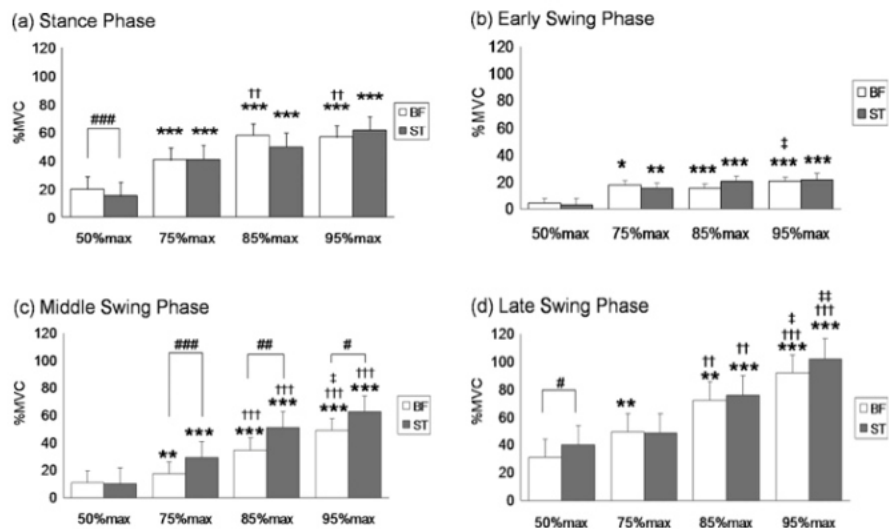


Figure 12: Mean %MVC values for the biceps femoris (BF) and semitendinosus (ST) muscles at each phase during different running speeds. * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$ (vs. 50%max); † $P < 0.05$; †† $P < 0.01$; ††† $P < 0.001$ (vs. 75%max); # $P < 0.05$; ## $P < 0.01$; ### $P < 0.001$ (BF vs. ST). adapted from (Higashihara, Ono et al. 2010).

2.3.2.2 Influence of hamstring and quadriceps strength on acceleration and sprint performance

As mentioned earlier, the sprint performance depends on multiple factors with different movements requiring different combinations of speed and strength muscular contractions. The

lower limb muscles strength as the basic physical capacity play always important role in determining the sprint performance. It should note that the lower limb strength could be expressed in different manner, such as maximal lower limb strength, explosive muscular capacity (RTD) through the different strength assessment (mono- and multi-articular assessment). For now, isokinetic dynamometry has already shown to discriminate between athletes of different performance abilities (Brown 2000). Of course, numerous studies have been attempted to identify the importance of isokinetic strength of knee extensor and flexor muscles on sprint performance. Alexandre (1989) found significant relationships between 100-m sprint performance and peak torque scores (Nm/kg) of fast concentric knee extension (Alexander 1989). Anderson et al. (1991) investigated the relationships among isometric, isotonic, and isokinetic concentric and eccentric quadriceps and hamstring force and 40-yard sprinting performance. They found that the of the peak isokinetic concentric force of hamstring at $60^{\circ}\cdot s^{-1}$ significantly correlated to 40-yard sprint performance ($r = 0.57$, $p < 0.05$) (Anderson, Gieck et al. 1991). In addition, Newman et al., (2004) also revealed that sprint performance correlated with peak extensor and flexor torques at $60^{\circ}\cdot s^{-1}$, $150^{\circ}\cdot s^{-1}$, and $240^{\circ}\cdot s^{-1}$ while the strongest correlation was observed between relative knee extensor torque ($N\cdot m\cdot kg^{-1}$) at $240^{\circ}\cdot s^{-1}$ and the initial short acceleration sprint (10m) performance ($r = 0.714$, $p < 0.01$) (Newman, Tarpinning et al. 2004). Of note is, previous research has produced the conflicting findings. Cronin et Hansen (2005) didn't found any significant relationship between the absolute concentric isokinetic peak torque of hamstring and quadriceps, and sprint times (i.e., split time of 5m, 10m, and 30m) in rugby (Cronin and Hansen 2005). Same for the IMVC testing, Ishøi et al., (2019) didn't found an association between hamstring peak torque and sprint performance in elite youth football players (Ishoi, Aagaard et al. 2019).

It must be noticed that the isokinetic strength assessment presents some limits to identify its partial variance for sprint performance. Actually, the sprint running performance is a multi-joint action that requires substantial and concentrated muscle effort from the ankle, knee, and hip joints, whereas the isokinetic movements are single-joint movements, which could make it difficult to completely explain the sprint performance. In addition, isokinetic strength tests are confined to reproducing isokinetic speeds which cannot account for the varying speeds and accelerations of movement in athletic performance. Constant velocity movements are seldom found in sports, and even the maximal velocities of the isokinetic dynamometer do not reach the velocities often

observed in athletic movements, especially for sprint running within the highest angular velocity exceeding $2000^{\circ} \cdot s^{-1}$. Furthermore, Morin et al., (2015) reported that the eccentric hamstring strength with high muscular activation during swing phase related to the horizontal force production. In a laboratory study, the combination of maximal eccentric hamstring muscle strength and muscle activity of the biceps femoris during the late swing phase showed a strong positive association with the ability to produce horizontal ground reaction force during the sprint acceleration phase (Morin, Gimenez et al. 2015). As a result, a single strength measurement of hamstring and quadriceps muscles through mono-articular exercise may not be the best parameter of explaining the sprint performance.

Thus, the lower limb strength/power can be measured in multiple joint movement such as jumping test, and the results indicated a significant association with sprint performance. Cronin et al., (2005) found that the squat and countermovement jump height as well as squat jump relative power output were significantly greater in the fastest players (Cronin and Hansen 2005). Furthermore, the analyze of sprinting kinematics reported a mean contact time shorter than 200ms, within approximately 120-ms at 70% running speed and 80-ms at full speed (Kuitunen, Komi et al. 2002, Nummela, Hämmäläinen et al. 2007, Morin, Bourdin et al. 2012), indicating that athletes need to rapidly produce the propulsive force within very short duration during the stance phase. Therefore, this suggests that ability to produce muscle force or torque as quickly as possible is at least as important as the maximal torque production capacity for sprint performance. This evidence was demonstrated by numerous previous investigations. Cuhua et al., (2007) found that the athlete that presents superior capability to produce rapid force (RTD) during the leg-press could perform the faster 60m sprint velocity (Cunha, Ribeiro et al. 2007). West et al.,(2011) reported a significant relationship between the absolute early phase (100ms) RTD calculated during a maximal mid-thigh pull and 10-m sprinting time ($r = -0.54$, $p < 0.01$) (West, Owen et al. 2011). Moreover, Wang et al., (2016) find the same results in agreement with West and revealed that the 5m split time was significantly correlated with peak absolute RFD ($r = -0.539$) and early phase RFD 30ms and 50ms calculated during an isometric mid-thigh pull (IMTP) test ($r = -0.570$ and -0.527 , respectively) (Wang, Hoffman et al. 2016). Besides, Tillin et al., (2013) revealed that the sprint performance was related to early phase RTD (≤ 100 ms) normalized to maximal force measured during an isometric explosive squat (5 m, $r = 0.63$, $P < 0.005$; and 20 m, $r = 0.54$, $P < 0.020$) (Tillin, Pain et

al. 2013). Moreover, Chelly et Denis (2001) found the forward leg power on the treadmill ergometer was correlated with the initial sprint acceleration ($r = 0.80$) and the maximal sprint velocity ($r = 0.73$). (Chelly and Denis 2001).

Meanwhile, the hamstring muscle seems very important to generate a large hip extension moment to produce the propulsive force during the stance phase (Morin, Gimenez et al. 2015), and has a crucial role for the production of the horizontal force. Ishøi et al., (2019) investigated the association between hamstring peak torque and RTD with sprint performance in elite youth football players. The linear regression analysis showed a significant positive association between the early phase (0-100ms) RTD and horizontal force ($r^2 = 0.241$, $p = 0.006$), power ($r^2 = 0.227$, $p = 0.008$), and sprint split time (5-m, 15-m, 30-m) (Ishoi, Aagaard et al. 2019). This finding also demonstrated the importance of RTD for sprint performance. Of course, we couldn't ignore the importance of the isokinetic test to evaluate muscle strength. Morin et al., (2015) tested the impact of hamstrings and quadriceps's isokinetic strength on sprint acceleration mechanics. In addition, high eccentric hamstring muscle force production during the transition from eccentric to concentric contraction, just prior to initial stance phase, would be expected to transfer into an enlarged hip extensor moment during the late propulsive stance phase. Although none of the isokinetic strength were significantly correlated to the horizontal force production, multiple linear regression analysis showed a significant relationship ($P = 0.024$) between horizontal force production and the combination of biceps femoris EMG activity during the end of the swing and the knee flexors eccentric peak torque. (Morin, Gimenez et al. 2015). It could be deduced that the high hamstring activation undergo a forceful stretch-shortening cycle (SSC) from the swing phase to the propulsive phase (ground contact) (Thelen, Chumanov et al. 2005, Thelen, Chumanov et al. 2005) which could enhanced SSC-efficiency (Cormie, McGuigan et al. 2010) to potentially enhance the sprint performance (Hennessy and Kilty 2001, Cronin and Hansen 2005).

2.3.3 Influence of hamstring and quadriceps neuromuscular performance on deceleration performance

2.3.3.1 Fundamental of deceleration biomechanics

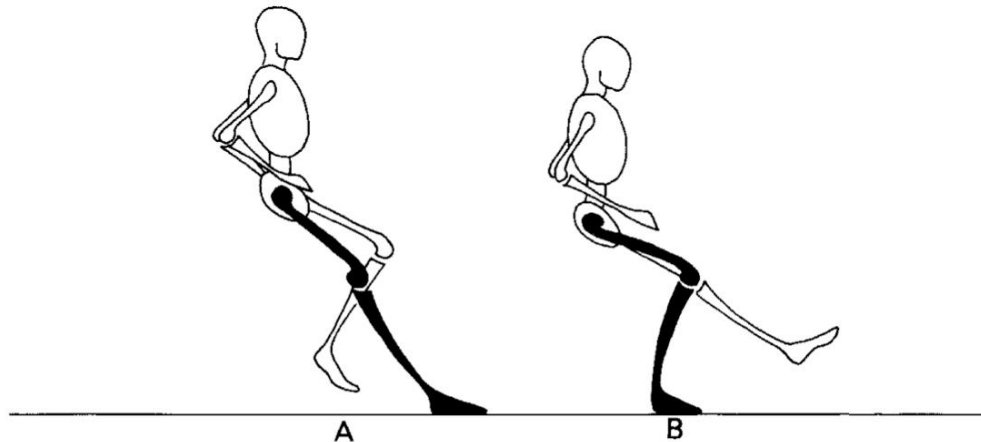


Figure 13: Body position during the support phase during deceleration (Andrews, McLeod et al. 1977).

Comparing to the acceleration, few studies analyzed the biomechanics of deceleration. As mentioned above, the sprint gait cycle consisted of two phases, namely, stance phase and swing phase, which constitutes normal running. In contrast, the deceleration interrupts the orderly progression of the gait cycle of running (Andrews, McLeod et al. 1977). But then, the deceleration could also be divided into two general phases, namely, flight phase and support phase, but without regularity (Hewit, Cronin et al. 2011). (Condello, Kernozek et al. 2016, de Hoyo, Sanudo et al. 2016). During the deceleration, the ground contact occurs ahead of the center of mass with an extended knee and a flexed hip angle, which results in high horizontal braking forces (Hewit, Cronin et al. 2011). As a result, comparing to the acceleration, the average ground contact time is much longer during deceleration phase within approximately 200-230ms, and more than 300ms until 400ms (Graham-Smith and Pearson 2005, Barnes, Schilling et al. 2007). The deceleration task produces larger mechanical loads than a predominantly concentric task (e.g., accelerations) (Hewit, Cronin et al. 2011, Franchi, Reeves et al. 2017, Harper and Kiely 2018, Mateus, Ferrer-Roca et al. 2020).

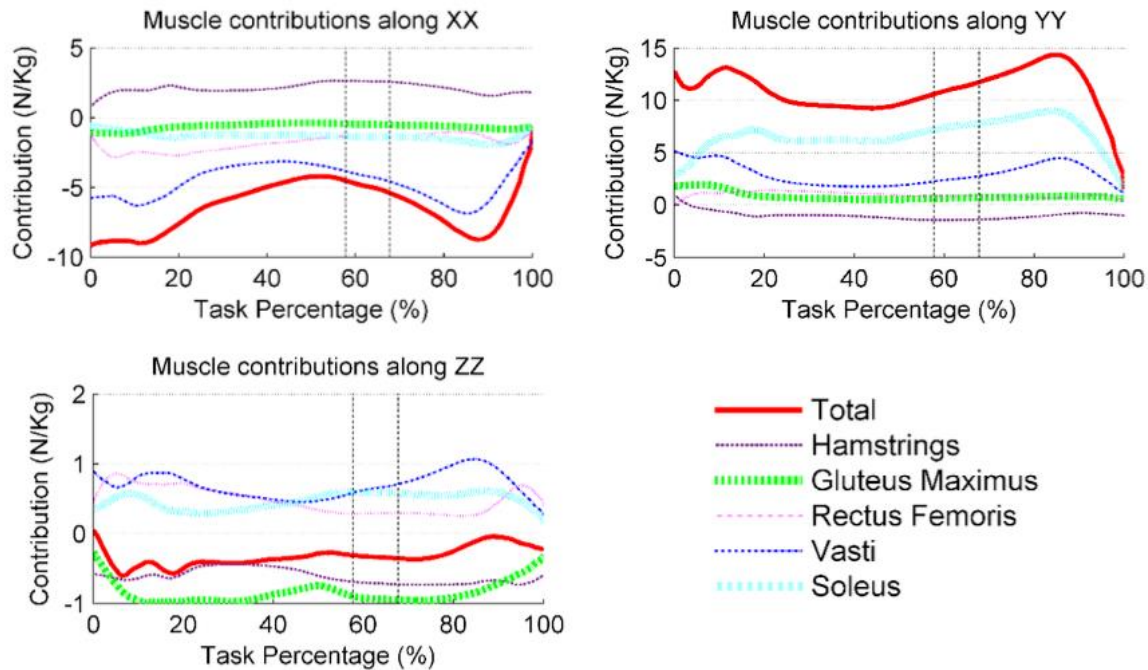


Figure 14: Muscle contributions along all three directions, averaged across fourteen subjects. XX represents the A/P direction, YY vertical direction and ZZ Medio lateral direction. The vertical lines present in each graph correspond the period of direction change during this task. Adapted from (Mateus, Ferrer-Roca et al. 2020).

Williams et al., 2017 measured the sagittal plane mechanical work of lower extremity joints during acceleration, deceleration and steady state running. Their results indicated that the deceleration is dominated by greater contribution of the knee to negative work while acceleration is associated with a greater ankle contribution to positive work (Williams, Cole et al. 2017). Furthermore, Mateus et al., (2020) investigated the muscle coordination and contribution to joint and whole body deceleration profiles during deceleration task (Mateus, Ferrer-Roca et al. 2020). They found that along the anterior-posterior direction (Figure 14), the vasti muscle (~76% of peak braking and ~82% of peak propulsion) are the main contributors to the deceleration of the COM. They are aided by the contribution of the rectus femoris, whose contributions amounted to approximately 33% of the peak accelerations during the braking and backward acceleration phase (Mateus, Ferrer-Roca et al. 2020). In consequence, the higher braking force requires the quadriceps to do greater negative work to absorb the kinetic energy, applying force over a greater eccentric range of motion during the support phase for an efficient deceleration (Hewitt, Cronin et al. 2011).

2.3.3.2 Influence of hamstring and quadriceps strength on deceleration performance

The deceleration task is a predominantly eccentric motion, where quadriceps are subjected to active lengthening in an eccentric manner to absorb the impact and decelerate the COM (LaStayo, Woolf et al. 2003). The eccentric force of quadriceps is correlated with COD deceleration and braking force output (Graham-Smith and Pearson 2005, Jones, Bampouras et al. 2009, Nimphius, McGuigan et al. 2010, Jones, Thomas et al. 2017, Northeast, Russell et al. 2019). During the maximal deceleration task, the high knee extensor eccentric strength could better tolerate the greater ground reaction force (GRF) associated with a high intensity sprint running before deceleration (i.e., more than $7\text{m}\cdot\text{s}^{-1}$) (Graham-Smith, Atkinson et al. 2009). This is supported by previous research that has shown an association between penultimate contact braking forces and COD performance (Graham-Smith, Atkinson et al. 2009, Dos'Santos, Thomas et al. 2017). Graham-Smith et al. (2009) found a significant association between peak horizontal braking forces during penultimate contact and COD performance ($r = -0.674$) (Graham-Smith, Atkinson et al. 2009); whilst Dos'Santos et al., (2017) found an association between greater horizontal braking forces during penultimate contact ($r = -0.337$) and horizontal braking force ratio (i.e., peak horizontal braking force final/peak horizontal braking force penultimate) ($r = -0.429$) with COD performance, and that faster athletes were significantly lower with regard to the latter (i.e., produce greater force in penultimate relative to final contact) in similar 180° COD tasks (Dos'Santos, Thomas et al. 2017). Moreover, Jones et al., (2017) have reported that the relative eccentric knee extensor peak torque at $60^\circ\cdot\text{s}^{-1}$ largely correlated to 180° COD task ($r = -0.63$) and change of velocity from start of penultimate contact to final contact ($r = -0.562$) in female soccer players (Jones, Thomas et al. 2017). Furthermore, the higher eccentric force could contribute to the application of greater braking force and impulse during the deceleration phase resulting in an increased storage and utilization of elastic energy. Subsequently, allowing greater propulsive force and impulse from transition into propulsive phase, results in shorter ground contact times, and greater exit velocities (Dos'Santos, Thomas et al. 2017). This could be supported by Hoyo et al., (2016) who investigated the effects of 10-week eccentric overload on kinetic parameters during change of direction task in football player (de Hoyo, Sanudo et al. 2016). The contact time during the COD at 2.5m after 20m acceleration was 140ms and 130ms before and after eccentric overload training, respectively, thereby indicating the eccentric training could improve the efficiency of

absorption of the braking force. As consequence, the improvement in force absorption capabilities and joint stabilization may also enable athletes to adopt a better body position during COD movements (Myer, Ford et al. 2005).

Although, most studies investigate the relationships between the lower limb strength and the COD performance, only one study have directly investigated the association between the lower limb strength and the linear deceleration performance. Harper et al. (2018) found that the eccentric force of quadriceps at low angular velocity ($60^{\circ} \cdot s^{-1}$) in both dominant and non-dominant leg was related to the linear deceleration performance (time to stop and distance to stop) after 20m sprint running in soccer players (Harper, Jordan et al. 2021). Also, concentric torque of hamstring strength in the non-dominant leg, at higher angular velocities, demonstrated an influence on deceleration ability ($r = -0.61$). It's no surprise for this finding due to the importance of hamstring in determining body stability, which could assist the success of the deceleration task. This finding was in agreement with Naylor et Greig (2015) who reported that the eccentric hamstring strength accounted for 62% of the variance in COD performance (Naylor and Greig 2015). Indeed, the magnitude of the braking force during the deceleration task need the higher ability to maintain trunk position and assist knee dynamic stability in the stance phase of deceleration.

The bi-articular hamstring muscle group has been described as a dynamic stabilizer both for hip and knee joint, considering as contributing towards the maintenance of equilibrium and stability of whole-body, in particular concerning the anterior shear of the tibia during the deceleration task and supporting the role of the anterior cruciate ligament (Sole, Milosavljevic et al. 2008). During the deceleration task, the hamstring muscles group work as the hip extensor which could assist to maintain the hip joint stability to control trunk position, while the hamstring co-activates with the quadriceps to provide rotational forces on the knee joint, thus maintaining the knee joint stability to protect the knee joint structures. As a result, the better dynamic balance ability allows the athlete to maintain an optimal body position, improving the GRF absorption to deceleration (Myer, Ford et al. 2005, Spiteri, Cochrane et al. 2013). For example, Spiteri et al., (2013) have reported that individuals with greater relative lower body strength produced higher magnitude plant foot kinetics and modified lower body positioning while producing faster COD performances with greater braking force production (Spiteri, Cochrane et al. 2013).

2.3.4 Conclusion

Taken together, the discussion above highlights the importance of hamstring and quadriceps strength in determining both sprint performance and deceleration performance. This suggests the lower limb strength training appear to be consistently beneficial in acceleration and deceleration performance. It would also appear that the strength assessment of quadriceps and hamstring muscles is determinant to understand sprinting performance and prevent injury risks. Future research should examine the association between linear deceleration performance and knee joint muscles strength in male and female soccer players.

2.4 Influence of hamstring and quadriceps strength on Hamstring Strain Injury and Anterior Cruciate Ligament injury

2.4.1 Introduction

Previous prospective epidemiological studies reported that the incidence of injury was approximately 0.6 to 20.3 injuries per 1000h of exposure in soccer players (Klein, Henke et al. 2018). The most injuries were the non-contact muscle injuries, and thigh was the most common site of injury while the muscle strains accounted for 41.2% of all injuries (Ekstrand, Häggglund et al. 2011, Jones, Jones et al. 2019). Besides, a higher incidence of muscle injury occurred during the competitive matches, accounting 6 ~ 9 times higher than training (Hawkins and Fuller 1999, Rahnama, Reilly et al. 2003, Petersen, Thorborg et al. 2010, Ekstrand, Häggglund et al. 2011, Ekstrand, Waldén et al. 2016, Jones, Jones et al. 2019).

2.4.2 General epidemiology of HSIs and ACL injury in soccer

Hamstring strain injuries (HSIs) and anterior cruciate ligament (ACL) rupture are, respectively, the most prevalent non-contact injuries (Ekstrand, Häggglund et al. 2011) and the most serious injuries considering time to return to play in professional soccer players (Brooks, Fuller et al. 2006, Ekstrand, Häggglund et al. 2011, Elliott, Zarins et al. 2011, Waldén, Häggglund et al. 2016). Both account for a significant amount of lost time in a range of soccer and associated with high recurrence rates, since a history of each injury is a very strong predictor of the same injury in the future (Alentorn-Geli, Myer et al. 2009, Opar and Serpell 2014, Green, Bourne et al. 2020). Within

football, particularly, hamstring strain injuries (HSIs) (Woods, Hawkins et al. 2004, Hägglund, Waldén et al. 2005, Ekstrand, Hagglund et al. 2011) and anterior cruciate ligament (ACL) injuries (De Ste Croix, Priestley et al. 2015, Walden, Hagglund et al. 2016) represent a significant proportion of recorded injuries and require further investigation to aid in improved prevention strategies.

HSIs were the most frequently strained muscle group, accounting for 37% to 39.5% of all muscle strains and from 16.3% to 31% of all injuries (Ekstrand, Hagglund et al. 2011, Jones, Jones et al. 2019) with higher re-injury recurrence ratio ranging from 12% to 63% (Orchard 2001, Hagglund, Walden et al. 2006, Malliaropoulos, Isinkaye et al. 2011, Malliaropoulos, Isinkaye et al. 2011, Brukner, Nealon et al. 2014). A 13-years longitudinal analysis of UEFA elite injury study reported that the hamstring injuries have increased by 4% annually in male professional soccer players (Ekstrand, Waldén et al. 2016). In parallel with HSIs, the ACL injury was the other high incidence non-contact injury with an incidence of between 0.04 to 1.08 per 1000h exposure (Schiffner, Latz et al. 2018), which represented the rate from 70 to 84 % of all ACL tears in soccer players (Gianotti, Marshall et al. 2009, Moses, Orchard et al. 2012, Della Villa, Buckthorpe et al. 2020). ACL injury has significant impact on playing time during a sporting career and can have a devastating effect on long term quality of life. Majority research and clinical efforts have been made to prevent ACL injuries; however, ACL injury rates have increased by 20 ~ 50% over the last 2 decades (Agel, Arendt et al. 2005, Hootman, Dick et al. 2007, Øiestad, Engebretsen et al. 2009, Gans, Retzky et al. 2018, Howard, Solaru et al. 2020). Therefore, understanding the risk factor of HSIs and ACL injuries should be investigated further by to reduce the injury incidence.

2.4.3 HSIs Mechanism

A muscle strain injury is characterized by a disruption of the muscle-tendon unit (Garrett 1990). In the basic of biomechanics of muscle strain injuries, the muscle strain occurs when the muscle is either stretched passively or activated during stretch (Garrett 1996). Animal models have been conducted to determine the general mechanisms of muscle strain injury, suggesting that excessive muscle strain in eccentric contractions or stretching is the main mechanism of muscle strain injury (Garrett 1996). Since eccentric modality provides a strong mechanical stress with low muscular stimulation comparing to concentric contraction, this induced a high risk of muscle strain injuries

(Feher 2017). The sprint running is the activity that is commonly associated with HSIs due to the presence of a high force eccentric contraction during the early stance (Yu, Queen et al. 2008, Orchard 2012, Ono, Higashihara et al. 2015, Sun, Wei et al. 2015, Liu, Sun et al. 2017), and terminal swing phases (Verrall, Slavotinek et al. 2003, Connell, Schneider-Kolsky et al. 2004, Thelen, Chumanov et al. 2005, Chumanov, Heiderscheit et al. 2011, Schache, Dorn et al. 2012, Askling, Koulouris et al. 2013, Schache, Dorn et al. 2013, Askling, Tengvar et al. 2014)., especially the latter usually proposed as the most dangerous one considering the high occurrence of HSIs.

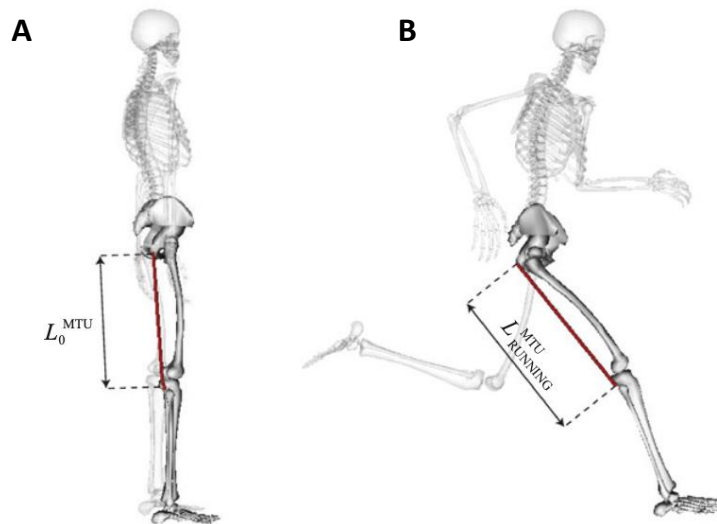


Figure 15: Right hamstring muscle MTU during static standing position (L_0^{MTU}) (A), and MTU during sprint running ($L_{RUNNING}^{MTU}$) (B). Adapted from (Schache, Dorn et al. 2013).

According to the kinetic and kinematic of sprint running, the hamstrings become highly activated and stretched, especially in the terminal phase of knee extension as they work eccentrically during the swing phase (Thelen, Chumanov et al. 2005), in an open-kinetic chain fashion to decelerate the forward swinging tibia and fibula and control extension of the knee joint. As mentioned earlier, hamstring eccentric contraction is used to control the rapid knee extension to finally decelerate the tibia in order to position the leg for the next stance phase, which serves to effectively stores elastic energy, and prepare for impact absorption, stiffen joints and decrease joint loading. Evidence is available indicating that the musculo-tendon unit (MTU) stretch (i.e., maximum change in MTU

length relative to that assumed in an upright stance posture) (Figure 15) and velocity during the terminal swing phase increase as sprinting velocity progress (Table 2) (Chumanov, Heiderscheit et al. 2011, Schache, Dorn et al. 2013).

Moreover, comparing the hamstrings, maximum MTU between muscles, it has been demonstrated that the stretch was largest for biceps femoris long head (BF^{LH}) (almost 110%) compared to semitendinosus (ST) and semimembranosus (SM) irrespective of running speed which could partly explain why the BF_{LH} was more often injured (De Smet and Best 2000, Askling, Koulouris et al. 2013, Crema, Guermazi et al. 2016), accounting 53 %, 16%, 13% for BF, ST, and SM, respectively (Woods, Hawkins et al. 2004).

Consequently, the current evidence base suggested that the terminal swing phase has been identified as the most likely period of HSIs, as the hamstring undergo active lengthening and experience peak lengths with high forces.

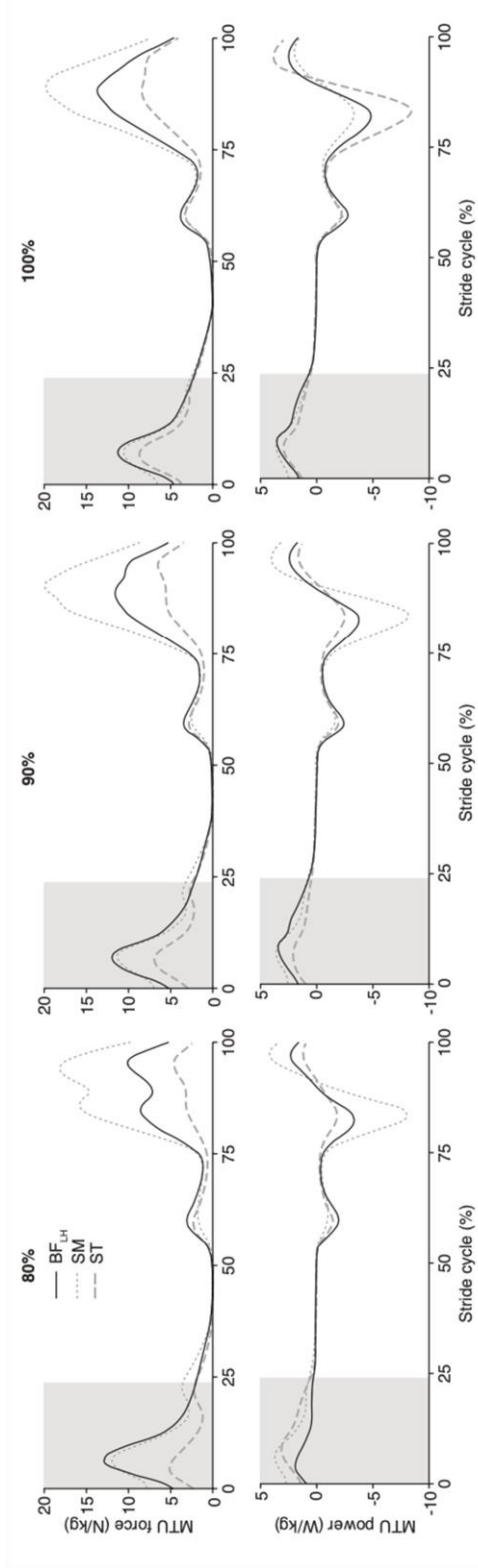


Figure 16: Hamstring musculotendon force and power at various sprint running velocity (expressed as % maximum sprint velocity). Shade region represents the stance phase; BFLH = biceps femoris long head, SM = semimembranosus, ST = semitendinosus. Adapted from (Chumanov, Heiderscheit et al. 2011).

Parameter	Muscle	Running speed			
		(1) 3.4 ± 0.1 m/s	(2) 5.0 ± 0.1 m/s	(3) 6.9 ± 0.1 m/s	(4) 9.0 ± 0.7 m/s
Maximum stretch*	(a) SM	7.8 ± 1.2 ^{2,3,4}	9.3 ± 1.3 ¹	10.3 ± 1.3 ^{1,b}	9.4 ± 1.4 ^{1,b}
	(b) ST	6.3 ± 1.3 ^{2,3,4}	7.9 ± 1.5 ¹	9.2 ± 1.4 ^{1,a,c}	8.3 ± 1.5 ^{1,a,c}
	(c) BF ^{LH}	8.4 ± 2.5 ^{2,3,4}	10.4 ± 2.9 ^{1,3}	12.1 ± 2.5 ^{1,2,b}	11.5 ± 2.5 ^{1,b}
Peak-to-peak stretch [#]	(a) SM	19.2 ± 1.1 ^{2,3,4,b,c}	23.3 ± 1.5 ^{1,3,b,c}	25.4 ± 1.5 ^{1,2,b,c}	25.0 ± 1.1 ^{1,b,c}
	(b) ST	19.6 ± 1.2 ^{2,3,4,a,c}	23.9 ± 1.7 ^{1,3,a,c}	26.3 ± 1.6 ^{1,2,a,c}	25.7 ± 1.3 ^{1,a,c}
	(c) BF ^{LH}	16.9 ± 1.5 ^{2,3,4,a,b}	21.3 ± 2.1 ^{1,3,4,a,b}	23.8 ± 1.7 ^{1,2,a,b}	23.5 ± 1.4 ^{1,2,a,b}
Peak stance shortening velocity [#]	(a) SM	-0.8 ± 0.1 ^{2,3,4,b,c}	-1.0 ± 0.1 ^{1,3,4,b,c}	-1.2 ± 0.1 ^{1,2,b}	-1.3 ± 0.1 ^{1,2}
	(b) ST	-0.9 ± 0.1 ^{2,3,4,a,c}	-1.1 ± 0.1 ^{1,3,4,a,c}	-1.3 ± 0.1 ^{1,2,a}	-1.4 ± 0.2 ^{1,2}
	(c) BF ^{LH}	-0.8 ± 0.1 ^{2,3,4,a,b}	-1.0 ± 0.1 ^{1,3,4,a,b}	-1.2 ± 0.1 ^{1,2,4}	-1.4 ± 0.1 ^{1,2,3}
Peak swing shortening velocity [#]	(a) SM	-0.9 ± 0.1 ^{2,3,4,b,c}	-1.2 ± 0.2 ^{1,3,4,b,c}	-1.6 ± 0.2 ^{1,2,4,b,c}	-2.0 ± 0.2 ^{1,2,3,b,c}
	(b) ST	-0.9 ± 0.1 ^{2,3,4,a,c}	-1.3 ± 0.2 ^{1,3,4,a,c}	-1.8 ± 0.2 ^{1,2,4,a,c}	-2.2 ± 0.2 ^{1,2,3,a,c}
	(c) BF ^{LH}	-0.7 ± 0.1 ^{2,3,4,a,b}	-1.0 ± 0.1 ^{1,3,4,a,b}	-1.3 ± 0.2 ^{1,2,4,a,b}	-1.6 ± 0.2 ^{1,2,3,a,b}
Peak swing lengthening velocity*	(a) SM	1.0 ± 0.2 ^{3,4}	1.4 ± 0.2 ^{3,4}	1.7 ± 0.2 ^{1,2,4,b,c}	2.0 ± 0.2 ^{1,2,3}
	(b) ST	1.1 ± 0.2 ^{3,4}	1.4 ± 0.3 ^{3,4}	1.9 ± 0.3 ^{1,2,4,a,c}	2.2 ± 0.3 ^{1,2,3}
	(c) BF ^{LH}	0.9 ± 0.1 ^{2,3,4}	1.5 ± 0.4 ^{1,3,4}	2.0 ± 0.3 ^{1,2,4,a,b}	2.2 ± 0.3 ^{1,2,3}

Table 2: Data for MTU stretch are expressed as a percentage of the anatomical reference MTU length (L_0^{MTU}), which was defined as the L^{MTU} during the static standing calibration trial. Data for MTU shortening and lengthening velocity are expressed in anatomical reference MTU lengths per second, or L_0^{MTU}/s ; SM = semimembranosus, ST = semitendinosus, BF^{LH} = biceps femoris long head; * Significant ($p < 0.01$) main effects found for (i) running speed, and (ii) running speed * hamstring muscle interaction; # Significant ($p < 0.01$) main effects found for (i) running speed, (ii) hamstring muscle, and (iii) running speed 9 hamstring muscle interaction; ^{1,2,3,4} Significantly different ($p < 0.01$) from running speeds (1) i.e. 3.4 ± 0.1 m/s, (2) i.e. 5.0 ± 0.1 m/s, (3) i.e. 6.9 ± 0.1 m/s, and (4) i.e. 9.0 ± 0.7 m/s; ^{a,b,c} Significantly different ($p < 0.01$) from hamstring muscle (a) i.e. semimembranosus (SM), (b) i.e. semitendinosus (ST), and (c) i.e. biceps femoris long head (BF^{LH}). Adapted from (Woods, Hawkins et al. 2004).

Meanwhile, Chumanov et al., (2011) studied the hamstring musculotendon dynamic using the forward dynamic simulation which aimed to compare hamstring musculotendon stretch, loading and work done during stance and swing phases of high speed running gait cycles (Chumanov, Heiderscheit et al. 2011). They found there was two distinct loading peaks which were present for the hamstrings (Figure 16); one during late swing (between 85 and 95% of the gait cycle) and the second during early stance phase (between 0 and 15% of the gait cycle). Also, the maximum hamstring musculotendon force during swing increased significantly ($p < 0.001$) with sprint running velocity whereas peak force during stance was independent of speed (Table 2).

2.4.4 ACL Injury Mechanism

The anterior cruciate ligament (ACL) is a band of dense connective tissue which courses from the femur to the tibia (Figure 17). The ACL is a key structure in the knee joint, as it resists anterior tibial translation and rotational loads (Duthon, Barea et al. 2006). In the basic of biomechanical analysis, the common mechanism of non-contact ACL injuries occurs in a dynamic movement, when the athletes land in a knock-knee position, such as dropping, cutting, and change of direction maneuvers (Zebis, Andersen et al. 2009, Havens and Sigward 2015, Fox 2018). The lower-limb kinetics and kinematics during these susceptible tasks, include the dynamic knee valgus motion, associated with either tibial internal or external rotation, hip adduction, maximum knee flexion, and peak ground reaction force that could induce the excessive anterior shear forces, resulting in the ACL injury (Yu and Garrett 2007). The observational studies of ACL injury provide two predominant movement patterns resulting in ACL injury due to an excessive strain: sagittal plane injury mechanism (i.e., anterior tibial shear), and dynamic knee valgus injury mechanism (i.e., pure frontal in valgus-varus, transverse in internal-external) (Table 3) (Quatman and Hewett 2009).

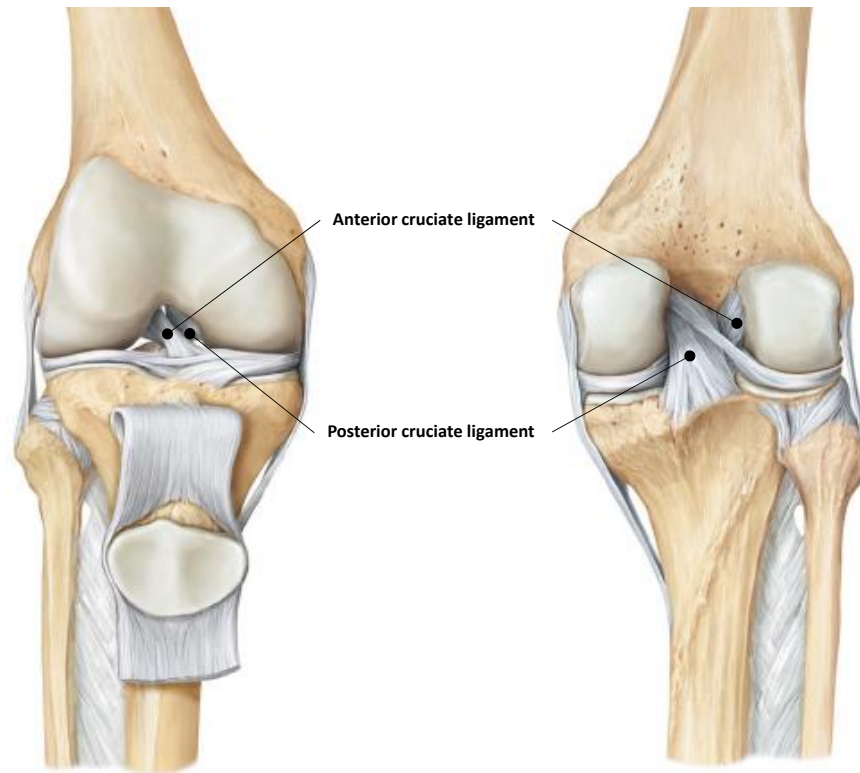


Figure 17: *The cruciate ligament of right knee joint. Adapted from (Schünke, Ross et al. 2006).*

The sagittal plane loading occurs during the movement as the acceleration-deceleration pattern. The ACL is loaded while an anterior force is directly applied to the tibia (Schilaty, Bates et al. 2019), namely, the anterior tibial shear force (ATSF). The primary role of the ACL here is to restraint anterior tibial displacement. The magnitude of ATSF could firmly push the tibia anteriorly to the femur, which could induce an excessive strain on the ACL and tear the ACL. During the movement, the posterior GRF was considered the primary part to generate the higher ATFS, which creates a knee flexion moment. In this case, the knee extension moment should be applied by the quadriceps in order to balance the knee flexion moment inducing the ATFS. While generating knee extension moment, the quadriceps muscle works to extend the knee and pull the tibia forwards based on the large moment arm at which the patellar tendon acts on the tibia. A high quadriceps contraction moment near full knee extension (i.e., low knee flexion angle), could increase significantly anterior translation of the tibia and induce a high magnitude of ATSF that tears ACL (Markolf, Burchfield et al. 1995, Li, Gil et al. 1999, DeMorat, Weinhold et al. 2004, Sell, Ferris et

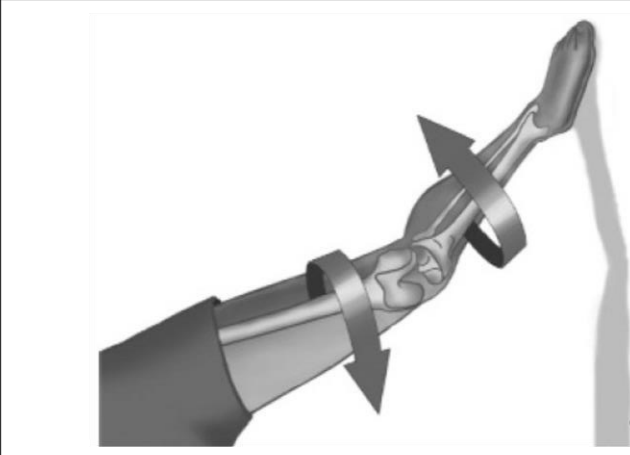
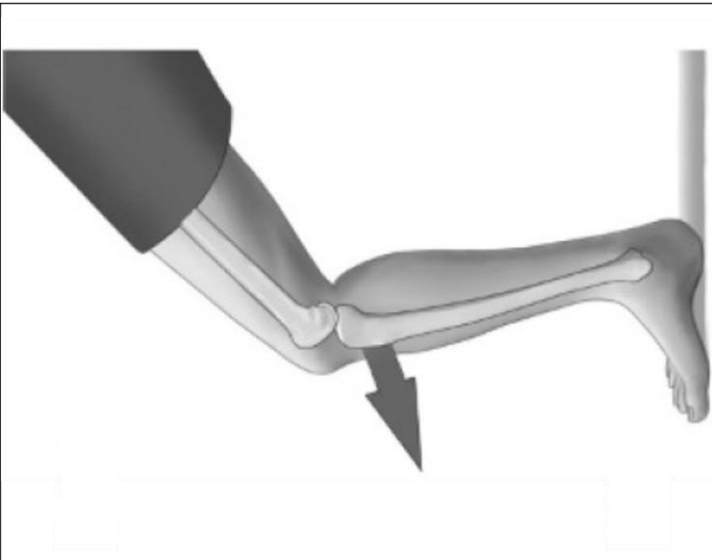
Dynamic knee valgus injury mechanism		Sagittal plane sagittal plane injury mechanism	
Back	Forward flexed Rotated opposite side	Back	Upright not rotated
Hips	Adduction internal rotation	Hips	Neural little adduction
Knee	Less flexed, valgus	Knee	More flexed less valgus
Tibial rotation	Internal or external	Tibial rotation	Minimal
Landing pattern	One foot out of control unbalanced	Landing pattern	Both feet in control balanced
			

Table 3: Multiplanar and sagittal plane loading. Adapted from (Quatman and Hewett 2009).

al. 2007). To reduce the tibia's anterior translation, the hamstring flexion moment is assumed to

produce posterior tibial shear forces (PTSF). Thus, the hamstring co-activation relative to quadriceps activation is required to counteract the ATSF, contributing to the reduction of ACL loading.

Furthermore, a deceleration combined with a COD or cutting maneuver has been identified as the movement that can induce ACL injury during the knee dynamic valgus collapse by multi-planar loading pattern (McLean, Lipfert et al. 2004, Hewett, Myer et al. 2005, Alentorn-Geli, Myer et al. 2009, Quatman and Hewett 2009) (Table 3). Dynamic knee valgus is a movement pattern that combines adduction and internal rotation of the hip, abduction of the knee, anterior tibial translation, external tibial rotation and ankle eversion (Hewett, Myer et al. 2005, Krosshaug, Nakamae et al. 2007, Quatman and Hewett 2009, Fox, Bonacci et al. 2014, Koga, Nakamae et al. 2018). Previous studies have been reported that ACL provides approximately 85% of the knee joint's total restraint to anterior tibial translation at 20~30° of knee flexion (Markolf, Mensch et al. 1976, Grood, Noyes et al. 1981). Based on the ACL injury mechanism's video analysis, the ACL frequently occurs at the initial ground contact moment between 17ms and 50ms and involves a dynamic knee valgus, with the low knee flexion between 0° to 30° during cutting, or change of direction maneuvers (Hollis, Takai et al. 1991, Markolf, Burchfield et al. 1995, DeMorat, Weinhold et al. 2004, Olsen, Myklebust et al. 2004, Krosshaug, Nakamae et al. 2007). The effectiveness of hamstring co-contractions permits to prevent ATSF, and also to reduce the knee valgus and improve the knee joint stability (More, Karras et al. 1993, Li, Rudy et al. 1999, Withrow, Huston et al. 2006).

In summary, the injury mechanism for ACL appeared to be a forceful dynamic knee valgus associated with low knee flexion angle combined with external or internal rotation of the tibia. Also, the hamstring muscle plays an essential role in reducing the ACL strain due to the PTSF production and knee stability contribution. Thus, examining hamstring function seems to be pertinent during the susceptible movement of ACL injury (i.e., deceleration, cutting).

2.4.5 Major risk factor of HSIs and ACL injury

Scientific evidence exists that the multiple risk factors of HSIs and ACL injury can be divided into non-modifiable risk factors and modifiable risk factors. For HSIs, the major non-modifiable risk

factors include previous HSIs injury (Orchard, Marsden et al. 1997, Arnason, Sigurdsson et al. 2004, Gabbe, Bennell et al. 2006, Engebretsen, Myklebust et al. 2010), age (Orchard 2001, Gabbe, Bennell et al. 2006), and the modifiable risk factors include poor hamstring flexibility (Witvrouw, Danneels et al. 2003, Bradley and Portas 2007, Henderson, Barnes et al. 2010), hamstring muscle weakness (Croisier 2004, Croisier, Ganteaume et al. 2008, Yeung, Suen et al. 2009), H/Q ratio, neuromuscular fatigue (Pinniger, Steele et al. 2000, Woods, Hawkins et al. 2004, Small, McNaughton et al. 2009, Ekstrand, Hägglund et al. 2011), short BF_{LH} fascicles (Askling, Tengvar et al. 2008, Timmins, Bourne et al. 2016). For ACL injury, the major non-modifiable risk factors include previous ACL injuries (Messina, Farney et al. 1999, Gianotti, Marshall et al. 2009), sex (Hewett, Myer et al. 2005, Hewett, Zazulak et al. 2007), and anatomy differences (Griffin, Agel et al. 2000, Myer, Ford et al. 2005, Gaillard, Magnussen et al. 2019), and the modifiable risk factors include hamstring muscle neuromuscular performance (Tsepis, Vagenas et al. 2004), co-activation between hamstring and quadriceps (Zebis, Andersen et al. 2009), H/Q ratio (Grygorowicz, Michalowska et al. 2017), neuromuscular fatigue (Alentorn-Geli, Myer et al. 2009, Waldén, Krosshaug et al. 2015). Obviously, the common risk factor for both HSIs and ACL injury are hamstring muscle neuromuscular performance (i.e., hamstring muscle strength and activation pattern, H/Q ratio and co-activation between hamstring to quadriceps) and neuromuscular fatigue, which have received growing interest over the recent years. This section focuses on these parameters related to the neuromuscular performance, impacting the HSIs and ACL strain during the susceptible injury phase.

2.4.6 Influence of hamstring neuromuscular performance and hamstring-to-quadriceps ratio on Hamstring strain injury

2.4.6.1.1 Hamstring strength and H/Q ratio and HSIs

Experimental investigation in vivo from the animal has shown that maximally stimulated muscles can endure greater amounts of stress before stretch-induced failure than partially activated muscles; therefore, it suggests that the stronger fully activated muscles would be more resilient to strain injury and the muscle weakness may be a risk factor to increase potential muscle strain (Garrett, Safran et al. 1987) due to reducing energy absorption capabilities (Garrett 1990). Previous studies have been conducted to examine the association between hamstring strength and HSIs, but there was no consensus (Yamamoto 1993, Orchard, Marsden et al. 1997, Bennell, Wajswelner et al.

1998). A two years follow-up research found the subject with HSIs have lower hamstring IMVC force than subjects without the HSIs (Yamamoto 1993). Also, Orchard et al., (1997) reported that the soccer player preseason hamstring weakness eccentric strength at $60^{\circ}.s^{-1}$ (injured leg: 1.75 ± 0.27 vs. uninjured leg: 2.08 ± 0.31) increases the risk of future HSIs (Orchard, Marsden et al. 1997). In contrast, Bennell, et al., (1998) didn't observed any significant association between lower peak concentric hamstring torque at $180^{\circ}.s^{-1}$ and subsequently injured Australian footballers in preseason (Bennell, Wajswelner et al. 1998). Given the HSIs mechanism, these inconsistent findings may be related to the muscle control during the muscle strain moment in sport movement, which should not correspond to the coordination pattern recorded during the muscle testing.

To date, the consensus for the mechanism of muscle strain identified that exercise involving lengthening of an activated muscle can cause injury (Garrett 1990, Garrett 1996, Fridén and Lieber 2001), and muscle strain injuries most often occur during eccentric contractions (Garrett, 1990, 1996). Considering the terminal swing phase during the high velocity sprint running is often identified as the primary activity for HSIs due to the high eccentric loading with high muscle strain placed on hamstring (Croisier 2004, Thelen, Chumanov et al. 2005, Chumanov, Heiderscheit et al. 2007, Yu, Queen et al. 2008, Opar, Williams et al. 2012). Namely, it should be kept in mind that the muscle strength is strongly dependent on the actual muscle length (Kaufman, Au et al. 1991). Indeed, some previous studies have been demonstrated the greater optimum length for peak force production of hamstring reduced the risk of HSIs during sprint running (Wan, Li et al. 2021). A prospective cohort study in elite Australian Rules Football identified eccentric weakness during the Nordic hamstring exercise as risk factor for a future HISs (Opar, Williams et al. 2015). More recently, Timmins et al., (2016) found the greater risk of a future HSIs in older players or those with a previous HSI is reduced when they have high levels of eccentric strength of hamstring measured by Nordic hamstring device (Timmins, Bourne et al. 2016). In addition, the intervention studies demonstrated the hamstring eccentric training by Nordic exercise could significantly reduce the future HSIs frequency (van der Horst, Smits et al. 2015, Al Attar, Soomro et al. 2017).

Besides, the impact of the H/Q strength ratio on HSIs has received greater attention aiming to assess the risk of HSIs in the last few decades. A lower H/Q ratio was widespread to predicting the HSIs occurrence. Knapik et al., (1991) found that the conventional H/Q of less than 0.75 at $180^{\circ}.s^{-1}$ induced higher HSIs frequency in female collegiate athletes (Knapik, Bauman et al. 1991).

Also, Orchard et al (1997) reported that the non-injured leg have high conventional H/Q ratio at $60^{\circ}.s^{-1}$ (0.662 ± 0.007) comparing to the injured leg (0.55 ± 0.06) in Australian footballers (Orchard, Marsden et al. 1997). More recently, Croisier et al., (2008) have demonstrated that the professional soccer player with conventional H/Q ratio ($60^{\circ}.s^{-1}$, $240.s^{-1}$) less than 0.45 were 4~5 times more likely to sustain a hamstring injury when compared with normal control group (Croisier, Ganteaume et al. 2008). Young et al., (2009) showed that a conventional H/Q ratio of less than 0.6 significantly increased the risk of the HSIs by 17 times (Yeung, Suen et al. 2009). However, in contrast, several previous studies failed to identify the conventional H/Q ratio as a risk factor for HSIs (Bennell, Wajswelner et al. 1998, Freckleton and Pizzari 2013, van Dyk, Bahr et al. 2016).

Actually, it could be considered that the conventional H/Q ratio neglects the functional role of the hamstring (i.e., eccentric contraction) at the terminal swing phase during the sprint running (Mair, Seaber et al. 1996, Thelen, Chumanov et al. 2005); therefore, this could explain why these studies couldn't identify a consensus on the relationship between the conventional H/Q ratio and HSIs. As a consequence, the functional H/Q ratio has been suggested to predict the HSIs (Dvir, Eger et al. 1989). Unfortunately, to date, the current investigations didn't provide consistent results about the relationship between the functional H/Q and prevalence of HSIs. Croisier et al., (2008) found that the players with a preseason functional H/Q ratio imbalance were approximately 4 times more at risk of HSIs (Croisier, Ganteaume et al. 2008). Inversely, Bonnell et al., (1998) didn't found significant difference of functional H/Q ratio between the injured and non-injured leg in Australian football players (Bennell, Wajswelner et al. 1998). More recently, a cohort study with the largest sample (n=614) carried out on players in Qatari elite soccer has reported no association between functional H/Q ratio and HSIs occurrence (van Dyk, Bahr et al. 2016). Yet, it suggested there is a difficulty in applying a widespread implementation of using the H/Q ratio to predict the HSIs due to the poor evidence. In fact, Heiser et al. (1984) firstly reported that the H_{con}/Q_{con} should be based on a minimum H_{con}/Q_{con} ratio of 0.60 at an angular velocity of $60^{\circ}.s^{-1}$ for HSIs prevention (Heiser, Weber et al. 1984). however, meta-analyses of isokinetic studies have demonstrated that even if H/Q ratio is lower than 0.6, it was not possible to demonstrate its association with HSIs (Green, Bourne et al. 2017).

Previous studies suggested to predict the HSIs in accordance to cut-offs of functional H/Q ratio higher than 0.8 in professional soccer player, but this value could not predict the further HSIs injury

(Orchard, Marsden et al. 1997, Daneshjoo, Rahnama et al. 2013, Dauty, Menu et al. 2018). It is evidencing this cut-off value not work due to the functional H/Q could attain more 2 when the knee joint angle increase (Evangelidis, Pain et al. 2015). As aforementioned, the terminal swing phase during the high-velocity sprint running is often identified as the primary activity to HSIs due to the strong mechanical stress at the longer muscle length under the higher angular velocity more than $1000^{\circ} \cdot s^{-1}$ at the lower knee flexion angle less than 30° during the high-speed sprint running (Guex and Millet 2013). Thus, the capacity to rapidly activate the hamstring and produce the force at the longer hamstring length (e.g., RTD) should be accountable for HSIs.

2.4.6.2 Neuromuscular fatigue on HSIs

As aforementioned in the literature review, neuromuscular fatigue during a competitive match in soccer players could reduce physical performance and increase musculoskeletal injuries risk (Bangsbo, Mohr et al. 2006, Reilly, Drust et al. 2008, Ekstrand, Häggglund et al. 2011, Mooney, Cormack et al. 2013). Moreover, according to some studies of injury incidence, HSIs usually occur at end of competitive matches (Hawkins and Fuller 1999, Woods, Hawkins et al. 2004, Ekstrand, Häggglund et al. 2011), which indicated the relationship between the fatigue and HSIs. Previous studies have addressed multiple mechanisms related to the influence of fatigue on HSIs occurrence. First of all, the basic mechanism that may explain the association between neuromuscular fatigue and muscle strain may be in part revealed by early in situ animal studies (Garrett, Safran et al. 1987, Mair, Seaber et al. 1996). These studies reported that the fatigue could impair the muscle's contractile function following muscle force decline, and reduce its energy-absorbing capacity (Garrett, Safran et al. 1987, Mair, Seaber et al. 1996). Besides, despite fatigued and fresh muscles failing at the same relative length (Mair, Seaber et al. 1996), the fatigued muscle could not absorb as much energy before stretch-induced muscular failure, which induces an inability to prevent over-lengthening and ultimately causing strain injury. Therefore, the combination of high force and reduced recruitment of motor units during eccentric contractions causes a high mechanical stress on the involved structures that may lead to focal microlesion of muscle fibers (Lieber and Fridén 1999).

Meanwhile, various studies have been reported that both simulated and actual soccer competitive match-play have been shown to decrease the hamstring force output likely to increase the potential

for HSIs occurrence (Gleeson, Reilly et al. 1998, Small, McNaughton et al. 2010, Rampinini, Bosio et al. 2011, Girard, Brocherie et al. 2015). For instance, Gleeson et al. (1998) investigated the effect of a soccer-related fatiguing protocol on muscle strength of lower limb in recreational soccer players (Gleeson, Reilly et al. 1998). They found the knee flexor peak torque decreased progressively within fatigue. More recently, Small et al., (2010) reported that the eccentric hamstring peak torque decreased significantly during each half of a soccer match in agreement with Gleeson et al., (1998) (Small, McNaughton et al. 2010). On the other hand, given the HSIs frequently occur at longer muscle lengths during the terminal swing phase of the running cycle; more recent attention has focused on modification of the mechanical parameter of sprint running such as hamstring strain after neuromuscular fatigue (Tupa 1995, Pinniger, Steele et al. 2000, Small, McNaughton et al. 2009, Grazioli, Lopez et al. 2019). Pinniger et al., (2000) and Tupa (1995) found that the hip and knee flexion angles decreased with a reduced muscular activity during the swing phase after fatigue, which may lead to potentially creating hamstring strain (Pinniger, Steele et al. 2000). In addition, Small et al., (2009) investigated the effect of multidirectional soccer-specific fatigue (SAFT) on sprinting kinematics parameter in relation to HSIs risk (Small, McNaughton et al. 2009). They found a reduction of maximum combined hip flexion and knee extension angle during the late swing phase of the sprinting cycle, which induces hamstring muscle over lengthening for the increased potential risk of strain injury.

2.4.7 Influence of hamstring strength and hamstring-to-quadriceps ratio on ACL injury

2.4.7.1 Hamstring strength and H/Q ratio on ACL injury

This part of the paper is justified considering that one of the roles of the hamstring muscle is to protect the ACL by reducing the anterior shear force. (Tsepis, Vagenas et al. 2004). Thus, it suggests that strong hamstring muscles are determinants of risk of ACL injury (Bencke, Naesborg et al. 2000). Effectively, in situ ACL force studies, Li et al., (1999) and Renstrom et al., (1986) already found that the ACL strain increased with isolated quadriceps load, significantly reduced with isolated hamstring activity and hamstring co-contraction between the 0° and 60° of knee flexion (Renström, Arms et al. 1986, Li, Rudy et al. 1999); Moreover, Withrow et al. (2008) found that increasing hamstring muscle force during a simulated jump landing significantly reduced peak relative ACL strain (Withrow, Huston et al. 2008). However, Bennett et al., (2008) didn't found that the hamstring muscle strength is indicative of sagittal-plane knee loading during jump landing

task (Bennett, Blackburn et al. 2008). In fact, as aforementioned earlier, the ACL injury usually occurs at the initial ground contact phase within 17 ~ 50ms time interval (Krosshaug, Nakamae et al. 2007), that require the hamstring and quadriceps muscles to activate quickly in order to maintain the stability of the knee joint (Li, Rudy et al. 1999, Zebis, Andersen et al. 2011); thereby, the strength measured by isokinetic torque is likely not representative of musculotendinous forces actually produced during landing task. This limit could also explain why no previous following-up studies provided the solid evidence that indicates the hamstring strength to be significantly related to both ACL injury occurrence and knee joint function (Hewett, Lindenfeld et al. 1999, Uhorchak, Scoville et al. 2003, Mandelbaum, Silvers et al. 2005, Hohmann, Bryant et al. 2016). Thus, it could speculate that the ability to rapidly activate and co-activate the hamstring and quadriceps muscles allows the athletes to have a better control of the knee joint stability during the risky maneuvers.

Numerous studies have been investigated the relationship between H/Q and ACL injury occurrence in an attempt to identify if there is an optimal H/Q ratio that prevents the ACL injury occurrence. For instance, Grace et al., (1984) have prospectively investigated the association between the H/Q strength imbalance (discrepancy of 10%) and knee joint injuries among 172 football players; however, they didn't find any relationship between the H/Q strength imbalance and knee joint injury occurrence (Grace, Sweetser et al. 1984). More recently, another prospective study including 146 players reported that the soccer players who suffered an ACL injury had a lower conventional H/Q ratio at $90^{\circ} \cdot s^{-1}$ (Söderman, Alfredson et al. 2001). Moreover, Myer et al., (2009) found the participant with ACL injury had lower H/Q ratio at $300^{\circ} \cdot s^{-1}$ comparing to the participant without ACL injury (Myer, Ford et al. 2009). On the other hand, several laboratory studies didn't find the H/Q ratio to be significantly related to the mechanical parameter related to the ACL injury mechanism. Bonnett et al., (2008) revealed that no significant relationship was found between H/Q at three different angular velocity (i.e., $60^{\circ} \cdot s^{-1}$, $180^{\circ} \cdot s^{-1}$, $300^{\circ} \cdot s^{-1}$) (quadriceps in eccentric, hamstring in concentric) and anterior tibial shear force (Bennett, Blackburn et al. 2008). In contrast, Walsh et al. (2012) indicated that the IMVC H/Q ratio was negatively correlated to the knee joint flexion angle during the landing task which may reveal the higher H/Q ratio decrease the ACL loading and the risk of ACL injury (Walsh, Boling et al. 2012).

These conflicting findings limit the solid evidence to ensure the relationship between the H/Q ratio and potential ACL injury occurrence. Moreover, it's evident that this discrepancy could be explained by the ACL mechanism. As mentioned above, the ACL injury occurred frequently at the initial ground contact phase due to the knee joint dynamic stability deficit in the short time period less than 50-ms. In contrast, the time taken to attain maximum torque or force during isokinetic and isometric contraction is typically more than 300-ms (Andersen, Andersen et al. 2010). Furthermore, studies have shown that during a side cutting maneuver where most noncontact ACL injuries are observed (Olsen, Myklebust et al. 2004), neuromuscular activation of the hamstrings are only 30–50% of maximum activation (Simonsen, Magnusson et al. 2000, Zebis, Bencke et al. 2008), supporting that activation pattern and contractile hamstring RFD rather than maximal strength are important parameters for the stabilization of the knee joint. Considering that the traditional H/Q calculated by the peak torque seem unlikely to be attained in the time available to maintain the knee joint stability, Zebis et al. (2011) suggested using the RTD H/Q to evaluate the knee joint stability during the explosive movement such as jumping, cutting, etc. (see 2.2.5.3) (Zebis, Andersen et al. 2011). In consequence, despite the hamstring strength and H/Q ratio have been widely studied in the prediction of ACL injury, there is still no consensus on the relationship between these parameters and the ACL injury occurrence (Grace, Sweetser et al. 1984, Söderman, Alfredson et al. 2001, Myer, Ford et al. 2009).

2.4.7.2 Hamstring to quadriceps co-activation on ACL injury

Given the knee joint's dynamic stabilization via neuromuscular control assists in protecting ACL, it has been suggested that a highly developed hamstring muscle activation to increase hamstring-to-quadriceps co-activation ratio, thereby reducing susceptibility to ACL injury (Baratta, Solomonow et al. 1988, Colby, Hintermeister et al. 1999, Reid, Birmingham et al. 2007). Knee muscle activity, notably hamstring and quadriceps must be coordinated and co-activated to protect the knee joint; thereby, the hamstring-to-quadriceps co-activation may be critical to maintain the knee joint stability and subsequently reduce the ACL loading. Thus, assessing the hamstring to quadriceps co-activation in a laboratory setting using different functional movements was usually used to evaluate the knee joint dynamic stability (Reid, Birmingham et al. 2007). As mentioned above, in vivo studies have already demonstrated that the hamstring to quadriceps co-activation could significantly reduce ACL strain indicating the importance of hamstring to

quadriceps synergistic work (Renström, Arms et al. 1986, Li, Rudy et al. 1999); Colby et al., (1999) qualitatively characterize quadriceps and hamstring muscle activation and determine the knee flexion angle during four different movements (i.e., sidestep cutting, cross-cutting, stopping, and landing). They found that the low level of hamstring muscle activity and low angle of knee flexion at foot strike and during the eccentric contraction, coupled with forces generated by the quadriceps muscles at the knee, could produce significant anterior displacement of the tibia, which may play a role in anterior cruciate ligament injury (Colby, Hintermeister et al. 1999). In agreement, Colby, Lloyd et al., (2005) used an EMG-driven neuromuscular biomechanical model to study how muscles stabilize the knee. They found that the most potent activation pattern to stabilize the knee is when the hamstrings or quadriceps are required to generate flexion or extension moments, individually. The next most effective knee stabilizing pattern is co-contraction of the hamstring and quadriceps (Lloyd, Buchanan et al. 2005). Besides, Chappell et al., (2006) reported that increased quadriceps activation and decreased hamstring activation could result in an increased ACL loading with decreased knee flexion during the landing of the stop-jump tasks (Chappell, Creighton et al. 2007). In summary, the many evidences presented above clearly demonstrated that the hamstring recruitment relative to the quadriceps recruitment could positively contribute in maintaining knee joint stability and reducing the ACL loading.

Furthermore, just like the ACL injuries occur too quickly for reflexive neuromuscular activation and recruitment, certain researchers speculate that the pre-activation of protective muscle groups such as hamstring and quadriceps allow athlete to adopt the safer movement pattern before ground contact phase during the landing maneuvers (Dyhre-Poulsen, Simonsen et al. 1991, Wojtys and Huston 1994). Zebis et al., (2009) tested the pre-activity (10ms before ground contact phase) of hamstring muscle during the side-cutting maneuver in fifty-five elite female athletes (i.e., handball and soccer players) to identify and registered ACL injury incidence in a short-term follow-up (two match seasons). They found the five injured players displayed a neuromuscular pattern that differed from the non-injured players. It was characterized by reduced EMG pre-activity for the ST and elevated EMG pre-activity for the VL; hence a lack of hamstring relatively to quadriceps muscle activation prior to ground contact (Zebis, Andersen et al. 2009). Their finding could be supported by another study which indicated the anticipated pre-activation of hamstring muscle contribute a significant reduced ACL loading in the sagittal plane during sidestep cutting task

(Weinhandl, Earl-Boehm et al. 2013). Meanwhile, a higher hamstring to quadriceps co-activation before the ground contact phase has been suggested to reduce the knee valgus during the landing task, and may help to diminish the risk of ACL injury (Zebis, Andersen et al. 2011). Moreover, Ebben et al. (2010) analysed the hamstring and quadriceps co-activation during jump landing and cutting maneuvers. They didn't find any significant difference in hamstring and quadriceps co-activation between drop jumping landing and cutting maneuvers, whereas the male subjects demonstrated a trend to a higher hamstring-to-quadriceps activation than the female athletes during the post contact phase of the cutting maneuvers (Ebben, Fauth et al. 2010). This finding may be related to the previous studies which indicated the female athletes to sustain more ACL injury (Agel, Arendt et al. 2005, Waldén, Hägglund et al. 2011). Based on the previous finding above, it is proposed that the high activation of the hamstring during the pre-active phase (i.e., a short period before ground contact) and the post-activation phase (i.e., less than 100-ms after ground contact) warrant to maintain the dynamic knee joint stability; thereby reducing the ACL loading. Thus, the assessment of hamstring-to-quadriceps co-activation during the different tests are necessary to screen the potential risk of ACL injury.

2.4.7.3 Neuromuscular fatigue on ACL injury

As partly discussed above, although the epidemiology study of ACL injuries in soccer indicated that fatigue didn't directly link to ACL occurrence, one may hypothesize that the neuromuscular fatigue can increase the risk for ACL injury since muscles contribute to knee joint stability (Gehring, Melnyk et al. 2009, Ortiz, Olson et al. 2010, Gillot, L'Hermette et al. 2019). It has been primary proposed that the fatigue could reduce the hamstring muscle force and alter the muscular activation pattern, subsequently altering the knee biomechanics parameter (e.g., stability, knee flexion, hip abduction) during the susceptible ACL injury movement (e.g., cutting, landing, deceleration, change of direction). Gehring et al., (2009) found that the lower limb fatigue (i.e., leg press in isotonic contraction) significantly increased the knee abduction angle associated with a reduction of the pre-activation of hamstring (i.e., medial and medial hamstring) during the two-legged landing task (Gehring, Melnyk et al. 2009). In line with their finding, Weinhandl et al., (2014) found that the special reduction of hamstring strength after fatigue (i.e., 50 repetition of maximum effort concentric knee flexion at $180^{\circ}.s^{-1}$) could increase by 36% the ACL strain during the side cutting maneuvers.

In addition, fatigue could increase ACL risk due to an impaired hamstring muscle activation pattern. For example, De Ste Croix et al., (2015) investigated the influence of the soccer specific fatigue (SAFT) on neuromuscular control of knee joint during the maximal isokinetic eccentric assessment of hamstring in young soccer players. They found the electromechanical delay (EMD) was significantly increased after fatigue inducing a failure of hamstring neuromuscular performance. As results, the fatigue could potentially impair the subsequent knee joint stability (De Ste Croix, Priestley et al. 2015).

Meanwhile, Zebis et al., (2011) investigated the effect of fatigue on the EMG activity of lower limb during the pre-landing and landing phase (10-ms and 50-ms before and after foot strike on the ground) of side-cutting maneuver. They found the hamstring activity to be significantly reduced after fatigue during the pre-landing phase both for 10ms and 50ms time interval, and during the landing phase for 10-ms time interval, respectively (Zebis, Bencke et al. 2011). (Zebis, Andersen et al. 2009), their finding revealed that fatigue induced deficits in agonist muscle activation during the ground landing phase that may, subsequently, increase the ACL injury risk. Furthermore, fatigue can also change intra and intermuscular coordination pattern between hamstring and quadriceps muscles following the knee kinetics and kinematics change (i.e., increase ACL strain, reduction knee joint dynamic stability), which may, potentially, increase the risk of ACL injury (Chappell, Herman et al. 2005, Kellis and Kouvelioti 2009, Ortiz, Olson et al. 2010, Grazioli, Lopez et al. 2019). Indeed, despite numerous studies support that the neuromuscular fatigue is a predominantly accepted risk factor for the ACL injury on the exact influence of fatigue on ACL injury occurrence is not obvious to date due to the lack of prospective studies and needs further investigations.

CHAPTER 3 Aim of thesis

3.1 Synthesis

Many previous studies focused on the influence of the knee muscles neuromuscular capacity on the acceleration performance (Morin, Edouard et al. 2011, Buchheit, Samozino et al. 2014, Ishoi, Aagaard et al. 2019), whereas rare studies investigated their contribution in linear deceleration performance (Harper, Jordan et al. 2021), notably in female soccer players. Furthermore, considering the deceleration is the negative acceleration movement, the objective of deceleration is to rapidly decrease the body's momentum by applying as much braking force as possible over minimal time to stop. Thus, the quadriceps should work through an eccentric manner to absorb the impact, that is, applying the maximal braking force. As aforementioned, several studies have been investigated the braking force production during the deceleration phase before change of the direction, which indicated the higher horizontal braking force induced better COD performance (Thomas, Dos'Santos et al. 2020). In addition, only one study investigated the knee muscle (i.e., hamstring and quadriceps) forces in relation with the linear deceleration performance, which indicated athlete presenting the higher knee muscles strength take less time and distance to stop. However, no mechanical parameter was evaluated in this study to explain their finding. Thus, the influence of the lower limb strength on kinematic and kinetic parameter such as braking force and power during the entire linear deceleration after high velocity sprint running should be investigated.

Meanwhile, although it is well described that the fatigue and H/Q ratio are related to risk factor of HSIs, there is a lack of prospective studies evidence. It is conflicting findings that may be due to the different H/Q ratios that are calculated at different velocities and it may also be explained by the fact that previous studies focused on the peak torques and didn't took into account the entire range of motion (knee angle specific torques and ratios). It has been reported that such calculations ignored the effect of the knee angle's role on force production whereas maximal hamstring muscle strain occurs in the terminal swing phase with longer hamstring length during sprint running. Thus, it's evidence to determine the influence of fatigue on the hamstring strength production at longer muscle length. Recently, an alternative method of analysis called statistical parametric mapping (SPM) considers the influence of time/angle on the entire force curve of the isokinetic test, which permits the identification of task features (Alhammad, Morel et al. 2019). Therefore, SPM analysis may detect the continuous interaction of the time (i.e., fatigue) and muscle length (i.e.,

knee angle) on the hamstring and quadriceps force production to enhance the understanding of the HSIs risk after fatigue.

Moreover, as mentioned above, deficits in lower limb kinematics and dynamic postural stability are predisposing factor to the development of ACL injury (Paterno, Schmitt et al. 2010, Mohammadi, Salavati et al. 2012, Delahunt, Chawke et al. 2013); thereby, the assessment of the dynamic postural stability during the jump landing maneuvers are frequently used to screen the potential ACL injury risk in the clinic and laboratory. Furthermore, consideration of H/Q co-activation plays an essential role in maintaining the knee joint stability and subsequently reducing the ACL loading during the landing maneuvers; some researchers also suggested evaluating the H/Q co-activation during the functional movement (e.g., cutting, jump landing). Besides, quadriceps and hamstring muscle ground makes the greatest muscular contribution to knee joint a center of mass stability. The muscles acting across the ankle and hip joints contribute to overall lower limb power that attenuates the force of landing due to dynamic coupling stemming from the multi-articular nature of the body (Zajac and Gordon 1989). Thus, it could be hypothesized that the H/Q co-activation might influence the dynamic postural stability performance during landing tasks. Considering that the females' athletes sustains more non-contact ACL, notably in the non-dominant leg (Ruedl, Webhofer et al. 2012) this parameter may be an interesting point to focus on. It appears that there is a need to determine the best test to evaluate stabilization capability and leg dominance in soccer players and to explore the influence of H/Q co-activation on the dynamic postural stability.

3.2 Purpose

To address the above, three studies were under taken in this thesis to investigate the:

- i)* Relationship between the lower limb strength and linear deceleration performance in professional female soccer players (Chapter 4).
- ii)* Influence of landing jump direction on hamstring to quadriceps co-activation ratio (Chapter 5).
- iii)* Impact of fatigue on the rapid explosive capacity of the lower limb and angle-specific H/Q ratio in younger semi-professional soccer players (Chapter 6).

**CHAPTER 4 Relationship between explosive strength capacity of
the knee muscles and deceleration performance in female
professional soccer players**

4.1 Abstract en Français

La présente étude visait à étudier la relation entre les performances de décélération linéaire et la capacité de force explosive des muscles du genou. 14 joueuses footballeuse professionnelles ont effectué les tests de décélération maximale du sprint et les contractions isocinétiques concentriques ($240^{\circ} \cdot s^{-1}$ et $60^{\circ} \cdot s^{-1}$) et excentriques ($30^{\circ} \cdot s^{-1}$) du fléchisseur du genou (KF) et de l'extenseur du genou (KE). Les performances de décélération linéaire ont été évaluées à partir de la force de rupture horizontale (FH), de la puissance (PH) et de l'impulsion (IH) pendant une décélération linéaire maximale. Le couple maximal de KF et KE, le rapport PT entre KF et KE (rapport H/Q), le taux de développement du couple (RTD) pour chaque groupe musculaire et le RTD entre KF et KE (RTD H/Q) ont été extraits de l'isocinétique contractions. Les coefficients de corrélation de Pearson ont révélé que le couple de crête KE excentrique ($30^{\circ} \cdot s^{-1}$) et concentrique ($60^{\circ} \cdot s^{-1}$, $240^{\circ} \cdot s^{-1}$) et le couple de crête concentrique KF ($240^{\circ} \cdot s^{-1}$) étaient significativement corrélés avec FH, PH et IH ($-0,75 < r < -0,54$). De plus, une corrélation significative a été trouvée entre KE RTD pendant la contraction excentrique et FH, PH et IH ($-0,63 < r < -0,54$). Par ailleurs, une corrélation significative a été observée entre RTD H/Q à $60^{\circ} \cdot s^{-1}$ et PH, IH ($-0,61 < r < -0,57$). Aucune relation significative n'a été observée entre le rapport H/Q, le RTD KF et les performances de décélération. Ces principales conclusions ont indiqué l'importance de la capacité à produire rapidement un couple excentrique KE élevé, contribuant à la production de force de freinage. Pendant ce temps, le RTD H/Q doit être évalué pour son rôle essentiel dans la stabilité dynamique de l'articulation du genou et peut être un indice pertinent pour déterminer les performances de décélération.

Mots clés: décélération performance, pic torque, RTD, H/Q ratio, footballeur

4.2 Abstract in English

The present study aimed to investigate the relationship between linear deceleration performance and explosive strength capacity of the knee muscles. Fourteen female professional soccer players completed the maximal sprint deceleration tests and knee flexor (KF) and knee extensor (KE) isokinetic concentric ($240^{\circ} \cdot s^{-1}$ and $60^{\circ} \cdot s^{-1}$) and eccentric contractions ($30^{\circ} \cdot s^{-1}$). Linear deceleration performance was evaluated from horizontal braking force (F_H), power (P_H), and impulse (I_H) during a maximal linear deceleration. The peak torque of KF and KE, PT ratio between KF and KE (H/Q ratio), rate of torque development (RTD) for each muscle group, and RTD between KF and KE (RTD H/Q) were extracted from the isokinetic contractions. Pearson's correlation coefficients revealed that the eccentric ($30^{\circ} \cdot s^{-1}$) and concentric ($60^{\circ} \cdot s^{-1}$, $240^{\circ} \cdot s^{-1}$) KE peak torque, and the concentric KF peak torque ($240^{\circ} \cdot s^{-1}$) were significantly correlated with F_H , P_H , and I_H ($-0.75 < r < -0.54$). Moreover, a significant correlation was found between KE RTD during eccentric contraction and F_H , P_H , and I_H ($-0.63 < r < -0.54$). Besides, a significant correlation was observed between RTD H/Q at $60^{\circ} \cdot s^{-1}$ and P_H , I_H ($-0.61 < r < -0.57$). No significant relationship was observed between the H/Q ratio, KF RTD and deceleration performance. These main findings indicated the importance of the ability to quickly produce high KE eccentric torque, contributing to braking force production. Meanwhile, RTD H/Q should be assessed for its essential role in knee joint dynamic stability and can be a relevant index to determine deceleration performance.

Keywords: deceleration performance, peak torque, RTD, H/Q ratio, soccer

4.3 Introduction

Acceleration, deceleration, and COD performance while sprinting at high speed is considered essential in most team sports such as soccer or rugby to overtake opponents in decisive situations (Buchheit, Samozino et al. 2014, Vigh-Larsen, Dalgas et al. 2018). Previous external movement analysis in soccer reported that the players perform approximately 14-26 high intensity of the acceleration ($\geq 3\text{m}\cdot\text{s}^{-2}$), and the 43-56 deceleration ($\leq -3\text{m}\cdot\text{s}^{-2}$) in short-duration less than 1 sec across the competitive match (Wehbe, Hartwig et al. 2014, Russell, Sparkes et al. 2015, de Hoyo, Cohen et al. 2016, Russell, Sparkes et al. 2016); therefore, interventions that seek to maintain players' acceleration and deceleration capacity throughout the entire duration of a soccer match warrant investigation (Russell, Sparkes et al. 2016). Also, numerous studies have suggested that one of the critical phases for COD is the rapid body deceleration before the re-acceleration phase (Dos'Santos, Thomas et al. 2017, Jones, Thomas et al. 2017). Yet, deceleration is employed to stop or quickly decrease the body's center of mass velocity before a COD (Hewitt, Cronin et al. 2011) inducing substantial braking force followed by a propulsive force with high sprint velocity, which requires high eccentric-concentric force capacities (Brughelli, Cronin et al. 2008). Moreover, deceleration combined with a COD or cutting maneuver has been identified as the movement that can induce non-contact injuries such as anterior cruciate ligament (ACL) injury (Alentorn-Geli, Myer et al. 2009) due to the high level of ACL strain induced by the substantial external knee valgus moment (McLean, Lipfert et al. 2004). Indeed, female soccer players are more likely to suffer ACL injury when compared with male players (Yu, Kirkendall et al. 2002). However, the kinematics and kinetics of running sprints and neuromuscular determinants of sprinting performance have been extensively studied in the literature. In contrast, deceleration performance has been less investigated, especially in female soccer players.

Performance in COD is influenced by numerous factors, including lower limb strength (Jones, Thomas et al. 2017, Harper, Jordan et al. 2021), reactive force (Castillo-Rodriguez, Fernandez-Garcia et al. 2012), body stability (Sasaki, Nagano et al. 2011) and/or deceleration technique (Brughelli, Cronin et al. 2008). During the deceleration maneuver, the lower limb absorbs the kinetic energy by contracting the knee extensor muscles eccentrically to decrease body momentum and stop as fast as possible in a stable posture. In this regard, the KE eccentric torque may be

essential to perform that kind of movement. Harper et al. (2018) indicated that KE eccentric torque at $60^{\circ} \cdot s^{-1}$ was largely correlated to deceleration performance (*i.e.*, time to stop, distance to stop) (Harper, Jordan et al. 2021). However, ground contact occurs ahead of the center of mass during deceleration with a more extended knee and a flexed hip angle compared to the acceleration phase (Hewitt, Cronin et al. 2011). This movement's organization induces large internal knee constraints due to the great braking forces requiring a fast contraction of agonist and antagonist muscles to protect the joint structures with a high knee joint stability. Therefore, a high coordination and torque balance between KF and KE should be considered as a potential determinant of knee joint stability, which may assist deceleration performance. From a clinical point of view, the hamstring-to-quadriceps strength ratio (H/Q ratio) was usually used to evaluate the balance between KF and KE. Additionally, a high rate of torque development (RTD) was suggested to be determinant in sport performance and musculoskeletal injuries prevention (Rodriguez-Rosell, Pareja-Blanco et al. 2018, Ishoi, Aagaard et al. 2019). More specifically, Zebis et al. (2011) suggested that a rapid hamstring-to-quadriceps strength ratio (RTD H/Q) appears of utmost interest to assess knee joint dynamic stability during explosive movement (Zebis, Andersen et al. 2011), indicating the ability to rapidly increase the level of force produced by KF and KE in order to maintain knee joint dynamic stability.

However, to the best of our knowledge, previous research only examined the relationships between the peak torque of the lower limb and deceleration performance but ignored the role of explosive neuromuscular capacity to rapidly produce torque and the balance between knee flexor and knee extensor contributions with regards to maximal deceleration performance. Therefore, the aims of the study were: *i*) to determine the relationships between the knee muscle isokinetic strength profile and sprint deceleration performance, and *ii*) to examine the relationship between explosive neuromuscular capacity (RTD and RTD H/Q) and deceleration performance. We hypothesized that *i*) knee extensor eccentric and knee flexor concentric peak torque should be correlated to deceleration performance with higher braking force and power production and *ii*) the explosive torque capacities of KF and KE, and their related ratios (RTD H/Q) may also significantly impact deceleration performance whereas no relationship between the traditional H/Q ratio and deceleration performance was expected.

4.4 Methods

The present study used a cross-sectional design to investigate the relationship between the knee muscle isokinetic torque and explosive neuromuscular capacity in both dominant leg (DL) and non-dominant leg (NDL), and deceleration performance in female professional soccer players. The deceleration performance was assessed by radar-derived kinetics measurements, including horizontal braking force, braking power, and braking impulse. The protocol consisted of two experimental testing sessions during the competitive season. The first session included the isokinetic torque testing of knee muscles, and the second testing session was the field assessment, including the linear deceleration test.

4.4.1 Participants

Fourteen French national-level female soccer players (Height: 166.1 ± 5.9 cm, Mass: 63.1 ± 7.3 kg, Age: 24.7 ± 4.2 years, training volume: 12.4 ± 2.7 h. week⁻¹, experience training: 11.4 ± 5.9 years) volunteered to participate, with 4 training sessions per week. The sample size was a priori calculated using a sample size calculator (G-Power 2.0, Brunsbüttel, Germany) assuming the effect size = 0.5 (moderate), the α -error = 0.05 and $1-\beta > 0.8$ (Faul, Erdfelder et al. 2007). All participants had had no lower extremity injury in the previous year. All participants gave their written informed consent to participate in the study after being informed about the procedure. Leading up to the experiments, participants followed their regular training program. Also, participants did not perform any unaccustomed or intense training session or match 48h before the protocol. All participants performed two experimental testing sessions at the same time of day separated by at least 48 hours during the players' regular training period (3 ~ 5 p.m.), aiming to diminish the effects of residual fatigue and circadian variation. The first session included all anthropometric measurements and the isokinetic torque testing of knee muscles. In the second session, participants performed sprint running tests, and deceleration performance was characterized.

4.4.2 Experimental procedures

4.4.2.1 Isokinetic Torque Evaluation

Isokinetic measures were taken on the dominant (*i.e.*, the kicking leg, DL) and non-dominant (*i.e.*, contralateral, NDL) legs in a random order. The participants performed a general warm-up for 10 min on a cycle ergometer at a resistance of 1 watt.kg⁻¹ (70-80 RPM). Thereafter, participants were seated on an isokinetic dynamometer (Contrex, CMV AG, Dübendorf, Switzerland) with hips flexed at 80° (0° = full hip extension), and standard stabilization strapping was placed across the chest, pelvis, and distal thigh (Zhang, Morel et al. 2021). The axis of the dynamometer was visually aligned with the lateral femoral condyle. The range of movement was set from 100° of knee flexion (starting position) to 20° (0° = knee fully extended). The torque and angle signals were recorded at 256 Hz. The gravity compensation procedure was performed according to the manufacturer's instructions. Before the isokinetic testing, all participants completed a familiarization of isokinetic contraction consisting of KE and KF submaximal contractions in concentric mode at 60°.s⁻¹ and 240°.s⁻¹, and in eccentric mode at 30°.s⁻¹. After a 5min recovery period, the participants performed three maximal knee extension-flexion concentric contraction tests (60°.s⁻¹, 240°.s⁻¹) and eccentric contraction tests (30°.s⁻¹) in a random order. The recovery period between each repetition and each trial was 30-s and 3-min, respectively. In the entire testing session, each participant was orally encouraged to give their maximal effort with a command to push (concentric) / pull (eccentric) as fast and hard as possible against the isokinetic dynamometer arm.

4.4.2.2 Maximal horizontal deceleration test

All testing procedures were completed on the same third-generation artificial turf surface with rubber granules, specifically for outdoor field-sport events with standard meteorological conditions (temperature: 9°-14°; wind < 2-m/s; degree of humidity < 52%). Each participant was asked to wear the same sprigged training shoes and team training attire as usual. All the participants performed a similar 20-min on-field dynamic warm-up protocol specific to soccer (*e.g.*, dynamic stretching, lunges, squat jump). Participants then performed three progressive 30-m sprints and 10-m of progressive deceleration phase representing a subjective moderate, intense, and quasi-maximal effort. Participants also performed three submaximal decelerations after a 20-m sprint run. After 4 min of passive rest, subjects performed three maximal sprints of 20-m from a

crouching position (staggered stance) finished by the fastest stop possible, interspersed by a 4-min passive recovery period.

A Stalker radar device (Stalker ATS II, Applied Concepts, Dallas, TX, USA, 46.9 Hz) was attached to a heavy-duty tripod positioned 5-m behind the starting line at a height of 0.9-m above the ground (corresponding approximately to subject's center of mass) which aimed to record the raw velocity-time curve during the maximum deceleration tests. Furthermore, the 20m sprint times were recorded using timing gates (TC Brower Timing System, Draper, USA) set to a height of 90-cm. Times were recorded to the nearest 0.01 s. Each sprint started from a stationary split stance position with the front foot positioned 30cm behind the timing gate to prevent a false trigger. Participants were instructed to initiate their start with no backward step or 'rocking motion' and sprint as fast as possible. Each participant performed two trials of maximal sprints interspersed by a passive recovery period of at least 4-min. The participants performed three maximal deceleration tests. During the maximal deceleration tests, subjects were instructed to stop immediately as quickly as possible after 20m sprint running (e.g., braking line) and then backpedal to the 20m line (Figure 18). Any 20m time that was 5% slower than the best 20-m split time achieved during the sprint test was disregarded for analysis.

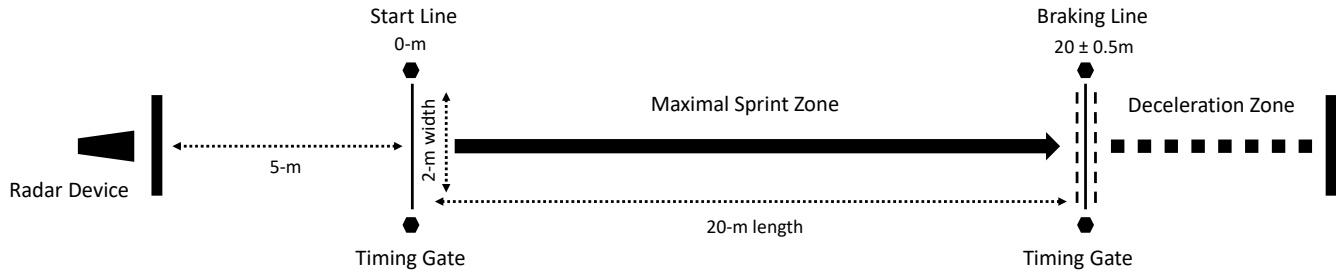


Figure 18: The linear deceleration assessment design.

4.4.3 Measurements and Data processing

4.4.3.1 Peak torque (PT) and H/Q ratio

Raw torque-time curves were extracted from the original instantaneous torque dataset. The torque threshold was set at 1% of the maximal peak torque for each angular velocity to determine the onset and offset of muscle contraction. The best PT value across the three maximal repetitions at $240^{\circ} \cdot s^{-1}$, $60^{\circ} \cdot s^{-1}$ and $-30^{\circ} \cdot s^{-1}$ was used for final analysis.

Conventional H/Q ratios were calculated by dividing KF concentric PT by KE concentric PT at $60^{\circ} \cdot s^{-1}$ (H_{con60}/Q_{con60}) and $240^{\circ} \cdot s^{-1}$ (H_{con240}/Q_{con240}). A functional H/Q ratio was calculated by dividing KF eccentric PT at $30^{\circ} \cdot s^{-1}$ by KE concentric PT at $60^{\circ} \cdot s^{-1}$ (H_{ecc30}/Q_{con60}) and $240^{\circ} \cdot s^{-1}$ (H_{ecc30}/Q_{con240}), respectively.

4.4.3.2 RTD and RTD H/Q ratio

The absolute RTD was calculated as the slope of the torque-time curve between 0-100ms interval (i.e., $\Delta\text{torque}/\Delta\text{time}$) after the contraction onset for KE and KF at $60^{\circ} \cdot s^{-1}$ and $-30^{\circ} \cdot s^{-1}$. RTD H/Q ratios were calculated by dividing the KF RTD with the KE RTD both for concentric ($\text{RTD } H_{con100}/Q_{con100}$) and eccentric ($\text{RTD } H_{con100}/Q_{ecc100}$) contractions.

4.4.3.3 Maximal deceleration mechanics

All data were collected using the software Stalker Acceleration Testing System (STATS) (v5.0.2.1, Applied Concepts, Dallas, TX, USA) provided by the radar device's manufacturer. A custom-made data analysis routine (MATLAB, R2018b, Natick, MA, USA) computed the kinetic

variable including the horizontal braking force (F_H), power (P_H), and impulse (I_H) calculated from the start to the end of the maximal sprint deceleration as previously reported (Harper, Morin et al. 2020). The instantaneous horizontal acceleration (a_H) was calculated by the gradient of the time-velocity curve as:

$$a_H(t) = \frac{\partial v}{\partial t}$$

And the net horizontal force $F_H(t)$ during the deceleration period was then modeled over time:

$$F_H(t) = m \cdot a_H(t) + F_{aero}$$

Where: $a_H(t)$ is the acceleration at time t and m is the body mass. In addition, ∂t is the variation in time, and ∂v is the variation in velocity. F_{aero} is the air friction, which was calculated with the equation F_{aero} as the aerodynamic friction force to overcome during sprint running computed from sprint velocity and an estimated body frontal area and drag coefficient (Arsac and Locatelli 2002).

$$F_{aero}(t) = (0.2025 * Height^{0.725} * Mass^{0.425}) * 0.266$$

Besides, the horizontal power ($P_H(t)$) was calculated with the following equation:

$$P_H(t) = F_H(t) * V_H(t)$$

Instantaneous horizontal impulse ($I_H(t)$) was calculated between each data point during the deceleration phase using the change in the momentum.

$$I_H(t) = \partial v * mass$$

The average horizontal braking force (F_{ave}), braking power (P_{ave}), and braking impulse (I_{ave}) were calculated using the average of all instantaneous F_H , P_H , and I_H , during the entire deceleration phase. Furthermore, the maximum braking force (F_{max}), power (P_{max}), and impulse (I_{max}) were obtained as the highest value of all instantaneous F_H , P_H , and I_H values during the entire deceleration phase (Figure 19).

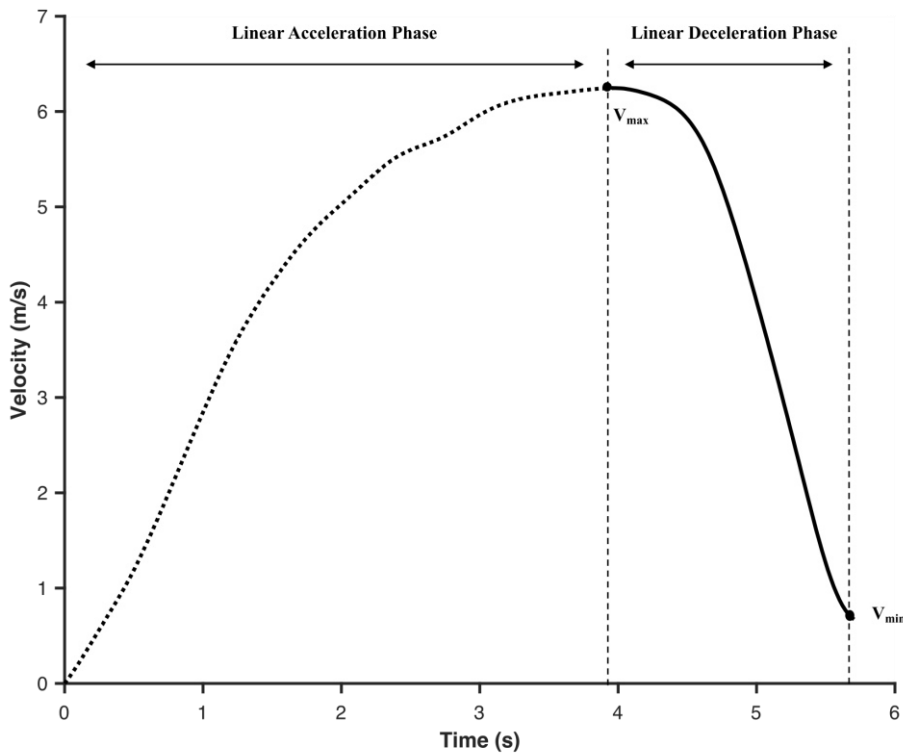


Figure 19: Example of velocity-time profile showing the acceleration and the deceleration phase. V_{max} : maximum velocity defining start of deceleration phase. V_{min} : lowest velocity defining end of deceleration phase.

4.4.4 Statistical Analyses

Before performing the statistical analysis, the Shapiro–Wilk test was used to assess the data's distribution normality. Pearson's product-moment correlation coefficients (r) were calculated to examine the relationship between deceleration variables and isokinetic test parameters. The magnitude of the correlation coefficient was interpreted using criteria: very weak (0.11- 0.19), weak (0.20 - 0.39), moderate (0.40 - 0.59), strong (0.60 - 0.79), and very strong (0.80-1.00) (Evans

1996). The coefficient of determination (r^2) was used to indicate the shared variance of correlation and presented as a % (r^2*100). The p-value was set at 0.05 significance level. All statistical procedures were performed with R software (R 3.5.0, RCore Team, Vienna, Austria).

4.5 Results

The isokinetic torque parameters are shown in Table 4 and 5. Kinematic and kinetic variables of the deceleration test are presented in Table 6. The significant correlation coefficients between the kinematic variables of maximal deceleration and lower limb torque profiles are presented in Table 7.

4.5.1 Relationship between peak torque, RTD, and deceleration performance

Strong correlation was found between KE PT at $-30^\circ \cdot s^{-1}$ in NDL and F_{ave} ($r = -0.71$, $p=0.044$), P_{ave} ($r = -0.70$, $p = 0.005$), I_{ave} ($r = -0.68$, $p = 0.008$), F_{max} ($r = -0.61$, $p = 0.02$), and I_{max} ($r = -0.75$, $p = 0.002$), respectively accounting for 51%, 49%, 46%, 38%, and 56% of the explained variance (Table 7). In addition, KE PT at $60^\circ \cdot s^{-1}$ in the NDL leg was moderate correlated with F_{ave} ($r = -0.54$, $p= 0.044$) and I_{ave} ($r = -0.55$, $p = 0.043$) accounting for 29% and 30% of the explained variance, respectively (Table 7). Furthermore, moderate correlations were found between P_{max} and KE PT at $240^\circ \cdot s^{-1}$ in DL ($r = -0.57$, $p = 0.033$), and NDL ($r = -0.58$, $p = 0.031$), accounting for 33% and 34% of the explained variance, respectively. Besides, there was a moderate correlation between KF PT at $240^\circ \cdot s^{-1}$ in the DL and P_{max} ($r = -0.58$, $p = 0.03$), accounting for 24%, of the variance (Table 7). Moreover, a moderate/strong relationship was found between RTD of KE at $-30^\circ \cdot s^{-1}$ in DL and F_{ave} ($r = -0.54$, $p=0.04$), I_{ave} ($r = -0.54$, $p = 0.044$), and P_{ave} ($r = -0.63$, $p = 0.015$), accounting for 29 %, 39%, and 29% of the explained variance, respectively (Table 7).

Velocity		Muscle	Variable	DL	NDL	
($^{\circ} \cdot s^{-1}$)						
240	KE	PT	89.89 \pm 20.23	[78.21 – 101.56]	91.46 \pm 21.48	[79.06 – 103.87]
	KF	PT	55.23 \pm 16.08	[45.95 – 64.51]	54.92 \pm 15.79	[45.80 – 64.04]
60	KE	PT	129.56 \pm 21.08	[117.39 – 141.73]	130.02 \pm 19.49	[118.76 – 141.27]
		RTD	658.23 \pm 224.91	[528.37 – 788.09]	612.15 \pm 139.11	[531.83 – 692.48]
	KF	PT	72.04 \pm 14.00	[63.96 – 80.12]	73.59 \pm 17.09	[63.72 – 83.46]
		RTD	488.01 \pm 193.75	[376.14 – 599.88]	485.5 \pm 151.00	[398.32 – 572.69]
-30	KE	PT	160.65 \pm 34.61	[140.66 – 180.63]	163.49 \pm 32.55	[144.69 – 182.28]
		RTD	263.19 \pm 81.48	[216.14 – 310.23]	219.53 \pm 94.61	[164.90 – 274.16]
	KF	PT	95.90 \pm 17.01	[86.07 – 105.72]	97.52 \pm 18.65	[86.75 – 108.29]
		RTD	174.28 \pm 61.30	[138.87 – 209.87]	142.30 \pm 70.89	[101.37 – 183.24]

Table 4: Peak torque (PT in N.m), rate of torque development (RTD in N.m.s⁻¹) of knee extensors (KE) and knee flexors (KF) in dominant leg (DL) and non-dominant leg (NDL). All data are presented as mean \pm standard deviation with 95% confidence interval.

4.5.2 Relationship between strength ratios and deceleration performance

Interestingly, strong correlations between P_{max} and RTD H/Q at $60^\circ \cdot s^{-1}$ in DL ($r = -0.61$, $p = 0.022$), and moderate correlation between RTD H/Q in NDL and P_{max} ($r = -0.59$, $p = 0.028$) were observed, accounting for 37% and 34% of the variance, respectively (Table 7). In the DL, a moderate correlation was observed between RTD H/Q at $60^\circ \cdot s^{-1}$ and I_{max} ($r = -0.57$, $p = 0.035$), accounting for 32% of the variance (Table 7). In contrast, no significant relationship was observed between conventional H/Q ratio, functional H/Q ratio and deceleration performance (all $p > 0.05$).

Variable		DL	NDL
Conventional H/Q	H_{con60}/Q_{con60}	0.56 ± 0.14 [0.49 – 0.64]	0.56 ± 0.08 [0.51 – 0.61]
	H_{con240}/Q_{con240}	0.61 ± 0.10 [0.55 – 0.67]	0.60 ± 0.09 [0.54 – 0.65]
Functional H/Q	H_{ecc30}/Q_{con60}	0.75 ± 0.16 [0.66 – 0.84]	0.75 ± 0.08 [0.70 – 0.80]
	H_{ecc30}/Q_{con240}	1.09 ± 0.19 [0.98 – 1.20]	1.09 ± 0.21 [0.97 – 1.21]
RTD H/Q	$RTD H_{con}/Q_{con}$	0.81 ± 0.24 [0.67 – 0.95]	0.74 ± 0.15 [0.66 – 0.83]
	$RTD H_{con}/Q_{ecc}$	2.07 ± 0.67 [1.67 – 2.46]	2.45 ± 0.94 [1.90 – 2.99]

Table 5: Traditional H/Q and KF RTD to KE RTD ratio (RTD H/Q) in dominant leg (DL) and non-dominant leg (NDL). Con = concentric contraction, Ecc = eccentric contraction. 240 = $240^\circ s^{-1}$, 60 = $60^\circ s^{-1}$, 30 = $-30^\circ s^{-1}$. All data are presented as mean \pm standard deviation with 95% confidence interval.

Variable	Mean \pm SD	[95% CI]
Kinematic		
V_{max} (m.s ⁻¹)	6.41 \pm 0.59	[6.13 – 6.69]
Kinetic		
F_{ave} (N)	-300.38 \pm 57.20	[-327.46 – -273.31]
P_{ave} (W)	-1007.24 \pm 207.33	[-1105.37 – -909.11]
I_{ave} (N.s ⁻¹)	-6.00 \pm 1.24	[-6.58 – -5.41]
F_{max} (N)	-444.18 \pm 119.97	[-500.96 – -387.40]
P_{max} (W)	-1694.72 \pm 360.72	[-1865.45 – -1523.99]
I_{max} (N.s ⁻¹)	-12.70 \pm 2.60	[-13.94 – -11.47]

Table 6: Kinematic and kinetic variables during maximum deceleration. F_{ave} = average braking force; P_{ave} = average braking power; I_{ave} = average braking impulse; F_{max} = maximum braking force; P_{max} = maximum braking power; I_{max} = maximum braking impulse. All data are presented as mean \pm standard deviation with 95% confidence interval.

Variable	Correlation coefficient (r) (95% CI)	Coefficient of (r ²)	Qualitative inference	p-value
<i>F_{ave}</i>				
PT ₆₀ _KE_Con_NDL	-0.54 [-0.83 – -0.02]	30%	Moderate	0.044
PT ₃₀ _KE_Ecc_NDL	-0.71 [-0.90 – -0.30]	51%	Strong	0.004
RTD_KE_Ecc_DL	-0.54 [-0.83 – -0.03]	29%	Moderate	0.040
<i>P_{ave}</i>				
PT ₃₀ _KE_Ecc_NDL	-0.70 [-0.90 – -0.27]	49%	Strong	0.005
RTD_KE_Ecc_DL	-0.63 [-0.87 – -0.16]	39%	Strong	0.015
<i>I_{ave}</i>				
PT ₆₀ _KE_Con_NDL	-0.55 [-0.84 – -0.02]	30%	Moderate	0.043
PT ₃₀ _KE_Ecc_NDL	-0.68 [-0.89 – -0.23]	46%	Strong	0.008
RTD_KE_Ecc_DL	-0.54 [-0.85 – -0.01]	29%	Moderate	0.044
<i>F_{max}</i>				
PT ₃₀ _KE_Ecc_NDL	-0.61 [-0.86 – -0.12]	38%	Large	0.020
<i>P_{max}</i>				
PT ₂₄₀ _KE_Con_DL	-0.57 [-0.85 – -0.06]	33%	Moderate	0.033
PT ₂₄₀ _KE_Con_NDL	-0.58 [-0.85 – -0.07]	33%	Moderate	0.031
PT ₂₄₀ _KF_Con_DL	-0.58 [-0.85 – -0.07]	34%	Moderate	0.030
RTD H _{con} /Q _{con} _DL	-0.61 [-0.86 – 0.11]	37%	Strong	0.022
RTD H _{con} /Q _{con} _NDL	-0.59 [-0.85 – -0.08]	34%	Moderate	0.028
<i>I_{max}</i>				
PT ₃₀ _KE_Ecc_NDL	-0.75 [-0.92 – -0.37]	56%	Strong	0.002
RTD H _{con} /Q _{con} _DL	-0.57 [-0.84 – -0.05]	32%	Moderate	0.035

Table 7: Pearson's significant correlation results between the deceleration ability variable and lower limb peak torque, RTD H/Q ratio in dominant leg (DL) and non-dominant leg (NDL). *F_{ave}* = average horizontal braking force; *P_{ave}* = average braking power; *I_{ave}* = average braking impulse; *F_{max}* = maximum braking; *P_{max}* = maximum force power; *I_{max}* = maximum impulse; *PT* = peak torque; *KE* = knee extensors; *KF* = knee flexors; *Con* = concentric contraction; *Ecc* = eccentric contraction; 240 = 240° s⁻¹; 60 = 60° s⁻¹; 30 = -30° s⁻¹.

4.6 Discussion

The present study is the first to investigate the relationships between the capacities of the knee muscles' rapid torque production and mechanical variables related to deceleration performance in female professional soccer players. The main finding indicated a moderate to strong correlation of the knee extensors' eccentric maximal isokinetic torque and early phase RTD with the horizontal braking force, power, and impulse (all $r < -0.54$). In addition, a moderate correlation was observed between RTD H/Q and horizontal braking force, power and impulse ($r < -0.57$). The peak isokinetic concentric torque values of KE muscles in female soccer players were in the same range as those reported in previous studies (130 vs. 135 N.m, at $60^\circ \cdot s^{-1}$ and 90 vs. 99 N.m at $240^\circ \cdot s^{-1}$), whereas slightly lower concentric KF torque values were reported for elite female soccer players (Manson, Brughelli et al. 2014, Vargas, Motta et al. 2020). Additionally, participants of the present study presented lower eccentric isokinetic torque values for thigh muscle groups (KE: 163 vs. 241 N.m, KF: 97 vs. ~153 N.m).

Numerous previous studies already demonstrated that a high level of lower limb eccentric strength promotes deceleration performance and COD performance (Lockie, Schultz et al. 2012, Spiteri, Cochrane et al. 2013, Jones, Thomas et al. 2017, Harper, Jordan et al. 2021). Nevertheless, no previous studies revealed that the athletes with the highest KE eccentric torque produce greater horizontal braking force during the deceleration maneuvers. Jones et al., (2017) indicated the KE eccentric force at $60^\circ \cdot s^{-1}$ strongly correlated to 180° COD performance (Jones, Thomas et al. 2017). Besides, Harper et al., (2018) found that the KE eccentric torque at $60^\circ \cdot s^{-1}$ provided significant correlation ($r = -0.63$) with deceleration time to stop after 20-m sprinting (Harper, Jordan et al. 2021). These results are in accordance with KE eccentric torque at low angular velocity ($-30^\circ \cdot s^{-1}$) which largely correlated with F_{max} and I_{max} in the current study. Thus, it appears that the eccentric KE torque at low velocity was the main predictor (37.2% ~ 50.4%) of deceleration performance due to the higher KE eccentric torque that can partly contribute to the braking force to decelerate. Besides, KE and KF concentric torque at high angular velocity largely correlates with the P_{max} , which confirms the influence of thigh concentric strength on deceleration performance previously reported (Harper, Jordan et al. 2021). Such a correlation can be explained by the fact that power output depends on force and velocity capacities, and then braking power

may be better correlated with torque production at high velocity. Furthermore, the KF concentric torque could help to maintain hip joint stability as well as dynamically control knee flexion and the whole-body position during the deceleration maneuvers, which could contribute to a better deceleration performance (Sole, Milosavljevic et al. 2008, Jones, Thomas et al. 2017). In contrast, no relationship was found between KF eccentric torque and braking ability which was in line with Harper et al. (2017). Even if further studies are still needed to determine the length changes of knee flexors during the braking phase, it can be hypothesized that they are mostly contracted in an “isometric” way, which may explain the absence of correlation between KF isokinetic eccentric torque and deceleration performance.

Interestingly, a negative correlation was found between KE RTD during eccentric contraction and F_{ave} , P_{ave} , I_{ave} , but no correlation between the KE RTD during concentric contraction was observed. These results indicated that a high ability to rapidly produce eccentric force during eccentric contraction following the onset of contraction plays an important role in predicting braking ability. As mentioned previously, the maximal deceleration maneuver requires higher motor control demands of the lower limb, including rapid neuromuscular recruitment with higher eccentric force output of KE, and neuromuscular efficiency. The magnitude of the rapid contractile impulse of KE represented by RTD could contribute to an effective neuromuscular activation property of KE at the initial ground contact instant (i.e., pre-heel strike phase) before the more prolonged stance phase (i.e., heel to toe-off phase) (Hewit, Cronin et al. 2011, Jordan, Aagaard et al. 2015, Maffiuletti, Aagaard et al. 2016, Dos'Santos, Thomas et al. 2017). Thus, the higher KE RTD in eccentric contraction may contribute to a better passive torque rise (higher contribution of passive elements) to counterbalance the magnitude of GRF during maximal deceleration maneuvers resulting in higher braking force production. Yet, no relationship between KE RTD in concentric contraction and deceleration performance suggests that it may not be pertinent to measure the RTD during the concentric contraction to predict the braking force, perhaps due to the KE eccentric work during the stance phase of deceleration.

Meanwhile, whereas knee joint stability was considered as the paramount capacity to maintain a stable body center of gravity during dynamic movements such as jumping, loading, and cutting, which depend on the ability to rapidly reach a given antagonist to agonist joint moment relationship measured by the RTD H/Q (Zebis, Andersen et al. 2009, Zebis, Andersen et al. 2011), a moderate

correlation was found between the RTD H_{con}/Q_{con} ratios and deceleration performance (e.g., P_{max} , I_{max}). It can be hypothesized that the ability to have optimal neuromuscular control between the KE and the KF following a higher RTD H/Q can increase the stiffness of the lower limb to efficiently and quickly absorb the GRF while maintaining knee joint dynamic stability (De Ste Croix, ElNagar et al. 2017). As a result, the higher RTD H_{con}/Q_{con} ratio could induce better knee joint dynamic stability following the rapid knee joint moment and contribute to efficient KE eccentric force output to absorb the impact force by the support and reduce the mechanical stress on joint structures when the trunk is oriented backward (Hewit, Cronin et al. 2011, Sasaki, Nagano et al. 2011), thus outputting a higher P_{max} , I_{max} . However, the extent of no relationship between RTD H_{con}/Q_{ecc} and deceleration performance remains poorly understood. In contrast, no correlation was found between the traditional H/Q ratio (i.e., conventional or functional ratios) and deceleration performance. This result is not surprising if one refers to recent articles investigating these ratios and their arguments for improving performance and preventing injury (Grygorowicz, Michalowska et al. 2017). Indeed, these ratios are criticized for being calculated on different angles of maximum torque production for the two muscle groups, which could detect knee force imbalance but do not predict knee muscle co-activation capacity. Thus, it seems interesting to measure the RTD H_{con}/Q_{con} ratios in soccer players to determine to what extent their deceleration performance is limited or not by an RTD H/Q ratio deficit. As results, it now seems preferable to focus on angle-specific H/Q ratios and explosive force ratios (RTD H/Q ratios) (Greco, Da Silva et al. 2012, Zhang, Morel et al. 2021).

Previous studies revealed that the symmetry between DL and NDL might play an essential role in COD performance (Thomas, Dos'Santos et al. 2020) and ACL injury (Brophy, Silvers et al. 2010). Soccer is a single-leg-dominant laterality sport because the soccer player nearly always uses the DL to manipulate the ball (i.e., kicking or passing), whereas the NDL is often used to control dynamic body stability (Wong, Chamari et al. 2007). Moreover, the most striking observation to emerge from the present results was that greater correlations were obtained between the peak torque of the NDL and braking ability as well as between the RTD H/Q of the DL and braking ability. Firstly, the fact that the DL RTD H/Q ratios were correlated to deceleration performance can be explained by the fact that this leg is not often used to stabilize the body in specific soccer movements. Therefore, the player's ability to be explosive while quickly stabilizing the knee with

this leg could be essential. We can assume that the DL became decisive in the ability to decelerate quickly and stop in a stable position before performing another explosive action because this is not the most common action performed by this leg. Therefore, other parameters must influence the relationship between muscle capacities of the DL and the NDL and braking ability. We can assume that the two legs have different functions in this type of movement. The NDL might cushion impacts while the other might be more involved in stabilizing the body and maintaining balance. This could explain why the PT of the DL and the RTD H/Q ratio of the DL was identically correlated to braking ability. The first one contributes to the dissipation of kinetic energy, and the second one participates in body stabilization.

4.7 Limitation

When interpreting the current findings, two limitations should be considered. Firstly, our population consisted merely of fourteen female professional football players. Thus, future studies should investigate male soccer players to confirm the present results. Secondly, isokinetic dynamometers are often more compliant due to the compression of soft-tissue at the beginning of the contraction and noisier than strain gauges, potentially increasing errors in the calculation of RFD (Maffiuletti, Aagaard et al. 2016).

4.8 Conclusion

Taken together, the present study highlights the close relationship of KE eccentric PT and RTD, as well as RTD H/Q and deceleration performance. These findings revealed that for athletes with greater KE torque in eccentric at a slow angular velocity and concentric contractions at moderate angular velocity, the KE RTD of eccentric contraction could produce higher horizontal braking force and impulse. Furthermore, the RTD H/Q ratio in concentric contraction might determine knee joint dynamic stability allowing to consider new goals for improving performance and preventing injuries in soccer players. Moreover, it appears that training should aim to reduce the asymmetry between the two legs and, if possible, improve the explosive neuromuscular force of the NDL because this could enhance deceleration performance and reduce the potential ACL injury risk factor during deceleration and COD tasks.

4.9 Practical applications

Given the high-intensity linear deceleration demand during the competitive match and its role in determining the change of direction performance, the current findings suggest that athlete requires to develop the eccentric strength of the knee extensor to improve the deceleration performance following the braking ability increased (i.e., braking force, braking power, braking impulse). For instance, an inertial eccentric-overload training program including flywheels device could be used to develop the eccentric strength (Petré, Wernstål et al. 2018) and also reduce the risk of musculoskeletal injury (i.e., ACL) associated with decelerating (Donelon, Dos'Santos et al. 2020). Besides, the present study also indicated the critical role of early RTD during the eccentric contraction in determining the deceleration performance, suggesting that resistance training with the highest possible acceleration should be performed to promote early RTD. Moreover, considering the early phase RTD H/Q ratio may more accurately reflect the potential for dynamic knee joint stabilization during rapid limb movement (Zebis, Andersen et al. 2011). It was suggested that early phase H/Q RTD might help identify players at a potentially greater risk for a knee injury during the deceleration task.

**CHAPTER 5 Influence of Jump-Landing on Dynamic Postural
Stability and Hamstring-to-Quadriceps Co-Activation Ratio**

5.1 Abstract en Français

Le but de cette enquête était de déterminer l'influence de la direction de saut et de la dominance des jambes sur l'indice de stabilité posturale dynamique (DPSI) et la relation entre cet indice et le rapport de co-activation ischio-jambiers / quadriceps chez les athlètes féminines. Quinze femmes en forme ($24,4 \pm 3,2$ ans, $59,3 \pm 3,4$ kg et $165,8 \pm 6,5$ m) se sont portées volontaires pour participer à cette enquête. Les participants devaient effectuer au hasard les manœuvres d'atterrissage unilatérales, à la fois pour la jambe dominante et non dominante dans différentes directions d'atterrissage, y compris l'atterrissage en saut antérieur (AJL), l'atterrissage en saut latéral (LJL) et l'atterrissage en saut d'obstacles (DJL). L'indice de stabilité posturale dynamique (DPSI) a été calculé en utilisant les 3 premières secondes des données de force de réaction au sol après le contact avec le sol (le DPSI le plus élevé, la stabilité dynamique la plus faible). Le rapport de co-activation ischio-jambiers-quadriceps (H/Q) a été calculé par rapport d'amplitude RMS EMG ischio-jambiers et quadriceps sur 110ms (10ms avant et 100ms après contact au sol). Ces résultats ont indiqué que le DPSI était plus élevé dans DJL que dans LJL et AJL (tous $p < 0,05$). Plus précisément, le score DPSI pendant DJL était plus élevé dans NDL par rapport à DL. Aucune différence significative dans le score DPSI n'a été trouvée entre AJL et LJL indépendamment de la dominance de la jambe. En outre, le rapport de co-activation H/Q était plus élevé dans DL que dans NDL pendant DJL, alors qu'aucune différence n'a été trouvée pendant AJL et LJL. De plus, une corrélation significative a été trouvée entre le rapport de co-activation H / Q et le DPSI moyen dans la jambe dominante pendant l'AJL ($r = -0,57$, $p = 0,02$). Les résultats actuels ont indiqué que DJL était plus approprié pour évaluer la stabilité posturale dynamique car il permet de provoquer l'asymétrie de dominance des membres et induit des forces de réaction au sol plus importantes. De plus, ces résultats démontrent que la co-activation H/Q joue un rôle essentiel dans la détermination de la stabilité dynamique lors de l'atterrissage. La présente étude pourrait être utilisée par les cliniciens lors du dépistage du risque potentiel de lésion du LCA et par les formateurs pour développer des programmes de prévention et de réadaptation.

Abstraction in English

The purpose of this investigation was to determine the influence of jump-landing direction and leg dominance on the Dynamic Postural Stability Index (DPSI) and the relationship between this index and the hamstring-to-quadriceps co-activation ratio in female athletes. Fifteen fitness females (24.4 ± 3.2 age, 59.3 ± 3.4 kg, and 165.8 ± 6.5 m) volunteered to participate in this investigation. Participants were required to randomly perform the unilateral landing maneuvers, both for the dominant and the non-dominant leg in different landing directions, including the anterior jump landing (AJL), lateral jump landing (LJL), and drop jump landing (DJL). Dynamic postural stability index (DPSI) was computed using the first 3-s of the ground reaction force data after ground contact (the highest DPSI, the lowest dynamic stability). Hamstring-to-quadriceps (H/Q) co-activation ratio was calculated by hamstring-to-quadriceps RMS EMG amplitude ratio over 110-ms (10-ms before and 100-ms after ground contact). These results indicated that the DPSI was higher in DJL compared to LJL and AJL (all $p < 0.05$). More specifically, the DPSI score during DJL was higher in NDL compared with DL. No significant difference in DPSI score was found between AJL and LJL irrespective of leg dominance. Besides, the H/Q co-activation ratio was higher in DL than in NDL during DJL, whereas no difference was found during AJL and LJL. Furthermore, a significant correlation was found between H/Q co-activation ratio and mean DPSI in the dominant leg during AJL ($r = -0.57$, $p = 0.02$). Current results indicated that DJL was more appropriate to evaluate the dynamic postural stability since it permits to elicit the limb dominance asymmetry and induces larger ground reaction forces. Moreover, these findings demonstrate that the H/Q co-activation plays an essential role in determining the dynamic stability during landing. The present study might be used by clinicians when screening the potential risk of ACL injury and by trainers to develop prevention and rehabilitation programs.

Keywords: landing maneuverer, ground reaction forces, knee joint stabilization

5.2 Introduction

Noncontact anterior cruciate ligament (ACL) injuries account for approximately 70~84 % of all knee injuries (Gianotti, Marshall et al. 2009, Moses, Orchard et al. 2012, Della Villa, Buckthorpe et al. 2020) . In the basic of biomechanical analysis, the common mechanism of ACL injuries occurs when the athletes land in a knock-knee position, such as dropping, cutting, and change of direction maneuvers (Zebis, Andersen et al. 2009, Havens and Sigward 2015, Fox 2018). It was considered that the lower-limb kinetics and kinematics during these susceptible tasks, including the dynamic knee valgus, associated with tibial rotation and hip adduction, maximum knee flexion, and peak ground reaction force, could induce the excessive anterior shear forces in the ACL (McLean, Lipfert et al. 2004, Hewett, Myer et al. 2005, Alentorn-Geli, Myer et al. 2009, Quatman and Hewett 2009). The knee flexor muscles are described as one of the primary active restraints for anterior tibial translation during susceptible tasks such as drop landing maneuvers (Renström, Arms et al. 1986). Also, the hamstring-to-quadriceps co-contraction might be an effective factor against ACL injuries in reducing excessive forces in the ACL, particularly after the initial ground contact phase within 37~50ms (Li, Rudy et al. 1999, Zebis, Andersen et al. 2011). Thus, the ability to rapidly co-activate the knee flexor (i.e., hamstring) in coordination with the quadriceps contraction is critical to determine the knee dynamic stability and to decrease the anterior shear forces of ACL. Previous research has already studied the hamstring to quadriceps muscle activation for female and male athletes during various functional movements (Krishnan and Williams 2009, Ebben, Fauth et al. 2010). Results from these studies indicated that the females showed higher activation of quadriceps comparing to males during the functional movement such as drop landing and cutting with similar activation of hamstrings. These findings could partially explain why female athletes sustain a greater risk for ACL injury.

The jump-landing test was usually used in a laboratory setting to assess the dynamic stability and the lower limb kinetics and kinematics parameters as well as the neuromuscular control associated (Myer, Ford et al. 2005, Reid, Birmingham et al. 2007). It has been suggested that the different jump-landing tasks (i.e., drop landing, lateral landing) could produce significantly different biomechanical results due to the variations in task parameters such as fall height, direction, subsequent action (Collings, Gorman et al. 2019). Wikstrom et al. (2008) reported that the jump-

landing direction could significantly affect the dynamic postural stability performance (Wikstrom, Tillman et al. 2008), and Mokhtarzadeh et al., (2017) found the landing from a greater height resulted in significant higher ACL loading (Mokhtarzadeh, Ewing et al. 2017). In addition, previous evidence regarding knee injuries has shown significant difference between dominant and non-dominant leg regarding the injury occurrence (Mokhtarzadeh, Ewing et al. 2017). Ruedl et al. (2012) indicated that the female athlete is more prone to suffering from an ACL injury on their non-dominant leg (Ruedl, Webhofer et al. 2012). This finding s could be supported by the recent study of Morishige et al. (2019), which investigated the relationship between leg dominance and knee biomechanics in females. They found that the peak knee abduction and internal rotation angle are significantly larger in the dominant leg compared to the non-dominant leg during the drop-landing task (Morishige, Harato et al. 2019), as a consequence, a higher risk of ACL injury displays in the non-dominant leg. Thus, it seems that evaluating dynamic stability in different landing tasks may permit to better understand and predict injury risk in female athletes. However, even if the influence of many parameters on the dynamic stability has been partly explored, in fact no study tried to determine which test is the more convenient to discriminate stabilization capacity between subjects and to investigate leg asymmetry.

This study aims to compare different jump tests to determine the level of ground reaction forces and the stability index for each direction. It was hypothesized that the more suitable test would induce higher force constraints and higher differences between dominant and non-dominant legs. Furthermore, such an evaluation may be associated with an assessment of hamstring and quadriceps activation and co-activation in order to explain the dynamic stability differences between jumps and between legs. We hypothesized that *i*) drop jump landing is the most suitable test because it induces higher ground reaction forces and lower dynamic stability, *ii*) the dominant leg displays the better stability index *iii*) the level of Hamstring muscles coactivation could partly explain the differences in dynamic stability between subjects.

5.3 Methods

5.3.1 Participants

Fifteen fitness females (24.4 ± 3.2 age, 59.3 ± 3.4 kg, and 165.8 ± 6.5 cm) volunteered to participate in this investigation. All participants had no history of traumatic lower limb injuries

(ACL rupture, ankle strain, etc.) preceding the study. The study was approved by the local ethics committee (i.e., Lyon II), conforming to the standards of the Declaration of Helsinki. All participants were recreationally active: defined as self-reporting participation in sports at least 6 hours per week. Sport practices included recreational fitness activities such as jogging, running, and weightlifting. They were free from lower extremity injuries and did not report sustaining an ankle sprain injury within the six weeks before the participation. All subjects have been informed about the procedure and gave their written informed consent to participate in the study. The estimated sample size ($n = 13$ at least) was a priori calculated using a sample size calculator (G-Power 3.1, Brunsbüttel, Germany) assuming the effect size = 0.5 (moderate), the α -error = 0.05 and $1-\beta > 0.8$ (Faul, Erdfelder et al. 2007).

5.3.2 Experimental procedures

A randomized measurement (jump-landing direction, leg dominance) study design was used for the present study. All the participants were tested in a biomechanics laboratory at a single occasion. On the test day, the participant was first introduced to the test protocol. A standard warm-up protocol was performed, consisting of 8 minutes of cycling (70 to 80 RPM at a self-paced power inducing heart rate lower than 75% of maximal heart rate) on a cycle ergometer, 10 SJ, and 8 CMJ. After that, the bipolar sEMG electrodes (Delsys Trigno™ Wireless EMG System, bipolar Ag: AgCl surface, 2 cm inter-electrode distance) (Delsys, Inc., Boston, United States) were fixed on the participant's rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), biceps femoris long-head (BF), and semitendinosus (ST) muscles both for dominant and non-dominant leg following the SENIAM guidelines. The skin was shaved and cleaned using an alcohol wipe before affixing the sEMG electrode. The sampling rate of sEMG was 2000 Hz, and the standard mode of rejection ratio was greater than 80 dB. Once the participants were equipped with the EMG electrodes, they were asked to perform the isometric maximum voluntary contraction (IMVC) of knee extensor and flexor muscles for the two legs according to the previous method described by Lsank et al., 2013 and using a portable hand-held dynamometry with a sampling frequency of 100Hz (Hoggan MicroFET2, Scientific L.L.C., Salt Lake City, USA) (Thorborg, Bandholm et al. 2013, Lesnak, Anderson et al. 2019). The knee angle was fixed at 90° and 20° for the knee extensor and flexor, respectively, during the IMVC test. Three isometric warm-up trials with contractions at approximately 50% of maximal were followed by three IMVC trials for a duration of 3~4

seconds, separated by 60 seconds (Mentiplay, Perraton et al. 2015). Both legs were tested separately in a randomized order and separated by 3-min.

After the IMVC test, the participants were asked to stand up straight on the force platform with feet together for 6-seconds to calculate the body weight. Afterward, the participants randomly performed the anterior-jump landing (AJL), lateral jump landing (LJL), and drop-jump landing (DJL) maneuver for a unilateral assessment, the dominant (DL) or non-dominant leg (NDL). The jump landing maneuver and leg dominance were randomly assigned to improve the generalization of the results. Limb dominance was defined as the limb that the subject preferentially used to kick a soccer ball. During the jump landing maneuver, ground reaction force data were collected using a Kistler force platform (Type 9286B, Kistler Instrument Corp., Amherst, NY). The force platform's analog signal was converted to a digital signal and acquired using Qualisys Analog Interface (Qualisys Motion Systems, Göteborg, Sweden) at 200 Hz, synchronized with Delsys EMG system. The force platform was mounted flush with the surrounding custom-built flooring from which the participants perform the barefoot jump landing maneuvers. Each participant was given at least six practice trials to familiarize each jump-landing task before recording the results. During the jump-landing maneuver, the participants were asked to keep their hands on the hips. For AJL and LJL, the participant stands on two feet at the jump distance, which was 40% and 33%, respectively of the participant's height from the edge of a force plate (Sell 2012). Participants were instructed to jump anterior facing the force plate over a 12-inch hurdle or jump laterally facing lateral the force plate over a 6-inch hurdle for AJL and LJL, respectively, and landed on a single leg on the force plate. For the DJL maneuver, the participant stands on two feet on a 30 cm platform, which was placed 10 cm posterior to the force plate. The participant was instructed to take off using a small jump with two feet, landing on the single leg on the force plate. The participants were asked to stabilize as quickly as possible after ground contact and remain as motionless as possible in a single-leg stance for 10-s. Measurement was continued until three successful trials were accomplished consecutively with a 2-minute recovery period to prevent fatigue. Trials were considered invalid if the participant's non-stance limb touched the stance limb or the ground around the force plate or if the participant's hands touched the floor or if the arm movement was used to regain balance or it came in contact with the hurdle (Sell 2012, Heebner,

Akins et al. 2015, Frasz, Huurnink et al. 2016). A total of three successful trials were collected for each jump-landing maneuver and each leg used for data analysis.

5.3.3 Measurements and Data processing

5.3.3.1 Dynamic Postural Stability Index (DPSI)

A custom MATLAB (v9.9.0, Natick, Massachusetts) script file was used to process the ground reaction force data for calculating the dynamic postural stability index (DPSI) and its directional components (Wikstrom, Tillman et al. 2005). This method reveals the stability indices (SI), which was calculated by the mean square deviations assessing fluctuations around a 0 of the ground reaction force (GRF) in the three directions during the landing task: anterior-posterior (APSI), medial-lateral (MLSI), vertical (VSI). Besides, the DPSI is a composite of the APSI, MLSI, and VSI. The DPSI calculation equation and its three directional composites are depicted in Table 8. DPSI score and its three directional composites were computed using the first 3-s of the ground reaction force immediately following initial contact identified as the instant the vertical ground reaction force exceeded 5% body weight (BW) (Heebner, Akins et al. 2015). The BW was determined before data collection and calculated as the average of the vertical GRF during a 5-second window static stance. The GRF in three directions as mentioned above, measured in Newtons, were expressed as the magnitude of the peak force divided by the subject's body weight (BW). Higher stability indices and DPSI scores represent worse dynamic postural stability. The three successful trials were averaged and used for further analysis. The previous investigations indicated this method demonstrated good test-retest reliability with ICC values 0.86 ~ 0.90 with SEM values 0.028 ~ 0.06 (Wikstrom, Tillman et al. 2005, Sell 2012).

5.3.3.2 Isometric Maximum Voluntary Contraction (IMVC)

The knee flexion and extension maximal torques were calculated as the average of three maximal contractions. All force measures were normalized to body weight and converted into knee flexor and extensor torque multiplying recorded force by the length of the external lever arm, defined as the distance from the knee joint line to the placement of the centre of pressure pad of the dynamometer (Thorborg, Bandholm et al. 2013).

5.3.3.3 Hamstring-to-Quadriceps (H/Q) Co-Activation Ratio

The EMG data were analyzed using a custom MATLAB script file. The raw EMG data were high-pass filtered with 4th order zero-lag Butterworth filter at a 5-Hz cutoff frequency. Subsequently, it was smoothed by a symmetrical moving root mean square (RMS) filter of 30 milliseconds. The RMS EMG amplitude was obtained instantly before ground contact, defined as 10 milliseconds before and 100ms as pre- and post-ground contact period after foot strike on the force plate, and subsequently normalized to the peak RMS EMG amplitude recorded IMVC testing (Zebis, Andersen et al. 2009). Then, Normalized RMS EMG were used to derive hamstring to quadriceps co-activation ratios for each jump-landing maneuvers in the different direction. The hamstring-to-quadriceps co-activation ratios were calculated by taking the collective average of the BF and ST RMS EMG and dividing the collective average of the RF, VL, and VM (Ebben, Fauth et al. 2010).

$$\text{Anterior-Posterior Stability Index} = \sqrt{\frac{\sum (0 - x)^2}{\text{number of data point}}}$$

$$\text{Medial-Lateral Stability Index} = \sqrt{\frac{\sum (0 - y)^2}{\text{number of data point}}}$$

$$\text{Vertical Stability Index} = \sqrt{\frac{\sum (0 - z)^2}{\text{number of data point}}}$$

$$\text{Dynamic Postural Stability Index} = \sqrt{\frac{\sum (0 - x)^2 + \sum (0 - y)^2 + \sum (0 - z)^2}{\text{number of data points}}}$$

Table 8: *Dynamic Postural Stability and directional stability indexes formulae. x, y, and z are the GRF in the anterior-posterior, medial-lateral, and vertical directions, respectively.*

5.3.4 Statistical Analysis

A linear mixed-effect model was then used to evaluate the interaction effect between movement (AJL vs. LJL vs. DJL) and the main effect of the leg (DL vs. NDL) on the DPSI score, GRF, and H/Q co-activation ratio. In the case of a significant interaction effect, A Tukey HSD post-hoc test pairwise comparisons were performed to determine where specific differences lay. The adjustment of the *p-value* obtained was multiplied by 15 comparisons with the new critical *p-value* of 0.003 (Bonferroni correction: 0.05/15). A paired t-test was used to compare the IMVC between dominant and non-dominant leg. Pearson's product-moment correlation coefficients (*r*) were calculated to examine the relationship between the H/Q co-activation ratio and DPSI score within three principal direction. The magnitude of the correlation coefficient was interpreted using criteria: very weak (0.11 ~ 0.19), weak (0.20 ~ 0.39), moderate (0.40 ~ 0.59), strong (0.60 ~ 0.79), and very strong (0.80 ~1.00) (Evans 1996). The *p-value* was set at a 0.05 significance level. All statistical procedures were performed with R software (R 3.5.0, RCore Team, Vienna, Austria). All data are presented as mean \pm SD.

5.4 Results

5.4.1 Dynamic Postural Stability Indexes

The APSI revealed a significant difference among the jump landing direction, while non-significant difference between DL and NDL ($p < 0.05$). Tukey's post-hoc test indicated that the APSI during DJL and AJL are higher than LJL, irrespective of the leg dominance ($p < 0.05$) (Figure 20). Also, a significant interaction effect between jump-landing direction and leg dominance was found for the MLSI score ($p < 0.05$). Tukey's post-hoc found that the LJL produces a significantly higher MLSI score compared to DJL ($p < 0.05$), whereas the MLSI score decreased progressively in order in NDL (DJL > LJL > AJL) ($P < 0.01$) (Figure 20). More specifically, the MLSI score was higher in NDL than DL during DJL ($p < 0.01$). Furthermore, the VSI score non-significant effect of jump landing direction in DL leg was found. In contrast, the Tukey post-hoc analysis indicated the VSI score in NDL during DJL was higher than that measured in LJL and AJL. Moreover, the VSI score in NDL was higher compared to DL during DJL ($p < 0.01$) (Figure 20). The DPSI score revealed a significant interaction effect between jump-landing direction and leg dominance. Holm's Bonferroni post-hoc test indicated that the DPSI score was significantly higher

in DJL than in AJL and LJL, whatever the leg dominance. Besides, no significant difference was found in the DPSI score between DL and NDL for AJL and LJL, whereas the DPSI score of NDL was significantly higher than DL during DJL ($p < 0.002$) (Figure 20). The descriptive data (mean \pm SD) of the Dynamic Postural Indexes (DPSI, APSI, MLSI, and VSI) are presented in the Table 9.

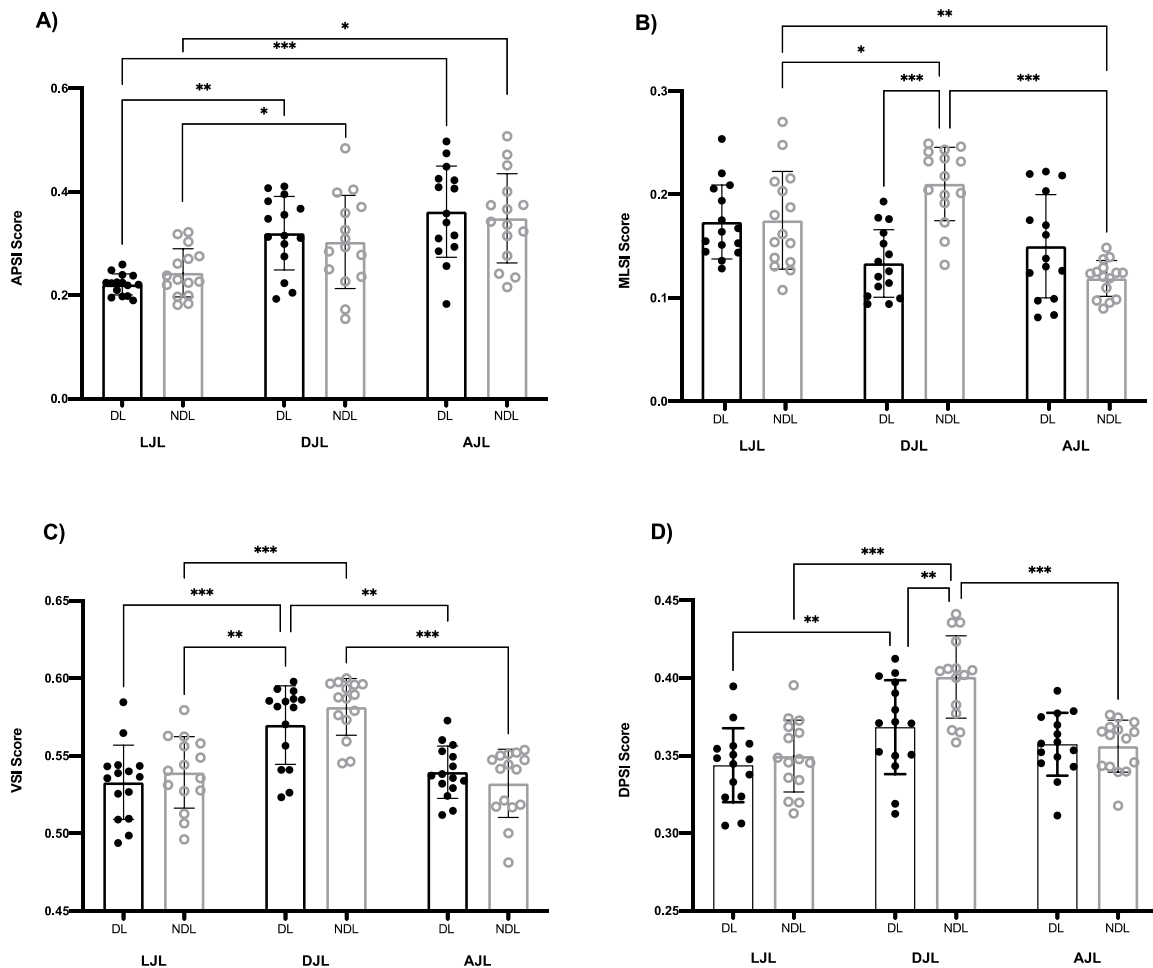


Figure 20: Dynamic stability score during lateral-jump landing (LJL), drop-jump landing (DJL), and anterior-jump landing (AJL). A): APSI = Anterior-posterior stability index, B): MLSI = Medial-lateral stability index, C): VSI = Vertical stability index, D): DPSI = Dynamic Postural Stability Index. DL = dominant leg, NDL = non-dominant. * significant difference for $p < 0.05$. ** Significant difference for $p < 0.01$. *** Significantly different for ($p < 0.001$).

	Lateral-jump landing		Drop-jump landing		Anterior-jump landing	
	DL	NDL	DL	NDL	DL	NDL
APSI	0.22 ± 0.02	0.24 ± 0.04	0.31 ± 0.07	0.28 ± 0.10	0.36 ± 0.08	0.34 ± 0.09
MLSI	0.17 ± 0.03	0.12 ± 0.02	0.12 ± 0.03	0.21 ± 0.04	0.15 ± 0.05	0.12 ± 0.1
VSI	0.53 ± 0.02	0.52 ± 0.02	0.55 ± 0.03	0.58 ± 0.03	0.54 ± 0.02	0.53 ± 0.02
DPSI	0.34 ± 0.3	0.35 ± 0.02†	0.37 ± 0.02	0.40 ± 0.03	0.35 ± 0.02	0.36 ± 0.01

Table 9: Dynamic postural stability score during lateral-jump landing, drop-jump landing, and anterior-jump landing. APSI: Anterior-posterior stability index, MLSI: Medial-lateral stability index, VSI: Vertical stability index, DPSI: Dynamic Postural Stability Index. DL: dominant leg, NDL: non-dominant. All data are presented as mean ± SD.

5.4.2 Ground reaction forces (GRF)

The anterior-posterior GRF reduced gradually in order of the AJL, DJL, and LJL irrespective of the leg dominance (all $p < 0.01$). In contrast, no influence of leg dominance was found whatever the jump-direction (all $p > 0.05$) (Figure 21-A). Besides, lateral-medial GRF was significantly higher during the LJL than DJL and AJL ($p < 0.05$). Tukey's post-hoc analysis found the lateral-medial GRF in the NDL was significantly higher than DL during the DJL and NDL during AJL (all $p < 0.05$), but the non-significant difference compared to NDL during LJL ($p > 0.05$) (Figure 21-B). Moreover, the vertical GRF during DJL was significantly higher compared to LJL and AJL irrespective of leg dominance (all $p < 0.01$), whereas no effect of leg dominance was found (all $p > 0.05$). In contrast, no significant difference between AJL and LJL was observed irrespective of leg dominance ($p > 0.05$) (Figure 21-C). The descriptive data (mean ± SD) of the GRF are presented in Table 10.

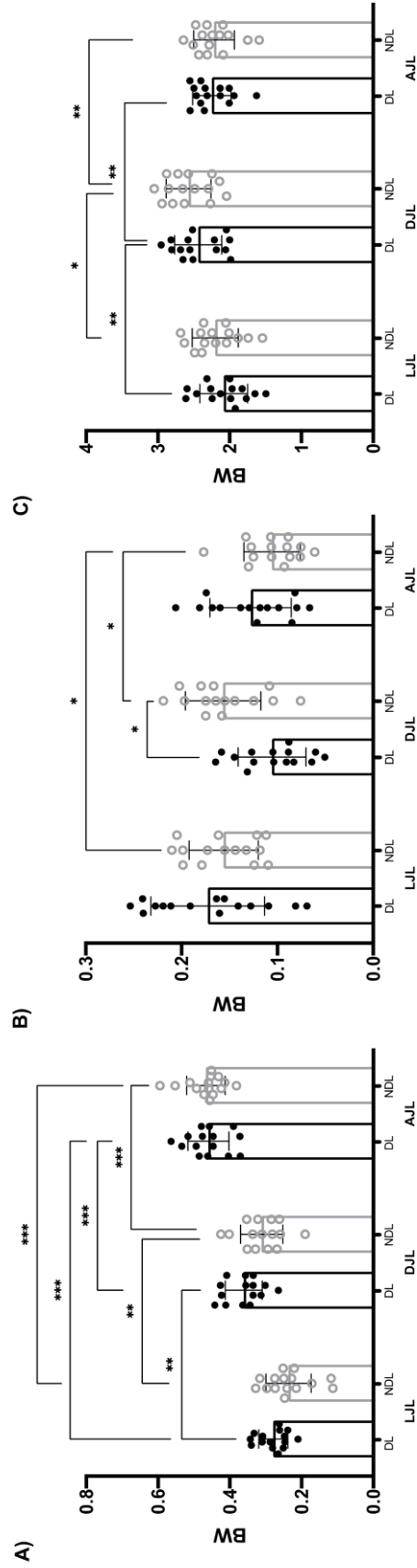


Figure 21: Ground Reaction Force (GRF) in Anterior-Posterior direction (A), Medial-Lateral direction (B), and Vertical direction (C) during lateral-jump landing (LJL), drop-jump landing (DJL), and anterior-jump landing (AJL). DL: dominant leg, NDL: non-dominant. * significant difference for $p < 0.05$. ** Significant difference for $p < 0.01$. *** Significant difference for $p < 0.001$.

	Lateral Jump Landing		Drop Jump Landing		Anterior Jump Landing	
	DL	NDL	DL	NDL	DL	NDL
GRF in Anterior-Posterior	0.27 ± 0.23	0.24 ± 0.06	0.36 ± 0.05	0.31 ± 0.06	0.46 ± 0.06	0.47 ± 0.05
GRF in Medial-Lateral	0.17 ± 0.05	0.15 ± 0.01	0.11 ± 0.06	0.15 ± 0.03	0.12 ± 0.04	0.11 ± 0.02
GRF in Vertical	2.08 ± 0.32	2.20 ± 0.32	2.44 ± 0.35	2.57 ± 0.34	2.25 ± 0.26	2.22 ± 0.28

Table 10: Ground reaction force (GRF) in body weight (BW) during lateral-jump landing, drop-jump landing, and anterior-jump landing. DL: dominant leg, NDL: non-dominant. All data are presented as mean ± SD.

5.4.3 Isometric Maximum Voluntary Contraction (IMVC)

Absolute and relative peak torque of knee extensor and flexor revealed significantly higher torques in DL compared to NDL (all $p < 0.05$) (Table 11).

	DL	NDL	Difference (95% CI)	Effect Size	p-value
Knee extensors					
Absolute PT	158.40 ± 45.51	141.20 ± 32.06	15.69 [6.5 to 24.86]	0.88	0.0023
Relative PT	2.69 ± 0.82	2.39 ± 0.59	0.30 [0.11 to 0.48]	0.89	0.0036
Knee flexors					
Absolute PT	92.83 ± 84.97	84.97 ± 17.51	7.85 [3.23 to 12.47]	0.87	0.0022
Relative PT	1.51 ± 0.34	1.41 ± 0.32	0.14 [0.06 to 0.22]	0.96	0.0024

Table 11: Absolute (Nm) and relative ($N.m.kg^{-1}$) Peak torque (PT) of knee extensor and flexor in both dominant (DL) and non-dominant leg (NDL). All data are presented as mean ± SD.

5.4.4 H/Q Co-Activation Ratio

Meanwhile, a significant interaction effect of leg dominance and jump-landing direction on the H/Q co-activation ratio was found. Holm's Bonferroni post-hoc test indicated that the H/Q co-activation ratio was significantly higher in DL compared to NDL during DJL ($p < 0.01$), whereas no significant difference was found in the H/Q co-activation between DL and NDL during AJL and LJL (all $p > 0.05$) (Figure 22-A). Besides, a significant correlation between DPSI score and H/Q co-activation ratio during AJL ($r = -0.57$, $p = 0.02$) in DL (Figure 22-B), whereas no significant correlation was found during AJL and LJL. The descriptive data (mean \pm SD) of the hamstring and quadriceps muscle activation, and H/Q coactivation ratio are presented in the table 12.

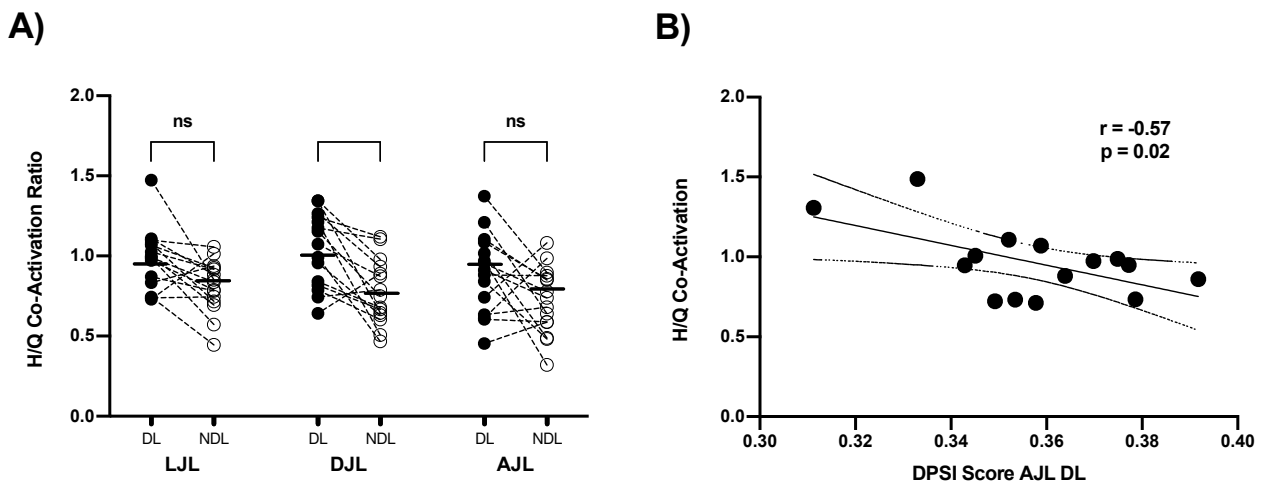


Figure 22: A) H/Q Co-Activation during lateral-jump landing (LJL), drop-jump landing (DJL), and anterior-jump landing (AJL). B) Significant Relationship between H/Q Co-activation Ratio and Dynamic Postural Stability Score (DPSI) in dominant leg during drop anterior jump landing maneuvers. *Significant difference for $p < 0.05$. ns: no-significant difference for $p > 0.05$. DL = dominant leg. NDL = non-dominant leg.

	Lateral Jump Landing		Drop Jump Landing		Anterior Jump Landing	
	DL	NDL	DL	NDL	DL	NDL
BF	56.81 ± 17.63	46.71 ± 19.61	62.62 ± 15.46	50.41 ± 22.72	48.72 ± 12.46	33.63 ± 17.91
ST	51.92 ± 12.52	42.92 ± 19.3	56.62 ± 16.53	44.25 ± 16.12	46.52 ± 13.62	33.12 ± 11.55
VL	57.15 ± 16.5	58.23 ± 30.7	56.15 ± 16.91	65.71 ± 33.43	54.12 ± 25.01	48.92 ± 25.02
RF	52.63 ± 14.62	54.91 ± 14.93	57.42 ± 20.75	53.52 ± 21.62	44.91 ± 23.33	44.93 ± 23.43
VM	55.73 ± 18.82	57.94 ± 16.91	63.42 ± 18.13	55.85 ± 32.14	48.25 ± 18.12	50.74 ± 27.72
H/Q Co-Activation Ratio	0.98 ± 0.21	0.78 ± 0.28	1.01 ± 0.27	0.81 ± 0.22	0.96 ± 0.40	0.71 ± 0.29

Table 12: The percentage of muscle activation relative to IMVC (%) for each muscle and Hamstring to Quadriceps co-activation ratio during lateral-jump landing, drop-jump landing, and anterior-jump landing. BF: biceps femoris, ST: semitendinosus, VL: vastus lateralis, RF: rectus femoris, VM: vastus medialis. DL: dominant leg. NDL: non-dominant leg. All data are presented as mean ± SD.

5.5 Discussion

The present study investigated the Dynamic Postural Index (DPSI) and H/Q co-activation ratio in the different jump-landing directions for DL and NDL legs. The main finding of the current study clearly indicated that the DPSI score is affected by the jump-landing direction. Also, the dominant leg showed better dynamic postural stability during the drop jump landing associated with a higher H/Q co-activation at the first milliseconds of the contact strike. Furthermore, a significant correlation was observed between H/Q coactivation and some stability indexes.

5.5.1 What does stability indexes measure exactly?

Measures of dynamic postural stability permit to evaluate how well the COM can be decelerated and the oscillation of the COM controlled (Ross and Guskiewicz 2004). The DPSI combines the mean squared deviations of GRF from 0 to 3 s following landing in vertical, anterior-posterior, and medial-lateral directions into one comprehensive measure, which globally reflect the ability to control directional components of the balance (Wikstrom, Tillman et al. 2005). Besides, apart from the DPSI, some authors used the time to stability (TTS) to assess dynamic stability, which evaluates the minimum time required to minimize the oscillations of the GRF (i.e., static position) (Huurnink, Fransz et al. 2019). Huurnink et al., (2019) investigated the relationship between the TTS, DPSI, and the static postural sway. They didn't found any significant relationship between the DPSI, and static postural sway, while the DPSI was most strongly related to the vertical peak force ($r = 0.85$) (Huurnink, Fransz et al. 2019). Thus, it seems that the DPSI mainly holds information about kinetic energy absorption. This may partly explain why DPSI was higher during DJL compared to other directions in the present study. This finding highlights the fact that DPSI takes more into account the impact dissipation at the initial ground phase (less than $\sim 0.4s$) rather than the stabilizing phase ($0.4s \sim 2.4s$) (Liu, Glutting et al. 2013, Huurnink, Fransz et al. 2019). That way, it is interesting to observe that VSI was higher than APSI which was also higher compared to MLSI (Figure 20). This is partly explained by the fact that peak forces are different in these three axes. For this reason, the DPSI seems to be more representative of a global knee stability capability in female soccer players compared to the stability indexes that can be calculated on each axe.

Meanwhile, it is very interesting to observe that additional results about differences between DL and NDL or relationships with H/Q coactivation were observed during vertical drop jump landing and not in other jumping directions. This may be linked to the fact that a higher mechanical stress on the musculoskeletal system emphasized the differences between the legs and between the subjects. In fact, a meta-analysis study has been demonstrated that the drop jump landing was more appropriate to evaluate dynamic stability in female athletes because it permits to distinguish kinetic and kinematic asymmetries between lower limbs (Collings, Gorman et al. 2019). This may be partly due to the higher ground reaction forces generated during the drop jump landing compared to other jump landing directions. In the present study, the DPSI score was higher during the drop jump landing, irrespective of the leg dominance in line with Huurnink et al. (2019).

5.5.2 Stability indexes in dominant and non-dominant legs

Present results showed that the dynamic stability was better in the DL compared to NDL during the drop jump landing. This cannot be explained by differences in the maximal GRF since no significant differences were observed between the legs (DL 2.44 ± 0.35 vs. NDL 2.57 ± 0.34 , $P = 0.47$) (Table 10). This may be more related to the higher ability of the female athletes to control the oscillations of the COM around the balanced resting position by activating lower leg muscles of the dominant leg. In fact, it is interesting to observe that H/Q coaction was also higher in the DL compared to the NDL. This has never been observed before. The effective control of dynamic stability depends on the interaction of many factors, including integration of visual and vestibular information's, muscle strength, muscular activation pattern, etc. (Meyer and Ayalon 2006). In general, maintenance of the postural stability during the dynamic task involves establishing an equilibrium between destabilizing and stabilizing force necessitating coordination among ankle, knee, and hip joint (Meyer and Ayalon 2006). However, the knee joint was considered as the most important joint that produces most of the work that contributes to the body stability, and quadriceps and hamstring muscles make the greatest muscular contribution to knee joint stability in association with muscles acting across the ankle and hip joints that contribute to the attenuation of the landing force (Zajac and Gordon 1989). Zhang et al. (2008) reported that the quadriceps were consistent contributors to energy dissipation during the drop jump landing task with an eccentric contraction during the flexion movement of the knee (Zhang, Bates et al. 2000). Thus, the better stability index observed for the DL may be attributed to the fact that muscles of that leg are stronger

and/or to the fact the motor control pattern was more efficient. Considering that maximal isometric torques of the knee flexors and extensors muscles were significantly higher in the dominant leg (Table 11), one may consider that the ability of the quadriceps muscle to dissipate kinetic energy was better in the DL and that it permitted to stabilize more efficiently the COM. In the same way, the ability of the knee flexors muscles to stiffen the hip joint may also contribute to a better stability index of this leg. However, considering that the dominant leg was determined considering the leg that the athletes preferentially used to kick the ball, it can be hypothesized that the muscle coordination was also more efficient that side. One of the coordination patterns that may significantly contribute to joint and body stabilization is the coactivation of antagonistic muscles.

5.5.3 About the importance of H/Q coactivation

It is really interesting to observe the differences in co-activation level of the knee flexor and extensor muscles between the dominant and the dominant leg. The fact that this coactivation level was significantly higher in the dominant leg may partly explain why this leg presented better stability indexes. It is commonly accepted that a good coactivation of antagonist muscles can contribute to a better orientation of the resultant forces at the extremity of the limb and a better stiffened joint (Baratta, Solomonow et al. 1988). So, it seems reasonable to imagine that the H/Q coactivation levels also partially explain the differences in stability observed when receiving jumps in different directions. The coactivation level of the dominant leg muscles was significantly higher compared to that of the non-dominant leg in drop jump in line with the DPSI index which was lower in the DL. In the same way, the correlations obtained between the DPSI index and the H/Q coactivation level in two landing directions tended to indicate that the ability of the subjects to produce an efficient coactivation of antagonist muscles around the knee joint contributes to their ability to quickly and efficiently stabilize the COM around a balanced resting position. This finding could be supported by the previous studies, which indicated the influence of the hamstring coactivation on the absorption of the impact force. During jump landing maneuvers, the landing limb is required to absorb the magnitude impact force to deceleration the COM. When sufficient activation of the hamstrings is present, it may provide knee stability to adequately control the lower limb that coincides with increased knee flexion to reduce the GRF (Hewett, Stroupe et al. 1996, Chappell, Creighton et al. 2007).

5.6 Limitation

This study suffers some limitations which should be noticed. Firstly, no kinematics variable was measured, such as ankle and knee joint angles during the jump landing task. Secondly, only the knee joint's isometric force was measured; namely, no dynamic lower limb strength profile provided complimentary neuromuscular characteristics when studying dynamic movement (Zhang, Morel et al. 2021). Finally, another limitation is that the present study's sample size is relatively small, and not having professional players within the sample may be considered as a limitation.

5.7 Conclusion

In summary, the present study found that the dynamic postural stability and H/Q co-activation ratio are influenced by the direction of the jump landing maneuvers and the leg dominance. Our finding also suggested that the drop jump landing test is more suitable for DPSI because it generates a higher mechanical stress which could elicit the inter-leg asymmetry. Furthermore, the H/Q co-activation ratio seems to be decisive during the drop landing tests. Therefore, it appears that neuromuscular training should aim to reduce the asymmetry between the two legs and, if possible, improve the agonist/antagonist activation pattern in the NDL to potentially reduce ACL injury occurrence.

5.8 Practical applications

Consideration of the present finding, it suggested that DPSI could be calculated during single-leg jump landing tests in different directions to determine the stabilization ability for the dominant and non-dominant legs in female athletes. This method could measure the dynamic postural stability in a laboratory or rehabilitation center. Besides, the assessment of the H/Q co-activation makes it possible to partly explain the dynamic postural stability indexes. Strength and conditioning interventions, such as resistance training and plyometrics, may offer the potential for increased rate and magnitude of hamstring muscle recruitment relative to the quadriceps muscle (Zbidi,

Zinoubi et al. 2017). Moreover, the lower limb neuromuscular train should be toward reducing the interlimb asymmetry aimed to reduce ACL injury occurrence.

**CHAPTER 6 Influence of fatigue on the rapid
hamstring/quadriceps force capacity in soccer players**

6.1 Abstract French Version

L'objectif de cette étude était d'examiner l'effet de la fatigue sur les capacités de force maximales et rapides et l'activation musculaire des extenseurs et fléchisseurs du genou. Dix-sept joueurs de football professionnels se sont portés volontaires pour participer à cette étude. Le couple maximal (T_{peak}) et le taux de développement du couple (RTD) des muscles fléchisseurs du genou ($90^{\circ} \cdot S^{-1}$, $-30^{\circ} \cdot S^{-1}$) et extenseurs ($90^{\circ} \cdot S^{-1}$) ont été mesurés avant et après la fatigue (soit 30 répétitions maximales d'extension et de flexion du genou à $180^{\circ} s^{-1}$) réalisées sur un dynamomètre isocinétique. La force maximale des ischio-jambiers au quadriceps et les rapports RTD ont été calculés. En outre, en utilisant l'EMG de surface, le niveau moyen d'activation (RMSmean), le taux de montée de l'EMG (RER) et les cartes EMG fréquence-temps ont été mesurés sur les quadriceps et les ischio-jambiers. Suite à la fatigue, T_{peak} , RTD, RER a diminué de manière significative dans les deux groupes musculaires (tous $p < 0,05$) sans modification de RMSmean. Aucune diminution des rapports H / Q conventionnels et fonctionnels n'a été observée après fatigue, à l'exception d'une augmentation significative des rapports H_{ecc30} / Q_{con180} ($1,03 \pm 0,19$ vs $1,36 \pm 0,33$, $p < 0,001$). En outre, les rapports RTD H/Q ont diminué de manière significative après la fatigue, et l'analyse de cartographie statistique paramétrique (SPM) réalisée sur les courbes EMG / angle, et les cartes EMG fréquence-temps ont montré que la fatigue influençait fortement l'activation musculaire pendant les 100 premières millisecondes du mouvement, suivant le décalage de la composante de fréquence EMG la plus élevée vers la composante de fréquence la plus basse. Nos résultats montrent que la réduction du RTD et du RER pendant les 100 premières millisecondes de la contraction après un exercice de fatigue a plus de sens que toute modification du rapport H / Q pour comprendre le risque de blessure chez les joueurs de football.

6.2 Abstraction in English

The objective of this study was to examine the effect of fatigue on maximal and rapid force capacities and muscular activation of the knee extensors and flexors. Seventeen professional soccer players volunteered to participate in this study. Peak torque (T_{peak}) and rate of torque development (RTD) of knee flexor ($90^\circ \cdot \text{s}^{-1}$, $-30^\circ \cdot \text{s}^{-1}$) and extensor ($90^\circ \cdot \text{s}^{-1}$) muscles were measured before and after fatigue (i.e., 30 maximal knee extension and flexion repetitions at $180^\circ \cdot \text{s}^{-1}$) performed on an isokinetic dynamometer. Hamstring to quadriceps peak strength and RTD ratios were calculated. Besides, using surface EMG, the mean level of activation (RMSmean), Rate of EMG Rise (RER), and EMG Frequency-Time maps were measured on quadriceps and hamstring muscles. Following fatigue, T_{peak} , RTD, RER declined significantly in the two muscle groups (all $p < 0.05$) without modification of RMSmean. No decrease in conventional and functional H/Q ratios was observed after fatigue except for a significant increase in the $H_{\text{ecc30}}/Q_{\text{con180}}$ ratios (1.03 ± 0.19 vs. 1.36 ± 0.33 , $p < 0.001$). Besides, the RTD H/Q ratios decreased significantly after fatigue, and the statistical parametric mapping analysis (SPM) performed on the EMG/angle curves, and EMG Frequency-Time maps showed that fatigue strongly influenced the muscle activation during the first 100 millisecond of the movement, following the higher EMG frequency component shift toward the lower frequency component. Our results show that the reduction of RTD and RER during the first 100 milliseconds of the contraction after fatigue exercise makes more sense than any H/Q ratio modification in understanding injury risk in soccer players.

6.3 Introduction

Hamstring strain injuries (HSIs) and anterior cruciate ligament (ACL) rupture are, respectively, the most prevalent noncontact injuries (Ekstrand, Hagglund et al. 2011) and the most serious injuries considering time to return to play (Walden, Hagglund et al. 2016) in professional soccer players (Ekstrand, Hägglund et al. 2011). During tasks such as sprinting, kicking or cutting, co-contraction of the hamstring and quadriceps muscles increases knee joint stability and prevents excessive knee joint constraints. That is why any deficit in hamstring strength or activation pattern may limit the protective effect of co-contraction on ACL and hamstring muscles. Thus, HSIs and ACL ruptures are frequently associated with strength imbalance between knee flexor and extensor muscles (Croisier, Ganteaume et al. 2008, Alhammoud, Morel et al. 2019, Baroni, Ruas et al. 2020). For this reason, isokinetic dynamometry is currently used by most of the professional soccer teams to calculate conventional and functional H/Q ratios to predict the strength imbalance between knee flexor and extensor muscles. Nevertheless, the predictive value of H/Q torque ratios for ACL ruptures and HSIs remains poor, maybe because they do not mimic the physiological and biomechanical ecological constraints such as joint angular position, contraction time, or fatigue (Croce and Miller 2006, Coratella, Bellin et al. 2015, Evangelidis, Pain et al. 2015, De Ste Croix, ElNagar et al. 2017, Alhammoud, Morel et al. 2019).

Accordingly, it has been suggested that modeling H/Q ratios with angle-specific metrics through range of motion may provide a more specific tool for analyzing thigh muscle balance. A recent study demonstrated that statistical parametric mapping analyses identified angle-specific differences between female and male elite skiers that could not be evidenced when analyzing only maximal torques and reconstructed ratios (Alhammoud, Morel et al. 2019). Thus, knee angle and muscle length are essential factors that have to be taken into account when interpreting the H/Q ratios. Moreover, considering that fatigue increases the injury risk in soccer, the modifications of this dynamic H/Q ratio under fatigue are of great importance.

Recent studies have suggested that the rate of torque development (RTD) during the first milliseconds of the contraction represents another functional outcome related to performance and injury risk (Alhammoud, Morel et al. 2018, Ishoi, Aagaard et al. 2019). For example, the study by Ishøi et al. (2019) indicates that early-phase (0-100 ms) rapid force capacity of the hamstring

muscles strongly influenced the acceleration capacity of elite soccer players (Ishoi, Aagaard et al. 2019). Besides, RTD is considered to be very important in the ability to stabilize the musculoskeletal system in response to mechanical perturbation (Angelozzi, Madama et al. 2012, Alhammoud, Morel et al. 2018). As there is no systematic link between the maximum force capacity and the relative RTD, screening for the risk of injury by measuring the traditional H/Q ratio can be difficult because of this inability to measure the capacity of rapid stabilization of the knee which may influence the risk of injury (i.e., HSIs, ACL injury). Furthermore, neuromuscular fatigue has been identified as a potential risk factor of HSIs (Croisier, Ganteaume et al. 2008), considering that HSIs preferentially occur in the later stage of the match (Hawkins, Hulse et al. 2001, Small, McNaughton et al. 2009). Fatigue can be defined as a reduction in the force-generating capacity of the neuromuscular system, regardless of the level of force required (Morel and Hautier 2017). Match-related fatigue in professional soccer players induces a reduction of jump ability, sprint performance (Krustrup, Mohr et al. 2006), peak torque in knee extension and flexion (Small, McNaughton et al. 2010, Marshall, Lovell et al. 2014) and rate of torque development (RTD) (Marshall, Lovell et al. 2014, Grazioli, Lopez et al. 2019). As hamstring strength is strongly affected after a simulated and a real soccer match, it may contribute to the strength imbalance between hamstring and quadriceps (Cohen, Zhao et al. 2015, Grazioli, Lopez et al. 2019), and may be considered as an injury risk factor (Lee, Mok et al. 2018). That way, Small et al. (2009) revealed a significant reduction in combined maximal hip flexion and knee extension angle resulting in shorter hamstring length during sprint running after soccer-specific fatigue, which potentially increase predisposition to hamstring strain (Small, McNaughton et al. 2009). It is also worth noting that a previous study reported a greater torque loss in hamstring compared to quadriceps muscles during 50 flexions-extensions at $180^{\circ} \cdot s^{-1}$ in concentric mode inducing H/Q ratio deterioration (Sangnier and Tourny-Chollet 2007). In addition, RTD has been demonstrated to be highly sensitive to fatigue (Morel, Rouffet et al. 2015, Grazioli, Lopez et al. 2019). For instance, Grazioli *et al.* (2019) reported that hamstring explosive force is more affected than maximal force after a professional soccer match (Grazioli, Lopez et al. 2019). Thus, the RTD H/Q ratio has been demonstrated to be an interesting way to characterize muscle function around the knee (Zebis, Andersen et al. 2011, Greco, da Silva et al. 2013). For this reason, studying angle-specific H/Q ratio and RTD H/Q ratio modifications after fatigue in soccer players appears to be a promising way to better understand and prevent HSIs and ACL injury occurrence.

Hence, the purpose of this study was to assess the effect of fatigue on angle-specific H/Q ratio and RTD H/Q ratio in soccer players. Furthermore, the present study will analyze the changes in muscle activation between the hamstring (i.e., Semitendinosus & Biceps femoris) and quadriceps (i.e., Rectus femoris & Vastus lateralis & vastus medialis) under fatigue. We hypothesized that *i*) the angle-specific H/Q ratio would be altered in certain knee angles without modification of the traditional H/Q ratio (i.e., conventional and functional H/Q ratio) and *ii*) diminution of RTD (i.e., knee extensor and flexor) and RTD H/Q ratio would be associated with muscular deficit activation during the initial phase of contraction (i.e., 50ms, 100ms).

6.4 Methods

6.4.1 Participants

Seventeen French semi-professional soccer players (Height: 173.5 ± 4.1 cm, Mass: 73.3 ± 6.3 kg, Age: 23.9 ± 2.2 years, training volume: 12 ± 2.2 h. wk^{-1}) playing at a national level volunteered to participate in this study. Included subjects had no history of traumatic lower limb injuries (e.g., ACL rupture, hamstring injuries) for at least one year before the study. The cumulated training and match time per season attained 330 hours (85 % training and 15 % competing). Leading up to the experiments, participants followed their regular training program avoiding any strenuous and high charge or match 48h before the study. The sample size ($n=17$) was estimated on the basis of the results of Sangnier and Tourny (2008), accepting a confidence rate of 95% and a margin of error of 5% with a statistical power of 0.90, and looking for a medium effect size of 0.5 (Sangnier and Tourny-Chollet 2008)

6.4.2 Experimental procedures

A randomized repeated measurement pre-/post-fatigue study design was used for this research (Fig 1). Isokinetic measures were performed on the dominant lower limb, which was determined by the preferred leg in kicking. The participants performed a general warm-up composed of 10min cycling (1 watt.kg^{-1} , 70-80 RPM) and mobility movements. After that, sEMG electrodes (Delsys Trigno™ Wireless EMG System, bipolar Ag: AgCl surface, 2cm inter-electrode distance) (Delsys, Inc., Boston, USA) were fixed on the rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), biceps femoris long-head (BF) and semitendinosus (ST) muscles following the SENIAM

guidelines. The skin was shaved and cleaned using an alcohol wipe before affixing the sEMG electrode. The sampling rate was 2000Hz, and the standard mode of rejection ratio was greater than 80 dB.

Once the participants were equipped with the EMG electrodes, they were afterwards seated on the Contrex isokinetic dynamometer (Contrex, CMV AG, Dübendorf, Switzerland) with flexed hips at 80° (0° = full hip extension), and standard stabilization strapping was placed across the chest, pelvis, and distal thigh. The sampling frequency was 256Hz. The axis of the dynamometer was visually aligned with the lateral femoral condyle. The range of movement was set from 100° of knee flexion (starting position) to 20° (0° was determined as the anatomical maximal voluntary knee extension for each participant). The subjects were required to grasp the handles of the dynamometer chair (Figure 23).

Before the isokinetic testing, all participants were asked to perform a familiarization session. During this session, the participants were asked to complete eight continuous reciprocal knee extensions and flexions between 50 and 60% of their maximal at two velocities 90°.s⁻¹ and 180°.s⁻¹ followed by eight hamstring eccentric contractions at -30°.s⁻¹. This allowed the participants to adapt to the isokinetic contractions and determined the quality of the sEMG signal. Before assessments, the gravity compensation procedure was performed according to the manufacturer's instructions. After ~3 minutes of passive recovery (Parcell, Sawyer et al. 2002), the participants performed the pre-fatigue tests, including five maximal knee extensors and flexors concentric contractions at 90°.s⁻¹ and five maximal knee flexors eccentric contractions at -30°.s⁻¹. Two minutes of recovery were included between concentric and eccentric sets. After 2 min of passive recovery, subjects performed 3 maximal knee extensors and flexors concentric contractions at



Figure 23: Example of participant during protocol.

$180^{\circ} \cdot s^{-1}$ immediately followed by the fatiguing exercise composed of 24 contractions at the same velocity. Immediately after the fatigue session, subjects repeated the pre-fatigue tests but with no rest between the contractions. During the entire protocol, the participants were verbally encouraged to give their maximal effort by the same manipulator.

6.4.3 Measurements and data analysis

Raw torque-angle curves were extracted from the original instantaneous torque dataset using custom routines to resynchronize the signal per degree of knee angle. Raw data were processed in MATLAB (MathWorks, version 2018b, Natick, MA, USA), a 2nd low-pass 20Hz was used to filter. Furthermore, a 1D polynomial spline fitting method was used to interpolate torque and angle values for each contraction to guarantee the same data length. The three best trials were extracted

for pre- and post-fatigue tests, and the first and last concentric contractions of the fatigue protocol were taken into account. The threshold of torque was fixed at 1% of local peak torque for determining the onset:offset of muscle contraction.

6.4.3.1 Non-Angle specific Peak Torque (T_{peak}) and H/Q ratios

Peak torque (T_{peak}) at $90^{\circ} \cdot \text{s}^{-1}$, $180^{\circ} \cdot \text{s}^{-1}$ and $-30^{\circ} \cdot \text{s}^{-1}$ were calculated as the average value of three contractions (the best ones of the five contractions for $90^{\circ} \cdot \text{sec}^{-1}$ and $-30^{\circ} \cdot \text{s}^{-1}$) performed before and after the fatigue protocol both for knee extensors (KE), and knee flexors (KF). Conventional non-angle specific H/Q ratios were calculated by dividing knee flexion concentric peak torque by knee extension concentric peak torque at $90^{\circ} \cdot \text{s}^{-1}$ ($H/Q_{\text{con}90}$) and $180^{\circ} \cdot \text{s}^{-1}$ ($H/Q_{\text{con}180}$). A functional non-angle specific H/Q ratio was calculated by dividing knee flexion eccentric Peak torque at $-30^{\circ} \cdot \text{s}^{-1}$ by knee extension concentric peak torque at $90^{\circ} \cdot \text{s}^{-1}$ ($H/Q_{\text{func}90}$) and $180^{\circ} \cdot \text{s}^{-1}$ ($H/Q_{\text{func}180}$).

6.4.3.2 Angle-specific peak torque and angle-specific H/Q ratios

All angle-specific measures were represented only between $30-90^{\circ}$ to account for the acceleration and deceleration phases and keep within the iso-velocity period (Alhammoud *et al.*, 2019). Based on these torque-angle curves, angle-specific conventional and functional H/Q dynamic ratios were continuously calculated by dividing hamstring torque by quadriceps torque at the same knee angle across the analyzed range of motion. Two conventional angle-specific dynamic ratios ($H/Q_{\text{conv}90}$ at $90^{\circ} \cdot \text{s}^{-1}$ and $H/Q_{\text{conv}180}$ at $180^{\circ} \cdot \text{s}^{-1}$) and two functional angle-specific dynamic ratios were calculated for knee extension (hamstring torque at $-30^{\circ} \cdot \text{s}^{-1}$ divided by quadriceps torque at $90^{\circ} \cdot \text{s}^{-1}$; $H/Q_{\text{func}90}$ and hamstring torque at $-30^{\circ} \cdot \text{s}^{-1}$ divided by quadriceps torque at $180^{\circ} \cdot \text{s}^{-1}$; $H/Q_{\text{func}180}$). A 1D polynomial spline fitting method was used to interpolate torque and angle values for all the curve between $30-90^{\circ}$ to normalize the torque: angle curves on the same number of points.

6.4.3.3 Rate of torque development (RTD) and RTD H/Q ratios

The absolute rate of torque development ($\text{Nm} \cdot \text{s}^{-1}$) was calculated from linear slope of the torque-time curve (i.e., $\Delta \text{torque} / \Delta \text{time}$) (Aagaard, Simonsen *et al.* 2002) at the 0-50ms and 0-100ms time interval during dynamic isokinetic concentric contractions at $90^{\circ} \cdot \text{s}^{-1}$, $180^{\circ} \cdot \text{s}^{-1}$ for the knee extensor and flexor muscles and during isokinetic eccentric contractions at $-30^{\circ} \cdot \text{s}^{-1}$ for the knee flexors

(Alhammoud, Morel et al. 2018). Besides, the RTD H/Q ratios were calculated by dividing the RTD of knee flexor by the RTD of knee extensor corresponding time intervals both for the 50ms (RTD_{50ms} H/Q Ratio) and 100ms (RTD_{100ms} H/Q Ratio).

6.4.3.4 EMG variables

The EMG Signal Processing of five muscles (e.g., BF, ST, RF, VL, VM) was performed using MATLAB software (R2018b, The MathWorks Inc., Natick, MA, USA). The root mean square values (RMS) were calculated with a 150-ms moving rectangular window based on the rectified EMG to determine the signal amplitude. The onset and offset of the EMG bursts were determined using a threshold of 5% of the muscle peak maximal activation found within the analysis period. RMS EMG signals were normalized to the peak RMS value measured for each muscle during the pre-fatigue maximal contraction at 90°.s⁻¹. A mean RMS value (RMS_{mean}) was then calculated between onset and offset for the five muscles during pre-and post-fatigue tests. The calculation of the rate of EMG rise (RER) was realized on a smoothed RMS curve (6Hz low-pass fourth-order Butterworth filter) and calculated by the slope of the RMS-Time envelope for 0-50ms and 0-100ms time intervals relative to the activation onset for the five muscles during pre-and post-fatigue tests (Morel, Rouffet et al. 2015).

A continuous wavelet transform (CWT) was made on raw EMG signals to investigate time-frequency domain for each muscle before and after fatigue, using a Morse mother wavelet with $\gamma = 3$ and $P^2 = 60$ (Lilly and Olhede 2009). The frequencies ranging from 20 to 500 Hz were analyzed. The pseudo frequency of each scale was obtained using the center of the frequency of each wavelet, and as the frequencies were logarithmically spaced, the maps were linearly interpolated by 4 Hz in the frequency domain. The time was normalized for all the maps corresponded to 200-time points. Thus, the number of nodes of the maps corresponded to 200 [time] \times 94 [frequency] = 18800 nodes. The modulus of the coefficient given by the wavelet transform was computed for each node. The frequency that split the spectrum in half was defined as the median frequency.

6.4.4 Statistical Analysis

Before performing the statistical analysis, the Shapiro–Wilk test and Levene’s test were respectively used to assess the normality of data and the equality of variance for isokinetic data and EMG data. Thereafter, a two-way (Angular velocity*Muscle) repeated measures (Pre- and Post-fatigue test) analysis of variance ANOVA was used on T_{peak} , RTD_{100ms} , RMS_{mean} , RER_{100ms} . Holm’s Bonferroni post-hoc test with correction of the p-value was used for multiple comparisons to determine the interaction effect between the test (Pre-fatigue vs. Post-fatigue condition), muscle (knee flexor vs. extensor for isokinetic variable and five-goal muscle (e.g., BF, ST, RF, VL, and VM) for EMG data and angular velocity ($90^{\circ}.s^{-1}$, $180^{\circ}.s^{-1}$). Besides, Student’s paired *t*-test was applied to analyze the different H/Q ratios and eccentric peak torque ($-30^{\circ}.s^{-1}$) before and after fatigue. Statistical significance was set at $p < 0.05$. All statistical procedures were performed with IBM SPSS 26 (IBM Corporation, Armonk, NY). All the data are presented as mean \pm SD, with a 95% confidence interval (95% CI).

Using SPM–1D package (© Todd Pataky, version M 0.4) in MATLAB (The MathWorks Inc, R2018b, Natick, MA) was conducted to performs Statistical Parametric (Pataky 2010, Pataky, Robinson et al. 2013). One dimensional paired *t*-test SPM statistics were performed to determine the main effects of fatigue on the angle-specific torque, angle-specific H/Q ratio, smoothed RMS curve, and a p-value was calculated for clusters crossing the critical threshold, with significance set at $p < 0.05$ (Pataky, Robinson et al. 2013). Besides, SPM analysis was conducted in two dimensions on the EMG Frequency-Time maps obtained from the wavelet transform. The mean maps of each subject's three contractions were considered for the analysis. As a 1D continuum is required to perform the SPM analysis, the maps were flattened into a 1D continuum for the analysis and then reshaped to their original dimensions for interpretation. For concentric contractions, maps were analyzed with a two-way ANOVA with two repeated measures (Fatigue: Pre vs. Post; Velocity: $90^{\circ}.s^{-1}$ vs. $180^{\circ}.s^{-1}$) and post hoc tests as paired *t*-tests with Bonferroni correction. An alpha error of 0.01 (0.05/5) was set as five muscles were analyzed. For eccentric contractions, paired *t*-tests were performed to compare maps (Pre versus Post) with an alpha error at 0.025 as two muscles were considered. To define the threshold of the statistical tests performed, permutation tests were used with 10000 permutations (Nichols and Holmes 2002).

6.5 Results

6.5.1 Peak torque (T_{peak}) and H/Q ratios

The knee extension T_{peak} reduced significantly after fatigue at $90^{\circ} \cdot \text{s}^{-1}$ and $180^{\circ} \cdot \text{s}^{-1}$ (all $p < 0.05$) (Table 13). The knee flexion T_{peak} reduced significantly after fatigue at $90^{\circ} \cdot \text{s}^{-1}$, $180^{\circ} \cdot \text{s}^{-1}$ and $-30^{\circ} \cdot \text{s}^{-1}$ (all $P < 0.05$) (Table 13). In addition, there was a significant interaction effect for different velocity (all $p < 0.05$). Holm's Bonferroni post-hoc tests indicated that the reduction of force was higher at an angular velocity of $180^{\circ} \cdot \text{s}^{-1}$ than $90^{\circ} \cdot \text{s}^{-1}$ (all $p < 0.01$). Besides, the t-test SPM analysis on torque-angle curves indicated a significant decrease in torque for knee extensor and flexor irrespective of knee angle (Figure 24). Moreover, the conventional ratios at $90^{\circ} \cdot \text{s}^{-1}$ and $180^{\circ} \cdot \text{s}^{-1}$ and the functional $H_{\text{ecc}30}/Q_{\text{conc}90}$ ratio were not affected by the fatigue protocol ($p > 0.05$) (Table 14). In contrast, the functional $H_{\text{ecc}30}/Q_{\text{con}180}$ ratio increased after fatigue ($p < 0.001$) (Table 14).

Also, the paired t-test SPM analysis showed a significant increase in the conventional $H_{\text{con}180\theta}/Q_{\text{con}180\theta}$ ratio between 30° and 32° knee angle ($p = 0.032$) (Figure 25) and the functional $H_{\text{ecc}30\theta}/Q_{\text{con}180\theta}$ ratio between 30° and 48° of knee angle range of motion ($p = 0.01$) (Figure 25) after fatigue. The conventional ratio $H_{\text{con}90\theta}/Q_{\text{con}90\theta}$ decreased significantly after fatigue for the knee angle range of motion between 68° and 88° degrees ($p = 0.003$) (Figure 25). Nevertheless, no significant effect of fatigue was indicated for dynamic functional ratio $H_{\text{ecc}30\theta}/Q_{\text{con}90\theta}$ ($p > 0.05$) (Figure 25).

6.5.2 Rate of torque development (RTD) and RTD H/Q ratios

Absolute $\text{RTD}_{50\text{ms}}$ and $\text{RTD}_{100\text{ms}}$ reduced significantly after fatigue for both knee extensors and knee flexor at $90^{\circ} \cdot \text{s}^{-1}$, $180^{\circ} \cdot \text{s}^{-1}$, and $-30^{\circ} \cdot \text{s}^{-1}$ (all $p < 0.05$) (Table 13). Meanwhile, Holm's Bonferroni post-hoc tests indicated that the reduction in RTD was higher at an angular velocity of $180^{\circ} \cdot \text{s}^{-1}$ (all $p < 0.01$). $\text{RTD}_{50\text{ms}}$ H/Q ratio at $90^{\circ} \cdot \text{s}^{-1}$ and $\text{RTD}_{50\text{ms}}$ at $180^{\circ} \cdot \text{s}^{-1}$ reduced following the fatigue protocol (all $p < 0.05$) (Table 13). In contrast, $\text{RTD}_{100\text{ms}}$ H/Q ratio at $90^{\circ} \cdot \text{s}^{-1}$ and $\text{RTD}_{50\text{ms}}$ at $180^{\circ} \cdot \text{s}^{-1}$ were not changed after the fatigue protocol ($p > 0.05$) (Table 14).

Velocity [$^{\circ} \cdot s^{-1}$]	Muscle	Variable	Pre-fatigue	Post-fatigue	Mean Difference [95% CI]	Change [%]
180	Knee Extensor	T _{peak}	153.7 ± 29.6	92.1 ± 11.2	-61.6 [47.1 - 76.2]	-40.1% ^{***}
		RTD _{50ms}	847.6 ± 348.4	420.7 ± 176.1	-427.8 [221.4 - 632.3]	-50.5% ^{***}
		RTD _{100ms}	1002.8 ± 341.0	509.8 ± 173.2	-493.0 [284.3 - 701.5]	-49.2% ^{***}
	Knee Flexor	T _{peak}	112.8 ± 30.2	69.1 ± 16.5	-43.7 [27.1 - 60.3]	-38.7% ^{***}
		RTD _{50ms}	744.1 ± 316.7	387.1 ± 142.1	-357.0 [151.6 - 562.4]	-47.9% ^{**}
		RTD _{100ms}	799.2 ± 294.4	465.2 ± 191.1	-334.1 [125.4 - 542.7]	-41.8% ^{**}
90	Knee Extensor	T _{peak}	201.1 ± 36.7	150.6 ± 25.7	-50.5 [31.9 - 69.1]	-25.1% ^{***}
		RTD _{50ms}	1131.1 ± 457.8	734.4 ± 419.4	-396.6 [191.2 - 602.0]	-35.1% ^{***}
		RTD _{100ms}	1174.4 ± 365.8	795.1 ± 386.2	-379.4 [170.7 - 587.9]	-32.3% ^{***}
	Knee Flexor	T _{peak}	126.8 ± 24.7	92.3 ± 22.9	-34.5 [16.5 - 52.5]	-27.2% ^{**}
		RTD _{50ms}	791.1 ± 318.7	554.7 ± 325.9	-236.5 [31.1 - 441.8]	-29.9% [*]
		RTD _{100ms}	924.7 ± 339.8	738.3 ± 337.2	-186.4 [-22.3 - 395.0]	-20.2% [*]
-30	Knee Flexor	T _{peak}	156.4 ± 33.2	140.7 ± 37.2	-15.8 [5.4 - 26.2]	-10.1% ^{**}
		RTD _{50ms}	895.3 ± 186.9	675.9 ± 135.8	-219.4 [13.9 - 424.7]	-24.5% ^{**}
		RTD _{100ms}	953.3 ± 224.5	749.2 ± 136.9	-204.1 [-4.5 - 412.7]	-21.4% ^{**}

Table 13: Effect of fatigue on peak torque (T_{peak}) in Nm, rate of torque development (RTD) in Nm. s⁻¹. *: Significantly different from fatigue for $p < 0.05$, **: Significantly different from fatigue for $p < 0.01$, ***: Significantly different from fatigue for $p < 0.001$. All data are presented as mean ± SD.

	Velocity	Pre-fatigue	Post-fatigue	Mean Difference [95% CI]	Change
Conventional H/Q Ratio	H_{con90}/Q_{con90}	0.63 ± 0.09	0.61 ± 0.11	-0.02 [-0.05 - 0.10]	-3.1%
	H_{con180}/Q_{con180}	0.73 ± 0.13	0.75 ± 0.15	0.01 [-0.10 - 0.07]	+2.1%
Functional H/Q Ratio	H_{ecc30}/Q_{con90}	0.78 ± 0.14	0.82 ± 0.14	0.04 [0.04 - 0.12]	+5.2%
	H_{ecc30}/Q_{con180}	1.03 ± 0.19	1.36 ± 0.33	0.33 [0.19 - 0.47]	+32.0% ^{***}
RTD _{50ms} H/Q Ratio	90°·s ⁻¹	1.10 ± 0.44	0.71 ± 0.26	-0.39 [-0.53 - -0.25]	-35.5% ^{**}
	180°·s ⁻¹	1.07 ± 0.59	0.96 ± 0.44	-0.11 [0.15 - 0.38]	-10.3%
RTD _{100ms} H/Q Ratio	90°·s ⁻¹	0.91 ± 0.18	0.85 ± 0.29	-0.06 [-0.08 - 0.22]	-6.6%
	180°·s ⁻¹	0.96 ± 0.35	0.82 ± 0.31	-0.14 [0.19 - 0.47]	-14.5% [*]

Table 14: Effect of fatigue on conventional and functional H/Q ratios and RTD H/Q ratio; *: Significantly different from fatigue for $p < 0.05$, **: Significantly different from fatigue for $p < 0.01$, ***: Significantly different from fatigue for $p < 0.001$. All data are presented as mean \pm SD.

6.5.3 Muscular activity

The level of activation (RMS_{mean}) during maximal contractions was not changed after the fatigue protocol, whatever the muscle and irrespective of the knee's angular velocity (all $p > 0.05$) (Table 15, 16, 17). In contrast, The RER_{50ms} , RER_{100ms} were significantly reduced after the fatigue protocol for all the muscles (e.g., biceps femoris [BF], semitendinosus [ST], rectus femoris [RF], vastus medial [VM], vastus lateralis [VL]) (all $p < 0.05$), irrespective of angular velocity (i.e., $180^{\circ}.s^{-1}$, $90^{\circ}.s^{-1}$, $-30^{\circ}.s^{-1}$) (Table 15, 16, 17).

The SPM t-test results showed the muscular activation to be slightly slower at $180^{\circ}.s^{-1}$ in the early phase of contraction for vastus medialis ($p = 0.048$), rectus femoris ($p < 0.001$), vastus lateralis ($p = 0.037$, $p = 0.002$), semitendinosus ($p = 0.05$, $p = 0.001$) but not for biceps femoris ($p > 0.05$) (Figure 26), whereas no significant effect of fatigue on the RMS curve was observed at $90^{\circ}.s^{-1}$ (Figure 27) and $-30^{\circ}.s^{-1}$ (all $p > 0.05$) (Figure 28).

Besides, the SPM ANOVA analysis on the EMG Frequency-Time maps indicated significant effect of fatigue (Pre vs. Post) (Figure 29) for all the muscles, whereas no effect of velocity ($90^{\circ}.s^{-1}$ vs. $180^{\circ}.s^{-1}$) (Figure 31-36). Similarly for all the muscles during concentric contractions, fatigue decreased the amplitude in high frequencies of EMG signals (above 100 Hz), while increasing the low frequencies amplitude (under 50 Hz) after 20% of contraction time. At the start of the contraction (0 to 20%), both high and low frequencies were decreased. Also, the SPM t-test revealed a significant fatigue effect on BF during the eccentric contraction ($-30^{\circ}.s^{-1}$), reducing the higher frequency component after fatigue (Figure 30), while no significant effect of fatigue was denoted for ST.

Velocity [$^{\circ} \cdot s^{-1}$]	Muscle	EMG	Pre-fatigue	Post-fatigue	Mean Difference [95% CI]	Change [%]
		RER _{50ms}	334.7 ± 128.8	240.3 ± 93.1	-94.3 [27.8 - 161.0]	-28.2% ^{**}
	BF	RER _{100ms}	311.0 ± 118.8	220.2 ± 72.9	-81.8 [20.1 - 143.4]	-26.4% ^{**}
		RMS _{mean}	53.1 ± 11.7	59.7 ± 15.1	6.6 [4.1-17.1]	12.4%
		RER _{50ms}	415.0 ± 189.1	277.1 ± 136.3	-137.9 [46.0 - 229.7]	-33.2% ^{***}
	ST	RER _{100ms}	344.3 ± 120.9	247.1 ± 88.6	-97.1 [32.6 - 161.7]	-28.2% ^{***}
		RMS _{mean}	56.6 ± 9.5	60.7 ± 10.6	4.1 [-1.7 - 6.5]	7.2%
		RER _{50ms}	392.7 ± 220.3	254.2 ± 168.7	-138.5 [55.9 - 221.1]	-35.3% [*]
	RF	RER _{100ms}	333.3 ± 137.4	273.9 ± 130.3	-59.4 [-3.7 - 122.6]	-17.8% [*]
		RMS _{mean}	62.7 ± 4.6	63.7 ± 11.7	0.9 [-10.0 - 8.2]	1.4%
		RER _{50ms}	493.3 ± 252.1	327.5 ± 145.3	165.9 [30.5 - 301.2]	-33.7% [*]
	VL	RER _{100ms}	393.3 ± 141.9	308.6 ± 86.6	-84.8 [1.4 - 168.1]	-21.6% [*]
		RMS _{mean}	73.9 ± 6.6	68.2 ± 8.9	-5.7 [0.8 - 10.5]	-7.7%
		RER _{50ms}	383.9 ± 214.3	288.7 ± 175.2	-95.1 [-3.0 - 193.1]	-24.8% [*]
	VM	RER _{100ms}	321.3 ± 147.5	263.1 ± 145.8	-58.2 [20.3 - 193.1]	-18.1% [*]
		RMS _{mean}	55.1 ± 9.2	51.6 ± 9.7	3.4 [-1.6 - 8.5]	-6.2%

Table 15: Effect of fatigue on mean RMS EMG (RMS_{mean}) in % of maximal EMG signal, EMG rise (RER) in $\% \cdot s^{-1}$ for hamstring (BF = biceps femoris, ST = semitendinosus) and quadriceps (RF = rectus femoris, VL = vastus lateralis, VM = vastus medialis) at 180°·s⁻¹. *: Significantly different from fatigue for $p < 0.05$, **: Significantly different from fatigue for $p < 0.01$, ***: Significantly different from fatigue for $p < 0.001$. All data are presented as mean ± SD.

Velocity [$^{\circ} \cdot s^{-1}$]	Muscle	EMG	Pre-fatigue	Post-fatigue	Mean Difference [95% CI]	Change [%]
BF		RER _{50ms}	520.5 ± 181.4	344.9 ± 217.1	-175.6 [37.7 - 313.6]	-33.7%*
		RER _{100ms}	447.8 ± 158.3	333.3 ± 166.8	-114.5 [3.9 - 225.1]	-25.6%*
		RMS _{mean}	66.1 ± 7.5	62.9 ± 8.3	-3.1 [-4.4 - 10.6]	-4.7%
ST		RER _{50ms}	545.1 ± 236.5	384.7 ± 196.8	-160.4 [53.7 - 267.1]	-29.4%*
		RER _{100ms}	428.2 ± 148.2	343.1 ± 107.5	-85.1 [3.8 - 166.]	-19.9%*
		RMS _{mean}	60.7 ± 8.1	64.6 ± 11.2	-3.8 [-7.1 - 17.9]	6.3%
90	RF	RER _{50ms}	548.7 ± 310.2	344.9 ± 269.4	-203.7 [54.7 - 352.1]	-37.1%*
		RER _{100ms}	436.7 ± 192.1	334.5 ± 190.3	-102.1 [24.0 - 180.5]	-23.4%*
		RMS _{mean}	68.3 ± 6.9	62.7 ± 14.0	-5.6 [2.8 - 13.9]	-8.2%
VL		RER _{50ms}	533.4 ± 204.7	343.9 ± 188.9	-189.4 [55.5 - 323.4]	-35.5%***
		RER _{100ms}	442.1 ± 140.1	347.6 ± 140.5	-94.5 [26.6 - 162.3]	-21.4%*
		RMS _{mean}	70.5 ± 6.9	71.7 ± 8.1	-1.1 [-5.3 - 3.1]	-1.6%
VM		RER _{50ms}	538.7 ± 226.7	371.7 ± 154.9	-167.0 [59.4 - 274.4]	-31.0%**
		RER _{100ms}	427.8 ± 138.6	336.4 ± 140.4	-91.4 [17.6 - 165.1]	-21.4%*
		RMS _{mean}	68.5 ± 7.2	72.3 ± 6.4	-3.8 [-8.9 - 1.3]	-5.5%

Table 16: Effect of fatigue on mean RMS EMG (RMS_{mean}) in %, of maximal EMG signal EMG rise (RER) in $\% \cdot s^{-1}$ for hamstring (BF = biceps femoris, ST = semitendinosus) and quadriceps (RF = rectus femoris, VL = vastus lateralis, VM = vastus medialis) at $90^{\circ} \cdot s^{-1}$. *: Significantly different from fatigue for $p < 0.05$, **: Significantly different from fatigue for $p < 0.01$, ***: Significantly different from fatigue for $p < 0.001$. All data are presented as mean ± SD.

Velocity [$^{\circ} \cdot s^{-1}$]	Muscle	EMG	Pre-fatigue	Post-fatigue	Mean Difference [95% CI]	Change [%]
-30	BF	RER _{50ms}	328.7 \pm 148.9	257.9 \pm 146.9	-70.7 [-45.3-186.9]	-21.5%*
		RER _{100ms}	389.1 \pm 190.6	265.5 \pm 148.1	-123.6 [10.4 - 239.9]	-31.8%**
		RMS _{mean}	54.6 \pm 9.9	49.1 \pm 10.7	-5.5 [0.5-10.4]	-10.1%
	ST	RER _{50ms}	371.1 \pm 235.6	299.9 \pm 184.4	-71.1 [-20.3-161.5]	-19.2%*
		RER _{100ms}	370.8 \pm 239.8	265.4 \pm 148.1	-97.8 [-7.8 - 203.4]	-26.4%**
		RMS _{mean}	49.8 \pm 11.1	48.4 \pm 10.2	-1.3 [-7.5-10.2]	-2.6%

Table 17: Effect of fatigue on mean RMS EMG (RMS_{mean}) in % of maximal EMG signal, EMG rise (RER) in $\% \cdot s^{-1}$ for hamstring (BF = biceps femoris, ST = semitendinosus) and quadriceps (RF = rectus femoris, VL = vastus lateralis, VM = vastus medialis) at $-30^{\circ} \cdot s^{-1}$. *: Significantly different from fatigue for $p < 0.05$, **: Significantly different from fatigue for $p < 0.01$, ***: Significantly different from fatigue for $p < 0.001$. All data are presented as mean \pm SD.

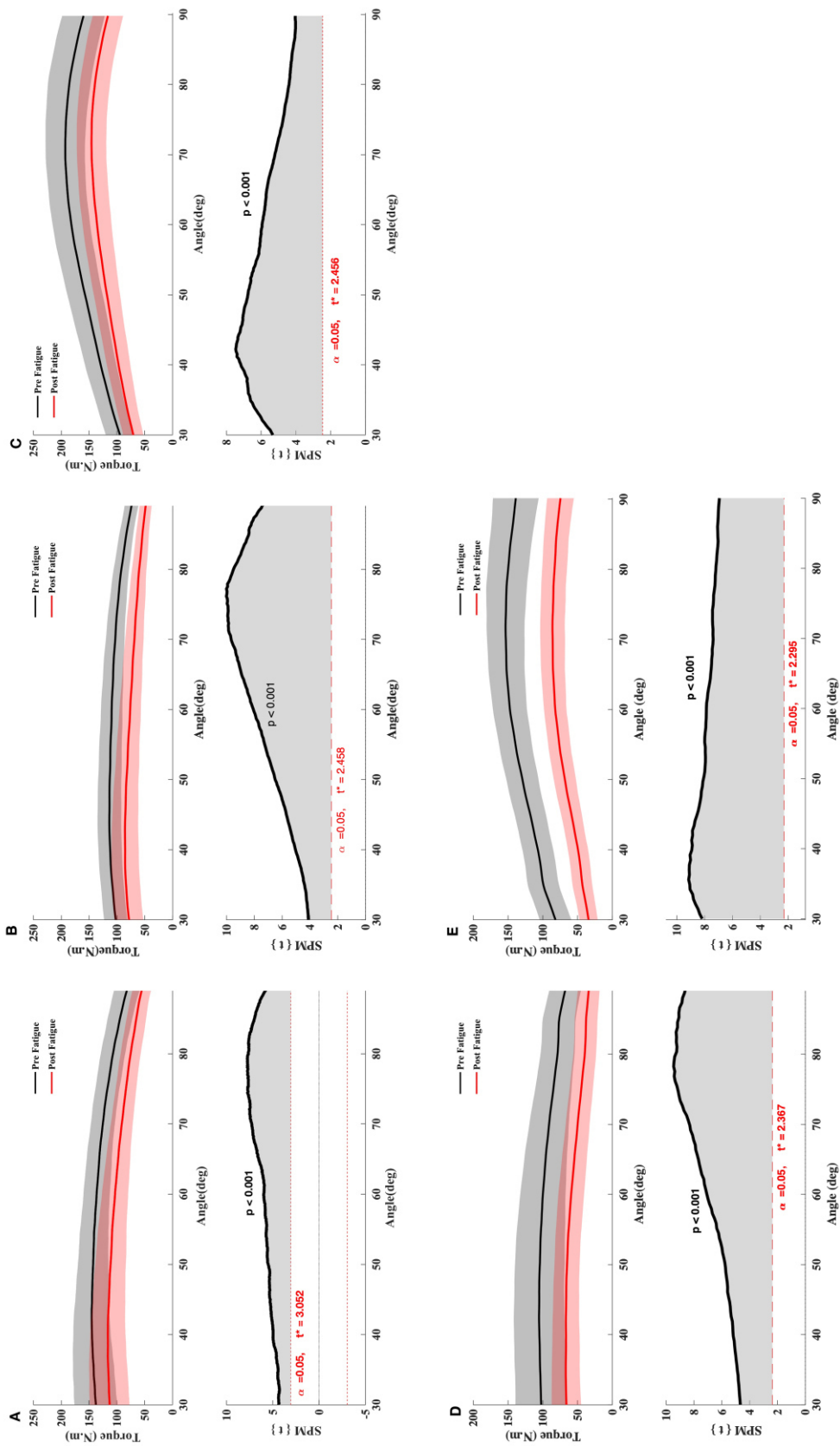


Figure 24: Effect of fatigue on knee flexor and extensor torque. A: Knee Flexor at $180^{\circ} \cdot s^{-1}$, B: Knee Flexor at $90^{\circ} \cdot s^{-1}$, C: Knee Extensor at $90^{\circ} \cdot s^{-1}$, D: Knee Extensor at $180^{\circ} \cdot s^{-1}$, E: Knee Extensor at $180^{\circ} \cdot s^{-1}$. Paired t SPM analysis. Mean \pm 95% confidence interval angle-series (upper panel) and corresponding SPM vector field statistical analysis (lower panel). The red dotted line represents the critical random field, the threshold value, t statistical set for $\alpha = 0.05$. The $p < 0.05$ portion of the curve is shaded.

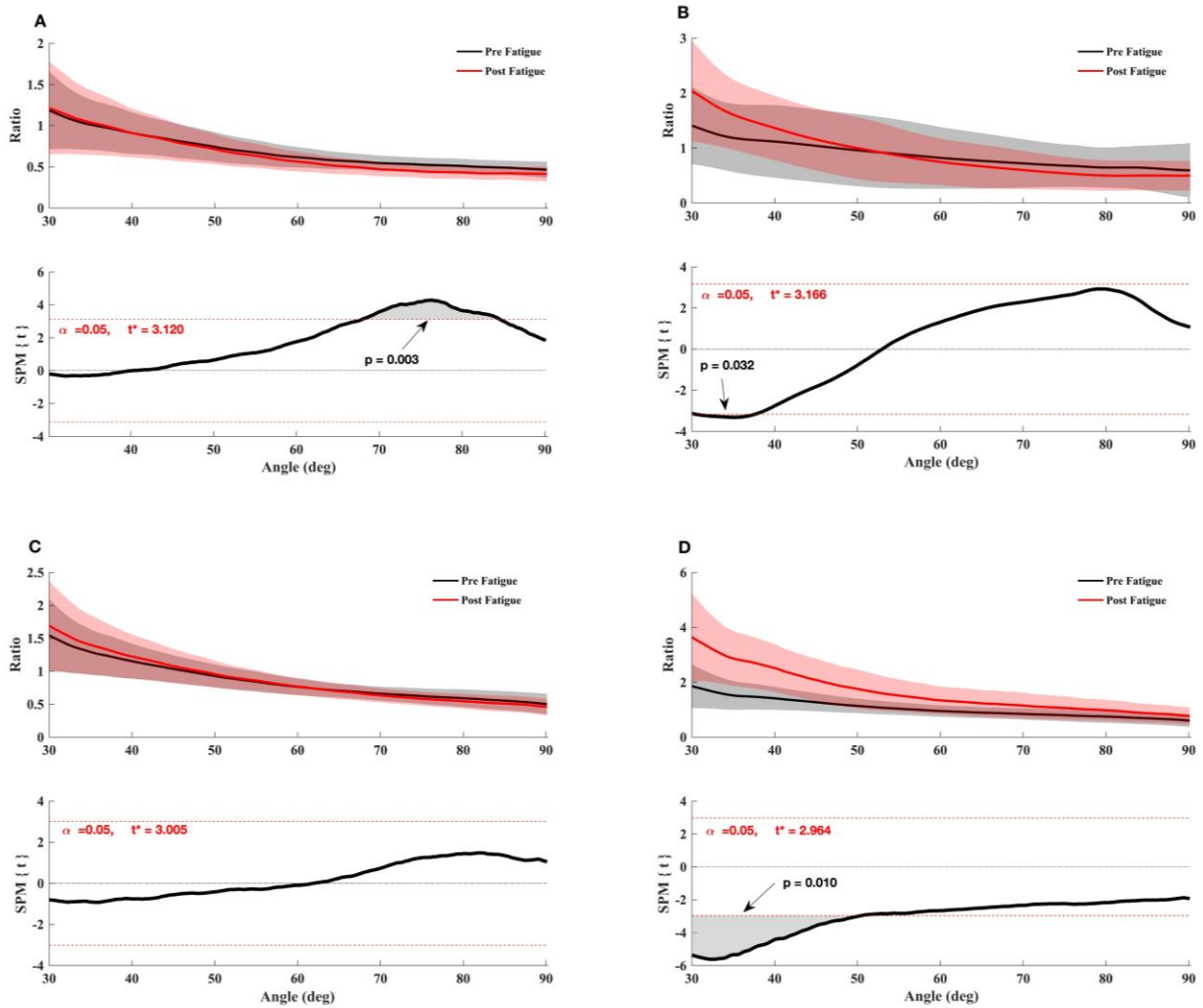


Figure 25: Effect of fatigue on the angle-specific ratio. A: $H/Q_{conv90\theta}$, B: $H/Q_{conv180\theta}$, C: $H/Q_{func90\theta}$, D: $H/Q_{func180\theta}$. Mean \pm 95% confidence interval angle-series (upper panel) and corresponding SPM vector field statistical analysis (lower panel). The red dotted line represents the critical random field, the threshold value, t statistical set for $\alpha = 0.05$. The $p < 0.05$ portion of the curve is shaded in grey.

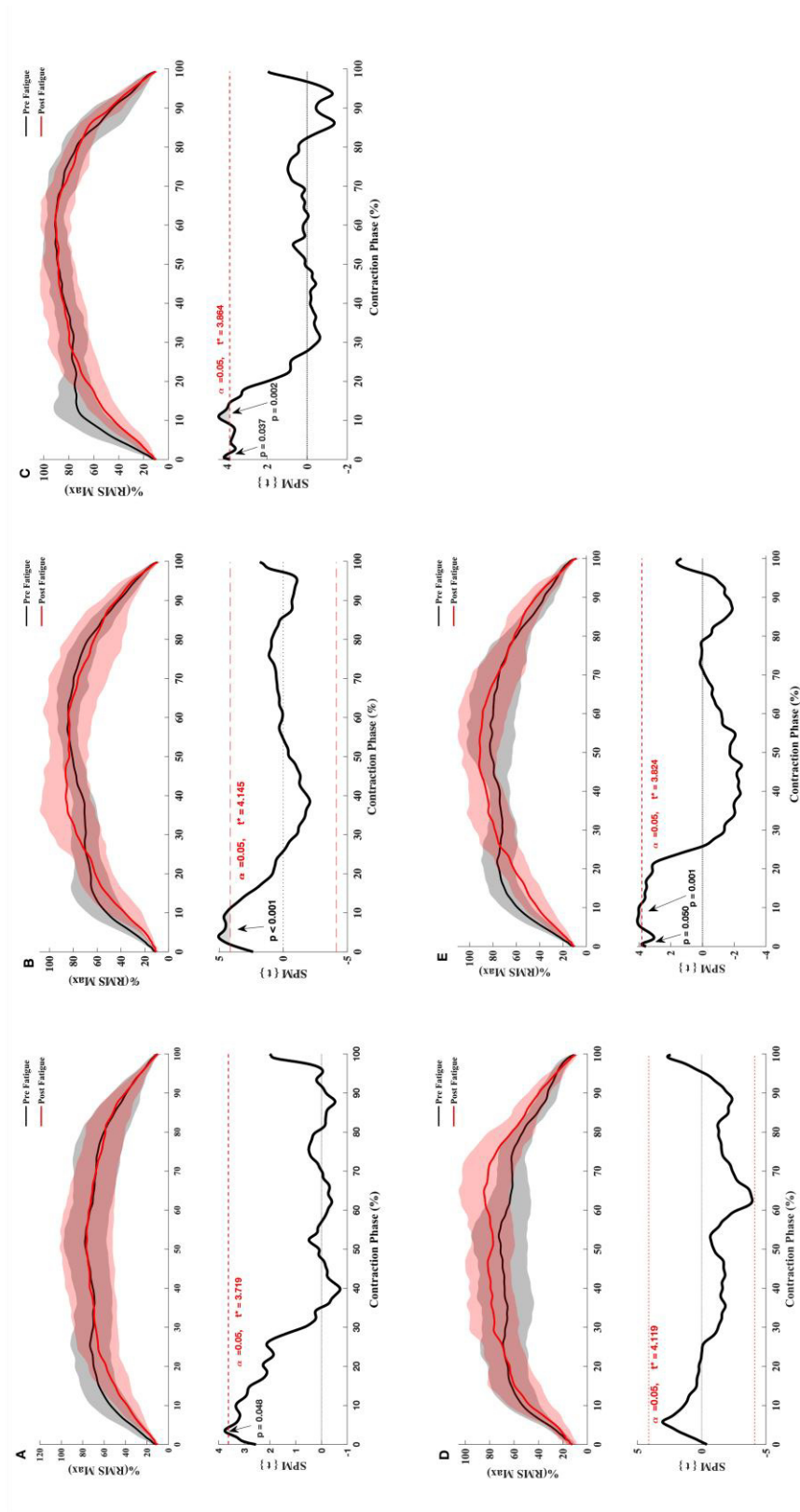


Figure 26: Effect of fatigue on EMG RMS curve of hamstring and quadriceps during knee flexion and extension at $180^{\circ} \cdot s^{-1}$. A: Vastus Medialis, B: Rectus Femoris, C: Vastus Lateralis, D: Biceps Femoris Long-Head, E: Semitendinosus. Mean \pm 95% confidence interval contraction period-series (upper panel) and corresponding SPM vector field statistical analysis (lower panel). The red dotted line represents the critical random field, the threshold value, t statistical set for $\alpha = 0.05$. The $p < 0.05$ portion of the curve is shaded in grey.

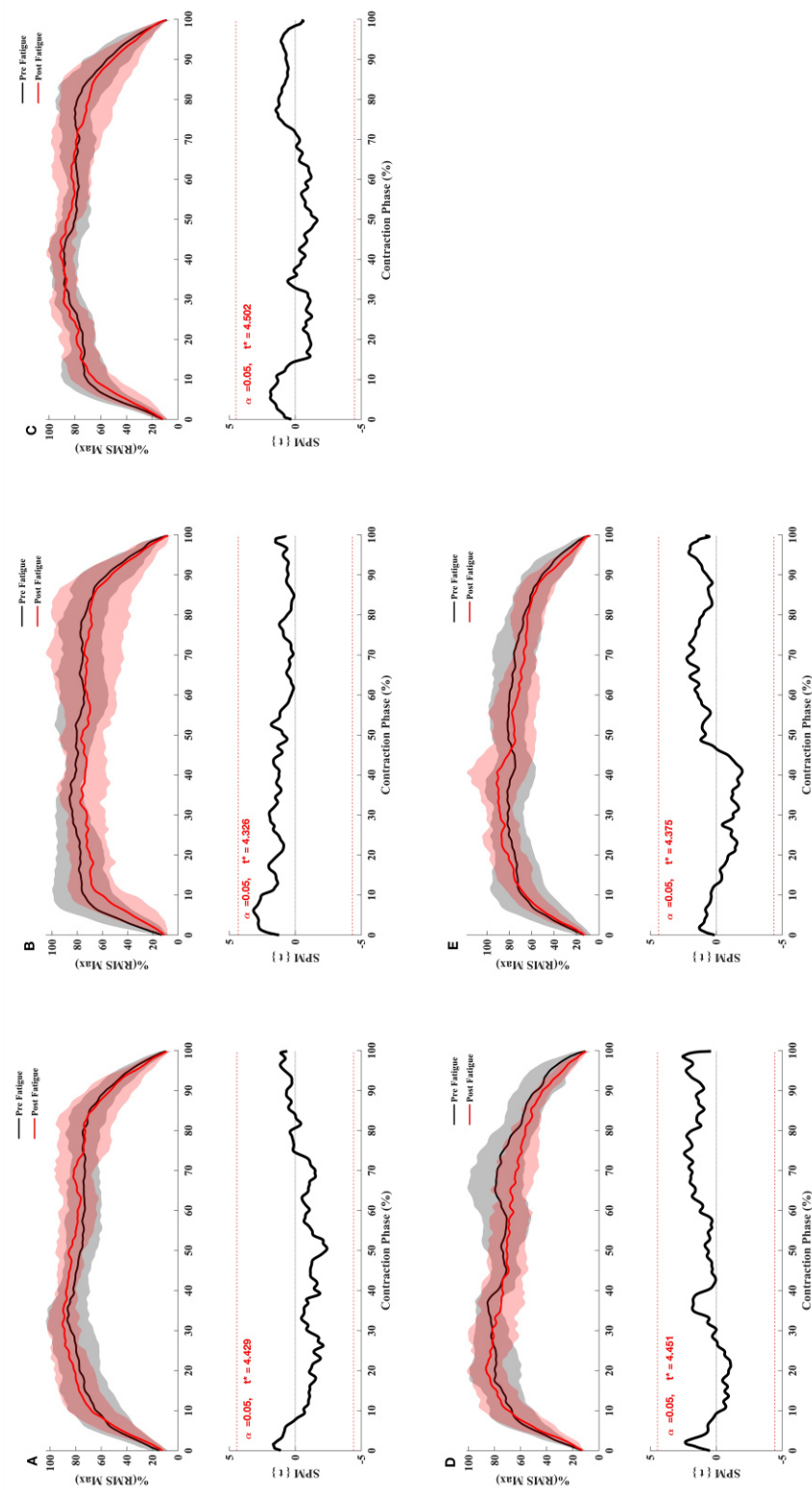


Figure 27: Effect of fatigue on EMG RMS curve of hamstring and quadriceps during knee flexion and extension at $90^\circ \cdot s^{-1}$. A: Vastus Medialis, B: Rectus Femoris, C: Vastus Lateralis, D: Biceps Femoris Long-Head, E: Semitendinosus. Mean \pm 95% confidence interval contraction period-series (upper panel) and corresponding SPM vector field statistical analysis (lower panel). The red dotted line represents the critical random field, the threshold value, t statistical set for $\alpha = 0.05$. The $p < 0.05$ portion of the curve is shaded in grey.

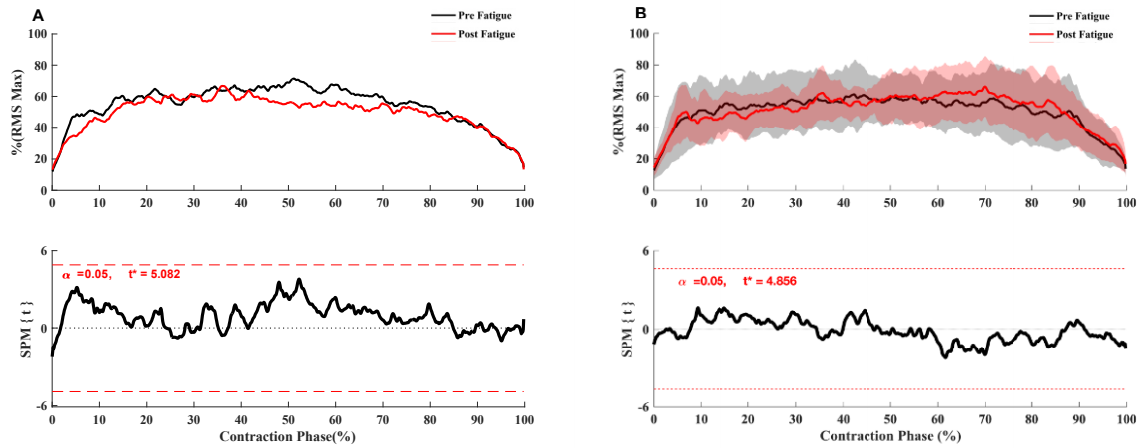


Figure 28: Effect of fatigue on EMG RMS curve of hamstring during eccentric knee extension at $-30^{\circ}\cdot s^{-1}$. (A) Biceps Femoris Long-Head, (B) Semitendinosus. Mean \pm 95% confidence interval contraction period-series (upper panel) and corresponding SPM vector field statistical analysis (lower panel). The red dotted line represents the critical random field, the threshold value, t statistical set for $\alpha = 0.05$. The $p < 0.05$ portion of the curve is shaded in gray.

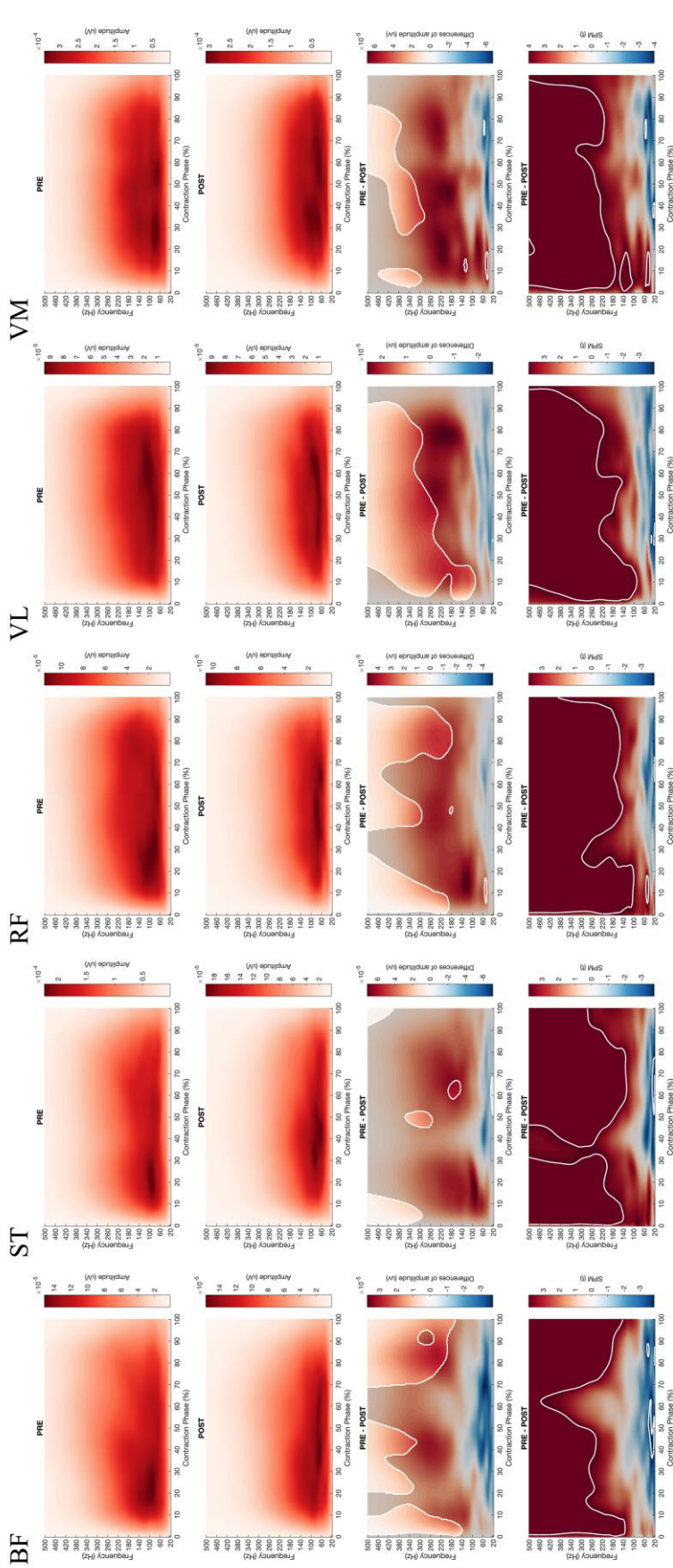


Figure 29: From top to bottom; rows 1 and 2: EMG Frequency-Time map during concentric contractions for BF, ST, RF, VL, VM before (PRE, row 1) and after (POST, row 2) the fatiguing exercise respectively; row 3: The magnitude of differences between PRE and POST. The enlighten clusters correspond to significant differences, considering the two-way ANOVA ($p < 0.05$ after Bonferroni correction); row 4: Results of the post hoc tests (SPM t -tests). The enlighten clusters correspond to significant differences without considering the ANOVA ($p < 0.05$ after Bonferroni correction). BF = Biceps femoris, ST = Semitendinosus, RF = Rectus femoris, VL = Vastus lateralis, VM = Vastus medialis.

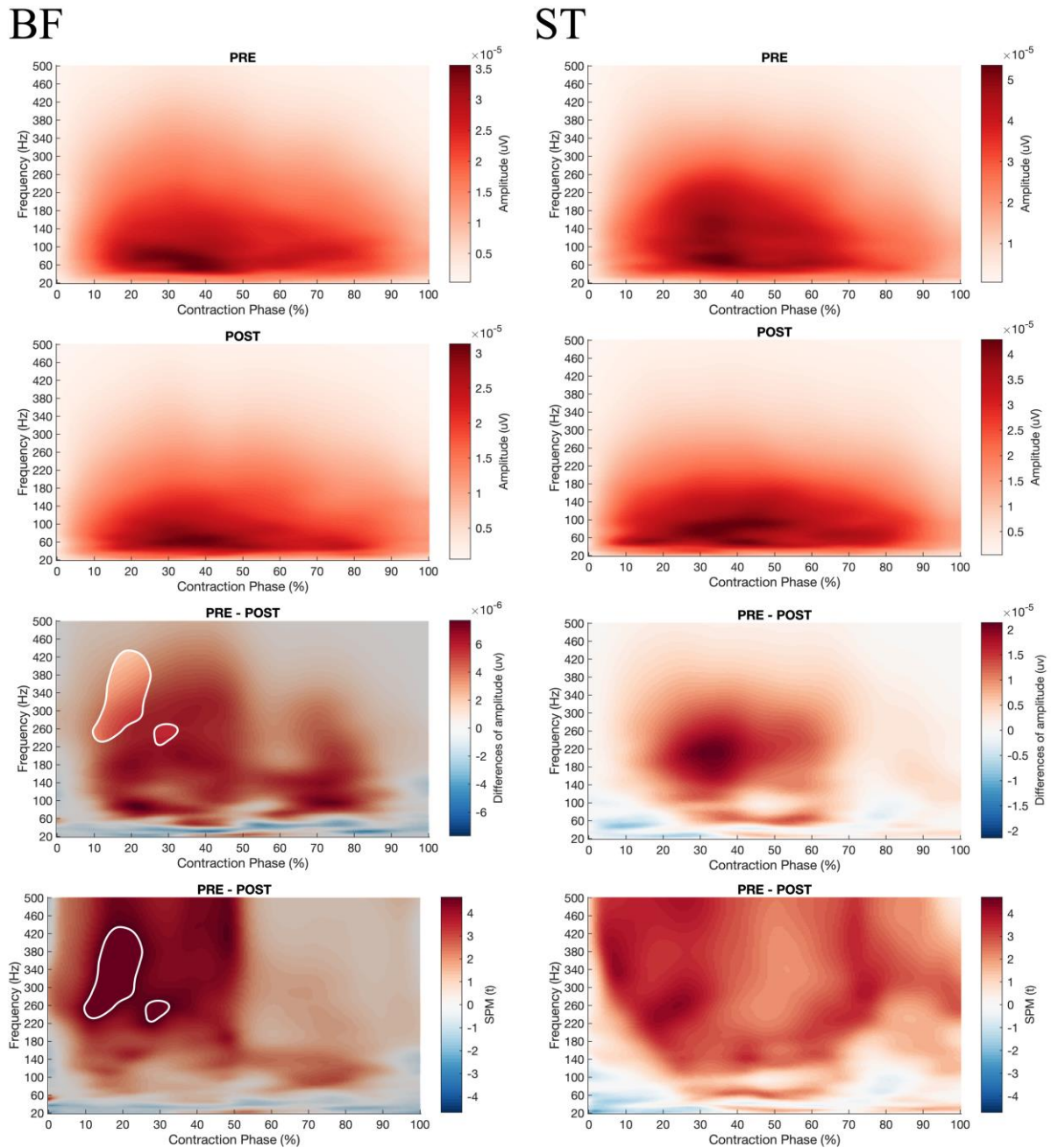


Figure 30: From top to bottom; rows 1 and 2: EMG Frequency-Time map during concentric contractions for BF and ST before (PRE, row 1) and after (POST, row 2) the fatiguing exercise respectively; row 3: The magnitude of differences between PRE and POST. The enlighten clusters correspond to significant differences ($p < 0.05$ after Bonferonni correction); row 4: Results of the post hoc tests (SPM t -tests). The enlighten clusters correspond to significant differences ($p < 0.05$ after Bonferonni correction). BF = Biceps femoris, ST = Semitendinosus.

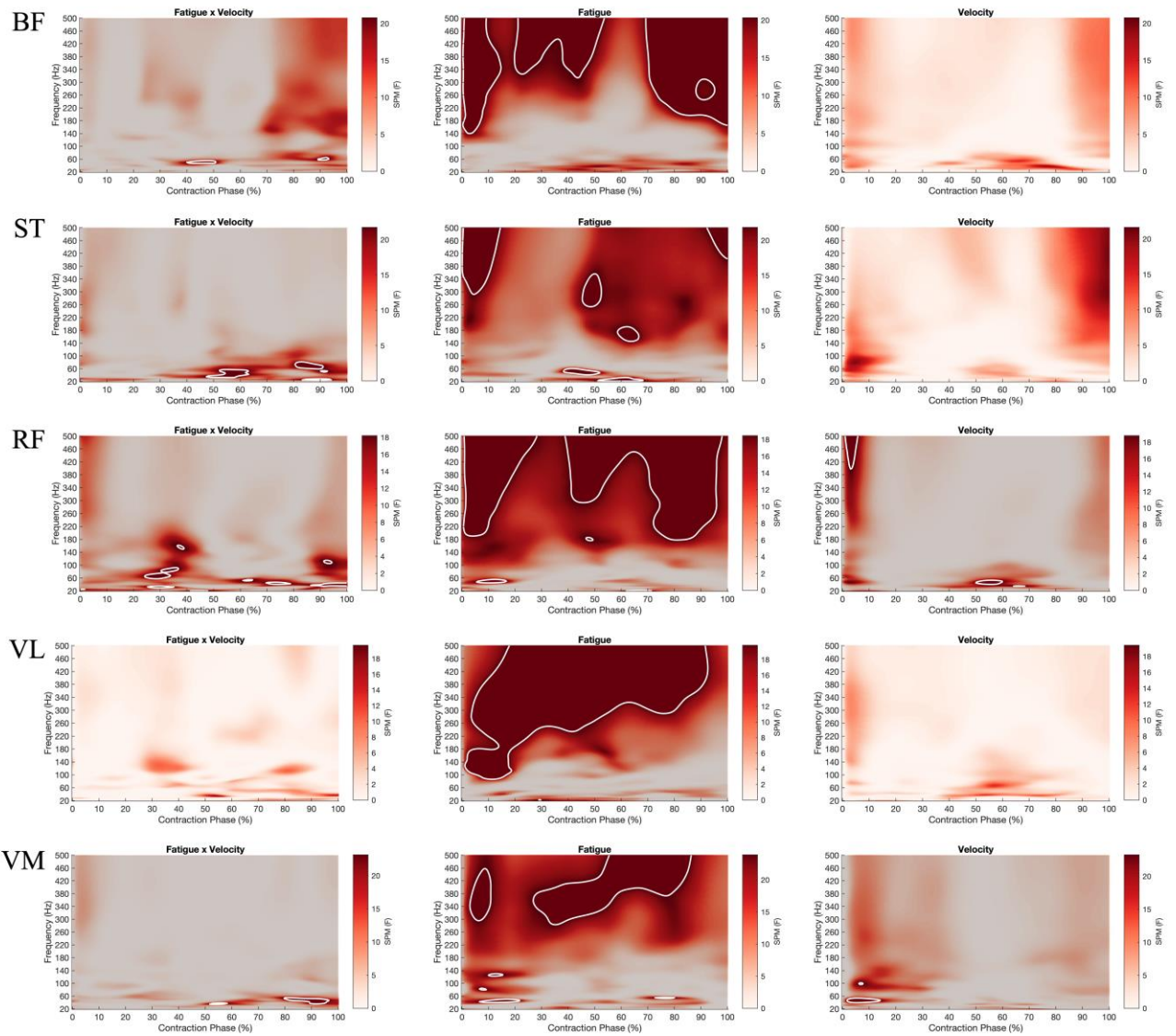


Figure 31: Two-way ANOVA SPM (Fatigue * Velocity) EMG Frequency-Time maps analysis for BF, ST, RF, VL, and VM. From left to right; column 1: the magnitude of differences from interaction Fatigue * Velocity, column 2: The magnitude of differences from Fatigue ($p < 0.05$), column 3: the magnitude of differences from Velocity; The enlighten clusters correspond to significant differences of the two-way ANOVA ($p < 0.05$). BF = Biceps femoris, ST = Semitendinosus, RF = Rectus femoris, VL = Vastus lateralis, VM = Vastus medialis.

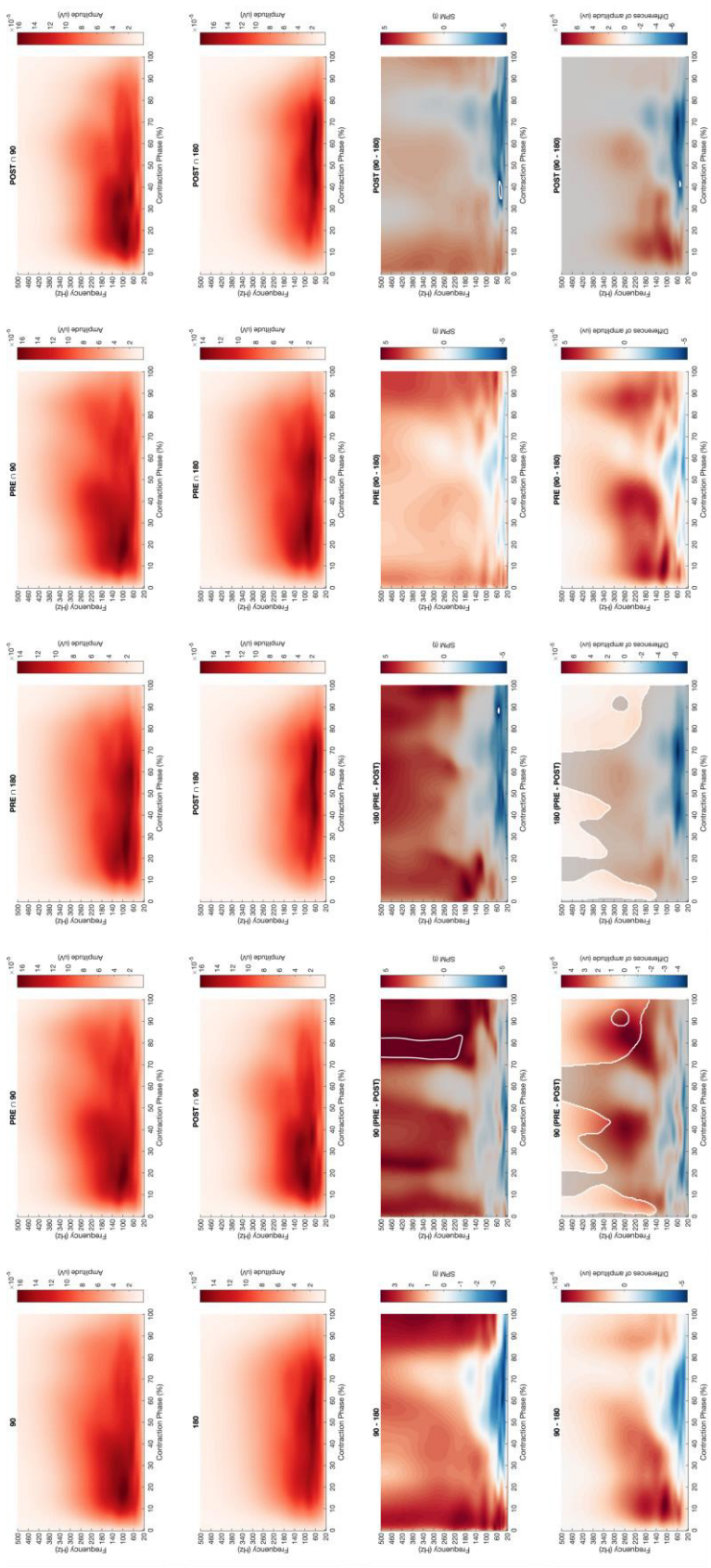


Figure 32: From top to bottom; rows 1 and 2: EMG Frequency-Time map during concentric contractions for Biceps Femoris before (PRE, row 1) and after (POST, row 2) the fatiguing exercise with/ without the interaction angular velocity ($90^{\circ}.s^{-1}$, $180^{\circ}.s^{-1}$) respectively; row 3: The magnitude of differences between PRE and POST. The enlighten clusters correspond to significant differences, considering the significance of the two-way ANOVA ($p < 0.05$ after Bonferroni correction); row 4: Results of the post hoc tests (SPM t-tests). The enlighten clusters correspond to significant differences without considering the ANOVA ($p < 0.05$ after Bonferroni correction).

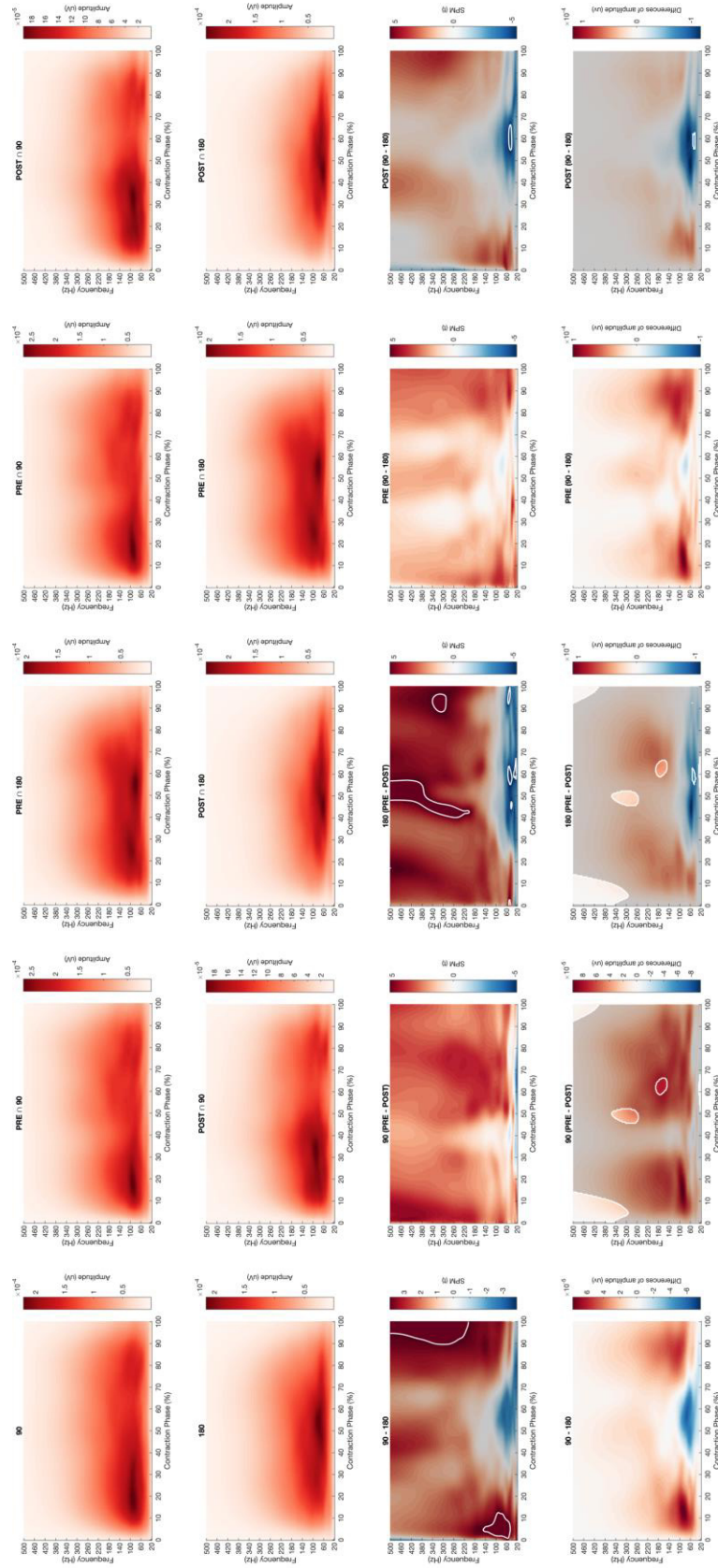


Figure 33: From top to bottom; rows 1 and 2: EMG Frequency-Time map during concentric contractions for Semitendinosus before (PRE, row 1) and after (POST, row 2) the fatiguing exercise with/ without the interaction angular velocity ($90^{\circ} \cdot s^{-1}$, $180^{\circ} \cdot s^{-1}$) respectively; row 3: The magnitude of differences between PRE and POST. The enlighten clusters correspond to significant differences, considering the significance of the two-way ANOVA ($p < 0.05$ after Bonferroni correction); row 4: Results of the post hoc tests (SPM t-tests). The enlighten clusters correspond to significant differences without considering the ANOVA ($p < 0.05$ after Bonferroni correction).

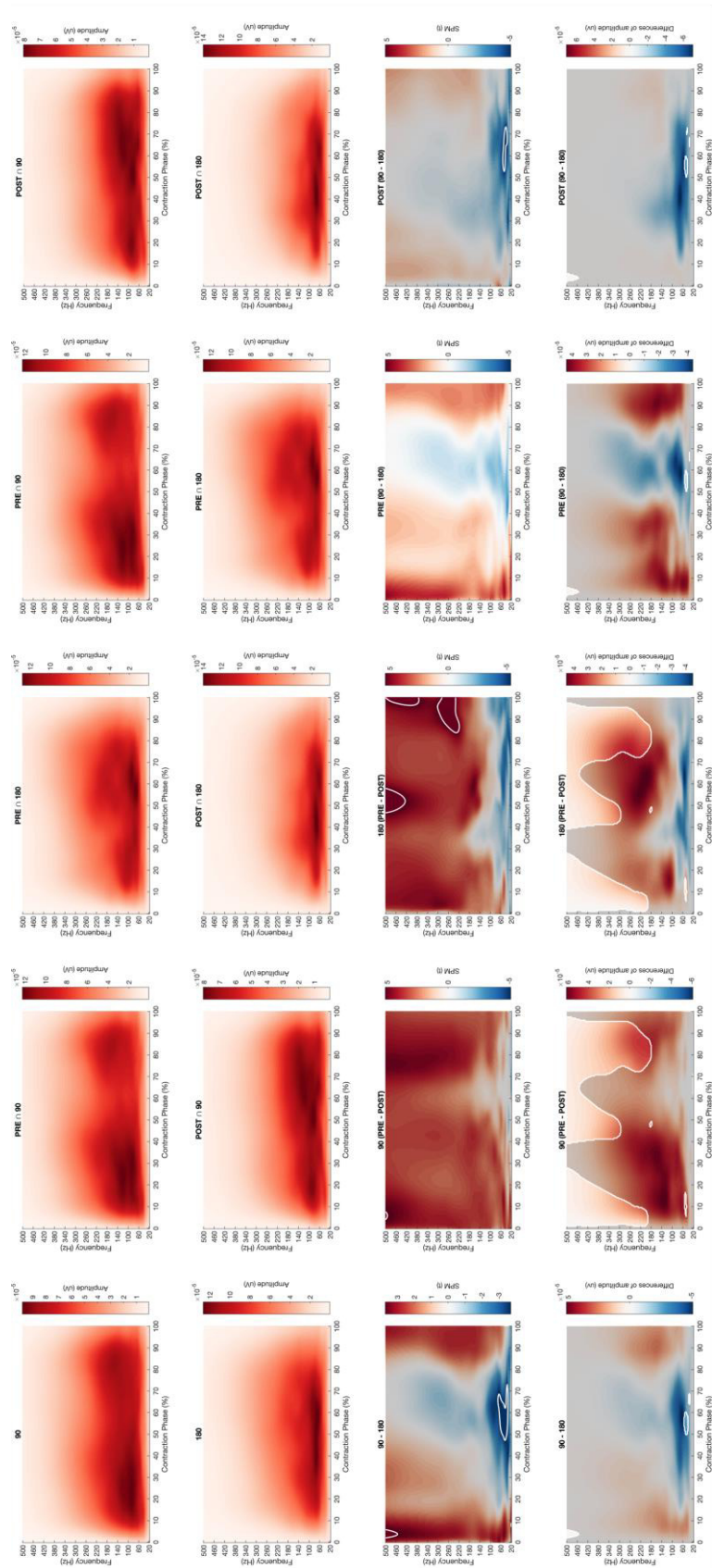


Figure 34: From top to bottom; rows 1 and 2: EMG Frequency-Time map during concentric contractions for Rectus Femoris before (PRE, row 1) and after (POST, row 2) the fatiguing exercise with/ without the interaction angular velocity ($90^{\circ} \cdot s^{-1}$, $180^{\circ} \cdot s^{-1}$) respectively; row 3: The magnitude of differences between PRE and POST. The enlighten clusters correspond to significant differences, considering the significance of the two-way ANOVA ($p < 0.05$ after Bonferroni correction); row 4: Results of the post hoc tests (SPM t-tests). The enlighten clusters correspond to significant differences without considering the ANOVA ($p < 0.05$ after Bonferroni correction).

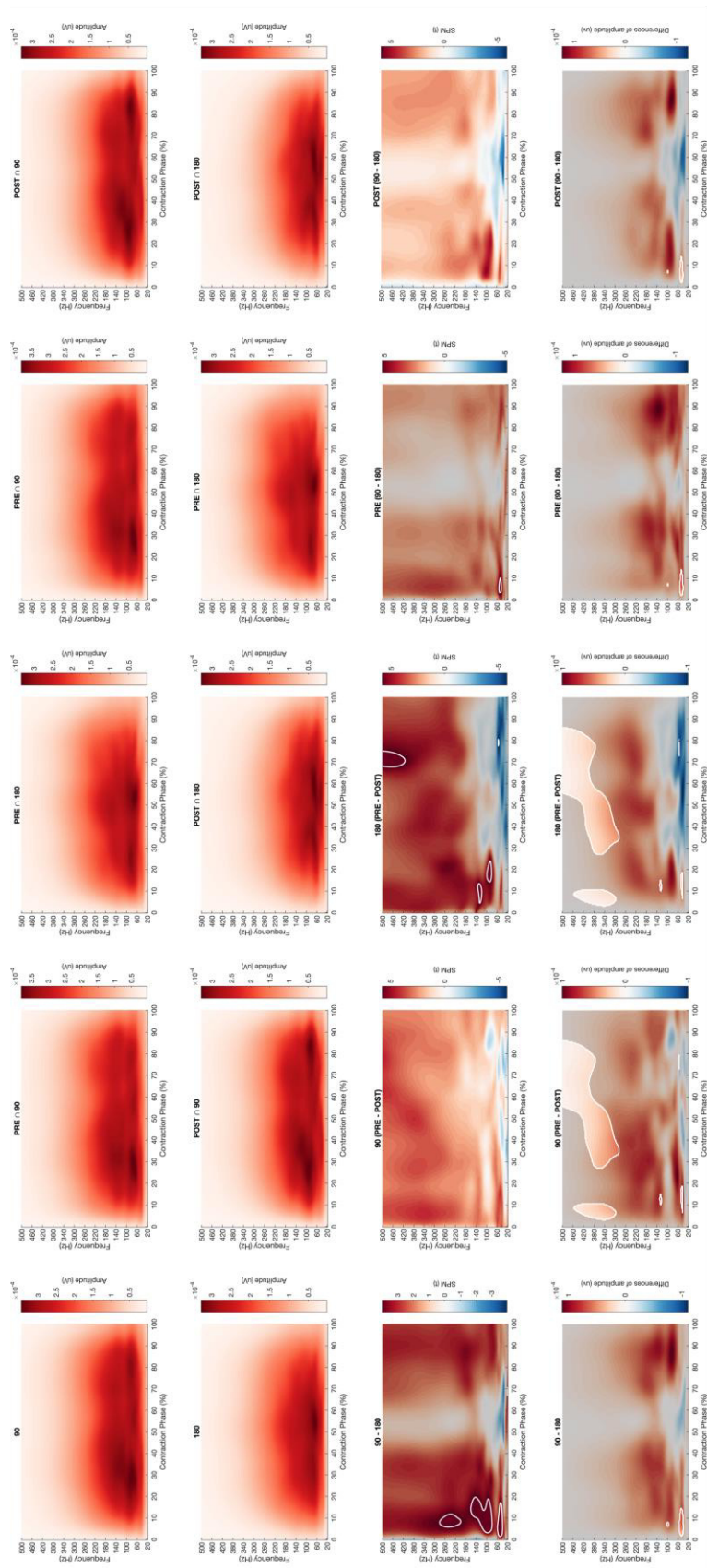


Figure 35: From top to bottom; rows 1 and 2: EMG Frequency-Time map during concentric contractions for Vastus Medialis before (PRE, row) and after (POST, row 2) the fatiguing exercise with/ without the interaction angular velocity ($90^{\circ} \cdot s^{-1}$, $180^{\circ} \cdot s^{-1}$) respectively; row 3: The magnitude of differences between PRE and POST. The enlighten clusters correspond to significant differences, considering the significance of the two-way ANOVA ($p < 0.05$ after Bonferroni correction); row 4: Results of the post hoc tests (SPM t-tests). The enlighten clusters correspond to significant differences without considering the ANOVA ($p < 0.05$ after Bonferroni correction).

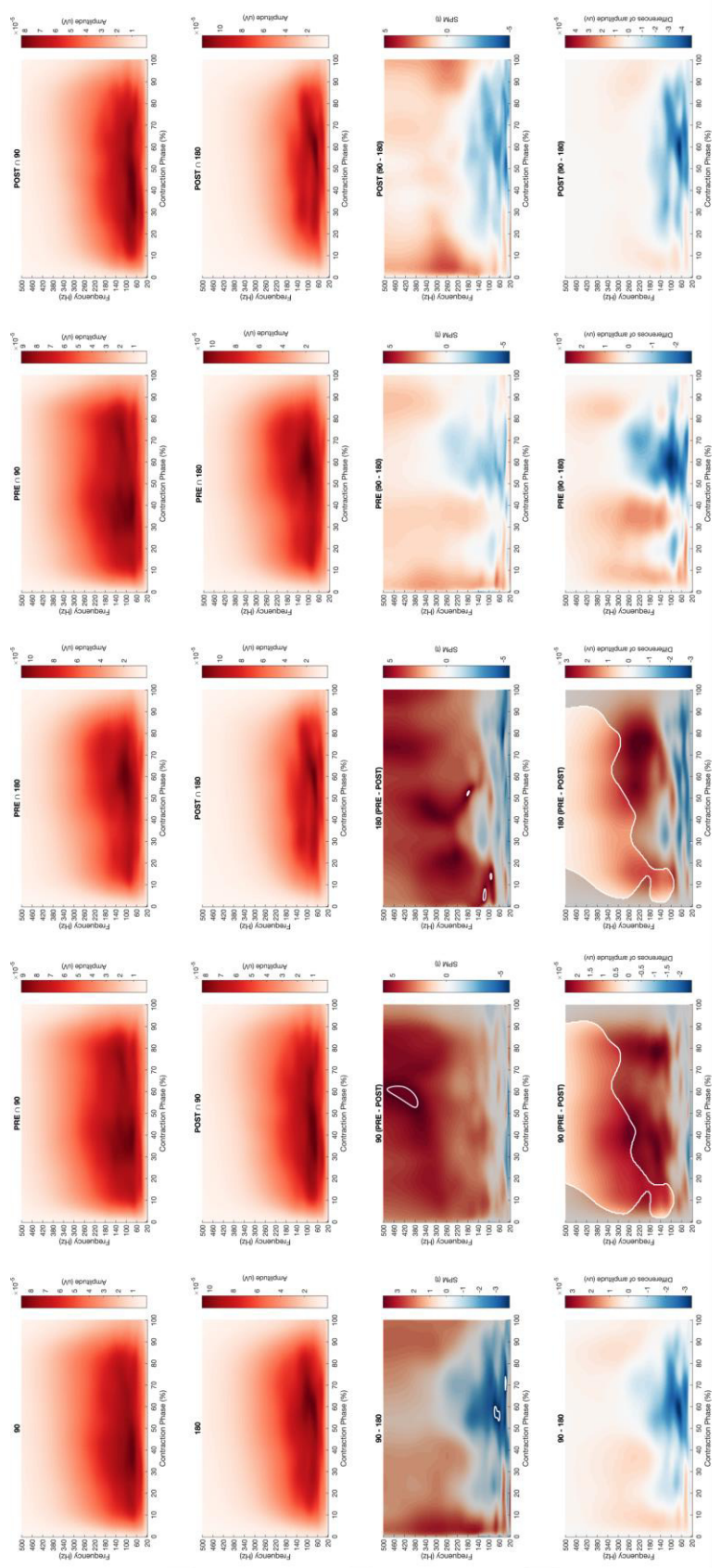


Figure 36: From top to bottom; rows 1 and 2: EMG Frequency-Time map during concentric contractions for Vastus Lateralis before (PRE, row 1) and after (POST, row 2) the fatiguing exercise with/ without the interaction angular velocity ($90^{\circ}.s^{-1}$, $180^{\circ}.s^{-1}$) respectively; row 3: The magnitude of differences between PRE and POST. The enlighten clusters correspond to significant differences, considering the significance of the two-way ANOVA ($p < 0.05$ after Bonferroni correction); row 4: Results of the post hoc tests (SPM t -tests). The enlighten clusters correspond to significant differences without considering the ANOVA ($p < 0.05$ after Bonferroni correction).

6.6 Discussion

The goal of the present study was to analyze the H/Q ratio taking into account timing and angle specificity during a fresh and fatigued state. The major finding of this study demonstrated an equivalent decrease in force-generating capacity of knee flexors and extensors after fatigue. Moreover, fatigue modified angle-specific H/Q ratios and lowered the rate of torque development and the EMG rise.

6.6.1 Influence of fatigue on torque production and H/Q ratios

Overall, the present results indicated that there was an equivalent and marked reduction of the peak torque of knee flexor and extensor muscles at each velocity of contraction. This is not in line with previous studies, since Sangnier and Tourny reported a greater torque loss in hamstring ($70 \pm 8.05\%$) compared to quadriceps ($60 \pm 9.50\%$) muscles after 25 maximal knee flexions/extensions at $180^\circ \cdot s^{-1}$ (Sangnier and Tourny-Chollet 2007). However, Kawabata *et al.* (2000) found that the strength decreased index (SDI) was more substantial for the quadriceps than for hamstring muscles in soccer players (Kawabata, Senda *et al.* 2000). Since one study reported a high proportion of fast-twitch fibers in the hamstring muscles in soccer players (Garrett, Califf *et al.* 1984), a higher fatigability of knee flexors was expected. However, the recent study by Evangelidis *et al.* (2017) reported a balanced myosin heavy chain composition of the biceps femoris long head (BF_{lh}) comparable to the vastus muscle (Evangelidis, Massey *et al.* 2017). Nevertheless, the analysis of conventional and functional H/Q ratios demonstrated that fatigue did not negatively impact muscle balance. Surprisingly, the functional H_{ecc30}/Q_{con180} ratio was even improved after fatigue. This could be explained by the fact that the fatigue session induced a deeper strength loss during the isokinetic contractions performed at $180^\circ \cdot s^{-1}$ compared to other velocities. Whatever the origin of these modifications, it seems that the increased injury risk of HSIs after fatigue or at the end of matches may not be explained by an impaired functional and conventional H/Q ratio. However, it has been demonstrated that the impact of fatigue on H/Q ratios can be advantageously reinforced using SPM analysis on torque-angle curves (Alhammoud, Morel *et al.* 2019). Surprisingly, the SPM analysis showed that H/Q ratios were improved after fatigue at low knee angles in a relatively extended knee position. In conclusion, SPM analysis demonstrated that angle-specific H/Q ratio

modifications after fatigue could not explain the increased occurrence of the HSIs and ACL injury at the end of an exercise.

6.6.2 Influence of fatigue on rapid torque production

Another factor that is known to be sensitive to fatigue and related to injury risk is the ability to produce force rapidly, which can be explored through RTD (Grazioli, Lopez et al. 2019). It is interesting to observe that peak torque reduction was stronger at $180^{\circ}.\text{sec}^{-1}$ compared to other isokinetic velocities. This point may be explained by the slowing of cross-bridge cycling rate after fatigue (De Ruyter and De Haan 2001) and by the higher fatigability of fast-twitch fibers (Hautier, Linossier et al. 1996). Similarly, an increased decline in explosive capacity RTD in the early phase of maximal contraction was observed after fatigue. This reduction in explosive capacity seems to be more marked than the peak torque decreases in line with Morel *et al.* (2015) (Morel, Rouffet et al. 2015). This can be explained by alterations of neural and contractile factors (Andersen and Aagaard 2006, Maffiuletti, Aagaard et al. 2016, Rodriguez-Rosell, Pareja-Blanco et al. 2018). Additionally, a significant reduction in the RTD_{50ms} H/Q ratios was observed after fatigue, indicating that the ability to strengthen and stabilize the knee during the first milliseconds of a contraction was significantly altered after fatigue (Grazioli, Lopez et al. 2019). This is particularly interesting considering the study by Correia *et al.* (2020), which reported a slight trend for a lower RTD H/Q ratio at 50ms in previously injured hamstrings (Correia, Santos et al. 2020), and the results of Grazioli R *et al.* (2019), which revealed that the RTD H/Q ratio in the early phase of contraction decreased by ~24% after match-induced fatigue (Grazioli, Lopez et al. 2019). Considering that the ability to produce torque during the first milliseconds of a contraction is considered as a critical factor for performance (Aagaard, Simonsen et al. 2002) and a determinant of injury risk (Grazioli, Lopez et al. 2019, Correia, Santos et al. 2020), it can be hypothesized that the increased risk of ACL injury after fatigue could be partly explained by the decrease in rapid force capacities RTD and RTD H/Q ratios rather than conventional or functional maximal H/Q ratio modifications.

6.6.3 Influence of EMG on rapid torque capacities after fatigue

The modifications of H/Q ratios and RTD after fatigue may be explained by alterations of neural and contractile factors (Morel, Rouffet et al. 2015, Rodriguez-Rosell, Pareja-Blanco et al. 2018). The present protocol did not enable us to explore the contractile factors, but the analysis of the EMG signal may provide insights about the causes of torque losses after fatigue. Firstly, the decrease in maximal torque measured within the fatigue protocol and during the maximum contractions was not associated with a reduction in the average level of RMS_{mean} EMG (Table 15,16,17). It can be considered that the average value of EMG RMS correctly described muscle activation during maximal and submaximal efforts which suggests that the capacity of the central nervous system to activate muscles entirely was unchanged. This is partly consistent with Morel *et al.* (2015), who reported a small and non-significant decrease in the level of voluntary activation ($-4.3 \pm 1.6\%$, $p = 0.08$) after repeated maximal knee extension to $240^\circ \cdot \text{s}^{-1}$ (Morel, Rouffet et al. 2015). However, if similar levels of maximum activation can be reached when the contraction time is long enough, it has been shown that this does not reflect the ability of the central nervous system to maximally activate the muscle during the first 100 milliseconds of the contraction (Morel, Rouffet et al. 2015). The present results show a significant decrease in RER for knee extensors and flexors regardless of the contraction velocity. Of course, RTD is influenced by many factors such as tissue stiffness, muscle typology, cross-bridge kinetics, and neural drive (Edman and Josephson 2007). However, in the present study, the decrease in RER could be related to the reduction in RTD (Morel, Rouffet et al. 2015). These results suggest that the ability of the central nervous system to activate the muscle quickly and to the maximum at the start of the contraction was altered after fatigue. Considering the study by Morel *et al.* (2015), this point should be analyzed considering the decrease in frequency content of the EMG signal (Morel, Rouffet et al. 2015). Present results show that repeated maximal contractions can induce alterations of the recruitment and firing frequency of the motor units during the early part of the contraction (Aagaard, Simonsen et al. 2002), which result in lowering RER and RTD. In the present study a SPM analysis was performed on the EMG Frequency-Time maps and the results demonstrated a significant reduction of the power contained in the high frequencies of the EMG signal for all the studied muscles during the concentric contractions, and merely for biceps femoris during eccentric contraction, respectively. However, this reduction was not specifically observed in the first 100

milliseconds of the contractions as reported by Morel et al. (2015) (Morel, Rouffet et al. 2015) but appeared all over the contractions except for the eccentric contractions of the BF muscle which demonstrated a significant reduction of the EMG frequency specifically during the first 30% of the movement. Thus, considering the study by Zebis M *et al.* (2009), such a difference in rapid muscle activation in hamstring and quadriceps muscles may be predictive of future ACL injury (Zebis, Andersen et al. 2009). It seems that fatigue can, therefore, increase the risk of injury in soccer players by decreasing their ability to activate muscles during the first 100 milliseconds of a contraction which may alter the knee joint stability.

6.7 Limitation

The study has some limitations that should be kept in mind. Firstly, the present study's sample size is relatively small and not having professional players within the sample may be considered as a limitation. Secondly, no electrical or magnetic stimulation was used in the present study and if the analysis of EMG signal can give some insights about the muscular activation during the exercise it didn't permit to conclude about the origin of fatigue. Lastly, it should be kept in mind that the RTD has been calculated during dynamic isokinetic contractions and it is well known that the isokinetic dynamometers are often more compliant at the beginning of the contraction and noisier than strain gauges which may induce a lower measurement precision for RTD calculation (Maffiuletti, Aagaard et al. 2016). Furthermore, it is impossible at the present time to determine precisely the predictive value of the studied variables in terms of injuries. However, we believe that this paper proposes new and convergent insights that may be used in future studies to determine this predictive value.

6.8 Conclusion

The purpose of this study was to assess the effect of fatigue on angle-specific H/Q ratios, RTD H/Q ratios, and muscle activation in soccer players in order to better understand the augmented risk of HSIs injury at the end of a match. This study demonstrates that conventional and functional ratio were not decreased after fatigue and nor was the ability to maximally activate the muscles. However, the rapid hamstring to quadriceps ratio RTD H/Q were more affected in association with an overall slowdown of RER during the first 100 ms of the contraction and a decrease in frequency

content of the EMG signal. Besides, fatigue seems to reduce the potential for knee joint stability due to the RER deficit during the initial phase of contraction. In accordance with recent studies, present outcomes may confirm the importance of explosive force testing before and after fatigue to improve performance and prevent injuries including (i.e., HSIs, ACL injury). In summary, the results of this study show that functional and conventional H/Q ratios carried out during the pre-season tests are not sensitive to fatigue. It seems, in agreement with many authors, that the evaluation of the capacities of rapid force production during the first 100 milliseconds of a contraction, with and without fatigue, is more appropriate to evaluate and prepare soccer players.

6.9 Practical applications

This study indicated that the traditional H/Q ratios calculated using the peak torque were not sensitive to fatigue whereas dynamic angle specific ratios seemed to give additional information about muscle weakness at some knee angles which may justify the utilization of this kind of analysis in soccer players evaluation before and after fatigue. Moreover, it appeared that RTD H/Q ratios were modified after fatigue. Considering that a short period (i.e., less than 50 milliseconds) is frequently available to stabilize the knee joint through knee muscle contraction after ground contact moment during braking or dropping maneuver 3, 4 one may consider that the measurement of this parameter with and without fatigue is relevant for injury prevention in soccer. From a general point of view and as hypothesised by other authors, it seems that the evaluation of knee stability in soccer players may now incorporate specific angle H/Q ratios, rapid torque development capacities of extensor and flexor muscles and be performed under fatigue state to provide efficient and meaningful indicators to players, coaches and therapists.

CHAPTER 7 General Discussion and Conclusion

7.1 General discussion

7.1.1 Introduction

The main work of the present thesis investigated the neuromuscular performance of hamstring and quadriceps, such as strength, strength imbalance, and co-activation on the explosive performance (i.e., deceleration) and risk factor of lower limb injury (i.e., HSIs, ACL injury). The first study determined the relationship between lower limb strength and the maximum linear deceleration performance. A second study was conducted to investigate the influence of the jump landing direction on the dynamic postural stability and hamstring-to-quadriceps co-activation. The final study investigated the effect of fatigue on the traditional H/Q ratio and RTD H/Q ratio. In this section, the major finding from these studies will be consolidated and generally discussed in reference to the previous studies.

7.1.2 Quadriceps and hamstring strength on deceleration performance

As previously mentioned in the literature review section, a large amount of soccer-based research has focused on determining the lower limb strength on acceleration capacity and sprint performance in professional soccer players (Morin, Edouard et al. 2011, Morin, Bourdin et al. 2012, Buchheit, Samozino et al. 2014, Morin, Gimenez et al. 2015). The higher explosive ability of the quadriceps and hamstring contributes to the higher horizontal force production during the sprinting, improving the sprinting performance (Ishoi, Aagaard et al. 2019). In contrast, only a limited number of studies have investigated the impact of lower limb strength on deceleration performance (Harper, Jordan et al. 2021). The finding of study one (see chapter 3) demonstrated that the lower limb strength (i.e., knee extensor eccentric force, knee flexor concentric force) is strongly related to the deceleration performance evaluated by the kinetic variable (i.e., braking force, braking power, braking impulse), which could be partially explained by the higher eccentric strength could better absorb the impact force to decelerate (Barth, Freeman et al. 2001, Hewitt, Cronin et al. 2011). The present finding provides a piece of complementary evidence to support the previous result of Harper et al. (2015), who indicated the lower limb strength related to the deceleration performance (i.e., time and distance to stop).

Furthermore, the interesting finding is that the RTD of the knee extensor during eccentric contraction is related to the deceleration performance (mean braking force, mean braking power, mean braking impulse), accounting for its essential role in determining the deceleration performance. However, it should note that the RTD was measured during the isokinetic test, which suggests discreetly interpret the present finding. While RTD is an indicator to reflect the ability to rapidly produce muscle force related to an effective neuromuscular activation property, the passive eccentric contraction at lower angular velocity may not adapt to this condition. Therefore, it could be supposed that the RTD in eccentric contraction is mainly related to the contribution of passive elements. Besides, the RTD H/Q ratio related to the deceleration performance (i.e., maximal braking power and impulse), whereas no relationship was found between the traditional H/Q ratio and deceleration performance. The hypothesis to explain this finding is that the RTD H/Q could reflect the ability to reach a given antagonist and agonist joint moment rapidly compared to the traditional H/Q ratio during the explosive movement, which provides the standardized estimate of the potential for dynamic knee joint stabilization (Zebis, Andersen et al. 2011). Therefore, the improvement in RTD H/Q contributes may enable athletes to increase the force absorption capabilities due to higher dynamic knee joint stabilization. Some studies have argued that the traditional H/Q ratio could not describe the reciprocal muscle function of the knee joint (see section 2.2.5). Besides, no relationship was found between the traditional H/Q ratio and RTD H/Q ratio, which emphasizes discriminating these two H/Q during the explosive movement (Greco, Da Silva et al. 2012). In contrast, the present study didn't have enough evidence, such as kinetic analysis to support the relationship between the RTD H/Q and deceleration performance, which requires verifying the present finding in further study.

7.1.3 Postural dynamic stability and H/Q co-activation

Hamstring-to-quadriceps co-activation was usually used to reflect the knee joint stability during the functional movement, potentially predicting the risk of ACL injury (Hewett, Myer et al. 2005, Urabe, Kobayashi et al. 2005). Decreased activation ratio of the hamstring to quadriceps may alter the dynamic knee joint stability. It may increase the risk of ACL injury at the initial landing phase due to increased ACL elongation (Hewett, Myer et al. 2005, Urabe, Kobayashi et al. 2005, Krosshaug, Nakamae et al. 2007, Serpell, Scarvell et al. 2015). The finding from study two is that the hamstring-to-quadriceps co-activation is higher in the dominant leg than the non-dominant leg

only during the drop jump landing (see chapter 4). This finding could partially explain that the non-dominant leg is more at the risk of ACL injury due to the lower H/Q co-activation. Although no significant bilateral difference in vertical GRF was found, it also could be speculated that the magnitude of vertical GRF during the drop jump landing is the primary factor to differ the neuromuscular pattern between dominant and non-dominant leg.

Furthermore, the dominant leg represents the better dynamic postural stability only during the drop landing. This is likely that the stronger knee muscle could better dissipate kinetic energy in the dominant leg, which permitted the dominant leg to stabilize more efficiently the COM during the vertical jump-landing (S. N. Zhang, Bates, & Dufek, 2000). As results, the oscillation in the frontal plane is lower in the dominant leg compared to the non-dominant leg (figure 20). Besides, based on the previous study, it is commonly accepted that a good co-activation of antagonist's muscles can contribute to a better orientation of the resultant forces at the extremity of the limb and a better-stiffened joint (Baratta, Solomonow et al. 1988). As the knee joint is the major contributors to energy absorption during landing (Zhang, Bates et al. 2000) and the DPSI reflect more over the kinetic energy absorption to dissipate the impact (Liu, Glutting et al. 2013, Huurnink, Fransz et al. 2019), it's clear that a significant relationship between the H/Q co-activation and the dynamic postural stability was found. Although no previous study reported similar results, we feel confident that the higher agonist-antagonist coordination could induce this finding to have better dynamic postural stability. Furthermore, it should be noted that the drop-jump landing is critical to discriminate the influence of leg dominance on the neuromuscular pattern to screen the potential risk of ACL injury occurrence.

7.1.4 Fatigue on H/Q ratio

Neuromuscular fatigue was always considered as the potential risk factor for HSIs and ACL injuries due to reducing the hamstring strength (Sangnier and Tourny-Chollet 2007), alter the hamstring activation pattern (Opar, Williams et al. 2012, Fyfe, Opar et al. 2013), or impair knee joint stability (Hiemstra, Lo et al. 2001). The finding of study three indicated that the fatigue-inducing by isokinetic fatigue protocol reduced the concentric peak torque of knee flexor and extensor torque equivalently; thus, no modification of the conventional H/Q ratio in contrast with the previous studies (Sangnier and Tourny-Chollet 2007). Surprisingly, given the lower reduction

in the eccentric peak torque of the knee flexor compared to the peak torque of the concentric knee extensor, the function H/Q ratio increased after fatigue. Besides, the SPM analysis found that the fatigue didn't decrease the H/Q ratio at an extended knee joint position. As mentioned earlier, the current evidence suggested that HSIs occur frequently at the terminal swing during high-speed running, as the hamstring undergo active lengthening and experience peak lengths with the high eccentric force production; thus, it seems that the increased injury risk of HSIs after fatigue maybe not clear.

Meanwhile, the fatigue reduced the early phase (100 ms) RTD H/Q, which revealed that the hamstring explosive ability is more affected by fatigue than the quadriceps. Consideration, the RTD H/Q, reflect the ability to stabilize the joint, it could speculate that the fatigue seems to increase the ACL injury might due to impair dynamic knee joint stability (Ortiz, Olson et al. 2010). Furthermore, given the importance of rapid muscular activation to bring about specific muscular adaptation, a deficit of the RER may limit optimal motor control performance due to reduced alterations of the motor units' recruitment and firing frequency (Aagaard, Simonsen et al. 2002). Considering RER at the initial contraction reduced significantly for knee flexor, it might suggest that the reduction of capacity to voluntarily active the hamstring during the eccentric contraction increase the potential risk for strain-induced muscle failure (Morel, Rouffet et al. 2015).

7.2 Future perspectives

According to the finding of the present thesis, three recommendations for further research are suggested. Firstly, given that only female subjected were used in the first study, these protocols should be implemented using professional male soccer players to determine whether these results are gender-specific. Although the first study found the lower limb strength related to the kinetic variable, the force plate measurement did not validate this method. Besides, as the previous studies indicated the important role of the skill on the deceleration performance, the complementary measure needs to implement to find how the lower limb strength to influent the deceleration performance via the kinetic and kinematic variable (e.g., ground contact time, foot strike pattern, knee, and hip joint angle). Secondly, a further area for future research would be to confirm the same findings in professional soccer players. The second study found the dominant leg represents the better dynamic postural stability only in the fitness participants. Given the soccer is a single-

leg-dominant laterality sport, the soccer player nearly always uses the DL to manipulate the ball (i.e., kicking or passing). In contrast, the NDL is often used to control dynamic body stability (Wong, Chamari et al. 2007). It could be speculated that the NDL leg might display better dynamic postural stability in professional soccer players compared to the fitness participant. Furthermore, isokinetic dynamometers are often more compliant due to the compression of soft tissue at the beginning of the contraction and noisier than strain gauges, potentially increasing errors in the calculation of RFD (Maffiuletti, Aagaard et al. 2016). Thus, using the MVIC to measure the RTD is warranted to confirm our finding. Thirdly, given that the fatigue protocol is induced by repeated isokinetic contraction, further study needs to use the competitive-match stimulation or soccer-specific fatigue protocol to verify our finding. Besides, if possible, large prospective studies need to confirm the relationship between the angle-specific H/Q ratio, early phase RTD H/Q ratio, HSIs, and ACL injury in soccer players.

7.3 Conclusion

In consequence, the highlighted conclusions of this thesis were that

- i) The soccer players with the greater knee extensor eccentric strength within higher ability to rapidly produce force have better linear deceleration performance.
- ii) The higher H/Q co-activation contributes the better dynamic postural stability during the jump-landing maneuvers.
- iii) The explosive capacity of hamstring and quadriceps measured by early RTD was more affected by the fatigue following a deficit of muscular activation during the initial phase of contraction.

CHAPTER 8 References

Aagaard, P., E. B. Simonsen, J. L. Andersen, P. Magnusson and P. Dyhre-Poulsen (2002). "Increased rate of force development and neural drive of human skeletal muscle following resistance training." Journal of Applied Physiology **93**(4): 1318-1326.

Aagaard, P., E. B. Simonsen, J. L. Andersen, S. P. Magnusson, F. Bojsen-Møller and P. Dyhre-Poulsen (2000). "Antagonist muscle coactivation during isokinetic knee extension." Scand J Med Sci Sports **10**(2): 58-67.

Aagaard, P., E. B. Simonsen, N. Beyer, B. Larsson, P. Magnusson and M. Kjaer (1997). "Isokinetic muscle strength and capacity for muscular knee joint stabilization in elite sailors." Int J Sports Med **18**(7): 521-525.

Aagaard, P., E. B. Simonsen, S. P. Magnusson, B. Larsson and P. Dyhre-Poulsen (1998). "A new concept for isokinetic hamstring: quadriceps muscle strength ratio." Am J Sports Med **26**(2): 231-237.

Aagaard, P., E. B. Simonsen, M. Trolle, J. Bangsbo and K. Klausen (1995). "Isokinetic hamstring/quadriceps strength ratio: influence from joint angular velocity, gravity correction and contraction mode." Acta Physiol Scand **154**(4): 421-427.

Abbott, B. C. and X. M. Aubert (1952). "The force exerted by active striated muscle during and after change of length." The Journal of physiology **117**(1): 77-86.

Agel, J., E. A. Arendt and B. Bershadsky (2005). "Anterior Cruciate Ligament Injury in National Collegiate Athletic Association Basketball and Soccer: A 13-Year Review." The American Journal of Sports Medicine **33**(4): 524-531.

Akenhead, R., P. R. Hayes, K. G. Thompson and D. French (2013). "Diminutions of acceleration and deceleration output during professional football match play." J Sci Med Sport **16**(6): 556-561.

Al Attar, W. S. A., N. Soomro, P. J. Sinclair, E. Pappas and R. H. Sanders (2017). "Effect of Injury Prevention Programs that Include the Nordic Hamstring Exercise on Hamstring Injury Rates in Soccer Players: A Systematic Review and Meta-Analysis." Sports Med **47**(5): 907-916.

Alegre, L. M., A. Ferri-Morales, R. Rodriguez-Casares and X. Aguado (2014). "Effects of isometric training on the knee extensor moment-angle relationship and vastus lateralis muscle architecture." Eur J Appl Physiol **114**(11): 2437-2446.

Alentorn-Geli, E., G. D. Myer, H. J. Silvers, G. Samitier, D. Romero, C. Lazaro-Haro and R. Cugat (2009). "Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors." Knee Surg Sports Traumatol Arthrosc **17**(7): 705-729.

Alentorn-Geli, E., G. D. Myer, H. J. Silvers, G. Samitier, D. Romero, C. Lázaro-Haro and R. Cugat (2009). "Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 2: a review of prevention programs aimed to modify risk factors and to reduce injury rates." Knee Surg Sports Traumatol Arthrosc **17**(8): 859-879.

Alexander, M. J. (1989). "The relationship between muscle strength and sprint kinematics in elite sprinters." Can J Sport Sci **14**(3): 148-157.

Alhammoud, M., B. Morel, O. Girard, S. Racinais, V. Sevrez, A. Germain, T. Chamu and C. Hautier (2018). "Hypoxia and Fatigue Impair Rapid Torque Development of Knee Extensors in Elite Alpine Skiers." Front Physiol **9**: 962.

Alhammoud, M., B. Morel, C. Hansen, M. Wilson, R. Mecca, E. Nael and C. Hautier (2019). "Discipline and Sex Differences in Angle-specific Isokinetic Analysis in Elite Skiers." Int J Sports Med **40**(5): 317-330.

Andersen, L. L. and P. Aagaard (2006). "Influence of maximal muscle strength and intrinsic muscle contractile properties on contractile rate of force development." Eur J Appl Physiol **96**(1): 46-52.

Andersen, L. L., J. L. Andersen, M. K. Zebis and P. Aagaard (2010). "Early and late rate of force development: differential adaptive responses to resistance training?" Scandinavian Journal of Medicine & Science in Sports **20**(1): e162-e169.

Anderson, M. A., J. H. Gieck, D. H. Perrin, A. Weltman, R. A. Rutt and C. R. Denegar (1991). "The Relationships among Isometric, Isotonic, and Isokinetic Concentric and Eccentric Quadriceps and Hamstring Force and Three Components of Athletic Performance." J Orthop Sports Phys Ther **14**(3): 114-120.

Andrews, J. R., W. D. McLeod, T. Ward and K. Howard (1977). "The cutting mechanism." Am J Sports Med **5**(3): 111-121.

Andrzejewski, M., J. Chmura, B. Pluta and A. Kasprzak (2012). "Analysis of motor activities of professional soccer players." J Strength Cond Res **26**(6): 1481-1488.

Andrzejewski, M., J. Chmura, B. Pluta, R. Strzelczyk and A. Kasprzak (2013). "Analysis of sprinting activities of professional soccer players." J Strength Cond Res **27**(8): 2134-2140.

Angelozzi, M., M. Madama, C. Corsica, V. Calvisi, G. Properzi, S. T. McCaw and A. Cacchio (2012). "Rate of force development as an adjunctive outcome measure for return-to-sport decisions after anterior cruciate ligament reconstruction." J Orthop Sports Phys Ther **42**(9): 772-780.

Arnason, A., S. B. Sigurdsson, A. Gudmundsson, I. Holme, L. Engebretsen and R. Bahr (2004). "Risk factors for injuries in football." Am J Sports Med **32**(1 Suppl): 5S-16S.

Arsac, L. M. and E. Locatelli (2002). "Modeling the energetics of 100-m running by using speed curves of world champions." Journal of applied physiology (Bethesda, Md. : 1985) **92**(5): 1781-1788.

Ashton, J. and P. A. Jones (2019). "The Reliability of Using a Laser Device to Assess Deceleration Ability." Sports (Basel) **7**(8).

Askling, C. M., G. Koulouris, T. Saartok, S. Werner and T. M. Best (2013). "Total proximal hamstring ruptures: clinical and MRI aspects including guidelines for postoperative rehabilitation." Knee Surg Sports Traumatol Arthrosc **21**(3): 515-533.

Askling, C. M., M. Tengvar, T. Saartok and A. Thorstensson (2008). "Proximal hamstring strains of stretching type in different sports: injury situations, clinical and magnetic resonance imaging characteristics, and return to sport." Am J Sports Med **36**(9): 1799-1804.

Askling, C. M., M. Tengvar, O. Tarassova and A. Thorstensson (2014). "Acute hamstring injuries in Swedish elite sprinters and jumpers: a prospective randomised controlled clinical trial comparing two rehabilitation protocols." Br J Sports Med **48**(7): 532-539.

Baltzopoulos, V. and D. A. Brodie (1989). "Isokinetic dynamometry. Applications and limitations." Sports Med **8**(2): 101-116.

Bangsbo, J., M. Mohr and P. Krstrup (2006). "Physical and metabolic demands of training and match-play in the elite football player." J Sports Sci **24**(7): 665-674.

Baratta, R., M. Solomonow, B. H. Zhou, D. Letson, R. Chuinard and R. D'Ambrosia (1988). "Muscular coactivation: The role of the antagonist musculature in maintaining knee stability." The American Journal of Sports Medicine **16**(2): 113-122.

Baratta, R., M. Solomonow, B. H. Zhou, D. Letson, R. Chuinard and R. D'Ambrosia (1988). "Muscular coactivation. The role of the antagonist musculature in maintaining knee stability." Am J Sports Med **16**(2): 113-122.

Barnes, J. L., B. K. Schilling, M. J. Falvo, L. W. Weiss, A. K. Creasy and A. C. Fry (2007). "Relationship of jumping and agility performance in female volleyball athletes." J Strength Cond Res **21**(4): 1192-1196.

Baroni, B. M., C. V. Ruas, J. B. Ribeiro-Alvares and R. S. Pinto (2020). "Hamstring-to-Quadriceps Torque Ratios of Professional Male Soccer Players: A Systematic Review." J Strength Cond Res **34**(1): 281-293.

Baroni, B. M., C. V. Ruas, J. B. Ribeiro-Alvares and R. S. Pinto (2020). "Hamstring-to-Quadriceps Torque Ratios of Professional Male Soccer Players: A Systematic Review." The Journal of Strength & Conditioning Research **34**(1): 281-293.

- Barth, J. T., J. R. Freeman, D. K. Broshek and R. N. Varney (2001). "Acceleration-Deceleration Sport-Related Concussion: The Gravity of It All." Journal of athletic training **36**(3): 253-256.
- Bencke, J., H. Naesborg, E. B. Simonsen and K. Klausen (2000). "Motor pattern of the knee joint muscles during side-step cutting in European team handball. Influence on muscular co-ordination after an intervention study." Scand J Med Sci Sports **10**(2): 68-77.
- Bennell, K., H. Wajswelner, P. Lew, A. Schall-Riauour, S. Leslie, D. Plant and J. Cirone (1998). "Isokinetic strength testing does not predict hamstring injury in Australian Rules footballers." British journal of sports medicine **32**(4): 309-314.
- Bennett, D. R., J. T. Blackburn, M. C. Boling, M. McGrath, H. Walusz and D. A. Padua (2008). "The relationship between anterior tibial shear force during a jump landing task and quadriceps and hamstring strength." Clin Biomech (Bristol, Avon) **23**(9): 1165-1171.
- Bloomfield, J., R. Polman and P. O'Donoghue (2007). "Physical Demands of Different Positions in FA Premier League Soccer." Journal of sports science & medicine **6**(1): 63-70.
- Bohannon, R. W. (2005). "Manual muscle testing: does it meet the standards of an adequate screening test?" Clin Rehabil **19**(6): 662-667.
- Bradley, P. S. and M. D. Portas (2007). "The relationship between preseason range of motion and muscle strain injury in elite soccer players." J Strength Cond Res **21**(4): 1155-1159.
- Bradley, P. S., W. Sheldon, B. Wooster, P. Olsen, P. Boanas and P. Krusturup (2009). "High-intensity running in English FA Premier League soccer matches." J Sports Sci **27**(2): 159-168.
- Brockett, C. L., D. L. Morgan and U. Proske (2004). "Predicting hamstring strain injury in elite athletes." Med Sci Sports Exerc **36**(3): 379-387.
- Brooks, J. H., C. W. Fuller, S. P. Kemp and D. B. Reddin (2006). "Incidence, risk, and prevention of hamstring muscle injuries in professional rugby union." Am J Sports Med **34**(8): 1297-1306.
- Brophy, R., H. J. Silvers, T. Gonzales and B. R. Mandelbaum (2010). "Gender influences: the role of leg dominance in ACL injury among soccer players." British Journal of Sports Medicine **44**(10): 694-697.
- Brown, L. E. (2000). Isokinetics in human performance, Human Kinetics.
- Brownstein, C. G., J. P. Dent, P. Parker, K. M. Hicks, G. Howatson, S. Goodall and K. Thomas (2017). "Etiology and Recovery of Neuromuscular Fatigue following Competitive Soccer Match-Play." Front Physiol **8**: 831.
- Brughelli, M., J. Cronin, G. Levin and A. Chaouachi (2008). "Understanding Change of Direction Ability in Sport." Sports Medicine **38**(12): 1045-1063.

- Brughelli, M., J. Mendiguchia, K. Nosaka, F. Idoate, A. L. Arcos and J. Cronin (2010). "Effects of eccentric exercise on optimum length of the knee flexors and extensors during the preseason in professional soccer players." Phys Ther Sport **11**(2): 50-55.
- Brukner, P., A. Nealon, C. Morgan, D. Burgess and A. Dunn (2014). "Recurrent hamstring muscle injury: applying the limited evidence in the professional football setting with a seven-point programme." Br J Sports Med **48**(11): 929-938.
- Buchheit, M., H. Al Haddad, B. M. Simpson, D. Palazzi, P. C. Bourdon, V. Di Salvo and A. Mendez-Villanueva (2014). "Monitoring accelerations with GPS in football: time to slow down?" Int J Sports Physiol Perform **9**(3): 442-445.
- Buchheit, M., A. Mendez-villanueva, B. M. Simpson and P. C. Bourdon (2010). "Repeated-sprint sequences during youth soccer matches." Int J Sports Med **31**(10): 709-716.
- Buchheit, M., P. Samozino, J. A. Glynn, B. S. Michael, H. Al Haddad, A. Mendez-Villanueva and J. B. Morin (2014). "Mechanical determinants of acceleration and maximal sprinting speed in highly trained young soccer players." J Sports Sci **32**(20): 1906-1913.
- Burden, A. M., M. Trew and V. Baltzopoulos (2003). "Normalisation of gait EMGs: a re-examination." J Electromyogr Kinesiol **13**(6): 519-532.
- Burgess, D. J., G. Naughton and K. I. Norton (2006). "Profile of movement demands of national football players in Australia." Journal of Science and Medicine in Sport **9**(4): 334-341.
- Castillo-Rodriguez, A., J. C. Fernandez-Garcia, J. L. Chinchilla-Minguet and E. A. Carnero (2012). "Relationship between muscular strength and sprints with changes of direction." J Strength Cond Res **26**(3): 725-732.
- Celes, R., L. E. Brown, M. C. Pereira, F. P. Schwartz, V. A. Junior and M. Bottaro (2010). "Gender muscle recovery during isokinetic exercise." Int J Sports Med **31**(12): 866-869.
- Chaouachi, A., V. Manzi, A. Chaalali, P. Wong del, K. Chamari and C. Castagna (2012). "Determinants analysis of change-of-direction ability in elite soccer players." J Strength Cond Res **26**(10): 2667-2676.
- Chaouachi, A., V. Manzi, D. P. Wong, A. Chaalali, L. Laurencelle, K. Chamari and C. Castagna (2010). "Intermittent Endurance and Repeated Sprint Ability in Soccer Players." The Journal of Strength & Conditioning Research **24**(10).
- Chappell, J. D., R. A. Creighton, C. Giuliani, B. Yu and W. E. Garrett (2007). "Kinematics and electromyography of landing preparation in vertical stop-jump: risks for noncontact anterior cruciate ligament injury." Am J Sports Med **35**(2): 235-241.

- Chappell, J. D., D. C. Herman, B. S. Knight, D. T. Kirkendall, W. E. Garrett and B. Yu (2005). "Effect of Fatigue on Knee Kinetics and Kinematics in Stop-Jump Tasks." The American Journal of Sports Medicine **33**(7): 1022-1029.
- Chelly, S. M. and C. Denis (2001). "Leg power and hopping stiffness: relationship with sprint running performance." Med Sci Sports Exerc **33**(2): 326-333.
- Chumanov, E. S., B. C. Heiderscheit and D. G. Thelen (2007). "The effect of speed and influence of individual muscles on hamstring mechanics during the swing phase of sprinting." J Biomech **40**(16): 3555-3562.
- Chumanov, E. S., B. C. Heiderscheit and D. G. Thelen (2011). "Hamstring musculotendon dynamics during stance and swing phases of high-speed running." Med Sci Sports Exerc **43**(3): 525-532.
- Cohen, D. D., B. Zhao, B. Okwera, M. J. Matthews and A. Delextrat (2015). "Angle-specific eccentric hamstring fatigue after simulated soccer." Int J Sports Physiol Perform **10**(3): 325-331.
- Colby, S. M., R. A. Hintermeister, M. R. Torry and J. R. Steadman (1999). "Lower limb stability with ACL impairment." J Orthop Sports Phys Ther **29**(8): 444-451; discussion 452-444.
- Collings, T. J., A. D. Gorman, M. C. Stuelcken, D. B. Mellifont and M. G. L. Sayers (2019). "Exploring the Justifications for Selecting a Drop Landing Task to Assess Injury Biomechanics: A Narrative Review and Analysis of Landings Performed by Female Netball Players." Sports Medicine **49**(3): 385-395.
- Cometti, G., N. A. Maffiuletti, M. Pousson, J. C. Chatard and N. Maffulli (2001). "Isokinetic strength and anaerobic power of elite, subelite and amateur French soccer players." Int J Sports Med **22**(1): 45-51.
- Condello, G., T. W. Kernozek, A. Tessitore and C. Foster (2016). "Biomechanical Analysis of a Change-of-Direction Task in Collegiate Soccer Players." Int J Sports Physiol Perform **11**(1): 96-101.
- Connell, D. A., M. E. Schneider-Kolsky, J. L. Hoving, F. Malara, R. Buchbinder, G. Koulouris, F. Burke and C. Bass (2004). "Longitudinal study comparing sonographic and MRI assessments of acute and healing hamstring injuries." American Journal of Roentgenology **183**(4): 975-984.
- Coombs, R. and G. Garbutt (2002). "Developments in the use of the hamstring/quadriceps ratio for the assessment of muscle balance." J Sports Sci Med **1**(3): 56-62.
- Coratella, G., G. Bellin, M. Beato and F. Schena (2015). "Fatigue affects peak joint torque angle in hamstrings but not in quadriceps." J Sports Sci **33**(12): 1276-1282.
- Cormie, P., M. R. McGuigan and R. U. Newton (2010). "Adaptations in athletic performance after ballistic power versus strength training." Med Sci Sports Exerc **42**(8): 1582-1598.

Correia, P., P. Santos, P. Mil-Homens, M. Gomes, A. Dias and M. J. Valamatos (2020). "Rapid hamstrings to quadriceps ratio at long muscle lengths in professional football players with previous hamstring strain injury." Eur J Sport Sci: 1-9.

Crema, M. D., A. Guermazi, J. L. Tol, J. Niu, B. Hamilton and F. W. Roemer (2016). "Acute hamstring injury in football players: Association between anatomical location and extent of injury- A large single-center MRI report." J Sci Med Sport **19**(4): 317-322.

Croce, R. V. and J. P. Miller (2006). "Angle- and velocity-specific alterations in torque and semg activity of the quadriceps and hamstrings during isokinetic extension-flexion movements." Electromyogr Clin Neurophysiol **46**(2): 83-100.

Croisier, J. L. (2004). "Factors associated with recurrent hamstring injuries." Sports Med **34**(10): 681-695.

Croisier, J. L., S. Ganteaume, J. Binet, M. Genty and J. M. Ferret (2008). "Strength imbalances and prevention of hamstring injury in professional soccer players: a prospective study." Am J Sports Med **36**(8): 1469-1475.

Cronin, J. B. and K. T. Hansen (2005). "Strength and power predictors of sports speed." J Strength Cond Res **19**(2): 349-357.

Crossley, K. M., T. W. Dorn, H. Ozturk, J. van den Noort, A. G. Schache and M. G. Pandy (2012). "Altered hip muscle forces during gait in people with patellofemoral osteoarthritis." Osteoarthritis and Cartilage **20**(11): 1243-1249.

Cunha, L., J. Ribeiro, O. Fernandes, M. Valamatos, R. Pinto and P. Santos (2007). The relationships between sprint run and strength parameters in young athletes and non-athletes. ISBS-Conference Proceedings Archive.

Dalton, S. L., Z. Y. Kerr and T. P. Dompier (2015). "Epidemiology of Hamstring Strains in 25 NCAA Sports in the 2009-2010 to 2013-2014 Academic Years." Am J Sports Med **43**(11): 2671-2679.

Daneshjoo, A., N. Rahnema, A. H. Mokhtar and A. Yusof (2013). "Bilateral and unilateral asymmetries of isokinetic strength and flexibility in male young professional soccer players." J Hum Kinet **36**: 45-53.

Dauty, M., P. Menu and A. Fouasson-Chailloux (2018). "Cutoffs of isokinetic strength ratio and hamstring strain prediction in professional soccer players." Scand J Med Sci Sports **28**(1): 276-281.

de Hoyo, M., D. D. Cohen, B. Sañudo, L. Carrasco, A. Álvarez-Mesa, J. J. Del Ojo, S. Domínguez-Cobo, V. Mañas and C. Otero-Esquina (2016). "Influence of football match time-motion parameters on recovery time course of muscle damage and jump ability." J Sports Sci **34**(14): 1363-1370.

de Hoyo, M., D. D. Cohen, B. Sañudo, L. Carrasco, A. Álvarez-Mesa, J. J. del Ojo, S. Domínguez-Cobo, V. Mañas and C. Otero-Esquina (2016). "Influence of football match time–motion parameters on recovery time course of muscle damage and jump ability." Journal of Sports Sciences **34**(14): 1363-1370.

de Hoyo, M., B. Sanudo, L. Carrasco, J. Mateo-Cortes, S. Dominguez-Cobo, O. Fernandes, J. J. Del Ojo and O. Gonzalo-Skok (2016). "Effects of 10-week eccentric overload training on kinetic parameters during change of direction in football players." J Sports Sci **34**(14): 1380-1387.

De Ruitter, C. J. and A. De Haan (2001). "Similar effects of cooling and fatigue on eccentric and concentric force-velocity relationships in human muscle." J Appl Physiol (1985) **90**(6): 2109-2116.

De Smet, A. A. and T. M. Best (2000). "MR imaging of the distribution and location of acute hamstring injuries in athletes." AJR Am J Roentgenol **174**(2): 393-399.

De Ste Croix, M., Y. O. ElNagar, J. Iga, F. Ayala and D. James (2017). "The impact of joint angle and movement velocity on sex differences in the functional hamstring/quadriceps ratio." Knee **24**(4): 745-750.

De Ste Croix, M. B., A. M. Priestley, R. S. Lloyd and J. L. Oliver (2015). "ACL injury risk in elite female youth soccer: Changes in neuromuscular control of the knee following soccer-specific fatigue." Scand J Med Sci Sports **25**(5): e531-538.

Delahunt, E., M. Chawke, J. Kelleher, K. Murphy, A. Prendiville, L. Sweeny and M. Patterson (2013). "Lower limb kinematics and dynamic postural stability in anterior cruciate ligament-reconstructed female athletes." J Athl Train **48**(2): 172-185.

Delextrat, A., J. Baker, D. D. Cohen and N. D. Clarke (2013). "Effect of a simulated soccer match on the functional hamstrings-to-quadriceps ratio in amateur female players." Scand J Med Sci Sports **23**(4): 478-486.

Delextrat, A., J. Gregory and D. Cohen (2010). "The use of the functional H:Q ratio to assess fatigue in soccer." Int J Sports Med **31**(3): 192-197.

Della Villa, F., M. Buckthorpe, A. Grassi, A. Nabiuzzi, F. Tosarelli, S. Zaffagnini, A. Virgile and S. Della Villa (2020). "Infographic. Systematic video analysis of ACL injuries in professional male football (soccer): injury mechanisms, situational patterns and biomechanics study on 134 consecutive cases." British Journal of Sports Medicine: bjsports-2020-103241.

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

DeMorat, G., P. Weinholt, T. Blackburn, S. Chudik and W. Garrett (2004). "Aggressive quadriceps loading can induce noncontact anterior cruciate ligament injury." Am J Sports Med **32**(2): 477-483.

Di Salvo, V., W. Gregson, G. Atkinson, P. Tordoff and B. Drust (2009). "Analysis of high intensity activity in Premier League soccer." Int J Sports Med **30**(3): 205-212.

Donelon, T. A., T. Dos'Santos, G. Pitchers, M. Brown and P. A. Jones (2020). "Biomechanical Determinants of Knee Joint Loads Associated with Increased Anterior Cruciate Ligament Loading During Cutting: A Systematic Review and Technical Framework." Sports Medicine - Open **6**(1): 53.

Dos'Santos, T., C. Thomas, P. A. Jones and P. Comfort (2017). "Mechanical Determinants of Faster Change of Direction Speed Performance in Male Athletes." J Strength Cond Res **31**(3): 696-705.

Duthon, V. B., C. Barea, S. Abrassart, J. H. Fasel, D. Fritschy and J. Ménétrey (2006). "Anatomy of the anterior cruciate ligament." Knee Surg Sports Traumatol Arthrosc **14**(3): 204-213.

Dvir, Z., G. Eger, N. Halperin and A. Shklar (1989). "Thigh muscle activity and anterior cruciate ligament insufficiency." Clinical Biomechanics **4**(2): 87-91.

Dyhre-Poulsen, P., E. B. Simonsen and M. Voigt (1991). "Dynamic control of muscle stiffness and H reflex modulation during hopping and jumping in man." J Physiol **437**: 287-304.

Ebben, W. P., M. L. Fauth, E. J. Petushek, L. R. Garceau, B. E. Hsu, B. N. Lutsch and C. R. Feldmann (2010). "Gender-based analysis of hamstring and quadriceps muscle activation during jump landings and cutting." J Strength Cond Res **24**(2): 408-415.

Edman, K. A. and R. K. Josephson (2007). "Determinants of force rise time during isometric contraction of frog muscle fibres." J Physiol **580**(Pt.3): 1007-1019.

Edouard, P. and F. Degache (2016). Guide d'isocinétisme: l'évaluation isocinétique des concepts aux conditions sportives et pathologiques, Elsevier Masson.

Edouard, P., J. Mendiguchia, J. Lahti, P. J. Arnal, P. Gimenez, P. Jimenez-Reyes, M. Brughelli, P. Samozino and J. B. Morin (2018). "Sprint Acceleration Mechanics in Fatigue Conditions: Compensatory Role of Gluteal Muscles in Horizontal Force Production and Potential Protection of Hamstring Muscles." Front Physiol **9**: 1706.

Ekstrand, J., M. Hägglund and M. Waldén (2011). "Epidemiology of muscle injuries in professional football (soccer)." Am J Sports Med **39**(6): 1226-1232.

Ekstrand, J., M. Hägglund and M. Waldén (2011). "Epidemiology of muscle injuries in professional football (soccer)." The American journal of sports medicine **39**(6): 1226-1232.

Ekstrand, J., M. Hägglund and M. Waldén (2011). "Injury incidence and injury patterns in professional football: the UEFA injury study." Br J Sports Med **45**(7): 553-558.

Ekstrand, J., M. Waldén and M. Hägglund (2016). "Hamstring injuries have increased by 4% annually in men's professional football, since 2001: a 13-year longitudinal analysis of the UEFA Elite Club injury study." Br J Sports Med **50**(12): 731-737.

El-Ashker, S., J. M. Allardyce and B. P. Carson (2019). "Sex-related differences in joint-angle-specific hamstring-to-quadriceps function following fatigue." European Journal of Sport Science **19**(8): 1053-1061.

Elliott, M. C., B. Zarins, J. W. Powell and C. D. Kenyon (2011). "Hamstring muscle strains in professional football players: a 10-year review." Am J Sports Med **39**(4): 843-850.

Emery, C. A., W. H. Meeuwisse and S. E. Hartmann (2005). "Evaluation of risk factors for injury in adolescent soccer: implementation and validation of an injury surveillance system." Am J Sports Med **33**(12): 1882-1891.

Engebretsen, A. H., G. Myklebust, I. Holme, L. Engebretsen and R. Bahr (2010). "Intrinsic risk factors for hamstring injuries among male soccer players: a prospective cohort study." Am J Sports Med **38**(6): 1147-1153.

Eustace, S. J., R. M. Page and M. Greig (2020). "Angle-Specific Isokinetic Metrics Highlight Strength Training Needs of Elite Youth Soccer Players." J Strength Cond Res **34**(11): 3258-3265.

Evangelidis, P. E., G. J. Massey, R. A. Ferguson, P. C. Wheeler, M. T. G. Pain and J. P. Folland (2017). "The functional significance of hamstrings composition: is it really a "fast" muscle group?" Scand J Med Sci Sports **27**(11): 1181-1189.

Evangelidis, P. E., M. T. Pain and J. Folland (2015). "Angle-specific hamstring-to-quadriceps ratio: a comparison of football players and recreationally active males." J Sports Sci **33**(3): 309-319.

Evans, J. D. (1996). Straight forward statistics for the behavioral sciences, Thomson Brooks/Cole Publishing Co.

Faul, F., E. Erdfelder, A.-G. Lang and A. Buchner (2007). "G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences." Behavior Research Methods **39**(2): 175-191.

Feher, J. (2017). 3.4 - Skeletal Muscle Mechanics. Quantitative Human Physiology (Second Edition). J. Feher. Boston, Academic Press: 292-304.

Fousekis, K., E. Tsepis and G. Vagenas (2010). "Lower limb strength in professional soccer players: profile, asymmetry, and training age." Journal of sports science & medicine **9**(3): 364-373.

- Fox, A. S. (2018). "Change-of-Direction Biomechanics: Is What's Best for Anterior Cruciate Ligament Injury Prevention Also Best for Performance?" Sports Medicine **48**(8): 1799-1807.
- Fox, A. S., J. Bonacci, S. G. McLean, M. Spittle and N. Saunders (2014). "What is normal? Female lower limb kinematic profiles during athletic tasks used to examine anterior cruciate ligament injury risk: a systematic review." Sports Med **44**(6): 815-832.
- Franchi, M. V., N. D. Reeves and M. V. Narici (2017). "Skeletal Muscle Remodeling in Response to Eccentric vs. Concentric Loading: Morphological, Molecular, and Metabolic Adaptations." Front Physiol **8**: 447.
- Fransz, D. P., A. Huurnink, V. A. de Boode, I. Kingma and J. H. van Dieën (2016). "The effect of the stability threshold on time to stabilization and its reliability following a single leg drop jump landing." J Biomech **49**(3): 496-501.
- Freckleton, G. and T. Pizzari (2013). "Risk factors for hamstring muscle strain injury in sport: a systematic review and meta-analysis." Br J Sports Med **47**(6): 351-358.
- Fridén, J. and R. L. Lieber (2001). "Eccentric exercise-induced injuries to contractile and cytoskeletal muscle fibre components." Acta Physiol Scand **171**(3): 321-326.
- Fyfe, J. J., D. A. Opar, M. D. Williams and A. J. Shield (2013). "The role of neuromuscular inhibition in hamstring strain injury recurrence." J Electromyogr Kinesiol **23**(3): 523-530.
- Gabbe, B. J., K. L. Bennell and C. F. Finch (2006). "Why are older Australian football players at greater risk of hamstring injury?" J Sci Med Sport **9**(4): 327-333.
- Gabbe, B. J., K. L. Bennell, C. F. Finch, H. Wajswelner and J. W. Orchard (2006). "Predictors of hamstring injury at the elite level of Australian football." Scand J Med Sci Sports **16**(1): 7-13.
- Gaillard, R., R. Magnussen, C. Batailler, P. Neyret, S. Lustig and E. Servien (2019). "Anatomic risk factor for meniscal lesion in association with ACL rupture." Journal of Orthopaedic Surgery and Research **14**(1): 242.
- Gandevia, S. C. (2001). "Spinal and supraspinal factors in human muscle fatigue." Physiol Rev **81**(4): 1725-1789.
- Gans, I., J. S. Retzky, L. C. Jones and M. J. Tanaka (2018). "Epidemiology of Recurrent Anterior Cruciate Ligament Injuries in National Collegiate Athletic Association Sports: The Injury Surveillance Program, 2004-2014." Orthopaedic Journal of Sports Medicine **6**(6): 2325967118777823.
- Garrett, W. E., Jr. (1990). "Muscle strain injuries: clinical and basic aspects." Med Sci Sports Exerc **22**(4): 436-443.
- Garrett, W. E., Jr. (1996). "Muscle strain injuries." Am J Sports Med **24**(6 Suppl): S2-8.

Garrett, W. E., Jr., J. C. Califf and F. H. Bassett, 3rd (1984). "Histochemical correlates of hamstring injuries." Am J Sports Med **12**(2): 98-103.

Garrett, W. E., Jr., M. R. Safran, A. V. Seaber, R. R. Glisson and B. M. Ribbeck (1987). "Biomechanical comparison of stimulated and nonstimulated skeletal muscle pulled to failure." Am J Sports Med **15**(5): 448-454.

Garrett, W. E., M. R. Safran, A. V. Seaber, R. R. Glisson and B. M. Ribbeck (1987). "Biomechanical comparison of stimulated and nonstimulated skeletal muscle pulled to failure." The American Journal of Sports Medicine **15**(5): 448-454.

Gehring, D., M. Melnyk and A. Gollhofer (2009). "Gender and fatigue have influence on knee joint control strategies during landing." Clinical Biomechanics **24**(1): 82-87.

Gianotti, S. M., S. W. Marshall, P. A. Hume and L. Bunt (2009). "Incidence of anterior cruciate ligament injury and other knee ligament injuries: a national population-based study." J Sci Med Sport **12**(6): 622-627.

Gianotti, S. M., S. W. Marshall, P. A. Hume and L. Bunt (2009). "Incidence of anterior cruciate ligament injury and other knee ligament injuries: A national population-based study." Journal of Science and Medicine in Sport **12**(6): 622-627.

Gibson, H. and R. H. Edwards (1985). "Muscular exercise and fatigue." Sports Med **2**(2): 120-132.

Gillot, T., M. L'Hermette, T. Garnier and C. Tourny-Chollet (2019). "Effect of Fatigue on Functional Stability of the Knee: Particularities of Female Handball Players." Int J Sports Med **40**(7): 468-476.

Girard, O., F. Brocherie and G. P. Millet (2015). "Can analysis of performance and neuromuscular recoveries from repeated sprints shed more light on its fatigue-causing mechanisms?" Frontiers in Physiology **6**(5).

Gissis, I., C. Papadopoulos, V. I. Kalapotharakos, A. Sotiropoulos, G. Komsis and E. Manolopoulos (2006). "Strength and Speed Characteristics of Elite, Subelite, and Recreational Young Soccer Players." Research in Sports Medicine **14**(3): 205-214.

Gleeson, N. P., T. Reilly, T. H. Mercer, S. Rakowski and D. Rees (1998). "Influence of acute endurance activity on leg neuromuscular and musculoskeletal performance." Med Sci Sports Exerc **30**(4): 596-608.

Gordon, A. M., A. F. Huxley and F. J. Julian (1966). "Tension development in highly stretched vertebrate muscle fibres." The Journal of Physiology **184**(1): 143-169.

Grace, T. G., E. R. Sweetser, M. A. Nelson, L. R. Ydens and B. J. Skipper (1984). "Isokinetic muscle imbalance and knee-joint injuries. A prospective blind study." J Bone Joint Surg Am **66**(5): 734-740.

Graham-Smith, P., L. Atkinson, R. Barlow and P. Jones (2009). Braking characteristics and load distribution in 180 degree turns. Proceedings of the 5th annual UKSCA conference.

Graham-Smith, P., L. Atkinson, R. Barlow and P. Jones (2009). Braking characteristics and load distribution in 180 degree turns.

Graham-Smith, P. and S. Pearson (2005). "An investigation into the determinants of agility performance." Proceeding of the 3rd International Biomechanics of the lower limb in health, disease and rehabilitation: 5-7.

Gray, A. J. and D. G. Jenkins (2010). "Match analysis and the physiological demands of Australian football." Sports Med **40**(4): 347-360.

Grazioli, R., P. Lopez, L. L. Andersen, C. L. F. Machado, M. D. Pinto, E. L. Cadore and R. S. Pinto (2019). "Hamstring rate of torque development is more affected than maximal voluntary contraction after a professional soccer match." Eur J Sport Sci: 1-6.

Greco, C. C., W. L. Da Silva, S. R. A. Camarda and B. S. Denadai (2012). "Rapid hamstrings/quadriceps strength capacity in professional soccer players with different conventional isokinetic muscle strength ratios." Journal of sports science & medicine **11**(3): 418-422.

Greco, C. C., W. L. da Silva, S. R. A. Camarda and B. S. Denadai (2013). "Fatigue and rapid hamstring/quadriceps force capacity in professional soccer players." Clinical Physiology and Functional Imaging **33**(1): 18-23.

Green, B., M. N. Bourne and T. Pizzari (2017). "Isokinetic strength assessment offers limited predictive validity for detecting risk of future hamstring strain in sport: a systematic review and meta-analysis." Br J Sports Med.

Green, B., M. N. Bourne, N. van Dyk and T. Pizzari (2020). "Recalibrating the risk of hamstring strain injury (HSI): A 2020 systematic review and meta-analysis of risk factors for index and recurrent hamstring strain injury in sport." British Journal of Sports Medicine **54**(18): 1081.

Greig, M. (2008). "The influence of soccer-specific fatigue on peak isokinetic torque production of the knee flexors and extensors." Am J Sports Med **36**(7): 1403-1409.

Griffin, L. Y., J. Agel, M. J. Albohm, E. A. Arendt, R. W. Dick, W. E. Garrett, J. G. Garrick, T. E. Hewett, L. Huston, M. L. Ireland, R. J. Johnson, W. B. Kibler, S. Lephart, J. L. Lewis, T. N. Lindenfeld, B. R. Mandelbaum, P. Marchak, C. C. Teitz and E. M. Wojtyls (2000). "Noncontact anterior cruciate ligament injuries: risk factors and prevention strategies." J Am Acad Orthop Surg **8**(3): 141-150.

Grood, E. S., F. R. Noyes, D. L. Butler and W. J. Suntay (1981). "Ligamentous and capsular restraints preventing straight medial and lateral laxity in intact human cadaver knees." J Bone Joint Surg Am **63**(8): 1257-1269.

Grygorowicz, M., M. Michalowska, T. Walczak, J. Grabski, A. Pyda and T. Piontek (2017). "HAMSTRING/QUADRICEPS RATIO IN ACL INJURY PREDICTION IN ELITE FOOTBALL PLAYERS." British Journal of Sports Medicine **51**(4): 326.

Grygorowicz, M., M. Michalowska, T. Walczak, A. Owen, J. K. Grabski, A. Pyda, T. Piontek and T. Kotwicki (2017). "Discussion about different cut-off values of conventional hamstring-to-quadriceps ratio used in hamstring injury prediction among professional male football players." PLoS One **12**(12): e0188974.

Guex, K. and G. P. Millet (2013). "Conceptual framework for strengthening exercises to prevent hamstring strains." Sports Med **43**(12): 1207-1215.

Häggglund, M., M. Waldén, R. Bahr and J. Ekstrand (2005). "Methods for epidemiological study of injuries to professional football players: developing the UEFA model." British journal of sports medicine **39**(6): 340-346.

Hagglund, M., M. Walden and J. Ekstrand (2006). "Previous injury as a risk factor for injury in elite football: a prospective study over two consecutive seasons." Br J Sports Med **40**(9): 767-772.

Hannah, R., C. Minshull, S. L. Smith and J. P. Folland (2014). "Longer electromechanical delay impairs hamstrings explosive force versus quadriceps." Med Sci Sports Exerc **46**(5): 963-972.

Harbo, T., J. Brincks and H. Andersen (2012). "Maximal isokinetic and isometric muscle strength of major muscle groups related to age, body mass, height, and sex in 178 healthy subjects." Eur J Appl Physiol **112**(1): 267-275.

Harper, D. J., C. Carling and J. Kiely (2019). "High-Intensity Acceleration and Deceleration Demands in Elite Team Sports Competitive Match Play: A Systematic Review and Meta-Analysis of Observational Studies." Sports Med **49**(12): 1923-1947.

Harper, D. J., A. R. Jordan and J. Kiely (2021). "Relationships Between Eccentric and Concentric Knee Strength Capacities and Maximal Linear Deceleration Ability in Male Academy Soccer Players." J Strength Cond Res **35**(2): 465-472.

Harper, D. J. and J. Kiely (2018). "Damaging nature of decelerations: Do we adequately prepare players?" BMJ Open Sport Exerc Med **4**(1): e000379.

Harper, D. J., J. B. Morin, C. Carling and J. Kiely (2020). "Measuring maximal horizontal deceleration ability using radar technology: reliability and sensitivity of kinematic and kinetic variables." Sports Biomech: 1-17.

- Hassani, A., D. Patikas, E. Bassa, K. Hatzikotoulas, E. Kellis and C. Kotzamanidis (2006). "Agonist and antagonist muscle activation during maximal and submaximal isokinetic fatigue tests of the knee extensors." J Electromyogr Kinesiol **16**(6): 661-668.
- Haugen, T., D. McGhie and G. Ettema (2019). "Sprint running: from fundamental mechanics to practice-a review." Eur J Appl Physiol **119**(6): 1273-1287.
- Haugen, T., E. Tønnessen, J. Hisdal and S. Seiler (2014). "The role and development of sprinting speed in soccer." Int J Sports Physiol Perform **9**(3): 432-441.
- Hautier, C. A., M. T. Linossier, A. Belli, J. R. Lacour and L. M. Arsac (1996). "Optimal velocity for maximal power production in non-isokinetic cycling is related to muscle fibre type composition." Eur J Appl Physiol Occup Physiol **74**(1-2): 114-118.
- Havens, K. L. and S. M. Sigward (2015). "Cutting mechanics: relation to performance and anterior cruciate ligament injury risk." Med Sci Sports Exerc **47**(4): 818-824.
- Hawkins, R. D. and C. W. Fuller (1999). "A prospective epidemiological study of injuries in four English professional football clubs." Br J Sports Med **33**(3): 196-203.
- Hawkins, R. D., M. A. Hulse, C. Wilkinson, A. Hodson and M. Gibson (2001). "The association football medical research programme: an audit of injuries in professional football." British Journal of Sports Medicine **35**(1): 43-47.
- Heebner, N. R., J. S. Akins, S. M. Lephart and T. C. Sell (2015). "Reliability and validity of an accelerometry based measure of static and dynamic postural stability in healthy and active individuals." Gait Posture **41**(2): 535-539.
- Heiser, T. M., J. Weber, G. Sullivan, P. Clare and R. R. Jacobs (1984). "Prophylaxis and management of hamstring muscle injuries in intercollegiate football players." The American Journal of Sports Medicine **12**(5): 368-370.
- Henderson, G., C. A. Barnes and M. D. Portas (2010). "Factors associated with increased propensity for hamstring injury in English Premier League soccer players." J Sci Med Sport **13**(4): 397-402.
- Hennessy, L. and J. Kilty (2001). "Relationship of the stretch-shortening cycle to sprint performance in trained female athletes." J Strength Cond Res **15**(3): 326-331.
- Hermens, H., R. Merletti and B. Freriks (1996). European activities on surface electromyography. Proceedings of the first general SENIAM (Surface EMG for Non Invasive Assessment of Muscles) workshop.
- Hermens, H. J., B. Freriks, C. Disselhorst-Klug and G. Rau (2000). "Development of recommendations for SEMG sensors and sensor placement procedures." J Electromyogr Kinesiol **10**(5): 361-374.

Herzog, W. and T. R. Leonard (2000). "The history dependence of force production in mammalian skeletal muscle following stretch-shortening and shortening-stretch cycles." Journal of Biomechanics **33**(5): 531-542.

Hewett, T. E., T. N. Lindenfeld, J. V. Riccobene and F. R. Noyes (1999). "The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study." Am J Sports Med **27**(6): 699-706.

Hewett, T. E., G. D. Myer, K. R. Ford, R. S. Heidt, A. J. Colosimo, S. G. McLean, A. J. van den Bogert, M. V. Paterno and P. Succop (2005). "Biomechanical Measures of Neuromuscular Control and Valgus Loading of the Knee Predict Anterior Cruciate Ligament Injury Risk in Female Athletes: A Prospective Study." The American Journal of Sports Medicine **33**(4): 492-501.

Hewett, T. E., G. D. Myer, K. R. Ford, R. S. Heidt, Jr., A. J. Colosimo, S. G. McLean, A. J. van den Bogert, M. V. Paterno and P. Succop (2005). "Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study." Am J Sports Med **33**(4): 492-501.

Hewett, T. E., A. L. Stroupe, T. A. Nance and F. R. Noyes (1996). "Plyometric training in female athletes. Decreased impact forces and increased hamstring torques." Am J Sports Med **24**(6): 765-773.

Hewett, T. E., B. T. Zazulak and G. D. Myer (2007). "Effects of the menstrual cycle on anterior cruciate ligament injury risk: a systematic review." Am J Sports Med **35**(4): 659-668.

Hewitt, J., J. Cronin, C. Button and P. Hume (2011). "Understanding Deceleration in Sport." Strength & Conditioning Journal **33**(1): 47-52.

Hiemstra, L. A., I. K. Lo and P. J. Fowler (2001). "Effect of fatigue on knee proprioception: implications for dynamic stabilization." J Orthop Sports Phys Ther **31**(10): 598-605.

Higashihara, A., T. Ono, J. Kubota, T. Okuwaki and T. Fukubayashi (2010). "Functional differences in the activity of the hamstring muscles with increasing running speed." J Sports Sci **28**(10): 1085-1092.

Hill, A. V. (1938). "The heat of shortening and the dynamic constants of muscle." Proceedings of the Royal Society of London. Series B-Biological Sciences **126**(843): 136-195.

Hirano, M., M. Katoh, M. Gomi and S. Arai (2020). "Validity and reliability of isometric knee extension muscle strength measurements using a belt-stabilized hand-held dynamometer: a comparison with the measurement using an isokinetic dynamometer in a sitting posture." Journal of physical therapy science **32**(2): 120-124.

Hislop, H. J. and J. J. Perrine (1967). "The isokinetic concept of exercise." Phys Ther **47**(2): 114-117.

Hohmann, E., A. Bryant and K. Tetsworth (2016). "Strength does not influence knee function in the ACL-deficient knee but is a correlate of knee function in the and ACL-reconstructed knee." Arch Orthop Trauma Surg **136**(4): 477-483.

Hollis, J. M., S. Takai, D. J. Adams, S. Horibe and S. L. Woo (1991). "The effects of knee motion and external loading on the length of the anterior cruciate ligament (ACL): a kinematic study." J Biomech Eng **113**(2): 208-214.

Hootman, J. M., R. Dick and J. Agel (2007). "Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives." J Athl Train **42**(2): 311-319.

Howard, M., S. Solaru, H. P. Kang, I. K. Bolia, G. F. R. Hatch, J. E. Tibone, S. C. Gamradt and A. E. Weber (2020). "Epidemiology of Anterior Cruciate Ligament Injury on Natural Grass Versus Artificial Turf in Soccer: 10-Year Data From the National Collegiate Athletic Association Injury Surveillance System." Orthopaedic Journal of Sports Medicine **8**(7): 2325967120934434.

Howard, R. M., R. Conway and A. J. Harrison (2018). "Muscle activity in sprinting: a review." Sports Biomech **17**(1): 1-17.

Hunter, J. P., R. N. Marshall and P. J. McNair (2005). "Relationships between ground reaction force impulse and kinematics of sprint-running acceleration." J Appl Biomech **21**(1): 31-43.

Huurnink, A., D. P. Fransz, I. Kingma, V. A. de Boode and J. H. v. Dieën (2019). "The assessment of single-leg drop jump landing performance by means of ground reaction forces: A methodological study." Gait & Posture **73**: 80-85.

Ishoi, L., P. Aagaard, M. F. Nielsen, K. B. Thornton, K. K. Krommes, P. Holmich and K. Thorborg (2019). "The Influence of Hamstring Muscle Peak Torque and Rate of Torque Development for Sprinting Performance in Football Players: A Cross-Sectional Study." Int J Sports Physiol Perform **14**(5): 665-673.

Jones, A., G. Jones, N. Greig, P. Bower, J. Brown, K. Hind and P. Francis (2019). "Epidemiology of injury in English Professional Football players: A cohort study." Physical Therapy in Sport **35**: 18-22.

Jones, P., T. M. Bampouras and K. Marrin (2009). "An investigation into the physical determinants of change of direction speed." J Sports Med Phys Fitness **49**(1): 97-104.

Jones, P. A., C. Thomas, T. Dos'Santos, J. J. McMahon and P. Graham-Smith (2017). "The Role of Eccentric Strength in 180° Turns in Female Soccer Players." Sports (Basel, Switzerland) **5**(2): 42.

Jordan, M. J., P. Aagaard and W. Herzog (2015). "Rapid hamstrings/quadriceps strength in ACL-reconstructed elite Alpine ski racers." Med Sci Sports Exerc **47**(1): 109-119.

Junge, A. and J. Dvorak (2004). "Soccer injuries: a review on incidence and prevention." Sports Med **34**(13): 929-938.

Junge, A., J. Dvorak, T. Graf-Baumann and L. Peterson (2004). "Football Injuries during FIFA Tournaments and the Olympic Games, 1998-2001: Development and Implementation of an Injury-Reporting System." The American Journal of Sports Medicine **32**(1_suppl): 80-89.

Kannus, P. and B. Beynon (1993). "Peak torque occurrence in the range of motion during isokinetic extension and flexion of the knee." Int J Sports Med **14**(8): 422-426.

Kaufman, K. R., K. N. Au, W. J. Litchy and E. Y. S. Chao (1991). "Physiological prediction of muscle forces—II. Application to isokinetic exercise." Neuroscience **40**(3): 793-804.

Kawabata, Y., M. Senda, T. Oka, Y. Yagata, Y. Takahara, H. Nagashima and H. Inoue (2000). "Measurement of fatigue in knee flexor and extensor muscles." Acta Med Okayama **54**(2): 85-90.

Kellis, E. (1999). "The effects of fatigue on the resultant joint moment, agonist and antagonist electromyographic activity at different angles during dynamic knee extension efforts." J Electromyogr Kinesiol **9**(3): 191-199.

Kellis, E. and V. Baltzopoulos (1996). "Agonist and antagonist moment and EMG-angle relationship during isokinetic eccentric and concentric exercise." Isokinetics and Exercise Science **6**(2): 79-87.

Kellis, E. and V. Kouvelioti (2009). "Agonist versus antagonist muscle fatigue effects on thigh muscle activity and vertical ground reaction during drop landing." J Electromyogr Kinesiol **19**(1): 55-64.

Kellis, E., A. Zafeiridis and I. G. Amiridis (2011). "Muscle coactivation before and after the impact phase of running following isokinetic fatigue." Journal of athletic training **46**(1): 11-19.

Kelly, A. L. and C. A. Williams (2020). "Physical Characteristics and the Talent Identification and Development Processes in Male Youth Soccer: A Narrative Review." Strength & Conditioning Journal **42**(6).

Klein, C., T. Henke and P. Platen (2018). "Injuries in football (soccer)—a systematic review of epidemiology and aetiological aspects." German Journal of Exercise and Sport Research **48**(3): 309-322.

Knapik, J. J., C. L. Bauman, B. H. Jones, J. M. Harris and L. Vaughan (1991). "Preseason strength and flexibility imbalances associated with athletic injuries in female collegiate athletes." Am J Sports Med **19**(1): 76-81.

Koga, H., A. Nakamae, Y. Shima, R. Bahr and T. Krosshaug (2018). "Hip and Ankle Kinematics in Noncontact Anterior Cruciate Ligament Injury Situations: Video Analysis Using Model-Based Image Matching." Am J Sports Med **46**(2): 333-340.

- Kovacs, M. S., E. P. Roetert and T. S. Ellenbecker (2008). "Efficient Deceleration: The Forgotten Factor in Tennis-Specific Training." Strength & Conditioning Journal **30**(6): 58-69.
- Krishnan, C. and G. N. Williams (2009). "Sex differences in quadriceps and hamstrings EMG-moment relationships." Medicine and science in sports and exercise **41**(8): 1652-1660.
- Krosshaug, T., A. Nakamae, B. P. Boden, L. Engebretsen, G. Smith, J. R. Slauterbeck, T. E. Hewett and R. Bahr (2007). "Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases." Am J Sports Med **35**(3): 359-367.
- Krustrup, P., M. Mohr, A. Steensberg, J. Bencke, M. Kjaer and J. Bangsbo (2006). "Muscle and blood metabolites during a soccer game: implications for sprint performance." Med Sci Sports Exerc **38**(6): 1165-1174.
- Kuitunen, S., P. V. Komi and H. KyröLÄinen (2002). "Knee and ankle joint stiffness in sprint running." Medicine & Science in Sports & Exercise **34**(1).
- LaStayo, P. C., J. M. Woolf, M. D. Lewek, L. Snyder-Mackler, T. Reich and S. L. Lindstedt (2003). "Eccentric Muscle Contractions: Their Contribution to Injury, Prevention, Rehabilitation, and Sport." Journal of Orthopaedic & Sports Physical Therapy **33**(10): 557-571.
- Lee, J. W. Y., K. M. Mok, H. C. K. Chan, P. S. H. Yung and K. M. Chan (2018). "Eccentric hamstring strength deficit and poor hamstring-to-quadriceps ratio are risk factors for hamstring strain injury in football: A prospective study of 146 professional players." J Sci Med Sport **21**(8): 789-793.
- Lee, M. J., S. L. Reid, B. C. Elliott and D. G. Lloyd (2009). "Running biomechanics and lower limb strength associated with prior hamstring injury." Med Sci Sports Exerc **41**(10): 1942-1951.
- Lehance, C., J. Binet, T. Bury and J. L. Croisier (2009). "Muscular strength, functional performances and injury risk in professional and junior elite soccer players." Scand J Med Sci Sports **19**(2): 243-251.
- Lesnak, J., D. Anderson, B. Farmer, D. Katsavelis and T. L. Grindstaff (2019). "Validity of Hand-Held Dynamometry in Measuring Quadriceps Strength and Rate of Torque Development." Int J Sports Phys Ther **14**(2): 180-187.
- Li, G., J. Gil, A. Kanamori and S. L. Woo (1999). "A validated three-dimensional computational model of a human knee joint." J Biomech Eng **121**(6): 657-662.
- Li, G., T. W. Rudy, M. Sakane, A. Kanamori, C. B. Ma and S. L. Woo (1999). "The importance of quadriceps and hamstring muscle loading on knee kinematics and in-situ forces in the ACL." J Biomech **32**(4): 395-400.
- Lieber, R. L. and J. Fridén (1999). "Mechanisms of muscle injury after eccentric contraction." J Sci Med Sport **2**(3): 253-265.

- Lilly, J. M. and S. C. Olhede (2009). "Higher-Order Properties of Analytic Wavelets." IEEE Transactions on Signal Processing **57**(1): 146-160.
- Liu, K., J. Glutting, E. Wikstrom, G. Gustavsen, T. Royer and T. W. Kaminski (2013). "Examining the diagnostic accuracy of dynamic postural stability measures in differentiating among ankle instability status." Clin Biomech (Bristol, Avon) **28**(2): 211-217.
- Liu, Y., Y. Sun, W. Zhu and J. Yu (2017). "The late swing and early stance of sprinting are most hazardous for hamstring injuries." J Sport Health Sci **6**(2): 133-136.
- Lloyd, D. G., T. S. Buchanan and T. F. Besier (2005). "Neuromuscular biomechanical modeling to understand knee ligament loading." Med Sci Sports Exerc **37**(11): 1939-1947.
- Lockie, R. G., A. B. Schultz, M. D. Jeffriess and S. J. Callaghan (2012). "The relationship between bilateral differences of knee flexor and extensor isokinetic strength and multi-directional speed." Isokinetics and Exercise Science **20**(3): 211-219.
- Lord, J. P., S. G. Aitkens, M. A. McCrory and E. M. Bernauer (1992). "Isometric and isokinetic measurement of hamstring and quadriceps strength." Arch Phys Med Rehabil **73**(4): 324-330.
- Lu, W., S. Boyas, M. Jubeau and A. Rahmani (2019). "Reliability of force-velocity relationships during deadlift high pull." Sports Biomechanics **18**(3): 277-288.
- Maffiuletti, N. A., P. Aagaard, A. J. Blazevich, J. Folland, N. Tillin and J. Duchateau (2016). "Rate of force development: physiological and methodological considerations." Eur J Appl Physiol **116**(6): 1091-1116.
- Mair, S. D., A. V. Seaber, R. R. Glisson and W. E. Garrett, Jr. (1996). "The role of fatigue in susceptibility to acute muscle strain injury." Am J Sports Med **24**(2): 137-143.
- Malliaropoulos, N., T. Isinkaye, K. Tsitas and N. Maffulli (2011). "Reinjury after acute posterior thigh muscle injuries in elite track and field athletes." The American journal of sports medicine **39**(2): 304-310.
- Malliaropoulos, N., T. Isinkaye, K. Tsitas and N. Maffulli (2011). "Reinjury after acute posterior thigh muscle injuries in elite track and field athletes." Am J Sports Med **39**(2): 304-310.
- Mallo, J. and E. Navarro (2008). "Physical load imposed on soccer players during small-sided training games." J Sports Med Phys Fitness **48**(2): 166-171.
- Mandelbaum, B. R., H. J. Silvers, D. S. Watanabe, J. F. Knarr, S. D. Thomas, L. Y. Griffin, D. T. Kirkendall and W. Garrett, Jr. (2005). "Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up." Am J Sports Med **33**(7): 1003-1010.

- Manson, S. A., M. Brughelli and N. K. Harris (2014). "Physiological characteristics of international female soccer players." J Strength Cond Res **28**(2): 308-318.
- Mara, J. K., K. G. Thompson, K. L. Pumpa and S. Morgan (2017). "The acceleration and deceleration profiles of elite female soccer players during competitive matches." Journal of Science and Medicine in Sport **20**(9): 867-872.
- Markolf, K. L., D. M. Burchfield, M. M. Shapiro, M. F. Shepard, G. A. M. Finerman and J. L. Slauterbeck (1995). "Combined knee loading states that generate high anterior cruciate ligament forces." Journal of Orthopaedic Research **13**(6): 930-935.
- Markolf, K. L., J. S. Mensch and H. C. Amstutz (1976). "Stiffness and laxity of the knee--the contributions of the supporting structures. A quantitative in vitro study." J Bone Joint Surg Am **58**(5): 583-594.
- Marshall, P. W., R. Lovell, G. K. Jeppesen, K. Andersen and J. C. Siegler (2014). "Hamstring muscle fatigue and central motor output during a simulated soccer match." PLoS One **9**(7): e102753.
- Mateus, R. B., V. Ferrer-Roca, F. João and A. P. Veloso (2020). "Muscle contributions to maximal single-leg forward braking and backward acceleration in elite athletes." Journal of Biomechanics **112**: 110047.
- Matthews, M. J., K. Heron, S. Todd, A. Tomlinson, P. Jones, A. Delextrat and D. D. Cohen (2017). "Strength and endurance training reduces the loss of eccentric hamstring torque observed after soccer specific fatigue." Phys Ther Sport **25**: 39-46.
- McLean, S. G., S. W. Lipfert and A. J. van den Bogert (2004). "Effect of gender and defensive opponent on the biomechanics of sidestep cutting." Med Sci Sports Exerc **36**(6): 1008-1016.
- Meldrum, D., E. Cahalane, R. Conroy, D. Fitzgerald and O. Hardiman (2007). "Maximum voluntary isometric contraction: Reference values and clinical application." Amyotrophic Lateral Sclerosis **8**(1): 47-55.
- Meldrum, D., E. Cahalane, R. Conroy, D. Fitzgerald and O. Hardiman (2007). "Maximum voluntary isometric contraction: reference values and clinical application." Amyotroph Lateral Scler **8**(1): 47-55.
- Mentiplay, B. F., L. G. Perraton, K. J. Bower, B. Adair, Y.-H. Pua, G. P. Williams, R. McGaw and R. A. Clark (2015). "Assessment of Lower Limb Muscle Strength and Power Using Hand-Held and Fixed Dynamometry: A Reliability and Validity Study." PLOS ONE **10**(10): e0140822.
- Mero, A., P. V. Komi and R. J. Gregor (1992). "Biomechanics of sprint running. A review." Sports Med **13**(6): 376-392.

- Messina, D. F., W. C. Farney and J. C. DeLee (1999). "The incidence of injury in Texas high school basketball. A prospective study among male and female athletes." Am J Sports Med **27**(3): 294-299.
- Meyer, G. and M. Ayalon (2006). "Biomechanical aspects of dynamic stability." European Review of Aging and Physical Activity **3**(1): 29-33.
- Miyake, Y., T. Suga, M. Otsuka, T. Tanaka, J. Misaki, S. Kudo, A. Nagano and T. Isaka (2017). "The knee extensor moment arm is associated with performance in male sprinters." Eur J Appl Physiol **117**(3): 533-539.
- Mohammadi, F., M. Salavati, B. Akhbari, M. Mazaheri, M. Khorrami and H. Negahban (2012). "Static and dynamic postural control in competitive athletes after anterior cruciate ligament reconstruction and controls." Knee Surg Sports Traumatol Arthrosc **20**(8): 1603-1610.
- Mohr, M., P. Krstrup and J. Bangsbo (2003). "Match performance of high-standard soccer players with special reference to development of fatigue." J Sports Sci **21**(7): 519-528.
- Mohr, M., P. Krstrup and J. Bangsbo (2005). "Fatigue in soccer: a brief review." J Sports Sci **23**(6): 593-599.
- Mokhtarzadeh, H., K. Ewing, I. Janssen, C. H. Yeow, N. Brown and P. V. S. Lee (2017). "The effect of leg dominance and landing height on ACL loading among female athletes." J Biomech **60**: 181-187.
- Mooney, M. G., S. Cormack, B. J. O'brien, W. M. Morgan and M. McGuigan (2013). "Impact of neuromuscular fatigue on match exercise intensity and performance in elite Australian football." J Strength Cond Res **27**(1): 166-173.
- More, R. C., B. T. Karras, R. Neiman, D. Fritschy, S. L. Woo and D. M. Daniel (1993). "Hamstrings--an anterior cruciate ligament protagonist. An in vitro study." Am J Sports Med **21**(2): 231-237.
- Morel, B. and C. A. Hautier (2017). "The neuromuscular fatigue induced by repeated scrums generates instability that can be limited by appropriate recovery." Scand J Med Sci Sports **27**(2): 209-216.
- Morel, B., D. M. Rouffet, D. Saboul, S. Rota, M. Clemencon and C. A. Hautier (2015). "Peak torque and rate of torque development influence on repeated maximal exercise performance: contractile and neural contributions." PLoS One **10**(4): e0119719.
- Morin, J.-B., M. Bourdin, P. Edouard, N. Peyrot, P. Samozino and J.-R. Lacour (2012). "Mechanical determinants of 100-m sprint running performance." European Journal of Applied Physiology **112**(11): 3921-3930.

- Morin, J. B., P. Edouard and P. Samozino (2011). "Technical ability of force application as a determinant factor of sprint performance." Med Sci Sports Exerc **43**(9): 1680-1688.
- Morin, J. B., P. Gimenez, P. Edouard, P. Arnal, P. Jimenez-Reyes, P. Samozino, M. Brughelli and J. Mendiguchia (2015). "Sprint Acceleration Mechanics: The Major Role of Hamstrings in Horizontal Force Production." Front Physiol **6**: 404.
- Morin, J. B. and P. Samozino (2016). "Interpreting Power-Force-Velocity Profiles for Individualized and Specific Training." Int J Sports Physiol Perform **11**(2): 267-272.
- Morin, J. B., P. Samozino, M. Murata, M. R. Cross and R. Nagahara (2019). "A simple method for computing sprint acceleration kinetics from running velocity data: Replication study with improved design." J Biomech **94**: 82-87.
- Morin, J. B., J. Slawinski, S. Dorel, E. S. de Villareal, A. Couturier, P. Samozino, M. Brughelli and G. Rabita (2015). "Acceleration capability in elite sprinters and ground impulse: Push more, brake less?" J Biomech **48**(12): 3149-3154.
- Morishige, Y., K. Harato, S. Kobayashi, Y. Niki, M. Matsumoto, M. Nakamura and T. Nagura (2019). "Difference in leg asymmetry between female collegiate athletes and recreational athletes during drop vertical jump." Journal of Orthopaedic Surgery and Research **14**(1): 424.
- Moses, B., J. Orchard and J. Orchard (2012). "Systematic review: Annual incidence of ACL injury and surgery in various populations." Res Sports Med **20**(3-4): 157-179.
- Myer, G. D., K. R. Ford, K. D. Barber Foss, C. Liu, T. G. Nick and T. E. Hewett (2009). "The relationship of hamstrings and quadriceps strength to anterior cruciate ligament injury in female athletes." Clin J Sport Med **19**(1): 3-8.
- Myer, G. D., K. R. Ford and T. E. Hewett (2005). "The effects of gender on quadriceps muscle activation strategies during a maneuver that mimics a high ACL injury risk position." Journal of Electromyography and Kinesiology **15**(2): 181-189.
- Myer, G. D., K. R. Ford and T. E. Hewett (2005). "The effects of gender on quadriceps muscle activation strategies during a maneuver that mimics a high ACL injury risk position." J Electromyogr Kinesiol **15**(2): 181-189.
- Myer, G. D., K. R. Ford, J. P. Palumbo and T. E. Hewett (2005). "Neuromuscular training improves performance and lower-extremity biomechanics in female athletes." J Strength Cond Res **19**(1): 51-60.
- Nagahara, R., M. Mizutani, A. Matsuo, H. Kanehisa and T. Fukunaga (2018). "Association of Sprint Performance With Ground Reaction Forces During Acceleration and Maximal Speed Phases in a Single Sprint." J Appl Biomech **34**(2): 104-110.

- Naylor, J. and M. Greig (2015). "A hierarchical model of factors influencing a battery of agility tests." J Sports Med Phys Fitness **55**(11): 1329-1335.
- Nédélec, M., A. McCall, C. Carling, F. Legall, S. Berthoin and G. Dupont (2012). "Recovery in soccer: part I - post-match fatigue and time course of recovery." Sports Med **42**(12): 997-1015.
- Newans, T., P. Bellinger, K. Dodd and C. Minahan (2019). "Modelling the Acceleration and Deceleration Profile of Elite-level Soccer Players." Int J Sports Med **40**(5): 331-335.
- Newman, M. A., K. M. Tarpinning and F. E. Marino (2004). "Relationships between isokinetic knee strength, single-sprint performance, and repeated-sprint ability in football players." J Strength Cond Res **18**(4): 867-872.
- Nichols, T. E. and A. P. Holmes (2002). "Nonparametric permutation tests for functional neuroimaging: a primer with examples." Hum Brain Mapp **15**(1): 1-25.
- Nikolaidis, P. T., B. Knechtle, F. Clemente and G. Torres-Luque (2016). "Reference values for the sprint performance in male football players aged from 9–35 years." Biomedical Human Kinetics **8**(1): 103-112.
- Nimphius, S., M. R. McGuigan and R. U. Newton (2010). "Relationship between strength, power, speed, and change of direction performance of female softball players." J Strength Cond Res **24**(4): 885-895.
- Northeast, J., M. Russell, D. Shearer, C. J. Cook and L. P. Kilduff (2019). "Predictors of Linear and Multidirectional Acceleration in Elite Soccer Players." J Strength Cond Res **33**(2): 514-522.
- Novacheck, T. F. (1998). "The biomechanics of running." Gait Posture **7**(1): 77-95.
- Nummela, A., I. Hämmäläinen and H. Rusko (2007). "Comparison of maximal anaerobic running tests on a treadmill and track." Journal of Sports Sciences **25**(1): 87-96.
- O'Donoghue, P. G. (2002). "Time-motion analysis of work-rate in English FA Premier League soccer." International Journal of Performance Analysis in Sport **2**(1): 36-43.
- Øiestad, B. E., L. Engebretsen, K. Storheim and M. A. Risberg (2009). "Knee osteoarthritis after anterior cruciate ligament injury: a systematic review." Am J Sports Med **37**(7): 1434-1443.
- Olsen, O. E., G. Myklebust, L. Engebretsen and R. Bahr (2004). "Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis." Am J Sports Med **32**(4): 1002-1012.
- Ono, T., A. Higashihara, J. Shinohara, N. Hirose and T. Fukubayashi (2015). "Estimation of tensile force in the hamstring muscles during overground sprinting." Int J Sports Med **36**(2): 163-168.

- Opar, D. A. and B. G. Serpell (2014). "Is there a potential relationship between prior hamstring strain injury and increased risk for future anterior cruciate ligament injury?" Arch Phys Med Rehabil **95**(2): 401-405.
- Opar, D. A., M. D. Williams and A. J. Shield (2012). "Hamstring strain injuries: factors that lead to injury and re-injury." Sports Med **42**(3): 209-226.
- Opar, D. A., M. D. Williams, R. G. Timmins, J. Hickey, S. J. Duhig and A. J. Shield (2015). "Eccentric hamstring strength and hamstring injury risk in Australian footballers." Med Sci Sports Exerc **47**(4): 857-865.
- Orchard, J., J. Marsden, S. Lord and D. Garlick (1997). "Preseason hamstring muscle weakness associated with hamstring muscle injury in Australian footballers." Am J Sports Med **25**(1): 81-85.
- Orchard, J. and H. Seward (2002). "Epidemiology of injuries in the Australian Football League, seasons 1997-2000." Br J Sports Med **36**(1): 39-44.
- Orchard, J. W. (2001). "Intrinsic and extrinsic risk factors for muscle strains in Australian football." Am J Sports Med **29**(3): 300-303.
- Orchard, J. W. (2012). "Hamstrings are most susceptible to injury during the early stance phase of sprinting." Br J Sports Med **46**(2): 88-89.
- Ortiz, A., S. L. Olson, B. Etnyre, E. E. Trudelle-Jackson, W. Bartlett and H. L. Venegas-Rios (2010). "Fatigue effects on knee joint stability during two jump tasks in women." J Strength Cond Res **24**(4): 1019-1027.
- Osternig, L. R. (1986). "Isokinetic dynamometry: implications for muscle testing and rehabilitation." Exerc Sport Sci Rev **14**: 45-80.
- Parcell, A. C., R. D. Sawyer, V. A. Tricoli and T. D. Chinevere (2002). "Minimum rest period for strength recovery during a common isokinetic testing protocol." Med Sci Sports Exerc **34**(6): 1018-1022.
- Pataky, T. C. (2010). "Generalized n-dimensional biomechanical field analysis using statistical parametric mapping." J Biomech **43**(10): 1976-1982.
- Pataky, T. C., M. A. Robinson and J. Vanrenterghem (2013). "Vector field statistical analysis of kinematic and force trajectories." J Biomech **46**(14): 2394-2401.
- Paterno, M. V., L. C. Schmitt, K. R. Ford, M. J. Rauh, G. D. Myer, B. Huang and T. E. Hewett (2010). "Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport." Am J Sports Med **38**(10): 1968-1978.

- Petersen, J., K. Thorborg, M. B. Nielsen and P. Hölmich (2010). "Acute hamstring injuries in Danish elite football: a 12-month prospective registration study among 374 players." Scand J Med Sci Sports **20**(4): 588-592.
- Petré, H., F. Wernstål and C. M. Mattsson (2018). "Effects of Flywheel Training on Strength-Related Variables: a Meta-analysis." Sports Medicine - Open **4**(1): 55.
- Pincivero, D. M., S. M. Lephart and R. G. Karunakara (1997). "Effects of rest interval on isokinetic strength and functional performance after short-term high intensity training." Br J Sports Med **31**(3): 229-234.
- Pinniger, G. J., J. R. Steele and H. Groeller (2000). "Does fatigue induced by repeated dynamic efforts affect hamstring muscle function?" Med Sci Sports Exerc **32**(3): 647-653.
- Pinto, M. D., A. J. Blazeovich, L. L. Andersen, P. Mil-Homens and R. S. Pinto (2018). "Hamstring-to-quadriceps fatigue ratio offers new and different muscle function information than the conventional non-fatigued ratio." Scand J Med Sci Sports **28**(1): 282-293.
- Price, R. J., R. D. Hawkins, M. A. Hulse and A. Hodson (2004). "The Football Association medical research programme: an audit of injuries in academy youth football." British Journal of Sports Medicine **38**(4): 466.
- Quatman, C. E. and T. E. Hewett (2009). "The anterior cruciate ligament injury controversy: is "valgus collapse" a sex-specific mechanism?" British Journal of Sports Medicine **43**(5): 328.
- Rahmani, A., P. Samozino, J. B. Morin and B. Morel (2018). "A Simple Method for Assessing Upper-Limb Force-Velocity Profile in Bench Press." Int J Sports Physiol Perform **13**(2): 200-207.
- Rahnama, N., T. Reilly, A. Lees and P. Graham-Smith (2003). "Muscle fatigue induced by exercise simulating the work rate of competitive soccer." J Sports Sci **21**(11): 933-942.
- Rampinini, E., A. Bosio, I. Ferraresi, A. Petruolo, A. Morelli and A. Sassi (2011). "Match-related fatigue in soccer players." Med Sci Sports Exerc **43**(11): 2161-2170.
- Rampinini, E., A. J. Coutts, C. Castagna, R. Sassi and F. M. Impellizzeri (2007). "Variation in top level soccer match performance." Int J Sports Med **28**(12): 1018-1024.
- Reid, A., T. B. Birmingham, P. W. Stratford, G. K. Alcock and J. R. Giffin (2007). "Hop testing provides a reliable and valid outcome measure during rehabilitation after anterior cruciate ligament reconstruction." Phys Ther **87**(3): 337-349.
- Reilly, T., B. Drust and N. Clarke (2008). "Muscle fatigue during football match-play." Sports Med **38**(5): 357-367.

- Renström, P., S. W. Arms, T. S. Stanwyck, R. J. Johnson and M. H. Pope (1986). "Strain within the anterior cruciate ligament during hamstring and quadriceps activity." Am J Sports Med **14**(1): 83-87.
- Reurink, G., G. J. Goudswaard, M. H. Moen, J. L. Tol, J. A. N. Verhaar and A. Weir (2016). "Strength Measurements in Acute Hamstring Injuries: Intertester Reliability and Prognostic Value of Handheld Dynamometry." Journal of Orthopaedic & Sports Physical Therapy **46**(8): 689-696.
- Rodriguez-Rosell, D., F. Pareja-Blanco, P. Aagaard and J. J. Gonzalez-Badillo (2018). "Physiological and methodological aspects of rate of force development assessment in human skeletal muscle." Clin Physiol Funct Imaging **38**(5): 743-762.
- Ross, S. E. and K. M. Guskiewicz (2004). "Examination of Static and Dynamic Postural Stability in Individuals With Functionally Stable and Unstable Ankles." Clinical Journal of Sport Medicine **14**(6).
- Ruedl, G., M. Webhofer, K. Helle, M. Strobl, A. Schranz, C. Fink, H. Gatterer and M. Burtscher (2012). "Leg dominance is a risk factor for noncontact anterior cruciate ligament injuries in female recreational skiers." Am J Sports Med **40**(6): 1269-1273.
- Russell, M., W. Sparkes, J. Northeast, C. J. Cook, T. D. Love, R. M. Bracken and L. P. Kilduff (2016). "Changes in Acceleration and Deceleration Capacity Throughout Professional Soccer Match-Play." J Strength Cond Res **30**(10): 2839-2844.
- Russell, M., W. Sparkes, J. Northeast, C. J. Cook, T. D. Love, R. M. Bracken and L. P. Kilduff (2016). "Changes in Acceleration and Deceleration Capacity Throughout Professional Soccer Match-Play." The Journal of Strength & Conditioning Research **30**(10).
- Russell, M., W. Sparkes, J. Northeast and L. P. Kilduff (2015). "Responses to a 120 min reserve team soccer match: a case study focusing on the demands of extra time." Journal of Sports Sciences **33**(20): 2133-2139.
- Samozino, P., G. Rabita, S. Dorel, J. Slawinski, N. Peyrot, E. Saez de Villarreal and J. B. Morin (2016). "A simple method for measuring power, force, velocity properties, and mechanical effectiveness in sprint running." Scand J Med Sci Sports **26**(6): 648-658.
- Sangnier, S. and C. Tourny-Chollet (2007). "Comparison of the decrease in strength between hamstrings and quadriceps during isokinetic fatigue testing in semiprofessional soccer players." Int J Sports Med **28**(11): 952-957.
- Sangnier, S. and C. Tourny-Chollet (2008). "Study of the fatigue curve in quadriceps and hamstrings of soccer players during isokinetic endurance testing." J Strength Cond Res **22**(5): 1458-1467.
- Sarmiento, H., R. Marcelino, M. T. Anguera, J. CampaniCo, N. Matos and J. C. LeitAo (2014). "Match analysis in football: a systematic review." J Sports Sci **32**(20): 1831-1843.

Sasaki, S., Y. Nagano, S. Kaneko, T. Sakurai and T. Fukubayashi (2011). "The Relationship between Performance and Trunk Movement During Change of Direction." Journal of sports science & medicine **10**(1): 112-118.

Schache, A. G., T. W. Dorn, P. D. Blanch, N. A. Brown and M. G. Pandy (2012). "Mechanics of the human hamstring muscles during sprinting." Med Sci Sports Exerc **44**(4): 647-658.

Schache, A. G., T. W. Dorn, T. V. Wrigley, N. A. Brown and M. G. Pandy (2013). "Stretch and activation of the human biarticular hamstrings across a range of running speeds." Eur J Appl Physiol **113**(11): 2813-2828.

Schiffner, E., D. Latz, J. P. Grassmann, A. Schek, S. Thelen, J. Windolf, J. Schnependahl and P. Jungbluth (2018). "Anterior cruciate ligament ruptures in German elite soccer players: Epidemiology, mechanisms, and return to play." The Knee **25**(2): 219-225.

Schilaty, N. D., N. A. Bates, A. J. Krych and T. E. Hewett (2019). "Frontal Plane Loading Characteristics of Medial Collateral Ligament Strain Concurrent With Anterior Cruciate Ligament Failure." Am J Sports Med **47**(9): 2143-2150.

Schünke, M., L. M. Ross, E. Schulte, E. D. Lamperti, U. Schumacher, J. Rude, M. Voll and K. Wesker (2006). Thieme Atlas of Anatomy: General Anatomy and Musculoskeletal System, Thieme.

Schwartz, F. P., M. Bottaro, R. S. Celes, M. C. Pereira, V. d. A. Rocha Júnior and F. A. d. O. Nascimento (2014). "Study of muscle fatigue in isokinetic exercise with estimated conduction velocity and traditional electromyographic indicators." Revista Brasileira de Engenharia Biomédica **30**(4): 312-321.

Sell, T. C. (2012). "An examination, correlation, and comparison of static and dynamic measures of postural stability in healthy, physically active adults." Phys Ther Sport **13**(2): 80-86.

Sell, T. C., C. M. Ferris, J. P. Abt, Y. S. Tsai, J. B. Myers, F. H. Fu and S. M. Lephart (2007). "Predictors of proximal tibia anterior shear force during a vertical stop-jump." J Orthop Res **25**(12): 1589-1597.

Serpell, B. G., J. M. Scarvell, M. R. Pickering, N. B. Ball, P. Newman, D. Perriman, J. Warmenhoven and P. N. Smith (2015). "Medial and lateral hamstrings and quadriceps co-activation affects knee joint kinematics and ACL elongation: a pilot study." BMC Musculoskelet Disord **16**: 348.

Siff, M. (2008). Biomechanical Foundations of Strength and Power Training.

Silva, J. R., M. C. Rumpf, M. Hertzog, C. Castagna, A. Farooq, O. Girard and K. Hader (2018). "Acute and Residual Soccer Match-Related Fatigue: A Systematic Review and Meta-analysis." Sports Med **48**(3): 539-583.

- Simonsen, E. B., S. P. Magnusson, J. Bencke, H. Naesborg, M. Havkrog, J. F. Ebstrup and H. Sørensen (2000). "Can the hamstring muscles protect the anterior cruciate ligament during a side-cutting maneuver?" Scand J Med Sci Sports **10**(2): 78-84.
- Sinclair, J., D. Brooks, C. Edmundson and S. Hobbs (2012). "The efficacy of EMG MVC normalization techniques for running analyses." Journal of Biomechanics(45): S623.
- Sinclair, J., P. J. Taylor, J. Hebron, D. Brooks, H. T. Hurst and S. Atkins (2015). "The Reliability of Electromyographic Normalization Methods for Cycling Analyses." Journal of human kinetics **46**: 19-27.
- Small, K., L. McNaughton, M. Greig and R. Lovell (2010). "The effects of multidirectional soccer-specific fatigue on markers of hamstring injury risk." J Sci Med Sport **13**(1): 120-125.
- Small, K., L. R. McNaughton, M. Greig, M. Lohkamp and R. Lovell (2009). "Soccer fatigue, sprinting and hamstring injury risk." Int J Sports Med **30**(8): 573-578.
- Soderberg, G. L. (1992). Selected topics in surface electromyography for use in the occupational setting: expert perspectives, US Department of Health and Human Services, Public Health Service, Centers
- Söderman, K., H. Alfredson, T. Pietilä and S. Werner (2001). "Risk factors for leg injuries in female soccer players: a prospective investigation during one out-door season." Knee Surgery, Sports Traumatology, Arthroscopy **9**(5): 313-321.
- Sole, G., S. Milosavljevic, S. J. Sullivan and H. Nicholson (2008). "Running-related hamstring injuries: a neuromuscular approach." Physical Therapy Reviews **13**(2): 102-110.
- Spilker Jr, J. J., P. Axelrad, B. W. Parkinson and P. Enge (1996). Global positioning system: theory and applications, volume I, American Institute of Aeronautics and Astronautics.
- Spiteri, T., J. L. Cochrane, N. H. Hart, G. G. Haff and S. Nimphius (2013). "Effect of strength on plant foot kinetics and kinematics during a change of direction task." Eur J Sport Sci **13**(6): 646-652.
- Spiteri, T., R. U. Newton, M. Binetti, N. H. Hart, J. M. Sheppard and S. Nimphius (2015). "Mechanical Determinants of Faster Change of Direction and Agility Performance in Female Basketball Athletes." J Strength Cond Res **29**(8): 2205-2214.
- Stevens, T. G., C. J. de Ruyter, C. van Niel, R. van de Rhee, P. J. Beek and G. J. Savelsbergh (2014). "Measuring acceleration and deceleration in soccer-specific movements using a local position measurement (LPM) system." Int J Sports Physiol Perform **9**(3): 446-456.
- Stølen, T., K. Chamari, C. Castagna and U. Wisløff (2005). "Physiology of Soccer." Sports Medicine **35**(6): 501-536.

- Suchomel, T. J., S. Nimphius, C. R. Bellon and M. H. Stone (2018). "The Importance of Muscular Strength: Training Considerations." Sports Med **48**(4): 765-785.
- Sugiura, Y., T. Saito, K. Sakuraba, K. Sakuma and E. Suzuki (2008). "Strength Deficits Identified With Concentric Action of the Hip Extensors and Eccentric Action of the Hamstrings Predispose to Hamstring Injury in Elite Sprinters." Journal of Orthopaedic & Sports Physical Therapy **38**(8): 457-464.
- Sun, Y., S. Wei, Y. Zhong, W. Fu, L. Li and Y. Liu (2015). "How joint torques affect hamstring injury risk in sprinting swing-stance transition." Med Sci Sports Exerc **47**(2): 373-380.
- Swinton, P. A., R. Lloyd, J. W. L. Keogh, I. Agouris and A. D. Stewart (2014). "Regression Models of Sprint, Vertical Jump, and Change of Direction Performance." The Journal of Strength & Conditioning Research **28**(7): 1839-1848.
- Thelen, D. G., E. S. Chumanov, T. M. Best, S. C. Swanson and B. C. Heiderscheit (2005). "Simulation of Biceps Femoris Musculotendon Mechanics during the Swing Phase of Sprinting." Medicine & Science in Sports & Exercise **37**(11): 1931-1938.
- Thelen, D. G., E. S. Chumanov, D. M. Hoerth, T. M. Best, S. C. Swanson, L. I. Li, M. Young and B. C. Heiderscheit (2005). "Hamstring Muscle Kinematics during Treadmill Sprinting." Medicine & Science in Sports & Exercise **37**(1): 108-114.
- Thomas, C., T. Dos'Santos, P. Comfort and P. A. Jones (2020). "Effect of Asymmetry on Biomechanical Characteristics During 180° Change of Direction." J Strength Cond Res **34**(5): 1297-1306.
- Thorborg, K., T. Bandholm and P. Hölmich (2013). "Hip- and knee-strength assessments using a hand-held dynamometer with external belt-fixation are inter-tester reliable." Knee Surg Sports Traumatol Arthrosc **21**(3): 550-555.
- Thorborg, K., D. Opar and A. Shield (2020). Prevention and Rehabilitation of Hamstring Injuries, Springer.
- Thorlund, J. B., P. Aagaard and K. Madsen (2009). "Rapid muscle force capacity changes after soccer match play." Int J Sports Med **30**(4): 273-278.
- Tierney, P. J., A. Young, N. D. Clarke and M. J. Duncan (2016). "Match play demands of 11 versus 11 professional football using Global Positioning System tracking: Variations across common playing formations." Hum Mov Sci **49**: 1-8.
- Tillin, N. A., M. T. Pain and J. Folland (2013). "Explosive force production during isometric squats correlates with athletic performance in rugby union players." J Sports Sci **31**(1): 66-76.

- Timmins, R. G., M. N. Bourne, A. J. Shield, M. D. Williams, C. Lorenzen and D. A. Opar (2016). "Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): a prospective cohort study." Br J Sports Med **50**(24): 1524-1535.
- Tsepis, E., G. Vagenas, G. Giakas and A. Georgoulis (2004). "Hamstring weakness as an indicator of poor knee function in ACL-deficient patients." Knee Surg Sports Traumatol Arthrosc **12**(1): 22-29.
- Tupa, V. (1995). "Fatigue influenced changes to sprinting technique." Modern athlete and coach **33**(3): S.-7-10.
- Uhorchak, J. M., C. R. Scoville, G. N. Williams, R. A. Arciero, P. St Pierre and D. C. Taylor (2003). "Risk factors associated with noncontact injury of the anterior cruciate ligament: a prospective four-year evaluation of 859 West Point cadets." Am J Sports Med **31**(6): 831-842.
- Urabe, Y., R. Kobayashi, S. Sumida, K. Tanaka, N. Yoshida, G. A. Nishiwaki, E. Tsutsumi and M. Ochi (2005). "Electromyographic analysis of the knee during jump landing in male and female athletes." Knee **12**(2): 129-134.
- van Beijsterveldt, A. M., I. G. van de Port, A. J. Vereijken and F. J. Backx (2013). "Risk factors for hamstring injuries in male soccer players: a systematic review of prospective studies." Scand J Med Sci Sports **23**(3): 253-262.
- van der Horst, N., D. W. Smits, J. Petersen, E. A. Goedhart and F. J. Backx (2015). "The preventive effect of the nordic hamstring exercise on hamstring injuries in amateur soccer players: a randomized controlled trial." Am J Sports Med **43**(6): 1316-1323.
- van Dyk, N., R. Bahr, R. Whiteley, J. L. Tol, B. D. Kumar, B. Hamilton, A. Farooq and E. Witvrouw (2016). "Hamstring and Quadriceps Isokinetic Strength Deficits Are Weak Risk Factors for Hamstring Strain Injuries: A 4-Year Cohort Study." Am J Sports Med **44**(7): 1789-1795.
- Vargas, V. Z., C. Motta, B. Peres, R. L. Vancini, C. Andre Barbosa De Lira and M. S. Andrade (2020). "Knee isokinetic muscle strength and balance ratio in female soccer players of different age groups: a cross-sectional study." Phys Sportsmed **48**(1): 105-109.
- Verrall, G. M., J. P. Slavotinek, P. G. Barnes and G. T. Fon (2003). "Diagnostic and prognostic value of clinical findings in 83 athletes with posterior thigh injury: comparison of clinical findings with magnetic resonance imaging documentation of hamstring muscle strain." The American Journal of Sports Medicine **31**(6): 969-973.
- Vigh-Larsen, J. F., U. Dalgas and T. B. Andersen (2018). "Position-Specific Acceleration and Deceleration Profiles in Elite Youth and Senior Soccer Players." J Strength Cond Res **32**(4): 1114-1122.
- Vigne, G., C. Gaudino, I. Rogowski, G. Alloatti and C. Hautier (2010). "Activity profile in elite Italian soccer team." Int J Sports Med **31**(5): 304-310.

Walden, M., M. Hägglund, H. Magnusson and J. Ekstrand (2016). "ACL injuries in men's professional football: a 15-year prospective study on time trends and return-to-play rates reveals only 65% of players still play at the top level 3 years after ACL rupture." Br J Sports Med **50**(12): 744-750.

Waldén, M., M. Hägglund, H. Magnusson and J. Ekstrand (2016). "ACL injuries in men's professional football: a 15-year prospective study on time trends and return-to-play rates reveals only 65% of players still play at the top level 3 years after ACL rupture." British Journal of Sports Medicine **50**(12): 744.

Waldén, M., M. Hägglund, J. Werner and J. Ekstrand (2011). "The epidemiology of anterior cruciate ligament injury in football (soccer): a review of the literature from a gender-related perspective." Knee Surg Sports Traumatol Arthrosc **19**(1): 3-10.

Waldén, M., T. Krosshaug, J. Bjørneboe, T. E. Andersen, O. Faul and M. Hägglund (2015). "Three distinct mechanisms predominate in non-contact anterior cruciate ligament injuries in male professional football players: a systematic video analysis of 39 cases." Br J Sports Med **49**(22): 1452-1460.

Walsh, M., M. C. Boling, M. McGrath, J. T. Blackburn and D. A. Padua (2012). "Lower extremity muscle activation and knee flexion during a jump-landing task." J Athl Train **47**(4): 406-413.

Wan, X., S. Li, T. M. Best, H. Liu, H. Li and B. Yu (2021). "Effects of flexibility and strength training on peak hamstring musculotendinous strains during sprinting." Journal of Sport and Health Science **10**(2): 222-229.

Wan, X., F. Qu, W. E. Garrett, H. Liu and B. Yu (2017). "Relationships among hamstring muscle optimal length and hamstring flexibility and strength." Journal of Sport and Health Science **6**(3): 275-282.

Wang, R., J. R. Hoffman, S. Tanigawa, A. A. Miramonti, M. B. La Monica, K. S. Beyer, D. D. Church, D. H. Fukuda and J. R. Stout (2016). "Isometric Mid-Thigh Pull Correlates With Strength, Sprint, and Agility Performance in Collegiate Rugby Union Players." J Strength Cond Res **30**(11): 3051-3056.

Wehbe, G. M., T. B. Hartwig and C. S. Duncan (2014). "Movement Analysis of Australian National League Soccer Players Using Global Positioning System Technology." The Journal of Strength & Conditioning Research **28**(3).

Weinhandl, J. T., J. E. Earl-Boehm, K. T. Ebersole, W. E. Huddleston, B. S. Armstrong and K. M. O'Connor (2013). "Anticipatory effects on anterior cruciate ligament loading during sidestep cutting." Clin Biomech (Bristol, Avon) **28**(6): 655-663.

West, D. J., N. J. Owen, M. R. Jones, R. M. Bracken, C. J. Cook, D. J. Cunningham, D. A. Shearer, C. V. Finn, R. U. Newton, B. T. Crewther and L. P. Kilduff (2011). "Relationships between force-

time characteristics of the isometric midthigh pull and dynamic performance in professional rugby league players." J Strength Cond Res **25**(11): 3070-3075.

Wikstrom, E. A., M. D. Tillman, S. M. Schenker and P. A. Borsa (2008). "Jump-landing direction influences dynamic postural stability scores." J Sci Med Sport **11**(2): 106-111.

Wikstrom, E. A., M. D. Tillman, A. N. Smith and P. A. Borsa (2005). "A new force-plate technology measure of dynamic postural stability: the dynamic postural stability index." Journal of athletic training **40**(4): 305-309.

Williams, D. S., 3rd, J. H. Cole and D. W. Powell (2017). "Lower Extremity Joint Work During Acceleration, Deceleration, and Steady State Running." J Appl Biomech **33**(1): 56-63.

Williams, M. and L. Stutzman (1959). "Strength variation through the range of joint motion." Phys Ther Rev **39**(3): 145-152.

Wilson, G. J. and A. J. Murphy (1996). "The use of isometric tests of muscular function in athletic assessment." Sports Med **22**(1): 19-37.

Withrow, T. J., L. J. Huston, E. M. Wojtys and J. A. Ashton-Miller (2006). "The relationship between quadriceps muscle force, knee flexion, and anterior cruciate ligament strain in an in vitro simulated jump landing." Am J Sports Med **34**(2): 269-274.

Withrow, T. J., L. J. Huston, E. M. Wojtys and J. A. Ashton-Miller (2008). "Effect of varying hamstring tension on anterior cruciate ligament strain during in vitro impulsive knee flexion and compression loading." J Bone Joint Surg Am **90**(4): 815-823.

Witvrouw, E., L. Danneels, P. Asselman, T. D'Have and D. Cambier (2003). "Muscle flexibility as a risk factor for developing muscle injuries in male professional soccer players. A prospective study." Am J Sports Med **31**(1): 41-46.

Wojtys, E. M. and L. J. Huston (1994). "Neuromuscular performance in normal and anterior cruciate ligament-deficient lower extremities." Am J Sports Med **22**(1): 89-104.

Wollin, M., K. Thorborg and T. Pizzari (2017). "The acute effect of match play on hamstring strength and lower limb flexibility in elite youth football players." Scandinavian Journal of Medicine & Science in Sports **27**(3): 282-288.

Wong, P. and Y. Hong (2005). "Soccer injury in the lower extremities." British Journal of Sports Medicine **39**(8): 473-482.

Wong, P.-I., K. Chamari, A. Chaouachi, D. W. Mao, U. Wisløff and Y. Hong (2007). "Difference in plantar pressure between the preferred and non-preferred feet in four soccer-related movements." British Journal of Sports Medicine **41**(2): 84.

Woods, C., R. Hawkins, M. Hulse and A. Hodson (2002). "The Football Association Medical Research Programme: an audit of injuries in professional football-analysis of preseason injuries." Br J Sports Med **36**(6): 436-441; discussion 441.

Woods, C., R. D. Hawkins, S. Maltby, M. Hulse, A. Thomas, A. Hodson and P. Football Association Medical Research (2004). "The Football Association Medical Research Programme: an audit of injuries in professional football--analysis of hamstring injuries." British journal of sports medicine **38**(1): 36-41.

Woods, C., R. D. Hawkins, S. Maltby, M. Hulse, A. Thomas, A. Hodson and P. Football Association Medical Research (2004). "The Football Association Medical Research Programme: an audit of injuries in professional football--analysis of hamstring injuries." Br J Sports Med **38**(1): 36-41.

Wright, J., N. Ball and L. Wood (2009). "Fatigue, H/Q ratios and muscle coactivation in recreational football players." Isokinetics and Exercise Science **17**(3): 161-167.

Yamamoto, T. (1993). "Relationship between hamstring strains and leg muscle strength. A follow-up study of collegiate track and field athletes." J Sports Med Phys Fitness **33**(2): 194-199.

Yeung, S. S., A. M. Suen and E. W. Yeung (2009). "A prospective cohort study of hamstring injuries in competitive sprinters: preseason muscle imbalance as a possible risk factor." Br J Sports Med **43**(8): 589-594.

Yu, B., D. T. Kirkendall and W. E. Garrett, Jr. (2002). "Anterior Cruciate Ligament Injuries in Female Athletes: Anatomy, Physiology, and Motor Control." Sports Medicine and Arthroscopy Review **10**(1).

Yu, B., H. Liu and W. E. Garrett (2017). "Mechanism of hamstring muscle strain injury in sprinting." Journal of Sport and Health Science **6**(2): 130-132.

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

Zajac, F. E. and M. E. Gordon (1989). "Determining muscle's force and action in multi-articular movement." Exerc Sport Sci Rev **17**: 187-230.

Zbidi, S., B. Zinoubi, O. Hammouda, H. Vandewalle, V. Serrau and T. Driss (2017). "Co-contraction training, muscle explosive force and associated electromyography activity." J Sports Med Phys Fitness **57**(6): 725-733.

Zebis, M. K., L. L. Andersen, J. Bencke, M. Kjaer and P. Aagaard (2009). "Identification of athletes at future risk of anterior cruciate ligament ruptures by neuromuscular screening." Am J Sports Med **37**(10): 1967-1973.

Zebis, M. K., L. L. Andersen, H. Ellingsgaard and P. Aagaard (2011). "Rapid hamstring/quadriceps force capacity in male vs. female elite soccer players." J Strength Cond Res **25**(7): 1989-1993.

Zebis, M. K., J. Bencke, L. L. Andersen, T. Alkjaer, C. Suetta, P. Mortensen, M. Kjaer and P. Aagaard (2011). "Acute fatigue impairs neuromuscular activity of anterior cruciate ligament-agonist muscles in female team handball players." Scand J Med Sci Sports **21**(6): 833-840.

Zebis, M. K., J. Bencke, L. L. Andersen, S. Døssing, T. Alkjaer, S. P. Magnusson, M. Kjaer and P. Aagaard (2008). "The effects of neuromuscular training on knee joint motor control during sidecutting in female elite soccer and handball players." Clin J Sport Med **18**(4): 329-337.

Zhang, Q., B. Morel, R. Trama and C. A. Hautier (2021). "Influence of Fatigue on the Rapid Hamstring/Quadriceps Force Capacity in Soccer Players." Frontiers in Physiology **12**(35).

Zhang, S. N., B. T. Bates and J. S. Dufek (2000). "Contributions of lower extremity joints to energy dissipation during landings." Med Sci Sports Exerc **32**(4): 812-819.

CHAPTER 9 Appendix – Reprint of published articles

9.1 Appendix 1

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Running patterns and force-velocity sprinting profiles in elite training young soccer players: A cross-sectional study

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Abstract

The Volodalen® field method permits to classify runners into aerial or terrestrial, based on vertical oscillation, upper-body motion, pelvis and foot position at ground contact, and foot strike pattern. The present study aimed to compare the sprint running force-velocity profiles between aerial and terrestrial runners. Sixty-Four French National-Level young soccer players (28 females, 36 males) performed three trials of unloaded maximal 40 m sprints. External horizontal power-force-velocity relationships were computed using a validated biomechanical model and based on the velocity-time curve. Accordingly, the participants were classified into patterns in aerial and terrestrial runners. Terrestrial runners showed a higher maximal horizontal force (F_0) (6.73 ± 1.03 vs 6.01 ± 0.94 N·kg⁻¹), maximal horizontal power (P_{max}) (14.04 ± 3.24 vs 12.51 ± 3.31 W·kg⁻¹), maximal acceleration (Acc) (6.83 ± 0.85 vs 6.26 ± 0.89 m·s⁻²), and maximal rate of horizontal force (RF_{max}) (57.41 ± 4.64 vs $52.81 \pm 5.69\%$) compared to aerial runners. In contrast, terrestrial runners displayed a more negative rate of decrease of RF (D_{RF}) (-11.65 ± 1.71 vs $-10.23 \pm 1.66\%$) and slope of the Force-Velocity relationship (F-V slope) (-0.83 ± 0.11 vs -0.77 ± 0.10 N·s·m⁻¹·kg⁻¹) than aerial runners. The results indicate that terrestrial runners displayed more efficient force production in the forward direction and displayed more “force-oriented” F-V profiles. Nevertheless, aerial runners were more effective in maintaining a net horizontal force production with increasing speed. Our results suggest that terrestrial runners could be more adapted to the specific short distance and high acceleration sprints running.

Keywords: Sprint kinetics, mechanical properties, maximal force, maximal power

Highlights

- While previous studies have shown that the Volodalen® method allows classifying running patterns into aerial and terrestrial patterns, no study examined the influence of this running pattern on the sprinting performance and force-velocity profiles.
- Current results indicated that terrestrial runners displayed better acceleration capacity with higher horizontal force production, whereas the aerial runners could maintain the effective horizontal force production when velocity increased.
- Our finding allows the coach to design an individualized training session for soccer players according to the evaluation of Force-Velocity profile and running pattern profiles.

Introduction

Sprint running capacity is a key factor that is generally considered as one of the prerequisite physical components for successful soccer performance (Haugen, Tonnessen, Hisdal, & Seiler, 2014; Rodacki, Fowler, & Bennett, 2001). Soccer players continuously perform short-duration high-intensity activities, including approximately 220 high-

intensity short linear sprint running bouts during a competitive game (i.e. <30 m) (Andrzejewski, Chmura, Pluta, & Kasprzak, 2012; Andrzejewski, Chmura, Pluta, Strzelczyk, & Kasprzak, 2013; Miñano-Espin, Casáis, Lago-Peñas, & Gómez-Ruano, 2017; Mohr, Krustup, & Bangsbo, 2003; Sarmiento et al., 2014). According to recent literature, both high acceleration and maximal sprint

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velocity are two distinct components of sprint performance, which might allow soccer players to overtake opponents and win balls in decisive situations (Buchheit et al., 2014; Faude, Koch, & Meyer, 2012). The mechanics of sprint running have received considerable attention in the scientific literature over the years. Previous biomechanical analyses of sprint running have found that in most cases kinetic or kinematic variables (e.g. step frequency, step length, ground reaction force, stiffness of lower extremity, mechanical power) could determine sprint running performance; as a matter of fact, most biomechanical parameters are interdependent upon analysis of sprint running performance (Haugen, McGhie, & Ettema, 2019).

Recently, Samozino et al. (2016) proposed a simple field method to measure external mechanical effectiveness in sprint running in order to determine the mechanical properties of sprint running described by the force-power-velocity profile and its meaningful parameters (e.g. maximal acceleration (Acc), maximal horizontal force (F_0), maximal theoretical velocity (V_0), maximal power (P_{max}), decrease in the ratio of horizontal-to-resultant force (D_{RF}) and the maximal ratio of horizontal-to-resultant force (RF_{max})) (Samozino et al., 2016). Based on the force-velocity profile, high effectiveness in producing maximal horizontal force (F_0) and the maximal ratio of horizontal-to-resultant force (RF_{max}) was demonstrated to be the primary mechanical determinant of maximal acceleration in the shorter sprints which were up to 20 m in rugby or soccer (Morin et al., 2012; Morin & Samozino, 2016). As a consequence, coaches could design an individualized training programme based on this F-V profile evaluation.

In the last few decades, there has been a surge of interest in running techniques in order to gain the proper biomechanical parameters to enhance sprint performance and reduce musculoskeletal injuries (Romanov & Fletcher, 2007; Thompson, Bezodis, & Jones, 2009). Recently, Gindre, Lussiana, Hébert-Losier, and Mourot (2016) proposed a novel approach classifying runners into aerial patterns (AER) and terrestrial patterns (TER) based on a five-criteria scale (i.e. the vertical oscillation of the head, anteroposterior motion of the elbows, pelvis position at ground contact, foot position at ground contact, and strike pattern) (Gindre et al., 2016) which subdivides the optimal sprint technique according to multiple biomechanical parameters (Lussiana & Gindre, 2016; Lussiana, Gindre, Mourot, & Hébert-Losier, 2017). Based on the different kinetic parameters, TER runners rely more on forward propulsion, whereas AER runners are more capable of storing and releasing elastic energy (Lussiana, Gindre, Hébert-Losier, et al.,

2017). In view of all that has been demonstrated, the determination of aerial and terrestrial patterns could be useful for athletic training. For example, AER runners could benefit more efficiently from elastic energy in running, which may produce the same impulse for a lower metabolic cost compared to TER runners (Sandford, Kilding, Ross, & Laursen, 2019). Besides, TER runners could apply higher forward force onto the ground resulting in better sprint acceleration performance and higher maximal rate of horizontal force (RF_{max}) compared to AER runners (Lussiana, Gindre, Hébert-Losier, et al., 2017). In addition, aerial runners should present lower negative rate of decrease of $RF(D_{RF})$ because they may change the running pattern when running velocity increases. Therefore, they may be more effective in maintaining a net horizontal force production at higher running speed. In contrast, most runners become more aerial when running velocity increases. Consequently, the aerial runners could match the mechanical demands of sprint running more effectively once the faster running speeds are attained. Furthermore, no investigation determined the relationship between the running pattern and the sprint performance or the sprint mechanical force-velocity profiles until now.

Considering the potential influence of running pattern on sprint performance, it could be interesting to analyze the relationship between sprint force-velocity profile and aerial or terrestrial profiles in soccer players in order to orientate the training. Furthermore, the Volodalen® method has only been used to classify running patterns during steady-state sub-maximal running, and it could be interesting to test its application during sprint running. Thus, the present study aimed to (1) use this method to classify running pattern while performing sprint running, and (2) compare the sprint mechanical force-velocity profiles between aerial and terrestrial runners in soccer players. We hypothesized that aerial and terrestrial runners would present differences in their Force-Velocity profile and related variables.

Methods

Participants

A total of 64 high-level french young soccer players from three elite academies participated in the current study including 36 males (height: 170.2 ± 10.9 cm, body mass: 58.6 ± 12.2 kg, age: 16.1 ± 0.4 years) and 28 females (height: 164.3 ± 6.0 cm, body mass: 58.3 ± 7.0 kg, age: 17.1 ± 1.6 years). All players participated on average in ~ 15 h of training combining soccer-specific training and competitive play per week (5–9 soccer training sessions, 1–3

conditioning sessions, one competitive play per week). All players had a minimum of 4 years of prior soccer-specific training. All participants were free from lower extremity injuries and had been injury-free for the previous year. All subjects have been informed about the procedure and gave their written informed consent to participate in the study.

Additionally, participants refrained from high-intensity training or match activity 48 h before the study and avoided strenuous loading 48 h before this protocol. All participants had no history of traumatic lower limb injuries (ACL rupture, hamstring injuries, etc.) preceding the study, and the study was approved by the local ethics committee (i.e. Sud-Est II of Lyon). All procedures conformed to the standards of the Declaration of Helsinki. All participants provided written, voluntary informed consent before participation. Leading up to the experiment, participants followed their regular training programme.

Protocol

This cross-sectional study was designed to compare the different sprint mechanical force-velocity profiles between aerial runners and terrestrial runners (F_0 , V_0 , P_{\max} , D_{RF} , and RF_{peak}) and performance variables (5, 10, 15, 20 m sprint time). Players were tested in the afternoon between 1 pm and 2 pm during the competitive season. All testing procedures were completed on the same third-generation artificial turf surface with rubber granules, specialized for outdoor field-sport events with standard meteorological conditions (temperature: 9°–14°; wind < 10 km/h; the degree of humidity < 46%). Each participant was asked to wear the same sprigged training shoes and team training attire as usual.

All the participants performed a 20-minute on-field dynamic warm-up protocol specific to soccer (e.g. dynamic stretching), as this would most closely reflect the warm-up used before training, practice and competitive match. Participants then performed three progressive sprints of 40 m at 50%, 70%, and 90% effort. After 4 min of active rest, subjects performed three maximal sprints of 40 m from a crouching position (staggered stance) with a 4 min period of active recovery between each sprint. Athletes were encouraged to sprint “through” each distance marker (i.e. 5, 10, 15, 20 m, 25 m, 30 m, 35 m, 40 m) to ensure a full maximal collection devoid of deceleration. A Stalker Acceleration Testing System (ATS) II radar device (Stalker ATS II, Applied Concepts, Dallas, TX, USA, 46.9 Hz) was attached to a heavy-duty tripod positioned 10 m behind the starting line at the height of 0.9 m above the ground

(corresponding approximately to subject’s centre of mass) which aimed to record the velocity-time curve for 40 m. Besides, a 2D high-frequency camera (GoPro Hero 7 Black, Go Pro, USA, 200 Hz, resolution 1080p) was positioned 0.9 m above the ground and at 7 m on the side of the track in order to capture the movement between 10 m to 25 m of the sprint in the sagittal plane.

Data analysis

Sprint mechanics: All data were collected using STATS software (Model: Stalker ATS II Version 5.0.2.1, Applied Concepts, Dallas, TX, USA) provided by the radar device’s manufacturer. A custom-made MATLAB (The MathWorks Inc, R2018b, Natick, MA, USA) was developed to analyze sprint mechanical Force-Velocity profile [maximal acceleration (Acc), maximal theoretical force (F_0), maximal theoretical velocity (V_0), maximal power (P_{\max}), decrease in the ratio of horizontal-to-resultant force (D_{RF}), the slope of the linear Force-Velocity relationship (F-V slope) and maximal ratio of horizontal-to-resultant force (RF_{\max})] according to *Samozino’s* method (Samozino et al., 2016). This method has been validated for measuring mechanical effectiveness based on an inverse dynamic approach (Samozino et al., 2016). Based on this method, the sprint velocity-time curve $V(t)$ was fitted by a mono-exponential function using least-squares regression:

$$V(t) = V_{\max} * (1 - e^{-t/\tau})$$

with τ the acceleration time constant. The horizontal acceleration of the centre of mass can be expressed as a function of time, after derivation of velocity over time:

$$a(t) = \left(\frac{V_{\max}}{\tau}\right) * e^{-t/\tau}$$

Net horizontal force (F) was then modelled over time:

$$F(t) = m * a(t) + F_{\text{air}(t)}$$

with F_{air} as the aerodynamic friction force to overcome during sprint running computed from sprint velocity and an estimated body frontal area and drag coefficient. From the horizontal-force and sprint-velocity values, individual force-velocity relationships were determined with least-squares linear regressions. F_0 and V_0 were then identified from the force-velocity relationship as the x- and y-intercepts, respectively. Maximum horizontal power output was determined as ($F_0 * V_0/4$). Maximum velocity (V_0) was identified as the maximal

velocity obtained during the 40-m sprint. The ratio of force was calculated as the ratio of the horizontal component of the ground reaction force to the total ground-reaction force. RF_{peak} corresponded to the maximal value of the ratio of force. Besides, the linear decrease in the ratio of force with velocity was calculated as an index of the ability to maintain the ratio of force throughout the acceleration phase (D_{RF}). Relevant variables were determined by dividing the given absolute value by subject body mass. The best performance was retained for analysis (i.e. to assess the horizontal mechanical determinants of maximal acceleration and maximal velocity) (Buchheit et al., 2014).

Running pattern: An experimented examiner determined each subject's running pattern by giving a V-score using the Volodalen® method (Gindre et al., 2016). The scores were given based on sagittal plane video recording of each participant's running trials. The examiner focused on the global movement patterns of subjects with particular attention given to five key elements, i.e. vertical oscillation of the head, arm movement, vertical pelvis position at ground contact, foot position at ground contact, and foot strike during the sprints (between 10 m and 25 m). Each element was scored from 1 to 5. A global score (V_{score}) was then computed by summing the individual scores of each element. A $V_{\text{score}} \leq 15$ was considered as a terrestrial runner and >15 as an aerial runner. The reliability of subjective assessment V_{score} has previously been established with a high intraclass correlation coefficient (ICC) above 0.945 for both novice and expert athletes (Patoz, Gindre, Mourot, & Lussiana, 2019).

Statistical analyses

Prior to performing the statistical analysis, the Shapiro–Wilk test and Levene's test were used respectively to assess the normality of data and the equality of variance for maximal acceleration (Acc), maximal theoretical force (F_0), maximal theoretical velocity (V_0), maximal power (P_{max}), decrease in the ratio of horizontal-to-resultant force (D_{RF}) and the maximal ratio of horizontal-to-resultant force (RF_{max}), 5, 10, 15, 20 m. The two-way ANOVA analysis of variance was used to assess the interaction effect between sexes (Male vs Female) and the main effect of different sprint patterns (Aerial vs Terrestrial) on the variables cited above. When a significant interaction was detected, pairwise comparisons with a Bonferroni correction were performed to determine where specific differences lay, that is, P values obtained from statistical analyses were multiplied by six comparisons and compared with the critical p -value of 0.008 (Bonferroni correction: 0.05/6). Prior descriptive and outcome statistics are presented as mean \pm SD. In parallel, we

quantified the effect size between the two conditions to better understand the importance of the difference. We considered that a *Hedges'g* value below 0.2 signified negligible effect, between 0.2 and 0.5 signified a small effect, between 0.5 and 0.8 signified a medium effect, and larger than 0.8 signified the large effect (Hedges, 1981). All statistical procedures were performed with IBM SPSS 26 (IBM Corporation, Armonk, NY).

Results

The descriptive data (mean \pm standard deviation) of the Volodalen® score for aerial runners and terrestrial runners are presented in Table I. Irrespective of sex, terrestrial runners showed a higher maximal theoretical force (F_0) ($P < .001$), maximal power (P_{max}) ($P = .0053$), maximal acceleration (Acc) ($P = .0012$), maximal ratio of horizontal force (RF_{max}) ($P = .0017$), and more negative F-V slope value ($P = .032$) compared to aerial runners. Additionally, terrestrial runners displayed better 5 m ($P < .001$) 10 m ($P < .001$), and 15 m ($P < .001$) performance (Table II). In contrast, terrestrial runners displayed a more negative ratio of horizontal-to-resultant force (D_{RF}) ($P = .0039$) than aerial runners (Table II). No significant differences in maximal theoretical velocity (V_0) and 20 m performance were observed between terrestrial and aerial runners (Table II). Furthermore, no significant interaction was detected between sex and sprint pattern (all $P > .05$). Male results were significantly higher compared to female results (all $P < .05$), but no difference was observed in the repartition of terrestrial and aerial runners between sexes (Figure 1). Besides, the Force-Velocity profiles obtained by AER and TER runner, Male and Female were presented in Figure 2.

Discussion

This study was designed to investigate whether the F-V profiles differ between terrestrial and aerial sprint profiles amongst young soccer players. To the best of the authors' knowledge, this is the first study to compare the mechanical F-V properties of sprint running techniques in soccer players with different running patterns (i.e. terrestrial runners and aerial runners). The main findings of the investigation were that terrestrial runners and aerial runners significantly differed in their F-V profiles. Terrestrial runners displayed an F-V profile more oriented towards force capacities (i.e. slope F-V) while showing higher maximal horizontal force (F_0), maximal power (P_{max}), maximal ratio of horizontal force (RF_{peak}), and maximal acceleration (Acc). Contrastingly, terrestrial runners displayed more negative

Table I. Descriptive data of Volodalen® score for aerial runners and terrestrial runners.

Gender	Running pattern	No.	V_{score}	Vertical oscillation of head	Arm movement	Pelvis position at ground contact	Foot position	Strike pattern
Males ($n = 36$)	Aerial runners	18	19.2 ± 1.9	3.7 ± 0.5	4.3 ± 0.9	3.4 ± 0.5	4.1 ± 0.5	3.8 ± 0.8
	Terrestrial runners	18	10.9 ± 1.8	2.2 ± 0.5	1.8 ± 0.6	2.5 ± 0.3	2.3 ± 0.8	2.3 ± 0.9
Females ($n = 28$)	Aerial runners	13	19.6 ± 2.3	3.6 ± 0.5	4.0 ± 0.8	3.5 ± 0.5	4.1 ± 0.6	4.1 ± 0.5
	Terrestrial runners	15	10.0 ± 2.9	2.4 ± 0.6	1.9 ± 1.2	2.0 ± 0.8	2.3 ± 0.6	2.2 ± 0.9
Total ($n = 64$)	Aerial runners	31	19.4 ± 2.1	3.7 ± 0.5	4.2 ± 0.9	3.5 ± 0.5	4.1 ± 0.5	4.0 ± 0.7
	Terrestrial runners	33	10.7 ± 2.4	2.3 ± 0.6	1.9 ± 0.9	2.2 ± 0.6	2.3 ± 0.7	2.3 ± 0.9

D_{RF} values than aerial runners. However, male players always displayed a higher value of F_0 , V_0 , P_{max} , D_{RF} , and RF_{max} , no matter what the running pattern (see Figures 1 and 2). Furthermore, no significant difference was found for V_0 and 20 m performance between terrestrial and aerial runners.

The external force determines the acceleration of the athlete's centre of mass (COM) during sprint running is GRF (i.e. ground reaction force, the overall magnitude of vertical, horizontal and resultant for each foot strike). During the acceleration phase of sprint running, the forward orientation of GRF has been demonstrated to be strongly related to sprint acceleration performance (Kawamori, Nosaka, & Newton, 2013; Morin, Edouard, & Samozino, 2011). Through the F-V profile method, F_0 is the maximal force output in the horizontal direction, which corresponds to the initial push-off of the athlete onto the ground during the initial sprint acceleration. The higher the value, the higher the sprint-specific horizontal force production (Morin &

Samozino, 2016). As expected, the terrestrial pattern is characterized by a more grounded horizontal gait, which follows the kinetic analysis of the running patterns of terrestrial and aerial runners. Terrestrial runners are considered to rely more on forward propulsion, whereas aerial runners are more capable of storing and releasing elastic energy with higher lower extremity stiffness (Lussiana & Gindre, 2016). Indeed, terrestrial runners presented higher horizontal force production capacities (i.e. propulsion phase), especially at the beginning of the sprint and notably due to higher effectiveness of ground-force application (i.e. RF_{max}). In particular, F_0 , P_{max} and RF_{max} are critical in short sprint-acceleration performance (Morin & Samozino, 2016). The terrestrial runner presents a better ability to transfer the overall strength level (interaction of the overall strength capability of the athlete at each lower-limb extension) to the specific, forward sprint motion at the first step (as evidenced by RF_{max}). Owing to the positive relationship between

Table II. Effect of running pattern on sprint mechanical force-velocity variables.

	Aerial runners	Terrestrial runners	Mean difference	95% CI	Effect size (Hedges' g)	Qualitative inference
F_0 (N·kg ⁻¹)	6.01 ± 0.94	6.73 ± 1.03	0.72***	[0.43–1.03]	0.43	Small
V_0 (m·s ⁻¹)	8.02 ± 0.86	8.09 ± 0.73	0.07	[−0.39–0.26]	0.08	Negligible
P_{max} (W·kg ⁻¹)	12.51 ± 3.31	14.04 ± 3.24	1.53**	[0.45–2.82]	0.61	Medium
F-V slope (N·s·m ⁻¹ ·kg ⁻¹)	-0.78 ± 0.10	-0.83 ± 0.11	0.05*	[0.01–0.94]	0.43	Small
D_{RF} (%)	-10.23 ± 1.66	-11.65 ± 1.71	1.42**	[0.63–2.21]	0.51	Medium
RF_{max} (%)	52.81 ± 5.69	57.41 ± 4.64	4.61**	[3.18–6.61]	0.54	Medium
Acc (m/s ²)	6.26 ± 0.89	6.83 ± 0.85	0.57**	[0.27–0.98]	0.44	Small
5-m (s)	1.54 ± 0.12	1.46 ± 0.09	0.08***	[0.04–0.17]	0.41	Small
10-m (s)	2.35 ± 0.16	2.24 ± 0.11	0.11***	[0.05–0.18]	0.37	Small
15-m (s)	3.09 ± 0.24	2.93 ± 0.13	0.16***	[0.09–0.26]	0.34	Small
20-m (s)	3.73 ± 0.27	3.65 ± 0.15	0.08	[0.02–0.23]	0.30	Small

F_0 : maximal theoretical force, V_0 : maximal theoretical velocity, P_{max} : maximal power, F-V slope: slope of the force-velocity relationship, D_{RF} : decrease in the ratio of horizontal-to-resultant force, RF_{max} : maximal ratio of horizontal-to-resultant force, Acc : maximal acceleration, and sprint running performance variables (5 m, 15 m, 20 m sprint time). *Significant difference from running pattern for $p < .05$, **Significant difference from running pattern for $p < .01$, ***Significant difference from running pattern for $p < .001$. All data are presented as mean \pm standard deviation.

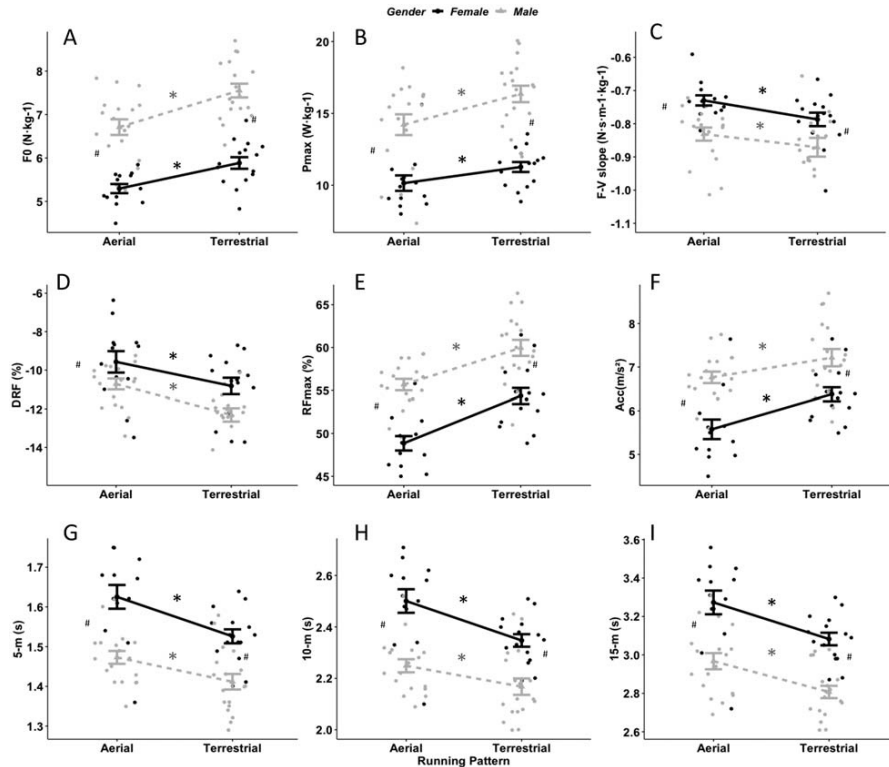


Figure 1. Mean \pm standard deviation of Sprint mechanical force-velocity variables displayed (A: F_0 , B: P_{max} , C: F-V slope, D: DRF , E: RF_{max} , F: Acc , G: 5 m, H: 10 m, I: 15 m) by gender and running pattern. * Significant difference from running pattern. # Significant difference from gender.

acceleration and F_0 , the short sprint performance, we also found that terrestrial runners presented higher acceleration (i.e. maximal acceleration: 6.83 ± 0.85 vs 6.26 ± 0.89 $m \cdot s^{-2}$) and better sprint performance in short distances (i.e. 5, 10, 15 m).

On the basis of a biomechanical analysis of sprint running, F_0 could be influenced by multiple parameters (i.e. strength level, contact time, foot strike pattern) (Clark, Ryan, & Weyand, 2014; Hunter, Marshall, & McNair, 2005). The athlete must increase the net horizontal GRF production by increasing the propulsive duration of contact time. Hayes and Caplan (2012) demonstrated that contact time was significantly correlated with the foot strike pattern since forefoot and midfoot strikes had significantly shorter contact times compared to heel strike (Hayes & Caplan, 2012). Because the

foot strike pattern of the terrestrial runner was closer to the rearfoot strike pattern (i.e. strike pattern score: 2.2), they may be able to produce higher horizontal forward acceleration at the beginning of the sprint when the contact time is high. However, the ability of these terrestrial runners to produce horizontal forces at higher velocities may be decreased when they have to change their running pattern to a more aerial one. Furthermore, terrestrial runners displayed lower vertical oscillation, which could induce less vertical work, which may improve the effectiveness of the running pattern (Lussiana, Gindre, Mouro, et al., 2017). It can be hypothesized that a better orientation of the ground force vector in the forward direction should benefit terrestrial runners by reducing the vertical work. As a result, terrestrial runners demonstrated

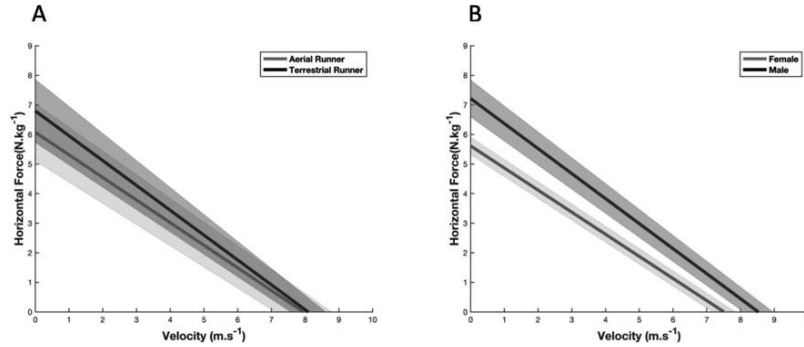


Figure 2. Comparison of the force-velocity profiles between running pattern (A) and gender (B). The solid black line represents the mean F-V relationship from terrestrial runners and males, respectively. The grey line represents the mean F-V relationship from aerial runners and females, respectively. The surrounding grey area represents the SD of each mean F-V relationship.

higher RF_{max} than aerial runners in the present study. Because aerial runners with forefoot strike could activate earlier and longer plantar flexor, they could likely enhance elastic energy storage (Ahn, Brayton, Bhatia, & Martin, 2014), with a more spring-like vertical bouncing pattern (i.e. more vertical work due to higher COM in the vertical direction) (Gindre et al., 2016) comparing with TER runners. Thus, considering that the beginning of a sprint is preferentially done using concentric contractions whereas high velocity running needs elastic energy utilization to maintain high forces despite short contact times, it should be hypothesized that aerial runners are more likely to present lower D_{RF} compared to TER. From what was discussed above, terrestrial runners could rely on their ability to generate force over a longer period of contact time with less flight time, minimizing vertical displacement, and with a higher proportion of total force production in the forward direction. Also, an absolute difference has been observed in the present study considering the respective F-V slope (-0.83 ± 0.11 vs $-0.78 \pm 0.10 \text{ N}\cdot\text{s}\cdot\text{m}^{-1}\cdot\text{kg}^{-1}$) of aerial runners and terrestrial runners, which may be due to the higher force capabilities of terrestrial runners associated with no significant differences in maximal velocity (V_0). The lack of difference in V_0 between the two running pattern groups may be explained by the fact that the two groups were not exposed to maximal velocity performance since this parameter is hardly ever used in soccer speed training, neither during the competition, especially with young soccer players. As the previous finding, the majority of sprint acceleration for soccer players during a match is shorter than 20 m (Haugen et al., 2014). According to the general

sprint training content (e.g. short sprint running under 25 m) for the participants in this study, maximal velocity capacities could not be developed to distinguish the significant different V_0 between aerial and terrestrial runners (8.02 ± 0.86 vs $8.09 \pm 0.73 \text{ m}\cdot\text{s}^{-1}$). Moreover, the lack of differences in terms of maximal velocity may be explained by the age of the subjects (i.e. young soccer players) in the present study who may not have enough experience in maximal velocity sprinting or by the fact that maximal sprinting is considered as a high-risk activity for hamstring strain injuries (Ruddy et al., 2016) and, therefore, such exercises may scarcely be trained in this group. As a consequence, running pattern may influence force and acceleration capacities but not maximal velocity (V_0) in young soccer players.

Interestingly, terrestrial runners presented a more negative D_{RF} value compared to aerial runners indicating that their higher initial effectiveness decreased at a greater rate than aerial runners when velocities increased (Morin & Samozino, 2016). Typically, the D_{RF} is considered as an index of force application technique, which is calculated as the slope of linear decrease in RF with increasing running velocity. Lussiana et al. (2017) reported substantial modifications in running parameters when increasing running speed from $2.7 \text{ m}\cdot\text{s}^{-1}$ to $5.0 \text{ m}\cdot\text{s}^{-1}$ (i.e. vertical head oscillation decreased from 29.5% to 22.1%, strike angle increased from 9.5% to 31.9%) (Lussiana, Gindre, Mourot, et al., 2017). It could be hypothesized that terrestrial runners are more affected by velocity than aerial runners, which is confirmed by the results of Lussiana et al. (2017) (Lussiana, Gindre, Mourot, et al., 2017). Such running velocities could probably have a much greater effect

on running mechanics of the terrestrial runners who may develop towards aerial pattern when the running velocity increases, implying greater changes in running pattern for TER runners compared to AER runners. The differences between TER and AER runners may induce higher forces at low velocity, and better performances on short distances for TER whereas AER runners may present a lower decrease in force at higher velocities inducing equal performances on longer sprints.

In conclusion, the present study clearly demonstrated that significant differences existed in F-V capacities between terrestrial and aerial soccer runners. Terrestrial runners showed more “force-oriented” F-V profiles and displayed higher F_0 , Acc , RF_{max} , and steeper F-V slope compared to aerial runners. Based on the critical parameters of short sprint performance (i.e. greater horizontal force output and higher proportion of total force production in the forward direction), the terrestrial pattern could be more beneficial and favourable for some soccer players depending on playing positions. As discussed above, the different outcomes of the F-V profile could probably be associated with the foot strike pattern, contact time and the amount of vertical work, which should be addressed in future studies. Moreover, it has still not been demonstrated that changing from the aerial pattern to the terrestrial pattern can enhance short sprint performance and influence agility performance (e.g. change-of-direction (COD)). Thus this remains to be explored in future studies.

Another goal of the present study was to assess the feasibility of using the Volodalen® method to classify running pattern during sprint running acceleration (i.e. between 10 m and 25 m), rather than during constant sub-maximal running velocity as proposed by Gindre et al. (2016) (Gindre et al., 2016). Indeed, it is true this may impact the running pattern evaluation since we know that compared to sub-maximal steady-state running, sprint running shows less vertical oscillation, a greater proportion of forefoot strike patterns, a foot placement that is more underneath the body and a more pronounced arm swing. All of these running style parameters are criteria of the Volodalen® score. Therefore, it would be expected that a Volodalen® score during sprinting would differ from a score given during slower running. Perhaps the Volodalen® method could be modified to improve its sensitivity in sprinting, in particular by reducing the importance of the foot strike. However, it seems that this method works well during sprint running since we got two clearly differentiated groups of subjects which demonstrates the sensitivity of the method applied during a sprint running. Interestingly, one should also notice that half of the subjects kept a terrestrial pattern

despite the condition. Moreover, it would also be necessary to determine if the running pattern changes in different sprint running phases (i.e. drive phase: 0m–10 m, transition phase: 10m–20 m, maximal velocity phases: 20m–30 m), so as to know on which portion to apply the method with the greatest precision and reproducibility. We believe that the assessment of running patterns during sprint running, as performed in the present paper, resulted in a valid differentiation between aerial and terrestrial patterns. Nevertheless, future studies should determine how the Volodalen® score could be optimized for use during sprint running and how this sprint score would relate to a score given during steady-state sub-maximal running.

Conclusion

This study tended to demonstrate that the evaluation of the F-V profile and the running pattern profile in young soccer players may provide additional information to guide training content in order to improve acceleration and maximal velocity. Moreover, it tended to indicate that the aerial profile may not be an optimal one for defenders and midfielders since the terrestrial runner produced higher horizontal forces and better short-distance sprint running performance. On the contrary, the aerial profile may be more adapted to forwards who perform longer sprints (Vigne, Gaudino, Rogowski, Alloatti, & Hautier, 2010). These findings should enable coaches to identify a kinematic profile and key biomechanical performance factors for both techniques.

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Supplemental data

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References

- Ahn, A. N., Brayton, C., Bhatia, T., & Martin, P. (2014). Muscle activity and kinematics of forefoot and rearfoot strike runners. *Journal of Sport and Health Science*, 3(2), 102–112. doi:10.1016/j.jshs.2014.03.007
- Andrzejewski, M., Chmura, J., Pluta, B., & Kasprzak, A. (2012). Analysis of motor activities of professional soccer players. *Journal of Strength and Conditioning Research*, 26(6), 1481–1488. doi:10.1519/JSC.0b013e318231ab4c
- Andrzejewski, M., Chmura, J., Pluta, B., Strzelczyk, R., & Kasprzak, A. (2013). Analysis of sprinting activities of professional soccer players. *Journal of Strength and Conditioning Research*, 27(8), 2134–2140. doi:10.1519/JSC.0b013e318279423e
- Buchheit, M., Samozino, P., Glynn, J. A., Michael, B. S., Al Haddad, H., Mendez-Villanueva, A., & Morin, J. B. (2014). Mechanical determinants of acceleration and maximal sprinting speed in highly trained young soccer players. *Journal of Sports Sciences*, 32(20), 1906–1913. doi:10.1080/02640414.2014.965191
- Clark, K. P., Ryan, L. J., & Weyand, P. G. (2014). Foot speed, foot-strike and footwear: Linking gait mechanics and running ground reaction forces. *Journal of Experimental Biology*, 217(12), 2037–2040. doi:10.1242/jeb.099523
- Faude, O., Koch, T., & Meyer, T. (2012). Straight sprinting is the most frequent action in goal situations in professional football. *Journal of Sports Sciences*, 30(7), 625–631. doi:10.1080/02640414.2012.665940
- Gindre, C., Lussiana, T., Hebert-Losier, K., & Mourot, L. (2016). Aerial and terrestrial patterns: A novel approach to analyzing human running. *International Journal of Sports Medicine*, 37(1), 25–26. doi:10.1055/s-0035-1555931
- Haugen, T., McGhie, D., & Ettema, G. (2019). Sprint running: From fundamental mechanics to practice—a review. *European Journal of Applied Physiology*, 119(6), 1273–1287. doi:10.1007/s00421-019-04139-0
- Haugen, T., Tonnessen, E., Hisdal, J., & Seiler, S. (2014). The role and development of sprinting speed in soccer. *International Journal of Sports Physiology and Performance*, 9(3), 432–441. doi:10.1123/ijpp.2013-0121
- Hayes, P., & Caplan, N. (2012). Foot strike patterns and ground contact times during high-calibre middle-distance races. *Journal of Sports Sciences*, 30(12), 1275–1283. doi:10.1080/02640414.2012.707326
- Hedges, L. V. (1981). Distribution theory for glass's estimator of effect size and related estimators. *Journal of Educational Statistics*, 6(2), 107–128. doi:10.3102/10769986006002107
- Hunter, J. P., Marshall, R. N., & McNair, P. J. (2005). Relationships between ground reaction force impulse and kinematics of sprint-running acceleration. *Journal of Applied Biomechanics*, 21(1), 31–43. doi:10.1123/jab.21.1.31
- Kawamori, N., Nosaka, K., & Newton, R. U. (2013). Relationships between ground reaction impulse and sprint acceleration performance in team sport athletes. *Journal of Strength and Conditioning Research*, 27(3), 568–573. doi:10.1519/JSC.0b013e318257805a
- Lussiana, T., & Gindre, C. (2016). Feel your stride and find your preferred running speed. *Biology Open*, 5(1), 45–48. doi:10.1242/bio.014886
- Lussiana, T., Gindre, C., Hébert-Losier, K., Sagawa, Y., Gimenez, P., & Mourot, L. (2017). Similar running economy with different running patterns along the aerial-terrestrial continuum. *International Journal of Sports Physiology and Performance*, 12(4), 481–489. doi:10.1123/ijpp.2016-0107
- Lussiana, T., Gindre, C., Mourot, L., & Hébert-Losier, K. (2017). Do subjective assessments of running patterns reflect objective parameters? *European Journal of Sport Science*, 17(7), 847–857. doi:10.1080/17461391.2017.1325072
- Mañano-Espin, J., Casáis, L., Lago-Peñas, C., & Gómez-Ruano, M. (2017). High speed running and sprinting profiles of elite soccer players. *Journal of Human Kinetics*, 58, 169–176. doi:10.1515/hukin-2017-0086
- Mohr, M., Krustup, P., & Bangsbo, J. (2003). Match performance of high-standard soccer players with special reference to development of fatigue. *Journal of Sports Sciences*, 21(7), 519–528. doi:10.1080/0264041031000071182
- Morin, J.-B., Bourdin, M., Edouard, P., Peyrot, N., Samozino, P., & Lacour, J.-R. (2012). Mechanical determinants of 100-m sprint running performance. *European Journal of Applied Physiology*, 112(11), 3921–3930. doi:10.1007/s00421-012-2379-8
- Morin, J. B., Edouard, P., & Samozino, P. (2011). Technical ability of force application as a determinant factor of sprint performance. *Medicine & Science in Sports & Exercise*, 43(9), 1680–1688. doi:10.1249/MSS.0b013e318216ea37
- Morin, J. B., & Samozino, P. (2016). Interpreting power-force-velocity profiles for individualized and specific training. *International Journal of Sports Physiology and Performance*, 11(2), 267–272. doi:10.1123/ijpp.2015-0638
- Patoz, A., Gindre, C., Mourot, L., & Lussiana, T. (2019). Intra and inter-rater reliability of the Volodalen® scale to assess aerial and terrestrial running forms. *Journal of Athletic Enhancement*, 8, 2. doi:10.4172/2324-9080.1000316
- Rodacki, A. L., Fowler, N. E., & Bennett, S. J. (2001). Multi-segment coordination: Fatigue effects. *Medicine and Science in Sports and Exercise*, 33(7), 1157–1167. doi:10.1097/00005768-200107000-00013
- Romanov, N., & Fletcher, G. (2007). Runners do not push off the ground but fall forwards via a gravitational torque. *Sports Biomechanics*, 6(3), 434–452. doi:10.1080/14763140701491625
- Ruddy, J. D., Pollard, C. W., Timmins, R. G., Williams, M. D., Shield, A. J., & Opar, D. A. (2016). Running exposure is associated with the risk of hamstring strain injury in elite Australian footballers. *British Journal of Sports Medicine*, 52(14), 919–928. doi:10.1136/bjsports-2016-096777
- Samozino, P., Rabita, G., Dorel, S., Slawinski, J., Peyrot, N., de Villarreal, S., & Morin, J.-B. (2016). A simple method for measuring power, force, velocity properties, and mechanical effectiveness in sprint running. *Scandinavian Journal of Medicine & Science in Sports*, 26(6), 648–658. doi:10.1111/sms.12490
- Sandford, G. N., Kilding, A. E., Ross, A., & Laursen, P. B. (2019). Maximal sprint speed and the Anaerobic speed Reserve Domain: The untapped tools that differentiate the World's best Male 800 m runners. *Sports Medicine*, 49(6), 843–852. doi:10.1007/s40279-018-1010-5
- Sarmiento, H., Marcelino, R., Anguera, M. T., Campanico, J., Matos, N., & Leitao, J. C. (2014). Match analysis in football: A systematic review. *Journal of Sports Sciences*, 32(20), 1831–1843. doi:10.1080/02640414.2014.898852
- Thompson, A., Bezodis, I. N., & Jones, R. L. (2009). An in-depth assessment of expert sprint coaches' technical knowledge. *Journal of Sports Sciences*, 27(8), 855–861. doi:10.1080/02640410902895476
- Vigne, G., Gaudino, C., Rogowski, I., Alloatti, G., & Hautier, C. (2010). Activity profile in elite Italian soccer team. *International Journal of Sports Medicine*, 31(5), 304–310. doi:10.1055/s-0030-1248320



Influence of Fatigue on the Rapid Hamstring/Quadriceps Force Capacity in Soccer Players

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The objective of this study was to examine the effect of fatigue on maximal and rapid force capacities and muscular activation of the knee extensors and flexors. Seventeen professional soccer players volunteered to participate in this study. Peak torque (T_{peak}) and rate of torque development (RTD) of knee flexor ($90^\circ \cdot \text{s}^{-1}$, $-30^\circ \cdot \text{s}^{-1}$) and extensor ($90^\circ \cdot \text{s}^{-1}$) muscles were measured before and after fatigue (i.e., 30 maximal knee extension and flexion repetitions at $180^\circ \cdot \text{s}^{-1}$) performed on an isokinetic dynamometer. Hamstring to quadriceps peak strength and RTD ratios were calculated. Besides, using surface EMG, the mean level of activation (RMS_{mean}), Rate of EMG Rise (RER), and EMG Frequency-Time maps were measured on quadriceps and hamstring muscles. Following fatigue, T_{peak} , RTD, RER declined significantly in the two muscle groups (all $p < 0.05$) without modification of RMS_{mean} . No decrease in conventional and functional H/Q ratios was observed after fatigue except for a significant increase in the $H_{\text{ecc}30}/Q_{\text{con}180}$ ratios (1.03 ± 0.19 vs. 1.36 ± 0.33 , $p < 0.001$). Besides, the RTD H/Q ratios decreased significantly after fatigue, and the statistical parametric mapping analysis (SPM) performed on the EMG/angle curves, and EMG Frequency-Time maps showed that fatigue strongly influenced the muscle activation during the first 100 ms of the movement, following the higher EMG frequency component shift toward the lower frequency component. Our results show that the reduction of RTD and RER during the first 100 ms of the contraction after fatigue exercise makes more sense than any H/Q ratio modification in understanding injury risk in soccer players.

Keywords: peak torque, fatigue, rate of torque development, rate of EMG rise, H/Q ratio

INTRODUCTION

Hamstring strain injuries (HSIs) and anterior cruciate ligament (ACL) rupture are, respectively, the most prevalent non-contact injuries (Ekstrand et al., 2011a) and the most serious injuries considering time to return to play (Walden et al., 2016) in professional soccer players (Ekstrand et al., 2011b). During tasks such as sprinting, kicking or cutting, co-contraction of the hamstring and quadriceps muscles increases knee joint stability and prevents excessive knee joint constraints.

That is why any deficit in hamstring strength or activation pattern may limit the protective effect of co-contraction on ACL and hamstring muscles. Thus, HSIs and ACL ruptures are frequently associated with strength imbalance between knee flexor and extensor muscles (Croisier et al., 2008; Alhammoud et al., 2019; Baroni et al., 2020). For this reason, isokinetic dynamometry is currently used by most of the professional soccer teams to calculate conventional and functional H/Q ratios to predict the strength imbalance between knee flexor and extensor muscles. Nevertheless, the predictive value of H/Q torque ratios for ACL ruptures and HSIs remains poor, maybe because they do not mimic the physiological and biomechanical ecological constraints such as joint angular position, contraction time, or fatigue (Croce and Miller, 2006; Coratella et al., 2015; Evangelidis et al., 2015; De Ste Croix et al., 2017; Alhammoud et al., 2019).

Accordingly, it has been suggested that modeling H/Q ratios with angle-specific metrics through range of motion may provide a more specific tool for analyzing thigh muscle balance. A recent study demonstrated that statistical parametric mapping analyses identified angle-specific differences between female and male elite skiers that could not be evidenced when analyzing only maximal torques and reconstructed ratios (Alhammoud et al., 2019). Thus, knee angle and muscle length are essential factors that have to be taken into account when interpreting the H/Q ratios. Moreover, considering that fatigue increases the injury risk in soccer, the modifications of this dynamic H/Q ratio under fatigue are of great importance.

Recent studies have suggested that the rate of torque development (RTD) during the first milliseconds of the contraction represents another functional outcome related to performance and injury risk (Alhammoud et al., 2018; Ishoi et al., 2019). For example, the study by Ishoi et al. (2019) indicates that early phase (0–100 ms) rapid force capacity of the hamstring muscles strongly influenced the acceleration capacity of elite soccer players (Ishoi et al., 2019). Besides, RTD is considered to be very important in the ability to stabilize the musculoskeletal system in response to mechanical perturbation (Angelozi et al., 2012; Alhammoud et al., 2018). As there is no systematic link between the maximum force capacity and the relative RTD, screening for the risk of injury by measuring the traditional H/Q ratio can be difficult because of this inability to measure the capacity of rapid stabilization of the knee which may influence the risk of injury (i.e., HSIs, ACL injury). Furthermore, neuromuscular fatigue has been identified as a potential risk factor of HSIs (Croisier et al., 2008), considering that HSIs preferentially occur in the later stage of the match (Hawkins et al., 2001; Small et al., 2009). Fatigue can be defined as a reduction in the force-generating capacity of the neuromuscular system, regardless of the level of force required (Morel and Hautier, 2017). Match-related fatigue in professional soccer players induces a reduction of jump ability, sprint performance (Krustrup et al., 2006), peak torque in knee extension and flexion (Small et al., 2010; Marshall et al., 2014) and RTD (Marshall et al., 2014; Grazioli et al., 2019). As hamstring strength is strongly affected after a simulated and a real soccer match, it may contribute to the strength imbalance between hamstring and quadriceps (Cohen et al., 2013; Grazioli et al., 2019), and

may be considered as an injury risk factor (Lee et al., 2018). That way, Small et al. (2009) revealed a significant reduction in combined maximal hip flexion and knee extension angle resulting in shorter hamstring length during sprint running after soccer-specific fatigue, which potentially increase predisposition to hamstring strain (Small et al., 2009). It is also worth noting that a previous study reported a greater torque loss in hamstring compared to quadriceps muscles during 50 flexions-extensions at $180^\circ \cdot s^{-1}$ in concentric mode inducing H/Q ratio deterioration (Sangnier and Tourny-Chollet, 2007). In addition, RTD has been demonstrated to be highly sensitive to fatigue (Morel et al., 2015; Grazioli et al., 2019). For instance, Grazioli et al. (2019) reported that hamstring explosive force is more affected than maximal force after a professional soccer match (Grazioli et al., 2019). Thus, the RTD H/Q ratio has been demonstrated to be an interesting way to characterize muscle function around the knee (Zebis et al., 2011; Greco et al., 2013). For this reason, studying angle-specific H/Q ratio and RTD H/Q ratio modifications after fatigue in soccer players appears to be a promising way to better understand and prevent HSIs and ACL injury occurrence.

Hence, the purpose of this study was to assess the effect of fatigue on angle-specific H/Q ratio and RTD H/Q ratio in soccer players. Furthermore, the present study will analyze the changes in muscle activation between the hamstring (i.e., Semitendinosus and Biceps femoris) and quadriceps (i.e., Rectus femoris and Vastus lateralis and Vastus medialis) under fatigue. We hypothesized that (i) the angle-specific H/Q ratio would be altered in certain knee angles without modification of the traditional H/Q ratio (i.e., conventional and functional H/Q ratio) and (ii) diminution of RTD (i.e., knee extensor and flexor) and RTD H/Q ratio would be associated with muscular deficit activation during the initial phase of contraction (i.e., 50, 100 ms).

MATERIALS AND METHODS

Participants

Seventeen French semi-professional soccer players (Height: 173.5 ± 4.1 cm, Mass: 73.3 ± 6.3 kg, Age: 23.9 ± 2.2 years, training volume: 12 ± 2.2 h \cdot wk^{-1}) playing at a national level volunteered to participate in this study. Included subjects had no history of traumatic lower limb injuries (e.g., ACL rupture, hamstring injuries) for at least 1 year before the study. The cumulated training and match time per season attained 330 h (85% training and 15% competing). Leading up to the experiments, participants followed their regular training program avoiding any strenuous and high charge or match 48 h before the study. The sample size ($n = 17$) was estimated on the basis of the results of Sangnier and Tourny-Chollet (2008), accepting a confidence rate of 95% and a margin of error of 5% with a statistical power of 0.90, and looking for a medium effect size of 0.5 (Sangnier and Tourny-Chollet, 2008).

Experimental Design

A randomized repeated measurement pre-/post-fatigue study design was used for this research (Figure 1). Isokinetic measures were performed on the dominant lower limb, which was



FIGURE 1 | An example of participant experimenting.

determined by the preferred leg in kicking. The participants performed a general warm-up composed of 10 min cycling ($1 \text{ watt}\cdot\text{kg}^{-1}$, 70–80 RPM) and mobility movements. After that, sEMG electrodes (Delsys Trigno™ Wireless EMG System, bipolar Ag: AgCl surface, 2 cm inter-electrode distance) (Delsys, Inc., Boston, United States) were fixed on the rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), biceps femoris long-head (BF), and semitendinosus (ST) muscles following the SENIAM guidelines. The skin was shaved and cleaned using an alcohol wipe before affixing the sEMG electrode. The sampling rate was 2000 Hz, and the standard mode of rejection ratio was greater than 80 dB.

Once the participants were equipped with the EMG electrodes, they were afterward seated on the Contrex isokinetic dynamometer (Contrex, CMV AG, Dübendorf, Switzerland) with flexed hips at 80° (0° = full hip extension), and standard stabilization strapping was placed across the chest, pelvis, and distal thigh. The sampling frequency was 256 Hz. The axis of the dynamometer was visually aligned with the lateral femoral condyle. The range of movement was set from 100° of knee flexion (starting position) to 20° (0° was determined as the anatomical maximal voluntary knee extension for each participant). The subjects were required to grasp the handles of the dynamometer chair (Figure 1).

Experimental Sessions

Before the isokinetic testing, all participants were asked to perform a familiarization session. During this session, the participants were asked to complete eight continuous reciprocal knee extensions and flexions between 50 and 60% of their maximal at two velocities $90^\circ\cdot\text{s}^{-1}$, and $180^\circ\cdot\text{s}^{-1}$ followed by eight hamstring eccentric contractions at $-30^\circ\cdot\text{s}^{-1}$. This allowed the participants to adapt to the isokinetic contractions and determined the quality of the sEMG signal. Before assessments, the gravity compensation procedure was performed according to the manufacturer's instructions. After ~ 3 min of passive recovery (Parcell et al., 2002), the participants performed the pre-fatigue tests, including five maximal knee extensors and flexors concentric contractions at $90^\circ\cdot\text{s}^{-1}$ and five maximal knee flexors eccentric contractions at $-30^\circ\cdot\text{s}^{-1}$. Two minutes of recovery were included between concentric and eccentric sets. After 2 min of passive recovery, subjects performed three maximal knee extensors and flexors concentric contractions at $180^\circ\cdot\text{s}^{-1}$ immediately followed by the fatiguing exercise composed of 24 contractions at the same velocity. Immediately after the fatigue session, subjects repeated the pre-fatigue tests but with no rest between the contractions. During the entire protocol, the participants were verbally encouraged to give their maximal effort by the same manipulator.

Measurements and Data Analysis

Raw torque-angle curves were extracted from the original instantaneous torque dataset using custom routines to resynchronize the signal per degree of knee angle. Raw data were processed in MATLAB (MathWorks, version 2018b, Natick, MA, United States), a 2nd low-pass 20 Hz was used to filter. Furthermore, a 1D polynomial spline fitting method was used to interpolate torque and angle values for each contraction to guarantee the same data length. The three best trials were extracted for pre- and post-fatigue tests, and the first and last concentric contractions of the fatigue protocol were taken into account. The threshold of torque was fixed at 1% of local peak torque for determining the onset:offset of muscle contraction.

Non-angle Specific Peak Torque (T_{peak}) and H/Q Ratios

Peak torque (T_{peak}) at $90^\circ\cdot\text{s}^{-1}$, $180^\circ\cdot\text{s}^{-1}$ and $-30^\circ\cdot\text{s}^{-1}$ were calculated as the average value of three contractions (the best ones of the five contractions for $90^\circ\cdot\text{sec}^{-1}$ and $-30^\circ\cdot\text{sec}^{-1}$) performed before and after the fatigue protocol both for knee extensors (KE), and knee flexors (KF). Conventional non-angle specific H/Q ratios were calculated by dividing knee flexion concentric peak torque by knee extension concentric peak torque at $90^\circ\cdot\text{s}^{-1}$ ($H/Q_{\text{con}90}$) and $180^\circ\cdot\text{s}^{-1}$ ($H/Q_{\text{con}180}$). A functional non-angle specific H/Q ratio was calculated by dividing knee flexion eccentric Peak torque at $-30^\circ\cdot\text{s}^{-1}$ by knee extension concentric peak torque at $90^\circ\cdot\text{s}^{-1}$ ($H/Q_{\text{func}90}$) and $180^\circ\cdot\text{s}^{-1}$ ($H/Q_{\text{func}180}$).

Angle-Specific Peak Torque and Angle-Specific H/Q Ratios

All angle-specific measures were represented only between 30 and 90° to account for the acceleration and deceleration phases and keep within the iso-velocity period (Alhammoud et al., 2019). Based on these torque-angle curves, angle-specific conventional and functional H/Q dynamic ratios were continuously calculated by dividing hamstring torque by quadriceps torque at the same knee angle across the analyzed range of motion. Two conventional angle-specific dynamic ratios (H/Q_{conv90° at $90^\circ.s^{-1}$ and $H/Q_{conv180^\circ}$ at $180^\circ.s^{-1}$) and two functional angle-specific dynamic ratios were calculated for knee extension (hamstring torque at $-30^\circ.s^{-1}$ divided by quadriceps torque at $90^\circ.s^{-1}$; H/Q_{func90° and hamstring torque at $-30^\circ.s^{-1}$ divided by quadriceps torque at $180^\circ.s^{-1}$; $H/Q_{func180^\circ}$). A 1D polynomial spline fitting method was used to interpolate torque and angle values for all the curve between 30 and 90° to normalize the torque: angle curves on the same number of points.

Rate of Torque Development and RTD H/Q Ratios

The absolute RTD ($Nm.s^{-1}$) was calculated from linear slope of the torque-time curve (i.e., $\Delta\text{torque}/\Delta\text{time}$) (Aagaard et al., 2002) at the 0–50 ms and 0–100 ms time interval during dynamic isokinetic concentric contractions at $90^\circ.s^{-1}$, $180^\circ.s^{-1}$ for the knee extensor and flexor muscles and during isokinetic eccentric contractions at $-30^\circ.s^{-1}$ for the knee flexors (Alhammoud et al., 2018). Besides, the RTD H/Q ratios were calculated by dividing the RTD of knee flexor by the RTD of knee extensor corresponding time intervals both for the 50 ms (RTD_{50 ms} H/Q Ratio) and 100 ms (RTD_{100 ms} H/Q Ratio).

EMG Variables

The EMG Signal Processing of five muscles (e.g., BF, ST, RF, VL, VM) was performed using MATLAB software (R2018b, The MathWorks Inc., Natick, MA, United States). The root mean square values (RMS) were calculated with a 150-ms moving rectangular window based on the rectified EMG to determine the signal amplitude. The onset and offset of the EMG bursts were determined using a threshold of 5% of the muscle peak maximal activation found within the analysis period. RMS EMG signals were normalized to the peak RMS value measured for each muscle during the pre-fatigue maximal contraction at $90^\circ.s^{-1}$. A mean RMS value (RMS_{mean}) was then calculated between onset and offset for the five muscles during pre-and post-fatigue tests. The calculation of the rate of EMG rise (RER) was realized on a smoothed RMS curve (6 Hz low-pass fourth-order Butterworth filter) and calculated by the slope of the RMS-Time envelope for 0–50 ms and 0–100 ms time intervals relative to the activation onset for the five muscles during pre-and post-fatigue tests (Morel et al., 2015).

A continuous wavelet transform (CWT) was made on raw EMG signals to investigate time-frequency domain for each muscle before and after fatigue, using a Morse mother wavelet with $\gamma = 3$ and $P^2 = 60$ (Lilly and Olhede, 2009). The frequencies ranging from 20 to 500 Hz were analyzed. The pseudo frequency of each scale was obtained using the center of the frequency of each wavelet, and as the frequencies were logarithmically spaced, the maps were linearly interpolated by 4 Hz in the frequency domain. The time was normalized for all the maps corresponded to 200-time points. Thus, the number of nodes of the maps corresponded to 200 [time] \times 94 [frequency] = 18800 nodes. The modulus of the coefficient given by the wavelet transform was computed for each node. The frequency that split the spectrum in half was defined as the median frequency.

TABLE 1 | Effect of fatigue on peak torque (T_{peak}) in Nm, rate of torque development (RTD) in $Nm.s^{-1}$.

Velocity [$^\circ.s^{-1}$]	Muscle	Variable	Pre-fatigue	Post-fatigue	Mean Difference [95% CI]	Change [%]
180	Knee Extensor	T_{peak}	153.7 \pm 29.6	92.1 \pm 11.2	-61.6 [47.1 – 76.2]	-40.1%***
		RTD _{50 ms}	847.6 \pm 348.4	420.7 \pm 176.1	-427.8 [221.4 – 632.3]	-50.5%***
		RTD _{100 ms}	1002.8 \pm 341.0	509.8 \pm 173.2	-493.0 [284.3 – 701.5]	-49.2%***
	Knee Flexor	T_{peak}	112.8 \pm 30.2	69.1 \pm 16.5	-43.7 [27.1 – 60.3]	-38.7%***
		RTD _{50 ms}	744.1 \pm 316.7	387.1 \pm 142.1	-357.0 [151.6 – 562.4]	-47.9%**
		RTD _{100 ms}	799.2 \pm 294.4	465.2 \pm 191.1	-334.1 [125.4 – 542.7]	-41.8%**
90	Knee Extensor	T_{peak}	201.1 \pm 36.7	150.6 \pm 25.7	-50.5 [31.9 – 69.1]	-25.1%***
		RTD _{50 ms}	1131.1 \pm 457.8	734.4 \pm 419.4	-396.6 [191.2 – 602.0]	-35.1%***
		RTD _{100 ms}	1174.4 \pm 365.8	795.1 \pm 386.2	-379.4 [170.7 – 587.9]	-32.3%***
	Knee Flexor	T_{peak}	126.8 \pm 24.7	92.3 \pm 22.9	-34.5 [16.5 – 52.5]	-27.2%**
		RTD _{50 ms}	791.1 \pm 318.7	554.7 \pm 325.9	-236.5 [31.1 – 441.8]	-29.9%**
		RTD _{100 ms}	924.7 \pm 339.8	738.3 \pm 337.2	-186.4 [-22.3 – 395.0]	-20.2%*
-30	Knee Flexor	T_{peak}	156.4 \pm 33.2	140.7 \pm 37.2	-15.8 [5.4 – 26.2]	-10.1%**
		RTD _{50 ms}	895.3 \pm 186.9	675.9 \pm 135.8	-219.4 [13.9 – 424.7]	-24.5%**
		RTD _{100 ms}	953.3 \pm 224.5	749.2 \pm 136.9	-204.1 [-4.5 – 412.7]	-21.4%**

*Significantly different from fatigue for $p < 0.05$.

**Significantly different from fatigue for $p < 0.01$.

***Significantly different from fatigue for $p < 0.001$.

All data are presented as mean \pm SD.

Statistical Analysis

Before performing the statistical analysis, the Shapiro–Wilk test and Levene’s test were respectively used to assess the normality of data and the equality of variance for isokinetic data and EMG data. Thereafter, a two-way (Angular velocity*Muscle) repeated measures (Pre- and Post-fatigue test) analysis of variance ANOVA was used on T_{peak} , $RTD_{100\ ms}$, RMS_{mean} , $RER_{100\ ms}$. Holm’s Bonferroni *post hoc* test with correction of the p -value was used for multiple comparisons to determine the interaction effect between the test (Pre-fatigue vs. Post-fatigue condition), muscle (knee flexor vs. extensor for isokinetic variable and five-goal muscle (e.g., BF, ST, RF, VL, and VM) for EMG data and angular

velocity ($90^\circ.s^{-1}$, $180^\circ.s^{-1}$). Besides, Student’s paired t -test was applied to analyze the different H/Q ratios and eccentric peak torque ($-30^\circ.s^{-1}$) before and after fatigue. Statistical significance was set at $p < 0.05$. All statistical procedures were performed with IBM SPSS 26 (IBM Corporation, Armonk, NY, United States). All the data are presented as mean \pm SD, with a 95% confidence interval (95% CI).

Using SPM-1D package (©Todd Pataky, version M 0.1) in MATLAB (The MathWorks Inc, R2018b, Natick, MA, United States) was conducted to performs Statistical Parametric (Pataky, 2010). One dimensional paired t -test SPM statistics were performed to determine the main effects of fatigue on

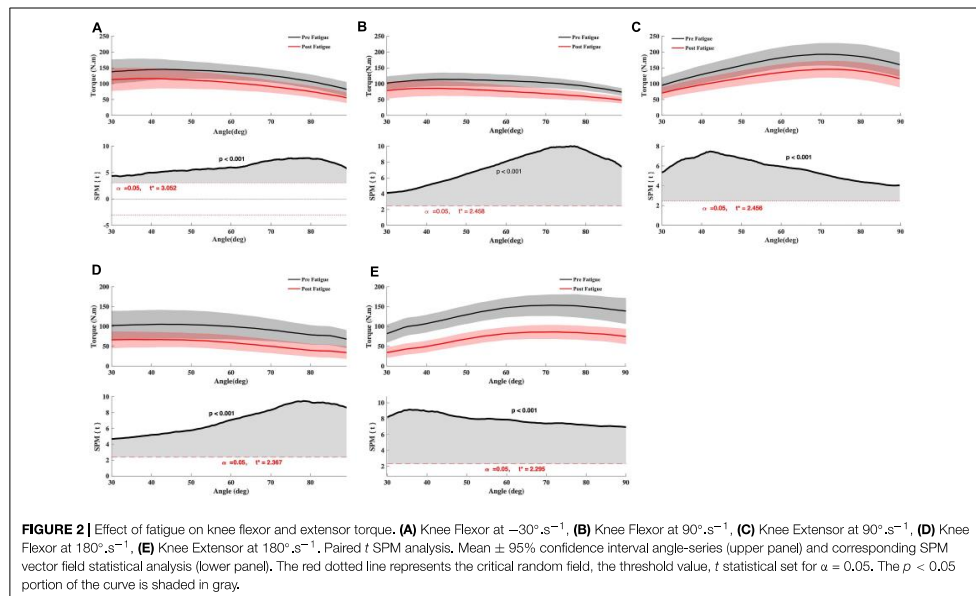


FIGURE 2 | Effect of fatigue on knee flexor and extensor torque. **(A)** Knee Flexor at $-30^\circ.s^{-1}$, **(B)** Knee Flexor at $90^\circ.s^{-1}$, **(C)** Knee Extensor at $90^\circ.s^{-1}$, **(D)** Knee Flexor at $180^\circ.s^{-1}$, **(E)** Knee Extensor at $180^\circ.s^{-1}$. Paired t SPM analysis, Mean \pm 95% confidence interval angle-series (upper panel) and corresponding SPM vector field statistical analysis (lower panel). The red dotted line represents the critical random field, the threshold value, t statistical set for $\alpha = 0.05$. The $p < 0.05$ portion of the curve is shaded in gray.

TABLE 2 | Effect of fatigue on conventional and functional H/Q ratios and RTD H/Q ratio.

	Velocity	Pre-fatigue	Post-fatigue	Mean Difference [95% CI]	Change
Conventional H/Q Ratio	H_{con90}/Q_{con90}	0.83 ± 0.09	0.61 ± 0.11	$-0.02 [-0.05 - 0.10]$	-3.1%
	H_{con180}/Q_{con180}	0.73 ± 0.13	0.75 ± 0.15	$0.01 [-0.10 - 0.07]$	+2.1%
Functional H/Q Ratio	H_{ecc30}/Q_{con90}	0.78 ± 0.14	0.82 ± 0.14	$0.04 [0.04 - 0.12]$	+5.2%
	H_{ecc30}/Q_{con180}	1.03 ± 0.19	1.36 ± 0.33	$0.33 [0.19 - 0.47]$	+32.0%***
RTD _{50 ms} H/Q Ratio	$90^\circ.s^{-1}$	1.10 ± 0.44	0.71 ± 0.26	$-0.39 [-0.53 - -0.25]$	-35.5%**
	$180^\circ.s^{-1}$	1.07 ± 0.59	0.96 ± 0.44	$-0.11 [0.15 - 0.38]$	-10.3%
RTD _{100 ms} H/Q Ratio	$90^\circ.s^{-1}$	0.91 ± 0.18	0.85 ± 0.29	$-0.06 [-0.08 - 0.22]$	-6.6%
	$180^\circ.s^{-1}$	0.96 ± 0.35	0.82 ± 0.31	$-0.14 [0.19 - 0.47]$	-14.5%*

*Significantly different from fatigue for $p < 0.05$.
 **Significantly different from fatigue for $p < 0.01$.
 ***Significantly different from fatigue for $p < 0.001$.
 All data are presented as mean \pm SD.

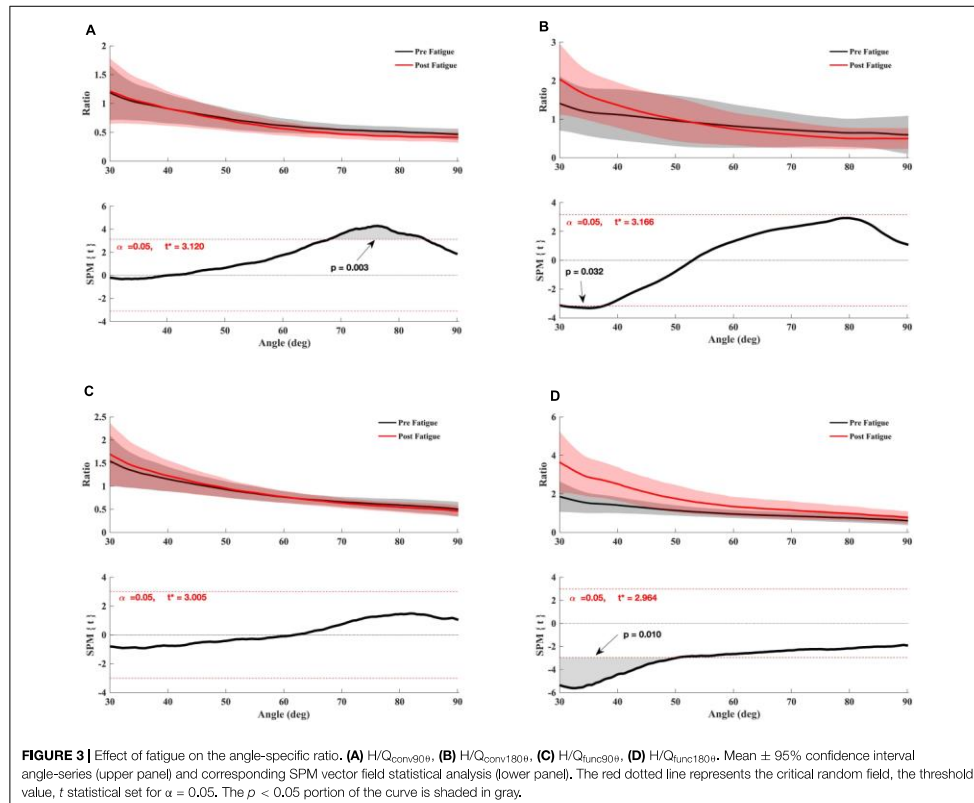
the angle-specific torque, angle-specific H/Q ratio, smoothed RMS curve, and a p -value was calculated for clusters crossing the critical threshold, with significance set at $p < 0.05$ (Pataky et al., 2013). Besides, SPM analysis was conducted in two dimensions on the EMG Frequency-Time maps obtained from the wavelet transform. The mean maps of each subject's three contractions were considered for the analysis. As a 1D continuum is required to perform the SPM analysis, the maps were flattened into a 1D continuum for the analysis and then reshaped to their original dimensions for interpretation. For concentric contractions, maps were analyzed with a two-way ANOVA with two repeated measures (Fatigue: Pre vs. Post; Velocity: $90^\circ.s^{-1}$ vs. $180^\circ.s^{-1}$) and *post hoc* tests as paired t -tests with Bonferroni correction. An alpha error of 0.01 (0.05/5) was set as five muscles were analyzed. For eccentric contractions, paired t -tests were performed to compare maps (Pre vs. Post) with an alpha error at 0.025 as two muscles were considered. To define the threshold of the statistical tests

performed, permutation tests were used with 10000 permutations (Nichols and Holmes, 2002).

RESULTS

Peak Torque (T_{peak}) and H/Q Ratios

The knee extension T_{peak} reduced significantly after fatigue at $90^\circ.s^{-1}$ and $180^\circ.s^{-1}$ (all $p < 0.05$) (Table 1). The knee flexion T_{peak} reduced significantly after fatigue at $90^\circ.s^{-1}$, $180^\circ.s^{-1}$, and $-30^\circ.s^{-1}$ (all $P < 0.05$) (Table 1). In addition, there was a significant interaction effect for different velocity (all $p < 0.05$). Holm's Bonferroni *post hoc* tests indicated that the reduction of force was higher at an angular velocity of $180^\circ.s^{-1}$ than $90^\circ.s^{-1}$ (all $p < 0.01$). Besides, the t -test SPM analysis on torque-angle curves indicated a significant decrease in torque for knee extensor and flexor irrespective of knee angle (Figure 2). Moreover, the conventional ratios at $90^\circ.s^{-1}$ and $180^\circ.s^{-1}$ and the functional



H_{ecc30}/Q_{con90} ratio were not affected by the fatigue protocol ($p > 0.05$) (Table 2). In contrast, the functional H_{ecc30}/Q_{con180} ratio increased after fatigue ($p < 0.001$) (Table 2).

Also, the paired *t*-test SPM analysis showed a significant increase in the conventional H_{con180}/Q_{con180} ratio between 30° and 32° knee angle ($p = 0.032$) (Figure 3) and the functional H_{ecc30}/Q_{con180} ratio between 30° and 48° of knee angle range of motion ($p = 0.01$) (Figure 3) after fatigue. The conventional ratio H_{con90}/Q_{con90} decreased significantly after fatigue for the knee angle range of motion between 68° and 88° degrees

($p = 0.003$) (Figure 3). Nevertheless, no significant effect of fatigue was indicated for dynamic functional ratio H_{ecc30}/Q_{con90} ($p > 0.05$) (Figure 3).

Rate of Torque Development and RTD H/Q Ratios

Absolute RTD_{50 ms} and RTD_{100 ms} reduced significantly after fatigue for both knee extensors and knee flexor at 90°.s⁻¹, 180°.s⁻¹, and -30°.s⁻¹ (all $p < 0.05$) (Table 1). Meanwhile,

TABLE 3 | Effect of fatigue on mean RMS EMG (RMS_{mean}) in % of maximal EMG signal, EMG rise (RER) in %·s⁻¹ for hamstring (BF, biceps femoris; ST, semitendinosus) and quadriceps (RF, rectus femoris; VL, vastus lateralis; VM, vastus medialis) at 180°.s⁻¹.

Velocity [°. s ⁻¹]	Muscle	EMG	Pre-fatigue	Post-fatigue	Mean Difference [95% CI]	Change [%]
180	BF	RER _{50 ms}	334.7 ± 128.8	240.3 ± 93.1	-94.3 [27.8 – 161.0]	-28.2%**
		RER _{100 ms}	311.0 ± 118.8	220.2 ± 72.9	-81.8 [20.1 – 143.4]	-26.4%**
		RMS _{mean}	53.1 ± 11.7	59.7 ± 15.1	6.6 [4.1 – 17.1]	12.4%
	ST	RER _{50 ms}	415.0 ± 189.1	277.1 ± 136.3	-137.9 [46.0 – 229.7]	-33.2%***
		RER _{100 ms}	344.3 ± 120.9	247.1 ± 88.6	-97.1 [32.6 – 161.7]	-28.2%***
		RMS _{mean}	56.6 ± 9.5	60.7 ± 10.6	4.1 [-1.7 – 6.5]	7.2%
	RF	RER _{50 ms}	392.7 ± 220.3	254.2 ± 168.7	-138.5 [55.9 – 221.1]	-35.3%*
		RER _{100 ms}	333.3 ± 137.4	273.9 ± 130.3	-59.4 [-3.7 – 122.6]	-17.8%*
		RMS _{mean}	62.7 ± 4.6	63.7 ± 11.7	0.9 [-10.0 – 8.2]	1.4%
	VL	RER _{50 ms}	493.3 ± 252.1	327.5 ± 145.3	-165.9 [30.5 – 301.2]	-33.7%*
		RER _{100 ms}	393.3 ± 141.9	308.6 ± 86.6	-84.8 [1.4 – 168.1]	-21.6%*
		RMS _{mean}	73.9 ± 6.6	68.2 ± 8.9	-5.7 [0.8 – 10.5]	-7.7%
VM	RER _{50 ms}	383.9 ± 214.3	288.7 ± 175.2	-95.1 [-3.0 – 193.1]	-24.8%*	
	RER _{100 ms}	321.3 ± 147.5	263.1 ± 145.8	-58.2 [20.3 – 193.1]	-18.1%*	
	RMS _{mean}	55.1 ± 9.2	51.6 ± 9.7	3.4 [-1.6 – 8.5]	-6.2%	

*Significantly different from fatigue for $p < 0.05$.
 **Significantly different from fatigue for $p < 0.01$.
 ***Significantly different from fatigue for $p < 0.001$.
 All data are presented as mean ± SD.

TABLE 4 | Effect of fatigue on mean RMS EMG (RMS_{mean}) in %, of maximal EMG signal EMG rise (RER) in %·s⁻¹ for hamstring (BF, biceps femoris; ST, semitendinosus) and quadriceps (RF, rectus femoris; VL, vastus lateralis; VM, vastus medialis) at 90°.s⁻¹.

Velocity [°. s ⁻¹]	Muscle	EMG	Pre-fatigue	Post-fatigue	Mean Difference [95% CI]	Change [%]
90	BF	RER _{50 ms}	520.5 ± 181.4	344.9 ± 217.1	-175.6 [37.7 – 313.6]	-33.7%*
		RER _{100 ms}	447.8 ± 158.3	333.3 ± 166.8	-114.5 [3.9 – 225.1]	-25.6%*
		RMS _{mean}	66.1 ± 7.5	62.9 ± 8.3	-3.1 [-4.4 – 10.6]	-4.7%
	ST	RER _{50 ms}	545.1 ± 236.5	384.7 ± 196.8	-160.4 [53.7 – 267.1]	-29.4%*
		RER _{100 ms}	428.2 ± 148.2	343.1 ± 107.5	-85.1 [3.8 – 166.]	-19.9%*
		RMS _{mean}	60.7 ± 8.1	64.6 ± 11.2	-3.8 [-7.1 – 17.9]	6.3%
	RF	RER _{50 ms}	548.7 ± 310.2	344.9 ± 269.4	-203.7 [54.7 – 352.1]	-37.1%*
		RER _{100 ms}	436.7 ± 192.1	334.5 ± 190.3	-102.1 [24.0 – 180.5]	-23.4%*
		RMS _{mean}	68.3 ± 6.9	62.7 ± 14.0	-5.6 [2.8 – 13.9]	-8.2%
	VL	RER _{50 ms}	533.4 ± 204.7	343.9 ± 188.9	-189.4 [55.5 – 323.4]	-35.5%***
		RER _{100 ms}	442.1 ± 140.1	347.6 ± 140.5	-94.5 [26.6 – 162.3]	-21.4%*
		RMS _{mean}	70.5 ± 6.9	71.7 ± 8.1	-1.1 [-5.3 – 3.1]	-1.6%
VM	RER _{50 ms}	538.7 ± 226.7	371.7 ± 154.9	-167.0 [59.4 – 274.4]	-31.0%**	
	RER _{100 ms}	427.8 ± 138.6	336.4 ± 140.4	-91.4 [17.6 – 165.1]	-21.4%*	
	RMS _{mean}	68.5 ± 7.2	72.3 ± 6.4	-3.8 [-8.9 – 1.3]	-5.5%	

*Significantly different from fatigue for $p < 0.05$.
 **Significantly different from fatigue for $p < 0.01$.
 ***Significantly different from fatigue for $p < 0.001$.
 All data are presented as mean ± SD.

TABLE 5 | Effect of fatigue on mean RMS EMG (RMS_{mean}) in % of maximal EMG signal, EMG rise (RER) in %, s^{-1} for hamstring (BF, biceps femoris; ST, semitendinosus) and quadriceps (RF, rectus femoris; VL, vastus lateralis; VM, vastus medialis) at $-30^{\circ}.s^{-1}$.

Velocity [$^{\circ}.s^{-1}$]	Muscle	EMG	Pre-fatigue	Post-fatigue	Mean Difference [95% CI]	Change [%]
-30	BF	RER _{50 ms}	328.7 ± 148.9	257.9 ± 146.9	-70.7 [-45.3 – 186.9]	-21.5%*
		RER _{100 ms}	389.1 ± 190.6	265.5 ± 148.1	-123.6 [10.4 – 239.9]	-31.8%*
		RMS _{mean}	54.6 ± 9.9	49.1 ± 10.7	-5.5 [0.5 – 10.4]	-10.1%
	ST	RER _{50 ms}	371.1 ± 235.6	299.9 ± 184.4	-71.1 [-20.3 – 161.5]	-19.2%*
		RER _{100 ms}	370.8 ± 239.8	265.4 ± 148.1	-97.8 [-7.8 – 203.4]	-26.4%**
		RMS _{mean}	49.8 ± 11.1	48.4 ± 10.2	-1.3 [-7.5 – 10.2]	-2.6%

*Significantly different from fatigue for $p < 0.05$.

**Significantly different from fatigue for $p < 0.01$.

***Significantly different from fatigue for $p < 0.001$.

All data are presented as mean ± SD.

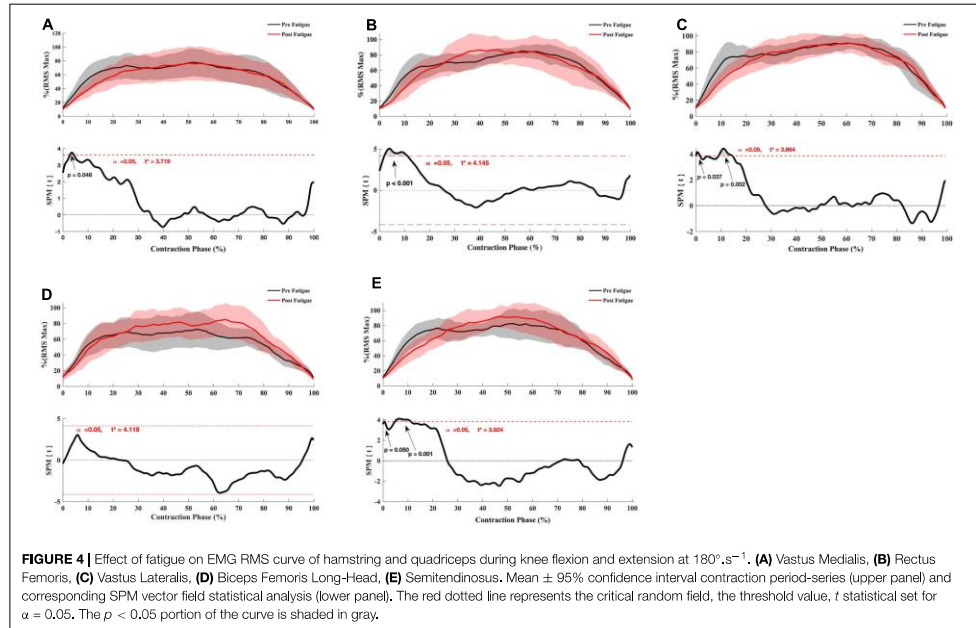
Holm's Bonferroni *post hoc* tests indicated that the reduction in RTD was higher at an angular velocity of $180^{\circ}.s^{-1}$ (all $p < 0.01$). RTD_{50 ms} H/Q ratio at $90^{\circ}.s^{-1}$ and RTD_{50 ms} at $180^{\circ}.s^{-1}$ reduced following the fatigue protocol (all $p < 0.05$) (Table 2). In contrast, RTD_{100 ms} H/Q ratio at $90^{\circ}.s^{-1}$ and RTD_{50 ms} at $180^{\circ}.s^{-1}$ were not changed after the fatigue protocol ($p > 0.05$) (Table 2).

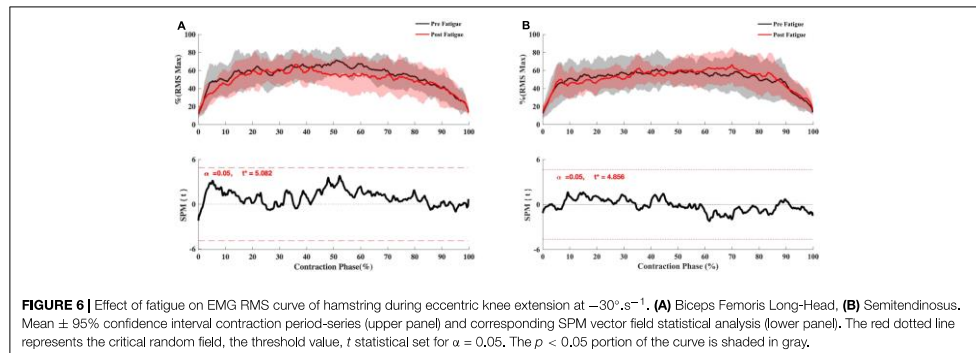
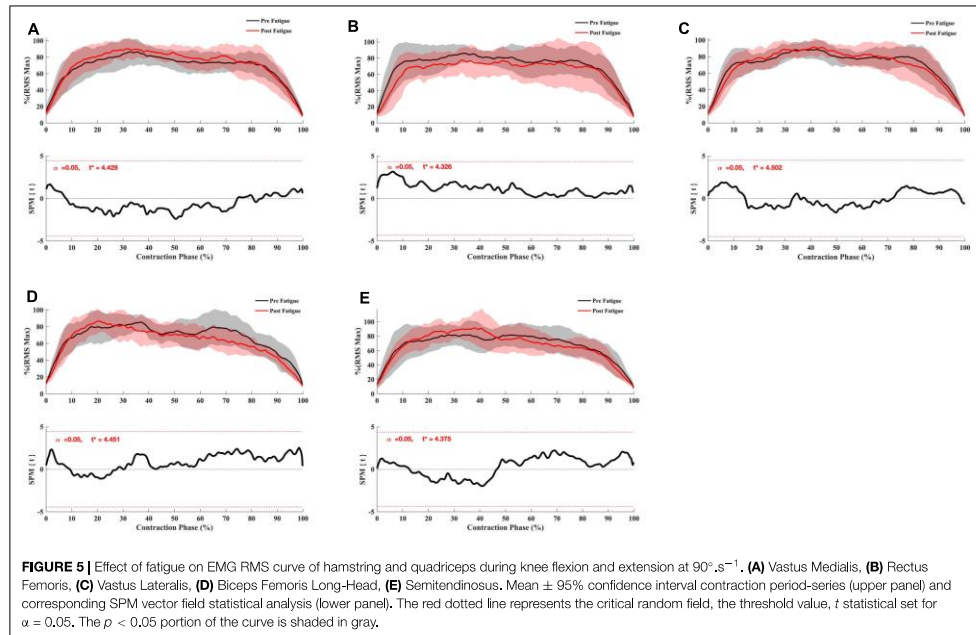
Muscular Activity

The level of activation (RMS_{mean}) during maximal contractions was not changed after the fatigue protocol, whatever the muscle and irrespective of the knee's angular velocity (all $p > 0.05$) (Tables 3–5). In contrast, The RER_{50 ms}, RER_{100 ms} were

significantly reduced after the fatigue protocol for all the muscles (e.g., biceps femoris [BF], semitendinosus [ST], rectus femoris [RF], vastus medial [VM], vastus lateralis [VL]) (all $p < 0.05$, irrespective of angular velocity (i.e., $180^{\circ}.s^{-1}$, $90^{\circ}.s^{-1}$, $-30^{\circ}.s^{-1}$) (Tables 3–5).

The SPM *t*-test results showed the muscular activation to be slightly slower at $180^{\circ}.s^{-1}$ in the early phase of contraction for VM ($p = 0.048$), RF ($p < 0.001$), vastus lateralis ($p = 0.037$, $p = 0.002$), ST ($p = 0.05$, $p = 0.001$) but not for biceps femoris ($p > 0.05$) (Figure 4), whereas no significant effect of fatigue on the RMS curve was observed at $90^{\circ}.s^{-1}$ (Figure 5) and $-30^{\circ}.s^{-1}$ (all $p > 0.05$) (Figure 6).



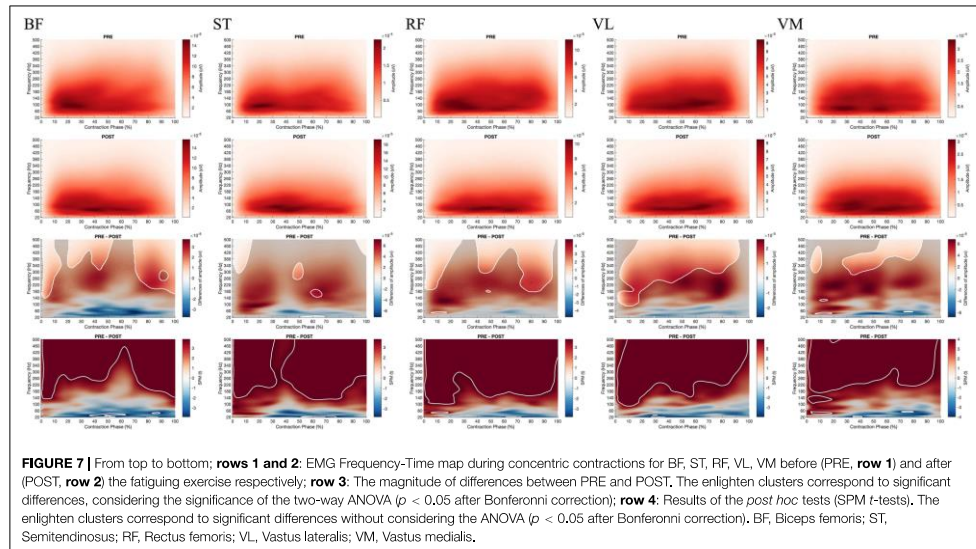


Besides, the SPM ANOVA analysis on the EMG Frequency-Time maps indicated significant effect of fatigue (Pre vs. Post) (Figure 7) for all the muscles, whereas no effect of velocity ($90^{\circ}\cdot s^{-1}$ vs. $180^{\circ}\cdot s^{-1}$) (Supplementary Figures 1–6). Similarly for all the muscles during concentric contractions, fatigue decreased the amplitude in high frequencies of EMG signals (above 100 Hz), while increasing the low frequencies amplitude (under 50 Hz) after 20% of contraction time. At the start of the contraction (0–20%), both high and low frequencies were decreased. Also, the SPM t -test revealed a significant fatigue effect

on BF during the eccentric contraction ($-30^{\circ}\cdot s^{-1}$), reducing the higher frequency component after fatigue (Figure 8), while no significant effect of fatigue was denoted for ST.

DISCUSSION

The goal of the present study was to analyze the H/Q ratio taking into account timing and angle specificity during a fresh and fatigued state. The major finding of this study demonstrated an



equivalent decrease in force-generating capacity of knee flexors and extensors after fatigue. Moreover, fatigue modified angle-specific H/Q ratios and lowered the RTD and the EMG rise.

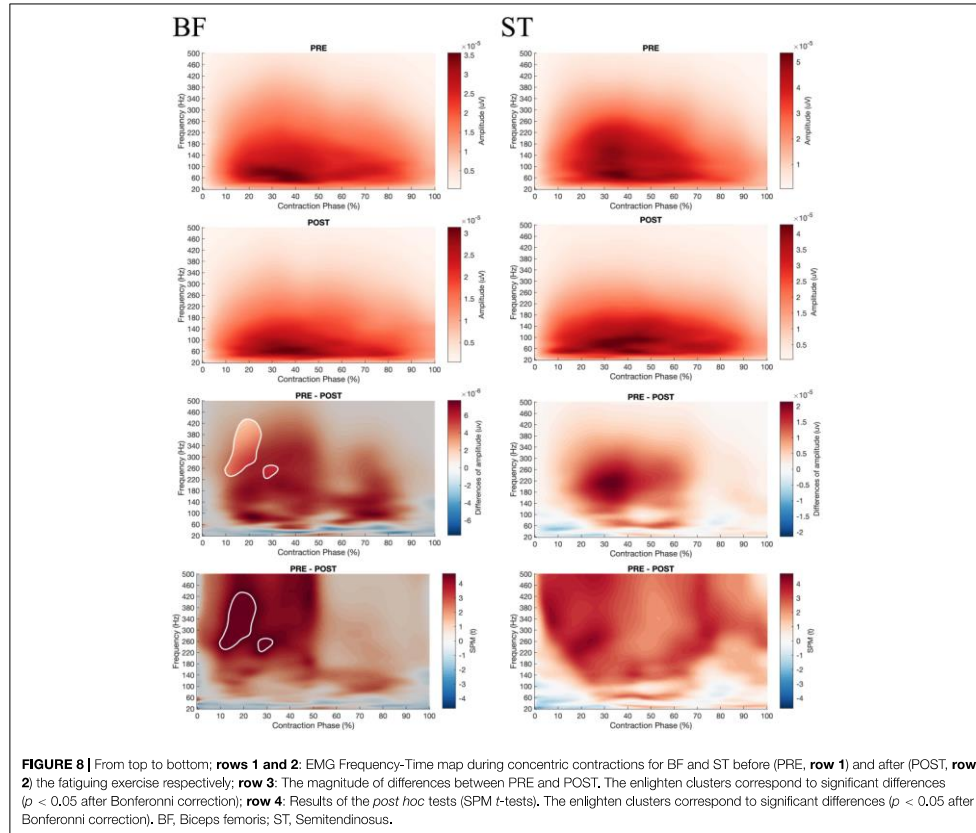
Influence of Fatigue on Torque Production and H/Q Ratios

Overall, the present results indicated that there was an equivalent and marked reduction of the peak torque of knee flexor and extensor muscles at each velocity of contraction. This is not in line with previous studies, since Sangnier and Tourny reported a greater torque loss in hamstring ($70 \pm 8.05\%$) compared to quadriceps ($60 \pm 9.50\%$) muscles after 25 maximal knee flexions/extensions at $180^\circ \cdot s^{-1}$ (Sangnier and Tourny-Chollet, 2007). However, Kawabata et al. (2000) found that the strength decreased index (SDI) was more substantial for the quadriceps than for hamstring muscles in soccer players (Kawabata et al., 2000). Since one study reported a high proportion of fast-twitch fibers in the hamstring muscles in soccer players (Garrett et al., 1984), a higher fatigability of knee flexors was expected. However, the recent study by Evangelidis et al. (2017) reported a balanced myosin heavy chain composition of the biceps femoris long head (BF_{lh}) comparable to the vastus muscle (Evangelidis et al., 2017). Nevertheless, the analysis of conventional and functional H/Q ratios demonstrated that fatigue did not negatively impact muscle balance. Surprisingly, the functional H_{ecc30}/Q_{con180} ratio was even improved after fatigue. This could be explained by the fact that the fatigue session induced a deeper strength loss during the isokinetic contractions performed at $180^\circ \cdot s^{-1}$ compared to other velocities. Whatever the origin of these modifications, it seems that the increased injury risk of HSIs after fatigue or

at the end of matches may not be explained by an impaired functional and conventional H/Q ratio. However, it has been demonstrated that the impact of fatigue on H/Q ratios can be advantageously reinforced using SPM analysis on torque-angle curves (Alhammoud et al., 2019). Surprisingly, the SPM analysis showed that H/Q ratios were improved after fatigue at low knee angles in a relatively extended knee position. In conclusion, SPM analysis demonstrated that angle-specific H/Q ratio modifications after fatigue could not explain the increased occurrence of the HSIs and ACL injury at the end of an exercise.

Influence of Fatigue on Rapid Torque Production

Another factor that is known to be sensitive to fatigue and related to injury risk is the ability to produce force rapidly, which can be explored through RTD (Grazioli et al., 2019). It is interesting to observe that peak torque reduction was stronger at $180^\circ \cdot sec^{-1}$ compared to other isokinetic velocities. This point may be explained by the slowing of cross-bridge cycling rate after fatigue (De Ruiter and De Haan, 2001) and by the higher fatigability of fast-twitch fibers (Hautier et al., 1996). Similarly, an increased decline in explosive capacity RTD in the early phase of maximal contraction was observed after fatigue. This reduction in explosive capacity seems to be more marked than the peak torque decrease in line with Morel et al. (2015). This can be explained by alterations of neural and contractile factors (Andersen and Aagaard, 2006; Maffiuletti et al., 2016; Rodriguez-Rosell et al., 2018). Additionally, a significant reduction in the $RTD_{50\ ms} H/Q$



ratios was observed after fatigue, indicating that the ability to strengthen and stabilize the knee during the first milliseconds of a contraction was significantly altered after fatigue (Grazioli et al., 2019). This is particularly interesting considering the study by Correia et al. (2020), which reported a slight trend for a lower RTD H/Q ratio at 50 ms in previously injured hamstrings (Correia et al., 2020), and the results of Grazioli et al. (2019), which revealed that the RTD H/Q ratio in the early phase of contraction decreased by ~24% after match-induced fatigue (Grazioli et al., 2019). Considering that the ability to produce torque during the first milliseconds of a contraction is considered a critical factor for performance (Aagaard et al., 2002) and a determinant of injury risk (Grazioli et al., 2019; Correia et al., 2020), it can be hypothesized that the increased risk of ACL injury after fatigue could be partly explained by the decrease in rapid force capacities RTD and RTD H/Q ratios rather than conventional or functional maximal H/Q ratio modifications.

Influence of EMG on Rapid Torque Capacities After Fatigue

The modifications of H/Q ratios and RTD after fatigue may be explained by alterations of neural and contractile factors (Morel et al., 2015; Rodriguez-Rosell et al., 2018). The present protocol did not enable us to explore the contractile factors, but the analysis of the EMG signal may provide insights about the causes of torque losses after fatigue. Firstly, the decrease in maximal torque measured within the fatigue protocol and during the maximum contractions was not associated with a reduction in the average level of RMS_{mean} EMG (Tables 3–5). It can be considered that the average value of EMG RMS correctly described muscle activation during maximal and submaximal efforts which suggests that the capacity of the central nervous system to activate muscles entirely was unchanged. This is partly consistent with Morel et al. (2015), who reported a small and non-significant decrease in the level of voluntary

activation ($-4.3 \pm 1.6\%$, $p = 0.08$) after repeated maximal knee extension to $240^\circ \cdot s^{-1}$ (Morel et al., 2015). However, if similar levels of maximum activation can be reached when the contraction time is long enough, it has been shown that this does not reflect the ability of the central nervous system to maximally activate the muscle during the first 100 ms of the contraction (Morel et al., 2015). The present results show a significant decrease in RER for knee extensors and flexors regardless of the contraction velocity. Of course, RTD is influenced by many factors such as tissue stiffness, muscle topology, cross-bridge kinetics, and neural drive (Edman and Josephson, 2007). However, in the present study, the decrease in RER could be related to the reduction in RTD (Morel et al., 2015). These results suggest that the ability of the central nervous system to activate the muscle quickly and to the maximum at the start of the contraction was altered after fatigue. Considering the study by Morel et al. (2015), this point should be analyzed considering the decrease in frequency content of the EMG signal (Morel et al., 2015). Present results show that repeated maximal contractions can induce alterations of the recruitment and firing frequency of the motor units during the early part of the contraction (Aagaard et al., 2002), which result in lowering RER and RTD. In the present study a SPM analysis was performed on the EMG Frequency-Time maps and the results demonstrated a significant reduction of the power contained in the high frequencies of the EMG signal for all the studied muscles during the concentric contractions, and merely for biceps femoris during eccentric contraction, respectively. However, this reduction was not specifically observed in the first 100 ms of the contractions as reported by Morel et al. (2015) but appeared all over the contractions except for the eccentric contractions of the BF muscle which demonstrated a significant reduction of the EMG frequency specifically during the first 30% of the movement. Thus, considering the study by Zebis et al. (2009), such a difference in rapid muscle activation in hamstring and quadriceps muscles may be predictive of future ACL injury (Zebis et al., 2009). It seems that fatigue can, therefore, increase the risk of injury in soccer players by decreasing their ability to activate muscles during the first 100 ms of a contraction which may alter the knee joint stability.

Limitation

The study has some limitations that should be kept in mind. Firstly, the present study's sample size is relatively small and not having professional players within the sample may be considered as a limitation. Secondly, no electrical or magnetic stimulation was used in the present study and if the analysis of EMG signal can give some insights about the muscular activation during the exercise it didn't permit to conclude about the origin of fatigue. Lastly, it should be kept in mind that the RTD has been calculated during dynamic isokinetic contractions and it is well known that the isokinetic dynamometers are often more compliant at the beginning of the contraction and noisier than strain gauges which may induce a lower measurement precision for RTD calculation (Maffiuletti et al., 2016). Furthermore, it is impossible at the present time to determine precisely the

predictive value of the studied variables in terms of injuries. However, we believe that this paper propose new and convergent insights that may be used in future studies to determine this predictive value.

CONCLUSION

The purpose of this study was to assess the effect of fatigue on angle-specific H/Q ratios, RTD H/Q ratios, and muscle activation in soccer players in order to better understand the augmented risk of HSLs injury at the end of a match. This study demonstrates that conventional and functional ratio were not decreased after fatigue and nor was the ability to maximally activate the muscles. However, the rapid hamstring to quadriceps ratio RTD H/Q were more affected in association with an overall slow down of RER during the first 100 ms of the contraction and a decrease in frequency content of the EMG signal. Besides, fatigue seems to reduce the potential for knee joint stability due to the RER deficit during the initial phase of contraction. In accordance with recent studies, present outcomes may confirm the importance of explosive force testing before and after fatigue to improve performance and prevent injuries including (i.e., HSLs, ACL injury). In summary, the results of this study show that functional and conventional H/Q ratios carried out during the pre-season tests are not sensitive to fatigue. It seems, in agreement with many authors, that the evaluation of the capacities of rapid force production during the first 100 ms of a contraction, with and without fatigue, is more appropriate to evaluate and prepare soccer players.

Practical Recommendation

This study indicated that the traditional H/Q ratios calculated using the peak torque were not sensitive to fatigue whereas dynamic angle specific ratios seemed to give additional information about muscle weakness at some knee angles which may justify the utilization of this kind of analysis in soccer players evaluation before and after fatigue. Moreover, it appeared that RTD H/Q ratios were modified after fatigue. Considering that a short period (i.e., less than 50 ms) is frequently available to stabilize the knee joint through knee muscle contraction after ground contact moment during braking or dropping maneuver 3, 4 one may consider that the measurement of this parameter with and without fatigue is relevant for injury prevention in soccer. From a general point of view and as hypothesized by other authors, it seems that the evaluation of knee stability in soccer players may now incorporate specific angle H/Q ratios, rapid torque development capacities of extensor and flexor muscles and be performed under fatigue state to provide efficient and meaningful indicators to players, coaches, and therapists.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by “Sud-Est II” of Lyon. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

QZ, BM, and CH conceived and designed the experiments, and wrote the manuscript. QZ and CH performed the experiments. QZ, RT, and CH analyzed the data and contributed materials and analysis tools. All the authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fphys.2021.627674/full#supplementary-material>

Supplementary Figure 1 | Two-way ANOVA SPM (Fatigue * Velocity) EMG Frequency-Time maps analysis for BF, ST, RF, VL, and VM. From left to right; **column 1**: the magnitude of differences from interaction Fatigue * Velocity, **column 2**: the magnitude of differences from Fatigue ($p < 0.05$), **column 3**: the

magnitude of differences from Velocity; the enlighten clusters correspond to significant differences of the two-way ANOVA ($p < 0.05$), BF, Biceps femoris; ST, Semitendinosus; RF, Rectus femoris; VL, Vastus lateralis; VM, Vastus medialis.

Supplementary Figure 2 | From top to bottom; **rows 1 and 2**: EMG Frequency-Time map during concentric contractions for Biceps Femoris before (PRE, **row 1**) and after (POST, **row 2**) the fatiguing exercise with/without the interaction angular velocity ($90^\circ.s^{-1}$, $180^\circ.s^{-1}$) respectively; **row 3**: the magnitude of differences between PRE and POST. The enlighten clusters correspond to significant differences, considering the significance of the two-way ANOVA ($p < 0.05$ after Bonferroni correction); **row 4**: results of the *post hoc* tests (SPM *t*-tests). The enlighten clusters correspond to significant differences without considering the ANOVA ($p < 0.05$ after Bonferroni correction).

Supplementary Figure 3 | From top to bottom; **rows 1 and 2**: EMG Frequency-Time map during concentric contractions for Semitendinosus before (PRE, **row 1**) and after (POST, **row 2**) the fatiguing exercise with/without the interaction angular velocity ($90^\circ.s^{-1}$, $180^\circ.s^{-1}$) respectively; **row 3**: the magnitude of differences between PRE and POST. The enlighten clusters correspond to significant differences, considering the significance of the two-way ANOVA ($p < 0.05$ after Bonferroni correction); **row 4**: results of the *post hoc* tests (SPM *t*-tests). The enlighten clusters correspond to significant differences without considering the ANOVA ($p < 0.05$ after Bonferroni correction).

Supplementary Figure 4 | From top to bottom; **rows 1 and 2**: EMG Frequency-Time map during concentric contractions for Rectus Femoris before (PRE, **row 1**) and after (POST, **row 2**) the fatiguing exercise with/without the interaction angular velocity ($90^\circ.s^{-1}$, $180^\circ.s^{-1}$) respectively; **row 3**: The magnitude of differences between PRE and POST. The enlighten clusters correspond to significant differences, considering the significance of the two-way ANOVA ($p < 0.05$ after Bonferroni correction); **row 4**: results of the *post hoc* tests (SPM *t*-tests). The enlighten clusters correspond to significant differences without considering the ANOVA ($p < 0.05$ after Bonferroni correction).

Supplementary Figure 5 | From top to bottom; **rows 1 and 2**: EMG Frequency-Time map during concentric contractions for Vastus Lateralis before (PRE, **row 1**) and after (POST, **row 2**) the fatiguing exercise with/without the interaction angular velocity ($90^\circ.s^{-1}$, $180^\circ.s^{-1}$) respectively; **row 3**: The magnitude of differences between PRE and POST. The enlighten clusters correspond to significant differences, considering the significance of the two-way ANOVA ($p < 0.05$ after Bonferroni correction); **row 4**: results of the *post hoc* tests (SPM *t*-tests). The enlighten clusters correspond to significant differences without considering the ANOVA ($p < 0.05$ after Bonferroni correction).

Supplementary Figure 6 | From top to bottom; **rows 1 and 2**: EMG Frequency-Time map during concentric contractions for Vastus Medialis before (PRE, **row 1**) and after (POST, **row 2**) the fatiguing exercise with/without the interaction angular velocity ($90^\circ.s^{-1}$, $180^\circ.s^{-1}$) respectively; **row 3**: The magnitude of differences between PRE and POST. The enlighten clusters correspond to significant differences, considering the significance of the two-way ANOVA ($p < 0.05$ after Bonferroni correction); **row 4**: Results of the *post hoc* tests (SPM *t*-tests). The enlighten clusters correspond to significant differences without considering the ANOVA ($p < 0.05$ after Bonferroni correction).

REFERENCES

- Aagaard, P., Simonsen, E. B., Andersen, J. L., Magnusson, P., and Dyhre-Poulsen, P. (2002). Increased rate of force development and neural drive of human skeletal muscle following resistance training. *J. Appl. Physiol.* 93, 1318–1326. doi: 10.1152/jappphysiol.00283.2002
- Alhammoud, M., Morel, B., Girard, O., Racinais, S., Sevez, V., Germain, A., et al. (2018). Hypoxia and fatigue impair rapid torque development of knee extensors in elite alpine skiers. *Front. Physiol.* 9:962. doi: 10.3389/fphys.2018.00962
- Alhammoud, M., Morel, B., Hansen, C., Wilson, M., Mecca, R., Nael, E., et al. (2019). Discipline and sex differences in angle-specific isokinetic analysis in elite skiers. *Int. J. Sports Med.* 40, 317–330. doi: 10.1055/a-0850-0016
- Andersen, L. L., and Aagaard, P. (2006). Influence of maximal muscle strength and intrinsic muscle contractile properties on contractile rate of force development. *Eur. J. Appl. Physiol.* 96, 46–52. doi: 10.1007/s00421-005-0070-z
- Angelozzi, M., Madama, M., Corsica, C., Calvisi, V., Properzi, G., McCaw, S. T., et al. (2012). Rate of force development as an adjunctive outcome measure for return-to-sport decisions after anterior cruciate ligament reconstruction. *J. Orthop. Sports Phys. Ther.* 42, 772–780. doi: 10.2519/jospt.2012.3780
- Baroni, B. M., Ruas, C. V., Ribeiro-Alvares, J. B., and Pinto, R. S. (2020). Hamstring-to-quadriceps torque ratios of professional male soccer players: a systematic review. *J. Strength Condition. Res.* 34, 281–293. doi: 10.1519/jsc.0000000000002609
- Cohen, D. D., Zhao, B., Okwera, B., Matthews, M. J., and Delextrat, A. (2015). Angle-specific eccentric hamstring fatigue after simulated soccer. *Int. J. Sports Physiol. Perform.* 10, 325–331. doi: 10.1123/ijspp.2014-0088
- Coratella, G., Bellin, G., Beato, M., and Schena, F. (2015). Fatigue affects peak joint torque angle in hamstrings but not in quadriceps. *J. Sports Sci.* 33, 1276–1282. doi: 10.1080/02640414.2014.986185
- Correia, P., Santos, P., Mil-Homens, P., Gomes, M., Dias, A., and Valamatos, M. J. (2020). Rapid hamstrings to quadriceps ratio at long muscle lengths in

- professional football players with previous hamstring strain injury. *Eur. J. Sport Sci.* 20, 1405–1413. doi: 10.1080/17461391.2020.1714741
- Croce, R. V., and Miller, J. P. (2006). Angle- and velocity-specific alterations in torque and semg activity of the quadriceps and hamstrings during isokinetic extension-flexion movements. *Electromyogr. Clin. Neurophysiol.* 46, 83–100.
- Croisier, J. L., Ganteaume, S., Binet, J., Genty, M., and Ferret, J. M. (2008). Strength imbalances and prevention of hamstring injury in professional soccer players: a prospective study. *Am. J. Sports Med.* 36, 1469–1475. doi: 10.1177/0363546508316764
- De Ruiter, C. J., and De Haan, A. (2001). Similar effects of cooling and fatigue on eccentric and concentric force-velocity relationships in human muscle. *J. Appl. Physiol.* 90, 2109–2116. doi: 10.1152/jappp.2001.90.6.2109
- De Ste Croix, M., ElNagar, Y. O., Iga, J., Ayala, F., and James, D. (2017). The impact of joint angle and movement velocity on sex differences in the functional hamstring/quadriceps ratio. *Knee* 24, 745–750. doi: 10.1016/j.knee.2017.03.012
- Edman, K. A., and Josephson, R. K. (2007). Determinants of force rise time during isometric contraction of frog muscle fibres. *J. Physiol.* 580(Pt.3), 1007–1019. doi: 10.1113/jphysiol.2006.119982
- Ekstrand, J., Hagglund, M., and Walden, M. (2011a). Epidemiology of muscle injuries in professional football (soccer). *Am. J. Sports Med.* 39, 1226–1232. doi: 10.1177/0363546510395879
- Ekstrand, J., Hagglund, M., and Walden, M. (2011b). Injury incidence and injury patterns in professional football: the UEFA injury study. *Br. J. Sports Med.* 45, 553–558. doi: 10.1136/bjsm.2009.060582
- Evangelidis, P. E., Massey, G. J., Ferguson, R. A., Wheeler, P. C., Pain, M. T. G., and Folland, J. P. (2017). The functional significance of hamstrings composition: is it really a “fast” muscle group? *Scand. J. Med. Sci. Sports* 27, 1181–1189. doi: 10.1111/sms.12786
- Evangelidis, P. E., Pain, M. T., and Folland, J. (2015). Angle-specific hamstring-to-quadriceps ratio: a comparison of football players and recreationally active males. *J. Sports Sci.* 33, 309–319. doi: 10.1080/02640414.2014.942680
- Garrett, W. E. Jr., Califf, J. C., and Bassett, F. H. III (1984). Histochemical correlates of hamstring injuries. *Am. J. Sports Med.* 12, 98–103. doi: 10.1177/036354658401200202
- Grazioli, R., Lopez, P., Andersen, L. L., Machado, C. L. F., Pinto, M. D., Cadore, E. L., et al. (2019). Hamstring rate of torque development is more affected than maximal voluntary contraction after a professional soccer match. *Eur. J. Sport Sci.* 19, 1336–1341. doi: 10.1080/17461391.2019.1620863
- Greco, C. C., da Silva, W. L., Camarda, S. R. A., and Denadai, B. S. (2013). Fatigue and rapid hamstring/quadriceps force capacity in professional soccer players. *Clin. Physiol. Funct. Imaging* 33, 18–23. doi: 10.1111/j.1475-097X.2012.01160.x
- Hautier, C. A., Linossier, M. T., Belli, A., Lacour, J. R., and Arsac, L. M. (1996). Optimal velocity for maximal power production in non-isokinetic cycling is related to muscle fibre type composition. *Eur. J. Appl. Physiol. Occup. Physiol.* 74, 114–118. doi: 10.1007/bf00376503
- Hawkins, R. D., Hulse, M. A., Wilkinson, C., Hodson, A., and Gibson, M. (2001). The association football medical research programme: an audit of injuries in professional football. *Br. J. Sports Med.* 35, 43–47. doi: 10.1136/bjism.35.1.43
- Ishoi, L., Aagaard, P., Nielsen, M. F., Thornton, K. B., Krommes, K. K., Holmich, P., et al. (2019). The influence of hamstring muscle peak torque and rate of torque development for sprinting performance in football players: a cross-sectional study. *Int. J. Sports Physiol. Perform.* 14, 665–673. doi: 10.1123/ijspp.2018-0464
- Kawabata, Y., Senda, M., Oka, T., Yagata, Y., Takahara, Y., Nagashima, H., et al. (2000). Measurement of fatigue in knee flexor and extensor muscles. *Acta Med. Okayama* 54, 85–90. doi: 10.18926/amo/32290
- Krustrup, P., Mohr, M., Steensberg, A., Bencke, J., Kjaer, M., and Bangsbo, J. (2006). Muscle and blood metabolites during a soccer game: implications for sprint performance. *Med. Sci Sports Exerc.* 38, 1165–1174. doi: 10.1249/01.mss.000022845.89262.cd
- Lee, J. W. Y., Mok, K. M., Chan, H. C. K., Yung, P. S. H., and Chan, K. M. (2018). Eccentric hamstring strength deficit and poor hamstring-to-quadriceps ratio are risk factors for hamstring strain injury in football: A prospective study of professional players. *J. Sci. Med. Sport* 21, 789–793. doi: 10.1016/j.jsams.2017.11.017
- Lilly, J. M., and Olhede, S. C. (2009). Higher-order properties of analytic wavelets. *IEEE Trans. Signal Process.* 57, 146–160. doi: 10.1109/TSP.2008.2007607
- Maffioletti, N. A., Aagaard, P., Blazevich, A. J., Folland, J., Tillin, N., and Duchateau, J. (2016). Rate of force development: physiological and methodological considerations. *Eur. J. Appl. Physiol.* 116, 1091–1116. doi: 10.1007/s00421-016-3346-6
- Marshall, P. W., Lovell, R., Jeppesen, G. K., Andersen, K., and Siegler, J. C. (2014). Hamstring muscle fatigue and central motor output during a simulated soccer match. *PLoS One* 9:e102753. doi: 10.1371/journal.pone.0102753
- Morel, B., and Hautier, C. A. (2017). The neuromuscular fatigue induced by repeated sprints generates instability that can be limited by appropriate recovery. *Scand. J. Med. Sci. Sports.* 27, 209–216. doi: 10.1111/sms.12646
- Morel, B., Roufflet, D. M., Sabou, D., Rota, S., Clemencon, M., and Hautier, C. A. (2015). Peak torque and rate of torque development influence on repeated maximal exercise performance: contractile and neural contributions. *PLoS One* 10:e0119719. doi: 10.1371/journal.pone.0119719
- Nichols, T. E., and Holmes, A. P. (2002). Nonparametric permutation tests for functional neuroimaging: a primer with examples. *Hum. Brain Mapp.* 15, 1–25. doi: 10.1002/hbm.1058
- Parcell, A. C., Sawyer, R. D., Tricoli, V. A., and Chinevere, T. D. (2002). Minimum rest period for strength recovery during a common isokinetic testing protocol. *Med. Sci. Sports Exerc.* 34, 1018–1022. doi: 10.1097/00005768-200206000-00018
- Pataky, T. C. (2010). Generalized n-dimensional biomechanical field analysis using statistical parametric mapping. *J. Biomech.* 43, 1976–1982. doi: 10.1016/j.jbiomech.2010.03.008
- Pataky, T. C., Robinson, M. A., and Vanrenterghem, J. (2013). Vector field statistical analysis of kinematic and force trajectories. *J. Biomech.* 46, 2394–2401. doi: 10.1016/j.jbiomech.2013.07.031
- Rodriguez-Rosell, D., Pareja-Blanco, F., Aagaard, P., and Gonzalez-Badillo, J. J. (2018). Physiological and methodological aspects of rate of force development assessment in human skeletal muscle. *Clin. Physiol. Funct. Imaging* 38, 743–762. doi: 10.1111/cpf.12495
- Sangnier, S., and Tourny-Chollet, C. (2007). Comparison of the decrease in strength between hamstrings and quadriceps during isokinetic fatigue testing in semiprofessional soccer players. *Int. J. Sports Med.* 28, 952–957. doi: 10.1055/s-2007-964981
- Sangnier, S., and Tourny-Chollet, C. (2008). Study of the fatigue curve in quadriceps and hamstrings of soccer players during isokinetic endurance testing. *J. Strength Cond. Res.* 22, 1458–1467. doi: 10.1519/JSC.0b013e318181ab41
- Small, K., McNaughton, L., Greig, M., and Lovell, R. (2010). The effects of multidirectional soccer-specific fatigue on markers of hamstring injury risk. *J. Sci. Med. Sport* 13, 120–125. doi: 10.1016/j.jsams.2008.08.005
- Small, K., McNaughton, L. R., Greig, M., Lohkamp, M., and Lovell, R. (2009). Soccer fatigue, sprinting and hamstring injury risk. *Int. J. Sports Med.* 30, 573–578. doi: 10.1055/s-0029-1202822
- Walden, M., Hagglund, M., Magnusson, H., and Ekstrand, J. (2016). ACL injuries in men's professional football: a 15-year prospective study on time trends and return-to-play rates reveals only 65% of players still play at the top level 3 years after ACL rupture. *Br. J. Sports Med.* 50, 744–750. doi: 10.1136/bjsports-2015-095952
- Zebis, M. K., Andersen, L. L., Bencke, J., Kjaer, M., and Aagaard, P. (2009). Identification of athletes at future risk of anterior cruciate ligament ruptures by neuromuscular screening. *Am. J. Sports Med.* 37, 1967–1973. doi: 10.1177/0363546509335000
- Zebis, M. K., Andersen, L. L., Ellingsgaard, H., and Aagaard, P. (2011). Rapid hamstring/quadriceps force capacity in male vs. female elite soccer players. *J. Strength Cond. Res.* 25, 1989–1993. doi: 10.1519/JSC.0b013e3181e50146

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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9.3 Appendix 3



The Immediate Effects of Self-Myofascial Release on Flexibility, Jump Performance and Dynamic Balance Ability

by

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Self-myofascial release (SMR) is a popular method to potentially increase the compliance and extensibility of the fascia and reduce muscle stiffness. The purpose of this study was to examine the acute effects of posterior muscle chain SMR on flexibility, vertical jump performance and balance ability. Eighteen young participants volunteered to take part in this crossover design study. They performed two self-massage sessions in randomized order separated by at least one week. One session consisted of posterior muscle chain SMR whereas the other one was performed on the upper limbs as a control intervention (CON). Flexibility was measured with the Toe Touch Test (TTT), Weight-Bearing Lunge Test (WBLT), and Straight Leg Raise Test (SLR). Jump performance was evaluated during a squat jump, a counter movement jump and a stiffness jump. Dynamic balance ability was assessed through the Star Excursion Balance Test. All these variables were measured before and after each intervention. A significant increase in flexibility ($+3.5 \pm 1.8$ cm, $+1.6 \pm 1.0^\circ$, and $+7.7 \pm 4.0^\circ$ for the TTT, WBLT, and SLR, respectively, $p < 0.003$) and balance performance (4.8 ± 3.9 cm, $p < 0.003$) was observed following SMR intervention compared to CON. Conversely, jumping performance was unchanged in both groups. SMR improves joint flexibility and dynamic balance ability.

Key words: roller massage, foam rolling, range of motion, jumping performance, balance ability.

Introduction

The fascia is a type of connective tissue that surrounds the nerves, blood vessels, but also tendons, ligaments and muscles. The myofascial network ensures the maintenance and consistency of skeletal muscle structures promoting the sliding between muscle structures, the transmission of muscular forces and the protection against muscle damage. It has been reported that when myofascia becomes dehydrated and loses its elasticity, this can lead to impaired structural alignment, decreased strength and endurance, as well as motor coordination (Barnes, 1997). During the last decade, self-myofascial release (SMR) has become a popular method which influences muscle and myofascial structures by increasing the compliance and extensibility of the fascia (Mohr et al., 2014) and reduces passive muscle stiffness (Morales-Artacho et al., 2017). It may also reduce muscle pain by

decreasing delayed onset muscle soreness after intense exercise (MacDonald et al., 2013; Pearcey et al., 2015).

More recently, a growing interest in self-myofascial release has emerged in sport, enabling the pursuance of the same goal as manual massage using the individual's mass itself and massage instruments such as a foam roller or balls. SMR has been demonstrated to provide a wide range of positive gains in physical performance. The most well-known positive effect of SMR is a gain in flexibility assessed by an increased joint range of motion in sport and rehabilitation contexts (Halperin et al., 2014; MacDonald et al., 2013; Sullivan et al., 2013). For instance, Sullivan et al. (2013) demonstrated that an intermittent 4 trial roller-massage protocol performed on the hamstring muscles increased knee joint flexibility by 4.3% (Sullivan et al., 2013), partly due to a reduced motor unit firing rate, and

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subsequently decreased muscle tension (Tozzi, 2012). MacDonald et al. (2013) reported similar results after hamstring SMR with an increased knee joint range of motion of 12.7% and 10.3% at the 2nd and 10th minute after SMR, respectively. Furthermore, the gain in flexibility after SMR was reported to be similar to those obtained after stretching interventions (Su et al., 2017). However, stretching interventions can negatively impact muscle performance (Behm and Kibele, 2007; Marchetti et al., 2014), while SMR was shown to have controversial effects on muscular performance. Sullivan et al. (2013) found no change in maximal isometric knee flexion torque after 1 or 2 bouts of 5 or 10 s of roller massage. In contrast, Su et al. (2017) indicated that the knee extension peak torque was increased after foam rolling massage. Moreover, Bradbury-Squires et al. (2015) demonstrated an increased neuromuscular efficiency during lunge (i.e., reduced VL EMG) as a result of roller massager application. Peacock et al. (2015) did not report any change in vertical jump performance after SMR sessions. Yet, a potential benefit of SMR to jump performance could be expected considering the decrease in muscular stiffness reported after SMR (Morales-Artacho et al., 2017) and then an increased ability to store elastic potential energy during the muscle lengthening phase of the vertical jump, especially the counter-movement jump (CMJ), as previously reported for triceps surae muscles after plyometric training (Fouré et al., 2011). Due to the variety in the design of SMR protocols, it remains difficult to determine the real effect of SMR on muscle force capacities and jump performance.

While there are numerous reports of SMR or myofascial therapy effects on joint flexibility and jump performance, only few studies have focused on dynamic balance ability and results have been quite controversial. Halperin et al. (2014) showed that static balance on one leg was not influenced by SMR. Junker and Stöggl (2019) reported that 4 weeks of SMR intervention on lower leg muscles had no effect on the dynamic balance ability using the Y balance test. Castro-Sanchez et al. (2011) assessed the effects of myofascial therapy on postural stability over a 20-week period, but failed to observe any effect. In contrast, Sefton et al. (2012) reported that 60 min of full-body manual massage (e.g., pressure

points, kneading, scalp) had a positive effect on balance performance measured on a functional scale platform. In the latter study, manual therapy was assumed to increase body stability by reducing muscle coactivation. In addition, the proprioceptive effect of massage may also increase some of the determining factors of body balance (Shin and Sung, 2015). Concerning the potential effect of SMR as manual massage on the determining factors of balance ability, acute neuromuscular adaptations can be assumed such as proprioception improvement (Weerapong et al., 2005).

As described above, previous studies have indicated that SMR has a positive effect by improving flexibility, yet its influence on balance is still debated. Therefore, the aim of this study was to assess the immediate effect of posterior muscle chain SMR on flexibility, jump performance and dynamic balance ability in the same experimental population. We hypothesized that the immediate effect of SMR using the foam roller and double ball massage on the posterior muscle chain would improve flexibility and balance ability without decreasing jump performance.

Methods

Participants

Fourteen men (174 ± 4 cm, 73 ± 6 kg, 24 ± 2 years) and four women (162 ± 3 cm, 50 ± 8 kg, 23 ± 1 years) volunteered to participate in the present study. They were recreationally active (7 ± 2 hr/wk), but were not practicing any form of SMR. In addition, they had not suffered from lower limb injuries and had no history of surgery (e.g., ACL reconstruction, ankle sprain) in the 6 months preceding the study. The study was approved by the local ethics committee, "Sud-Est II" of Lyon and all participants provided written informed consent. All procedures conformed to the standards of the last version of the Declaration of Helsinki. Leading up to the experiment, participants followed their regular physical activity, but avoided strenuous loading at least 48 hours prior to testing.

Measures

Flexibility tests

The Toe Touch Test (TTT) was performed to assess the mobility and flexibility of the lower back and hamstrings. Participants were seated,

legs stretched forward, feet together and bent the hip joint as far as possible without bending the knee. The furthest distance from the tip of the fingers to the bench was recorded as the best performance of the three attempts.

The Weight-Bearing Lunge Test (WBLT) was used to assess ankle dorsiflexion range of motion. Participants stood barefoot in front of the wall with 10 cm between feet and the wall. They were asked to move one leg back and then lunge forward with the front knee toward the wall. Participants moved the front foot further away from the wall if the front knee could touch the wall or, on the contrary, moved the foot closer to the wall. Participants repeated this process until achieving the optimal distance between feet and the wall with the heel remaining in contact with the ground. The maximal distance from the toe to the wall was measured with a ruler and the best performance was recorded (i.e. maximal ankle joint range of motion in dorsiflexion).

The Straight Leg Raise (SLR) test was used to assess hamstring flexibility. The maximal hip leg-trunk angle attained without pain and change in the pelvis position was measured using a camera placed 2 m from the hip and perpendicular to the participant's sagittal plane (Gopro, Silver 4, sampling frequency 250 Hz, resolution 1080 p). Kinovea (v.0.8.27) was used to assess the SLR performance (Nor Adnan et al., 2018). Before the test, two black circle markers (25 mm diameter) were positioned on the greater trochanter and external femoral condyle to improve the spatial tracking accuracy. Participants were in a supine position on a massage table and raised the leg with the knee fully extended and the pelvis in a neutral position. The hip angle during flexion was then measured relative to the horizontal axis. All the participants performed 3 attempts for each leg. The best performance was recorded as the maximal range of motion.

Jump tests

Participants performed the conventional vertical counter-movement jump (CMJ), squat jump (SJ) and stiffness jumps (STIF). Jump performances (i.e. jump height in cm) were measured using the Optojump system (Microgate, Bolzano, Italy). Participants performed 3 jumps for each test with a 30 s rest interval between each jump. The maximal performance for each

modality was recorded for further analysis.

Balance Ability Test

The modified Star Excursion Balance Test (SEBT) was used to assess balance for both legs. Three labeled lines were extended from the center of the foot in anterior (ANT, at 90 degrees), posterolateral (PL, at 45 degrees) and posteromedial (PM, at 45 degrees) directions. Participants were instructed to maintain a single leg stance with a semi-flexed knee and hands on the hips while reaching with the other leg as far as possible along the three directions. Participants had to touch the furthest point possible on the line with the most distal part of their reach foot as lightly as possible using minimal pressure to ensure that the reach leg did not provide support in the maintenance of the upright posture and that stability was achieved through balance (Mütabaa et al., 2018). Participants returned to a bilateral stance while maintaining their equilibrium. The participant was asked to complete 5 trials of the SEBT and then each participant performed 3 trials in each of the three directions with 10 s recovery between subsequent attempts.

Design and procedures

A randomized crossover design was used for this study. The experimental session consisted of SMR on the posterior muscle chain (SMR), whereas the control session consisted of SMR on the upper limbs (CON). At least one week separated the two sessions that were performed at the same time of day. Each session was composed of a 15-min standardized warm-up followed by flexibility, jump performances, and balance assessments (PRE) performed in random order to avoid a potential systematic effect of each test on the others. Next, participants performed the SMR or CON session and immediately after (POST), the same assessments as for PRE (Figure 1).

During the first familiarization session, all participants filled out a questionnaire concerning their age, sport experience, training volume and an injury report. Height and body mass were also measured. Participants were briefly introduced to the SMR instruments (i.e. foam roller, double balls) and the SMR movements were demonstrated by the experimenter. The instructions were standardized in order to provide all participants with the same information. During the two experimental

sessions, participants performed a standardized warm-up that consisted of running at their self-paced velocity (15 min), submaximal squat jumps, counter movement jumps and stiffness jumps (5 jumps/modality with 30 s rest intervals between jumps). After the warm-up, participants performed the flexibility, jump and balance tests (Figure 1). Depending on the session, participants performed the SMR movements on the posterior muscle chain (SMR) or on the upper limbs (CON). Participants were instructed to roll the massage ball and the foam roller by applying the pressure with their bodyweight to reach discomfort yet without pain. The SMR experimental session was performed on the posterior muscle chain including the arches of the foot (60 s), calf muscles (80 s), hamstring muscles (80 s), gluteal muscles (50 s), lumbar muscles (50 s), and suboccipital muscles (40 s). SMR applications were interspaced with 10 s rest intervals. The massage of the foot arches was performed using a simple ball (TRIGGERPOINT® MB, 6.6 cm diameter, 5 g), whereas a double ball massage (PROCIRCLE®, 12.7 cm length, 6.35 cm diameter, 400 g) was used for the massage of the suboccipital zone and a foam roller (TRIGGERPOINT® EVA, 33 cm length, 14 cm diameter, 650 g) for the other muscles. For the control session, SMR was performed with the ball massage on the arm muscles with progression order that included forearm muscles (90 s), deltoid muscles (90 s), *biceps brachii* muscle (90 s) and *triceps brachii* muscles (90 s) for similar total duration of 6 minutes. All testing sessions were performed in the same location, at the same temperature and at the same time of day.

Statistical Analysis

The interaction effects between time (PRE vs. POST; fixed effect) and groups (CON vs. SMR; fixed effect) were tested using linear mixed models. The *p*-value was determined with a type III ANOVA using Satterthwaite's degrees of freedom method. The level of significance was set at $p < 0.0036$ (Bonferroni correction: 0.05/14). A Tukey HSD post-hoc test was performed when appropriate. Cohen's *d* value was calculated between the PRE and POST values for the SMR condition. The linearity and the homoscedasticity of the model residuals were graphically controlled. All models were executed from the package "lme4" (Bates et al., 2015), *p*-values were obtained using the

package "lmerTest" (Kuznetsova et al., 2017) and post-hoc pairwise comparisons were performed with the R software package "multcomp" (R 3.5.0, RCore Team, Vienna, Austria).

Results

Flexibility tests: A significant interaction was observed between flexibility variables ($p < 0.001$). The SMR group improved flexibility performance by an increased score in SLR ($11 \pm 7\%$), TTT ($50 \pm 40\%$) and WBLT ($22 \pm 17\%$) (Table 1). Balance ability tests: An interaction was found for the balance variables measured with the SEBT except for the lateral and medial axis of the right leg for which no main effect was found (Table 1). It should be noted that the CON group was significantly more balanced on the medial axis for the left leg as compared to the SMR group before the intervention ($p < 0.001$). However, the SMR group improved their performance in the post-test and there was no difference after the intervention between groups. Post-hoc pairwise comparisons showed that the SMR group improved balance up to 8%. At the end of the intervention, the performance of the SMR group was better than the CON group on the anterior axis, and the lateral axis with the left leg (Table 1). Vertical jump performances: No interaction and no main effect in jump performances were found ($p > 0.05$). Jump performances were similar before and after the intervention for both the SMR and CON groups (Table 1).

Discussion

To our knowledge, this study was the first to evaluate the immediate effect of posterior muscle chain SMR on flexibility, balance and jump performance on the same experimental population. The main finding was the enhanced balance ability and flexibility without a decrease in jump performances following posterior muscle chain SMR intervention.

The benefits of SMR to flexibility found in the present study were in accordance with previous studies which demonstrated a positive effect of SMR on the range of motion (Halperin et al., 2014; MacDonald et al., 2013; Sullivan et al., 2013). Changes in myofascial tissue mechanical properties could partly contribute to the positive effect of SMR on flexibility since the colloidal substance was shown to be sensitive to

mechanical stimulation and become more fluid after massage (Hotfiel et al., 2017). These modifications can reduce the adhesion between the different layers of the fascial tissues and increase connective tissues' extensibility and compliance (Kalichman and Ben David, 2017; Schleip, 2003). For instance, it has been demonstrated that SMR performed with a foam roller enables the improvement of joint range of motion (Halperin et al., 2014; McKechnie et al., 2007; Schleip, 2003; Sullivan et al., 2013). In the same way, Drust et al. (2003) reported that SMR could also increase the temperature of the muscle and then reduce the viscosity of muscle tissue. Additionally, Hotfiel et al. (2017) demonstrated that SMR increased the blood flow and perfusion which may influence muscle temperature and thus enhance flexibility. Although these variables have not been considered in the present study, it can be hypothesized that SMR improved flexibility partially by increasing the muscle blood flow and temperature (Drust et al., 2003). Meanwhile the increase in the range of motion may be explained by mechanical pressure which can overload the mechanical receptor in myofascia with some potentially pain-relieving effects (Bialosky et al., 2009; Voogt et al., 2015). It

may also decrease the stretching sensation (McKechnie et al., 2007) and thus increase stretching tolerance (Sayenko et al., 2009; Wepler and Magnusson, 2010). Surprisingly, the present study demonstrated stronger positive effects of SMR on flexibility ($11 \pm 7\%$ for SLR, $50 \pm 40\%$ for TTT and $22 \pm 17\%$ for the WBLT) compared to those reported in previous studies ranging from 4.3 to 18.7% (Halperin et al., 2014; Jay et al., 2014; MacDonald et al., 2013; Sullivan et al., 2013). This may be explained by the accumulated benefits of SMR to the different muscle groups in association with the Myers's "Anatomy Train" theory. Myers (2013) proposed that massage on a muscle group of the superficial back line including some muscle zone of the posterior muscle chain could modify the tension along the entire line. This can be related to the change in the ankle dorsiflexion range of motion with the modification of the hip angle (Andrade et al., 2016). We speculate that the accumulated benefits and SMR duration could induce a greater improvement in the range of motion. Further studies to test this hypothesis are needed to compare single and repeated bout effects of SMR on the range of motion improvement.

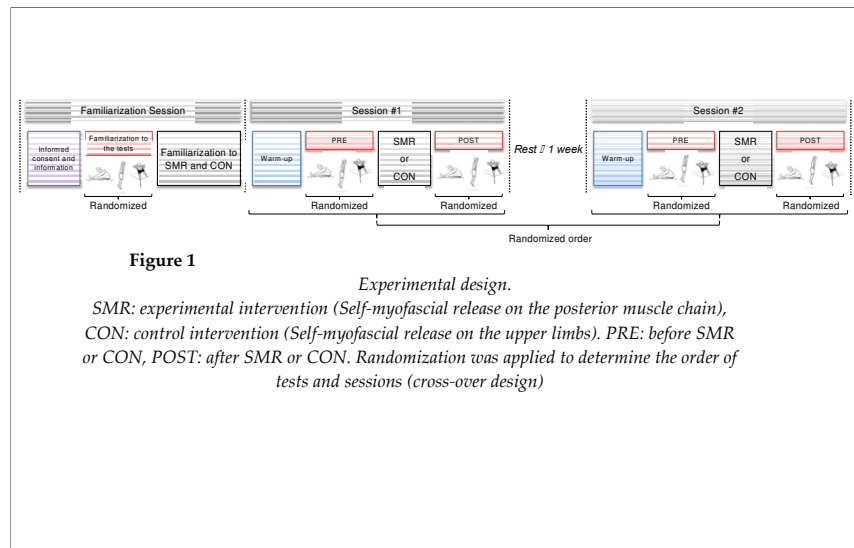


Table 1
Mean values (\pm SD) and relative changes in flexibility, balance, and power variables after self-myofascial release on the posterior muscle chain (SMR) and the control intervention (CON).

	Absolute data				Relative changes			
	SMR		CON		SMR	CON		
	PRE	POST	PRE	POST				
TTT (cm)	-5.92 \pm 10.05	-2.47 \pm 10.10 ^{*,#}	-5.27 \pm 9.58	-5.21 \pm 9.79	3.5 \pm 1.8	0.1 \pm 0.6		
Flexibility	WBLT (°)	Right	7.99 \pm 1.61	9.64 \pm 1.64 ^{*,#}	7.79 \pm 1.54	7.90 \pm 1.52	1.6 \pm 0.9	0.1 \pm 0.3
		Left	8.62 \pm 2.06	10.27 \pm 2.01 ^{*,#}	8.75 \pm 2.02	8.88 \pm 2.08	1.6 \pm 1.0	0.1 \pm 0.3
	SLR (°)	Right	75.00 \pm 15.74	82.28 \pm 16.23 ^{*,#}	73.17 \pm 15.16	72.17 \pm 14.63	7.3 \pm 3.9	-1.0 \pm 2.9
		Left	72.50 \pm 17.61	80.67 \pm 16.34 ^{*,#}	74.22 \pm 16.09	73.22 \pm 15.26	8.2 \pm 4.2	-1.0 \pm 1.8
SEBT	ANT (cm)	Right	58.63 \pm 6.04	63.32 \pm 7.11 ^{*,#}	59.58 \pm 5.48	59.92 \pm 4.98	4.7 \pm 3.3	0.3 \pm 1.2
		Left	60.22 \pm 5.97	64.92 \pm 7.59 ^{*,#}	61.39 \pm 5.47	61.17 \pm 5.53	4.7 \pm 2.9	-0.2 \pm 1.9
	PL (cm)	Right	97.33 \pm 6.16	100.53 \pm 5.97	100.28 \pm 6.00	101.92 \pm 5.30	3.2 \pm 5.1	1.6 \pm 4.4
		Left	95.96 \pm 7.63	102.44 \pm 6.79 ^{*,#}	98.31 \pm 6.32	98.61 \pm 6.30	6.5 \pm 3.3	0.3 \pm 2.6
	PM (cm)	Right	97.63 \pm 6.86	102.07 \pm 5.30	101.11 \pm 5.29	100.81 \pm 4.99	4.4 \pm 4.2	-0.3 \pm 2.9
		Left	96.49 \pm 6.15 ^r	101.97 \pm 6.21 [*]	101.11 \pm 5.42	100.47 \pm 5.00	5.5 \pm 4.6	-0.6 \pm 2.4
Jump Performance	SJ (cm)	33.42 \pm 8.91	32.47 \pm 8.69	33.14 \pm 8.80	32.38 \pm 8.43	-1.0 \pm 1.9	-0.8 \pm 1.5	
	CMJ (cm)	33.51 \pm 8.43	33.15 \pm 8.59	33.45 \pm 8.93	33.11 \pm 8.35	-0.4 \pm 2.0	-0.3 \pm 2.4	
	STIF (cm)	16.95 \pm 9.15	17.17 \pm 7.34	16.55 \pm 6.83	17.52 \pm 8.30	0.2 \pm 2.9	1.0 \pm 3.8	

TTT: toe touch test, WBLT: weight-bearing lunge test, SLR: straight leg raise test, SEBT: star excursion balance test in three directions: anterior (ANT), posterolateral (PL) and posteromedial (PM), SJ: squat jump, CMJ: counter movement jump, STIF: stiffness jumps.

*: Significantly different from PRE, #: Significantly different from CON.

Although many studies reported benefits to the joint range of motion following a single session of myofascial release, only few examined the dynamic balance ability. In the present study, a significant improvement in dynamic balance ability following postural muscle chain SMR was quantified. The present results are in line with a Sefton et al.'s study which showed that 60-min of manual therapy improved dynamic balance ability measured with the functional single leg balance test (Sefton et al., 2012). Such an improvement could be attributed to numerous factors like muscle contractions, proprioception or central nervous system activation (Weerapong et al., 2005). In addition, myofascia includes a multitude of sensory nerves related to proprioceptive and mechanical receptors like Golgi receptors or Pacini receptors (Tozzi, 2012). Therefore, the pressure exerted during the SMR intervention may stimulate these mechanical receptors and improve the proprioceptive information integrated by the central nervous system to tune the activation level of the motor units (Schleip, 2003). Moreover, it has been demonstrated that ankle dorsiflexion range of motion is significantly related to the dynamic balance ability (Basnett et al., 2013; Hoch et al., 2011). Thus, the significant improvement of the ankle dorsiflexion range of motion reported in the present study may partly explain the increased performance in the SEBT. In contrast, no previous study has reported deleterious effects of SMR on dynamic balance ability. Junker and Stöggel (2019) and Halperin et al. (2014) found no chronic/acute effect of SMR on Y balance test performances. Considering the variability in SMR interventions and the few studies of SMR effects on balance ability, further studies are needed to explore more deeply the positive effects of SMR on the balance ability found in the present study, using additional investigation methods including for instance surface electromyography.

In contrast, no significant effect of SMR on jump performances was found whatever the test (i.e., CMJ, SJ, STIF). This result is in accordance with previous research (Behara and Jacobson, 2017; Healey et al., 2014) and especially the results reported by Behara and Jacobson (2017) who observed no significant difference in power and velocity during the CMJ after a single SMR intervention. Conversely, Sagioglu et al. (2017)

observed a detrimental effect on the CMJ following a single session of SMR with a grid foam roller on hamstring, quadriceps, hip and gastrocnemius muscles after aerobic running (Sagioglu et al., 2017). Decreased CMJ performance was assumed to be related to the increased flexibility after SMR which might temporarily decrease the muscle ability to generate power output due to the increased stretch tolerance (Behm and Kibele, 2007; Marchetti et al., 2014; McKechnie et al., 2007; Sayenko et al., 2009). However, the present study showed increased ankle dorsiflexion after SMR without any change in jump performances, although increased ankle dorsiflexion may also improve jump performance (Papaikovou, 2013). Nevertheless, the vertical jump is a multi-joint movement that requires complex motor coordination and the muscle activation pattern has to be continuously adapted to the joint flexibility to maintain or increase jump performance (Babault et al., 2003; Kirby et al., 2011). According to different results, it can be assumed that duration, muscle groups, pressure or material used for SMR may modulate the effects on muscle force and joint flexibility. Although no quantitative assessment of the pressure was made during SMR interventions in the present study, qualitative assessment was performed throughout the experimental protocol by the same experimenter (Q.S.Z.).

The present study aimed at determining the functional effects of SMR on flexibility, balance ability, and jump performance in the same experimental population. This study addressed the effectiveness of SMR on the superficial posterior muscle chain for an immediate gain in flexibility of the hip joint with an increased dynamic balance ability and no effect on vertical jump performance. Thus, SMR can be easily integrated into the warm-up of athletes, given that a roller and a massage ball are very simple, easy-to-use, and cheap tools. It remains to determine the effect of integrated SMR as a warm-up option on the occurrence, frequency, and extent of muscle injury in the athlete's population. Based on the current study, further studies should be performed to assess the most effective pressure to be applied and the influence of SMR on mechanical and physiological variables (e.g., electromyographic muscle activity) to better

explain the positive effects of SMR, especially on the dynamic balance ability. In addition, further studies are needed to evaluate the efficacy of such

an SMR prevention protocol in the warm-up to reduce the occurrence of injuries in sport.

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References

- Andrade RJ, Lacourpaille L, Freitas SR, McNair PJ, Nordez A. Effects of hip and head position on ankle range of motion, ankle passive torque, and passive gastrocnemius tension. *Scand J Med Sci Sports*, 2016; 26: 41-47
- Babault N, Pousson M, Michaut A, Van Hoecke J. Effect of quadriceps femoris muscle length on neural activation during isometric and concentric contractions. *J Appl Physiol (1985)*, 2003; 94: 983-990
- Barnes MF. The basic science of myofascial release: morphologic change in connective tissue. *Journal of Bodywork and Movement Therapies*, 1997; 1: 231-238
- Basnett CR, Hanish MJ, Wheeler TJ, Miriovsky DJ, Danielson EL, Barr JB, Grindstaff TL. Ankle dorsiflexion range of motion influences dynamic balance in individuals with chronic ankle instability. *Int J Sports Phys Ther*, 2013; 8: 121-128
- Bates D, Machler M, Bolker BM, Walker SC. Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software*, 2015; 67: 1-48
- Behara B, Jacobson BH. Acute Effects of Deep Tissue Foam Rolling and Dynamic Stretching on Muscular Strength, Power, and Flexibility in Division I Linemen. *J Strength Cond Res*, 2017; 31: 888-892
- Behm DG, Kibele A. Effects of differing intensities of static stretching on jump performance. *Eur J Appl Physiol*, 2007; 101: 587-594
- Bialosky JE, Bishop MD, Price DD, Robinson ME, George SZ. The mechanisms of manual therapy in the treatment of musculoskeletal pain: a comprehensive model. *Man Ther*, 2009; 14: 531-538
- Bradbury-Squires DJ, Nofall JC, Sullivan KM, Behm DG, Power KE, Button DC. Roller-massager application to the quadriceps and knee-joint range of motion and neuromuscular efficiency during a lunge. *J Athl Train*, 2015; 50: 133-140
- Drust B, Atkinson G, Gregson W, French D, Binningsley D. The effects of massage on intra muscular temperature in the vastus lateralis in humans. *Int J Sports Med*, 2003; 24: 395-399
- Fouré A, Nordez A, McNair P, Cornu C. Effects of plyometric training on both active and passive parts of the plantarflexors series elastic component stiffness of muscle-tendon complex. *Eur J Appl Physiol*, 2011; 111: 539-548
- Halperin I, Aboodarda SJ, Button DC, Andersen LL, Behm DG. Roller massager improves range of motion of plantar flexor muscles without subsequent decreases in force parameters. *Int J Sports Phys Ther*, 2014; 9: 92-102
- Healey KC, Hatfield DL, Blanpied P, Dorfman LR, Riebe D. The effects of myofascial release with foam rolling on performance. *J Strength Cond Res*, 2014; 28: 61-68
- Hoch MC, Staton GS, McKeon PO. Dorsiflexion range of motion significantly influences dynamic balance. *J Sci Med Sport*, 2011; 14: 90-92
- Hotfiel T, Swoboda B, Krinner S, Grim C, Engelhardt M, Uder M, Heiss RU. Acute Effects of Lateral Thigh Foam Rolling on Arterial Tissue Perfusion Determined by Spectral Doppler and Power Doppler Ultrasound. *J Strength Cond Res*, 2017; 31: 893-900

- Jay K, Sundstrup E, Sondergaard SD, Behm D, Brandt M, Saervoll CA, Jakobsen MD, Andersen LL. Specific and cross over effects of massage for muscle soreness: randomized controlled trial. *Int J Sports Phys Ther*, 2014; 9: 82-91
- Junker D, Stöggl T. The Training Effects of Foam Rolling on Core Strength Endurance, Balance, Muscle Performance and Range of Motion: A Randomized Controlled Trial. *J Sports Sci Med*, 2019; 18: 229-238
- Kalichman L, Ben David C. Effect of self-myofascial release on myofascial pain, muscle flexibility, and strength: A narrative review. *J Bodyw Mov Ther*, 2017; 21: 446-451
- Kirby TJ, McBride JM, Haines TL, Dayne AM. Relative net vertical impulse determines jumping performance. *J Appl Biomech*, 2011; 27: 207-214
- Kuznetsova A, Brockhoff PB, Christensen RHB. lmerTest Package: Tests in Linear Mixed Effects Models. *Journal of Statistical Software*, 2017; 82:
- MacDonald GZ, Penney MD, Mullaley ME, Cuconato AL, Drake CD, Behm DG, Button DC. An acute bout of self-myofascial release increases range of motion without a subsequent decrease in muscle activation or force. *J Strength Cond Res*, 2013; 27: 812-821
- Marchetti PH, Silva FH, Soares EG, Serpa EP, Nardi PSM, Vilela GdB, Behm DG. Upper limb static-stretching protocol decreases maximal concentric jump performance. *J Sports Sci Med*, 2014; 13: 945-950
- McKechnie CJ, Young WB, Behm DG. Acute effects of two massage techniques on ankle joint flexibility and power of the plantar flexors. *J Sports Sci Med*, 2007; 6: 498-504
- Mohr AR, Long BC, Goad CL. Effect of foam rolling and static stretching on passive hip-flexion range of motion. *J Sport Rehabil*, 2014; 23: 296-299
- Morales-Artacho AJ, Lacourpaille L, Guilhem G. Effects of warm-up on hamstring muscles stiffness: Cycling vs foam rolling. *Scand J Med Sci Sports*, 2017; 27: 1959-1969
- Mtibaa K, Thomson A, Nichols D, Hautier C, Racinais S. Hyperthermia-induced Neural Alterations Impair Proprioception and Balance. *Med Sci Sports Exerc*, 2018; 50: 46-53
- Nor Adnan NM, Ab Patar MNA, Lee H, Yamamoto S-I, Jong-Young L, Mahmud J. Biomechanical analysis using Kinovea for sports application. *IOP Conference Series: Materials Science and Engineering*, 2018; 342: 012097
- Papaikakou G. Kinematic and kinetic differences in the execution of vertical jumps between people with good and poor ankle joint dorsiflexion. *J Sports Sci*, 2013; 31: 1789-1796
- Pearcey GE, Bradbury-Squires DJ, Kawamoto JE, Drinkwater EJ, Behm DG, Button DC. Foam rolling for delayed-onset muscle soreness and recovery of dynamic performance measures. *J Athl Train*, 2015; 50: 5-13
- Sağiroğlu İ, Kurt C, Pekünlü E, Özsu İ. Residual effects of static stretching and self-myofascial-release exercises on flexibility and lower body explosive strength in well-trained combat athletes. *Isokinetics and Exercise Science*, 2017; 25: 135-141
- Sayenko DG, Vette AH, Obata H, Alekhina MI, Akai M, Nakazawa K. Differential effects of plantar cutaneous afferent excitation on soleus stretch and H-reflex. *Muscle Nerve*, 2009; 39: 761-769
- Schleip R. Fascial plasticity – a new neurobiological explanation: Part 1. *Journal of Bodywork and Movement Therapies*, 2003; 7: 11-19
- Sefton JM, Yarar C, Berry JW. Massage Therapy Produces Short-term Improvements in Balance, Neurological, and Cardiovascular Measures in Older Persons. *Int J Ther Massage Bodywork*, 2012; 5: 16-27
- Shin MS, Sung YH. Effects of Massage on Muscular Strength and Proprioception After Exercise-Induced Muscle Damage. *J Strength Cond Res*, 2015; 29: 2255-2260

- Su H, Chang NJ, Wu WL, Guo LY, Chu IH. Acute Effects of Foam Rolling, Static Stretching, and Dynamic Stretching During Warm-ups on Muscular Flexibility and Strength in Young Adults. *J Sport Rehabil*, 2017; 26: 469-477
- Sullivan KM, Silvey DB, Button DC, Behm DG. Roller-massager application to the hamstrings increases sit-and-reach range of motion within five to ten seconds without performance impairments. *Int J Sports Phys Ther*, 2013; 8: 228-236
- Tozzi P. Selected fascial aspects of osteopathic practice. *J Bodyw Mov Ther*, 2012; 16: 503-519
- Voogt L, de Vries J, Meeus M, Struyf F, Meuffels D, Nijs J. Analgesic effects of manual therapy in patients with musculoskeletal pain: a systematic review. *Man Ther*, 2015; 20: 250-256
- Weerapong P, Hume PA, Kolt GS. The mechanisms of massage and effects on performance, muscle recovery and injury prevention. *Sports Med*, 2005; 35: 235-256
- Weppeler CH, Magnusson SP. Increasing muscle extensibility: a matter of increasing length or modifying sensation? *Phys Ther*, 2010; 90: 438-449

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