



Hamstring injuries in football:  
an update on the intrinsic risk profile  
*Because the incidence is crying out  
for evidence*

*Joke Schuermans*

*Erik Witvrouw*

*Damien Van Tiggelen*



Doctoral Thesis submitted to fulfil the requirements for the degree of “ Doctor in Health Sciences”:

*“ Hamstring injuries in football: an update on the intrinsic risk profile.  
Because the incidence is crying out for evidence.”*

Doctoral Candidate: Joke Schuermans

Promotors: Erik Witvrouw<sup>1</sup> and Damien Van Tiggelen<sup>2</sup>

Department of Rehabilitation Sciences and Physiotherapy, Faculty of Medicine and Health Sciences, Ghent University

October 12<sup>th</sup>, 2016  
Ghent, Belgium





*“ Qui quaerit, inveniet ”*



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## List of abbreviations

$\alpha$	alpha, level of significance; cut-off value below which the probability of the demonstrated statistical effect cannot be attributed to coincidence (cannot considered to be <i>random</i> ); chance of running a statistical type I error
Ag	Silver
AgCl	Silver Chloride
ANOVA	Analysis of Variance
ASIS	Anterior Superior Iliac Spine
AUC	Area Under the Curve
$\beta$	chance of running a statistical type II error
BF	Biceps Femoris
BF <sub>LH</sub>	Biceps Femoris Long Head
BF <sub>SH</sub>	Biceps Femoris Short Head
Cf.	Confer
CI	Confidence Interval
cm	centimeter
cm <sup>2</sup>	square centimeter
CLES	Contralateral Lumbar Erector Spinae
CPMG	Carr Purcell Meiboom Gill
d	days
DOI	Digital Object Identifier
dr.	doctor
DTS	Direct Transmission System
ECG	Electrocardiography
e.g.	exempli gratia
EMG	electromyography
ES	Erector Spinae

ET	Echo Time
Etc.	et cetera
Exp	exponent
fMRI	functional Magnetic Resonance Imaging
FoV	Field of View
FTF	Finger To Floor
GIFMI	Ghent Institute for Functional and Metabolic Imaging
GM	Gluteus Maximus
H	Hamstrings
h	hours
Hz	Hertz
IBM	International Business Machines ( <i>Corporation</i> )
ICC	Intraclass Correlation Coefficient
i.e.	it est
IWT	Agency for Innovation by Science and Technology in Flanders
Kgs	kilograms
KU	Katholieke Universiteit
LES	Lumbar Erector Spinae
LJMU	Liverpool John Moores University
m	meter
m <sup>2</sup>	square meter
mfMRI	muscle functional Magnetic Resonance Imaging
MH	Medial Hamstrings
mm	millimeter
mo	months
MR	Magnetic Resonance
MRI	Magnetic Resonance Imaging
ms	milliseconds
msec	milliseconds

MANOVA	Multivariate Analysis of Variance
MH	Medial Hamstrings
MVC	Maximal Voluntary Contraction
MTJ	Musculotendinous Junction
n	sample size
OR	Odds Ratio
PCSA	Physiological Cross Sectional Area
pH	pH scale; <i>numeric scale used to specify the acidity or basicity of an aqueous solution</i>
PhD	Philosophical Doctor
PHE	Prone Hip Extension
PKE	Passive Knee Extension
RMS	Root Mean Square
ROC	Receiver Operating Characteristics
ROI	Region Of Interest
ROM	Range Of Motion
rpm	repetitions per minute
RTD	Rate of Torque Development
RTP	Return To Play
R <sup>2</sup>	determination coefficient
p	probability
PATS	Progressive Agility and Trunk Stability
Prof.	Professor
QTM	Qualisys Track Manager
s	seconds
SD	Standard Deviation
SE	Spin Echo
Sec	seconds
SENIAM	Surface Electromyography for the Non-Invasive Assessment of Muscle

sEMG	Surface Electromyography
SET1	Spin Echo T1 (imaging sequence)
SG	Slice Gap
SLHB	Single Leg Hamstring Bridge
SM	Semimembranosus
$S_n$	Signal Intensity at a given echo time (n)
SPM	Statistical Parametric Mapping
SPSS	Statistical Package for the Social Sciences
ST	Semitendinosus
$S_0$	Original Signal Intensity
T	Tesla
TE	Echo Time (Excitation Time)
TR	Repetition Time
TRIPP	Translating Research into Injury Prevention Practice
UEFA	Union of European Football Associations
UZ	Universitair Ziekenhuis
$\mu\text{V}$	microvolt
V	volt
VLAIO	(Vlaams) Agentschap Innoveren en Ondernemen
VMO	Vastus Medialis Obliquus
$\text{VO}_2$	oxygen consumption capacity
wks	weeks
y	years
$\chi^2$	Chi-square
°	degrees
%	percentage
3D	three-dimensional

## Preface

This thesis summarizes the research findings that have been gathered over the course of the last 4 years. It is the product of a close collaboration with supervisor Prof. dr. Erik Witvrouw and valuable advisory guidance by Prof. dr. Damien Van Tiggelen, Prof. dr. Lieven Danneels and Prof. dr. Dirk De Clercq. The research that gave rise to this dissertation was made possible by the financial support of the Agency of Innovation by Science and Technology in Flanders (IWT [*Agentschap voor innovatie door wetenschap en technologie*]), currently governed by the controlling unit VLAIO [*Vlaams agentschap Innoveren en Ondernemen*]), who lend me the honor of receiving a scholarship (Persoonsgebonden Onderzoeksmandaat voor Strategisch Basisonderzoek).

# **General Introduction**





## GENERAL INTRODUCTION

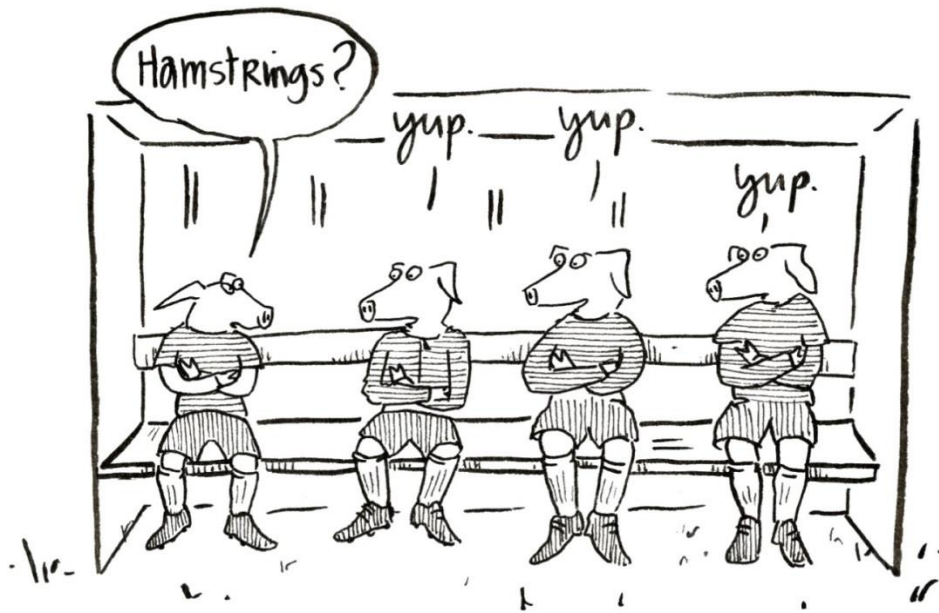
### Scope of the PhD research

#### Epidemiology and pathomechanism

To date, hamstring injuries are still the single most common injury in male football.<sup>15-16, 23, 25-26, 79, 84-85</sup> These injuries represent about 12% of all football related injuries, of which up to 30% reoccur within the same season after return to play.<sup>84-85</sup> Encountering for the fact that a team of 25 players can expect about 6 hamstring injuries per season,<sup>23</sup> each with an average absence from sports of approximately 20 days,<sup>8, 15, 24, 84</sup> the total number of days missed due to hamstring injury adds up to 120 days per team per season. This comes down to 18 matches played without full availability of the entire team, which evidently comes with bothersome repercussions at the level of the individual player, but just as much at team- and club level. The hamstring injury epidemic manifests itself both at the amateur<sup>75</sup> and elite divisions<sup>23-26, 84</sup>, with incidence rates up to 16 and 22% per season, respectively. More so, although the hamstring injury incidence during match play seems to have remained status quo over the years, the injury incidence during training demonstrated a 4% increase since 2001.<sup>24</sup> These unremittingly high (re)occurrence rates are presumably related to insufficient preventive management, incomplete rehabilitation, as well as (*and probably most likely*) to the increasing demands in sports performance. Much effort has already been invested in trying to fully understand the reason for the substantial prevalence of this injury within this athletic population. However, to date, researchers and clinicians are still lacking evidence concerning the exact cause of the particular vulnerability of the hamstring in football and how this should be addressed preferably. Therefore, being subject to a substantial amount of uncertainty, these muscle injuries are notorious rather than famous in the field of sports medicine. After all, due to their high occurrence, they are associated with high expenses in health care and cause the players to be out for prolonged periods of time which has a detrimental influence on performance, overall physical health and psychosocial wellbeing.<sup>34, 36</sup> Particularly, hamstring injuries do not only

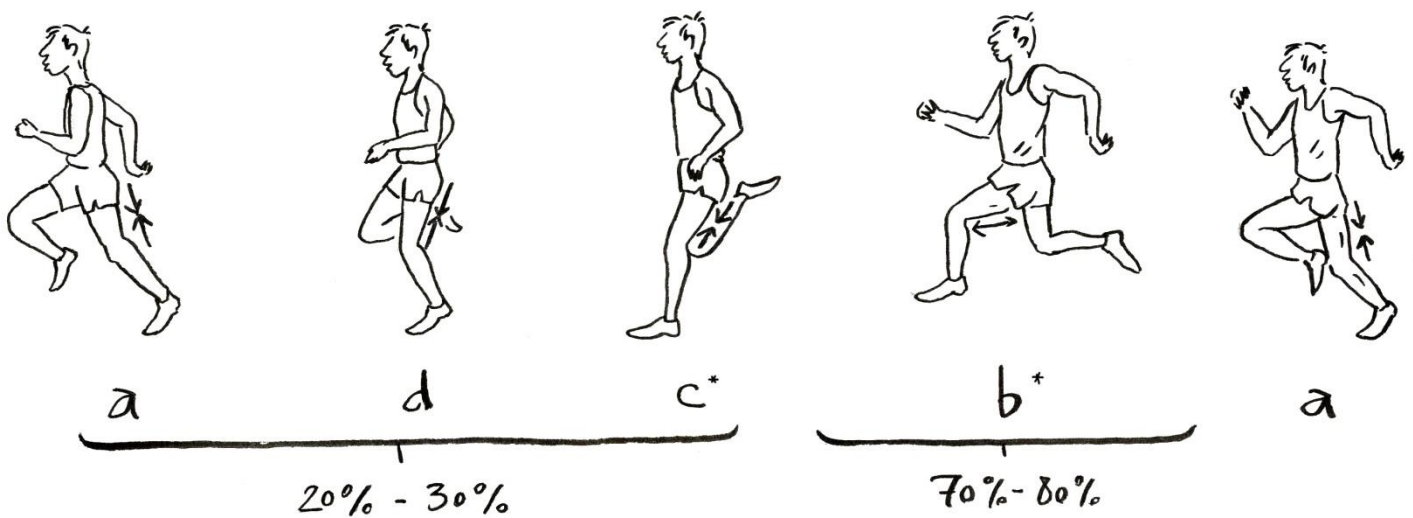
come with expenses in health care for diagnosis and treatment (doctor consults, medical imaging, rehabilitation). They also cause substantial financial losses in elite football due to the fact that the elite player is paid a fixed salary annually, without encountering for possible absence caused by injury. Therefore, an athlete who is unavailable to participate due to injury, is effectively providing less return for his club's financial investment. Let us take a look at possible financial implications of hamstring injuries in Belgium:

Bearing in mind the annual salary the average football player receives in **national competition** (Jupiler Pro League) and the average number of matches missed per season, one hamstring injury would cost the club about €40 000 on an annual basis.<sup>21, 24</sup> When looking at the financial repercussions at amateur level, only taking into account the amateur series of Oost-Vlaanderen for example, annual healthcare expenses are estimated to be as high as €160 000. This was estimated based on the average incidence numbers,<sup>8, 15, 23-24, 84</sup> our health care regulation and the most recent rates in the nomenclature of Belgian healthcare ([www.riziv.fgov.be](http://www.riziv.fgov.be)). Therefore, when encountering for the entire amateur and professional football population in Belgium, the total financial cost of hamstring injuries in football cannot be overlooked and the urgent need for better prevention is beyond dispute.



The biomechanical circumstances under which the hamstring muscle gets injured most often in football, occur during high speed running. In running, the hamstrings are responsible for propulsion through explosive concentric contraction from mid stance to back swing, and for deceleration of the rapid leg movement towards hip flexion and knee extension throughout front swing, by forceful eccentric muscle efforts [Figure 1]. Previous research even demonstrated that the hamstrings have the highest share in producing horizontal force during running acceleration (compared to the other muscles of the lower limb), which emphasizes their importance throughout sprinting.<sup>54</sup> Besides their crucial function in positive and negative torque generation for propulsion and control for (excessive) anterior translation and rotation around the knee and hip, they are responsible for providing the necessary force closure in these joints throughout the entire running cycle as well (due to their biarticular topography). In these terms, it can be stated that the hamstrings are essential in safeguarding lower limb arthrokinematics. For if they would not succeed in providing the necessary force closure (particular during eccentric control in front swing), the hip joints would be at constant risk of impingement, and the vital ligamentous structures within and surrounding the knee joint (anterior cruciate ligament, menisci, joint capsule) would risk being stressed excessively (and as a consequence, sustaining strain injuries and ruptures).

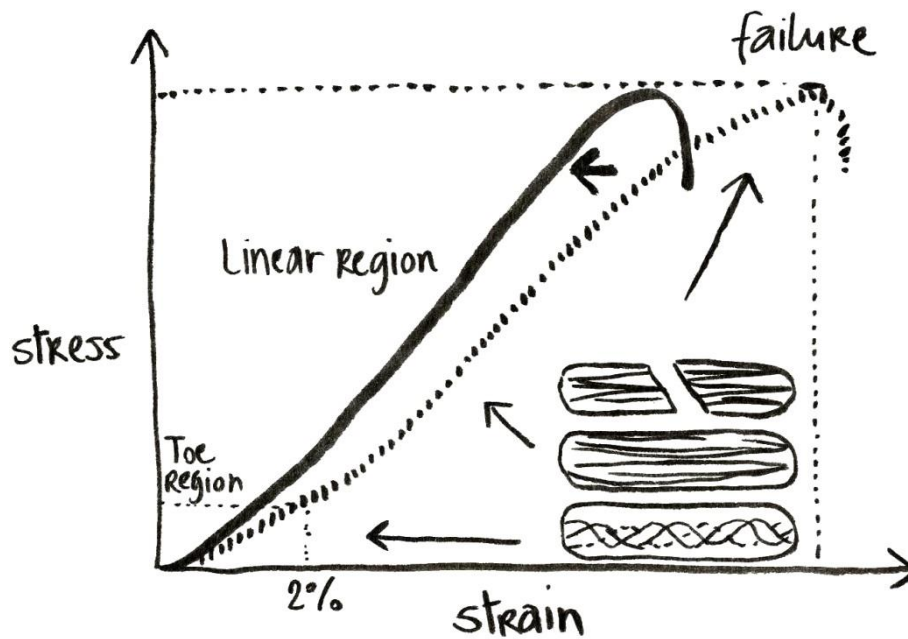
Next to providing the necessary stability in the hip- and knee joint, the negative work performed during front swing, allows the hamstring muscle-tendon continuum to absorb elastic energy. This energy can contribute to augmented force output during the subsequent stance phase, and as such, allows the hamstrings to go to less metabolic expenses and engage in more economic muscle performances. This plyometric muscle function throughout running entails a very efficient mechanism and permits the hamstrings to generate substantial torques towards knee flexion and hip extension (both positively and negatively) in accumulating active and passive force production. Nonetheless, it holds a risk for mechanical overload as well, certainly during explosive accelerations and sprinting where the metabolic and mechanical loads are maximal. Although the hamstrings are anatomically and morphologically ideally suited to engage in these repeated cycles of high speed plyometrics (cf. section ‘Anatomy’), biomechanical research has demonstrated that it is precisely the repeated and intense eccentric muscle-tendon loading during energy absorption in front swing, that ultimately causes the muscles to fail functionally and/or structurally.<sup>18-20, 56, 71</sup> Being exposed to repeated bouts of eccentric loading so frequently and intensely, the hamstrings develop microscopic lesions (micro tears) that cause the muscle-tendon tract to become less compliant and less stretch tolerant.<sup>10, 64, 71</sup> This decrease in muscle-tendon compliance is caused by an increase in connective tissue viscosity (embedded within the muscle fibers and tendon cells) and alterations in mechanical behavior of the muscle-tendon unit caused by these changes in connective tissue characteristics (a left-sided shift in the stress strain curve) [Figure 2]. This implies that the connective tissue will allow less deformation/elongation for the same amount of force/stress imposed on it and thus, will be prone to failure and structural damage prematurely. When not encountered and corrected for, these structural changes and microscopic lesions could ultimately lead to macroscopic strain injury, most frequently occurring during the terminal front swing or initial stance phase in explosive running, when mechanical loads imposed on the hamstring unit are maximized [Figure 1].<sup>18-20, 56</sup>



**Figure 1.** Different phases of the gait cycle in sprinting, where the airborne phase represents up to 80% of the entire gait cycle, whereas stance time is reduced to 20%. (in walking, the gait cycle consists of a 40% swing and a 60% stance phase for each leg). The push-off (a) is followed by the double float phase (b), in which the hamstrings of the front leg are working eccentrically to counteract knee extension and hip flexion and to warrantee a coordinated ground contact at touch down (c), whereas the hamstrings of the hind leg are still working concentrically in continuation of positive horizontal force production during push-off. This double float phase (b) does not only imply heavy loading of the hamstrings, but also requires solid core muscle coordination because the kinetic chain cannot appeal on a stable ground base nor can it benefit from ground reaction forces to amplify force output. The touch down phase (c) is characterized by rapid transition from eccentric towards concentric muscle work in the front leg, as positive horizontal force production needs to remain maximal and a decelerating influence of an inadequate foot strike (oriented too anteriorly of the body centre of mass) needs to be prevented. The mid stance phase (d) during which load transfer for subsequent forceful propulsion occurs, is kept short to optimize plyometric performance.

The arrows indicate where the hamstrings engage in concentric contractions, and where they are loaded eccentrically.

\* Phases of highest risk of strain injury, due to maximization of eccentric work load and hamstring stretch



**Figure 2.** The stress strain curve, representing the visco-elastic properties of connective tissue in function of mechanical load (stress).

Evidently, high speed running is not the only activity in football that holds a relative risk of hamstring injury. Epidemiological research demonstrated that hamstring strain injury occurs during other loading patterns like shooting, dribbling, heading, passing, twisting and jumping as well, albeit to a considerably lesser extent (60% of hamstring injuries are running related, whereas the other 40% happens due to over stretch or excessive loading during the other movement components previously mentioned).<sup>85</sup> Mostly due to the cyclic nature of sprinting biomechanics (same muscle effort / loading is repeated an almost uncountable amount of times during a football match), compared to the limitedly repeated character of the other football specific movements, hamstring injuries occur predominantly during high speed running efforts. Because the plyometric-, and particularly the eccentric loading, is much less voluminous and intense during the other activities also holding a potential biomechanical risk of strain injury, these will not tend give rise to (1) fatigue, (2) accumulation of micro-lesions and (3) changes in tissue properties equally manifestly. Interestingly and with respect to this issue, respective epidemiological studies reported that both the dominant and the non-dominant leg are frequently subject of a hamstring injury,<sup>26, 85</sup> with some evidence for slightly more involvement of the dominant

leg.<sup>70</sup> This could indicate that shooting holds an essential biomechanical risk of strain injury as well, given the fact that the football player will particularly load the hamstrings on his dominant side during shooting, whereas the hamstrings are loaded quite symmetrically in both legs throughout explosive running. To our opinion, and given the epidemiological data (60% of hamstring injuries are running related),<sup>85</sup> this discrete unilateral preference does not indicate that shooting might hold the primary injury mechanism just as much. On the contrary, it only confirms that football players are so susceptible to hamstring injuries due to eccentric overload: although mechanical and metabolic loading during eccentric contraction in shooting is not to be compared with the total amount of load imposed on the hamstrings during sprinting (cf. supra), repeated shooting implies voluminous and intense eccentric hamstring loading just as well. Therefore, although shooting activities only rarely hold the direct injury mechanism, they do make the hamstring more susceptible to injury during sprinting (in having their share in the total amount of eccentric overload).

Acknowledging that sprinting inevitably comes with the highest risk of hamstring injury and possesses the predominant injury mechanism in football, all hamstring injuries mentioned throughout this work will be considered to be running related ones.

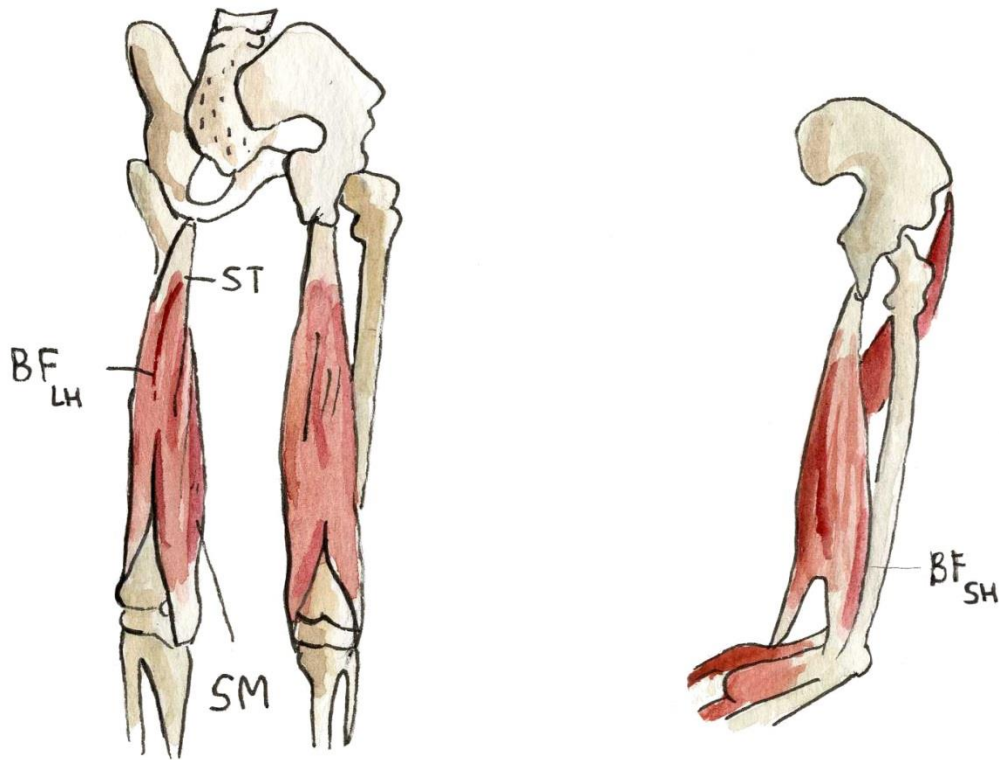
Besides their biomechanical preference which causes these muscle injuries to predominantly occur at terminal swing or initial stance of running, hamstring injuries in football have a topographic preference as well. In these terms, opposed to what has been established in gymnasts and dancers (where a “slow stretch” injury mechanism causes the Semimembranosus (SM) to get injured the most), explosive-running-related injuries practically always involve the long head of the Biceps Femoris (BF<sub>LH</sub>) and to a much lesser extent the Semitendinosus (ST).<sup>5-7, 85</sup> The exact cause of this predominant injury location in explosive running is still under debate. Biomechanical research, modelling hamstring mechanics during sprinting,<sup>18, 37-38, 56</sup> has demonstrated that the BF<sub>LH</sub> undergoes the highest amount of stretch throughout front swing (relative to its resting length). However, the ST has demonstrated having to withstand the highest lengthening velocity and it has been shown that each of the biarticular hamstring muscles significantly contribute to positive and negative work throughout the entire running cycle.<sup>18, 37-38, 56</sup> Therefore, this relative difference in muscle stretch throughout front



swing, cannot provide a robust explanation for the particular injury vulnerability of the  $BF_{LH}$ , compared to the ST. Among other things, it is particularly this  $BF_{LH}$  biased topographic preference of the lesion and the uncertainty around it, that indicates that we still not managed to identify the necessary hamstring injury risk predictors, which hampers successful (secondary) prevention. Attempting to improve our understanding regarding this issue, a first crucial step is acknowledging the structural particularities of each one of the hamstring muscles, because this will essentially influence their function. Therefore, a thorough survey of hamstring anatomy is imperative.

### Anatomy

Situated between the sciatic tuberosity and the proximity of the lower leg, the hamstring muscle unit (*the “ischiocrural” muscles*) covers the hind of the upper leg and controls for motion and stability in both the knee and hip joints. The hamstrings are composed of 4 separate muscle bellies, of which the smallest, the short head of the Biceps Femoris muscle ( $BF_{SH}$ ), only covers the knee joint and its function is limited accordingly. The other three, the  $BF_{LH}$ , the ST and the SM are biarticular, managing both hip and knee kinematics [Figure 3]. The laterally oriented  $BF_{SH}$  and  $BF_{LH}$  originate at the posterior aspect of the femoral bone and the sciatic tuberosity, respectively, and have a common insertion at the distal and lateral aspect of the knee joint, upon and around the head of the fibular bone. At their distal insertion they branch into multi-directory tendinous and fascial ramifications towards the collateral lateral ligament, joint capsule, lateral tibia and iliotibial tract. The ST and SM originate at the sciatic tuberosity as well and insert distally from the medial aspect of the knee joint. The ST has a medio-anterior insertion at the superficial Pes Anserinus on the proximity of the medial surface of the tibial bone, whereas the SM inserts at the postero-medial aspect of the joint capsule, deep from the ST trajectory. At their proximal insertion, the  $BF_{LH}$  and ST share a common tendon, whereas the SM has a separate tendinous origin [Figure 3].



**Figure 3.** Illustration of the biarticular muscle trajectory of the laterally oriented  $BF_{LH}$  and the medially oriented  $ST$  and  $SM$ , crossing both the hip and knee joints. In the right hand side flexed knee image, the mono-articular  $BF_{SH}$  can be identified underneath the  $BF_{LH}$ .

At both the proximal and distal muscle insertions, the biarticular muscle bellies consist of a large myotendinous junction (MTJ) and a free tendon. Taken together, this tendinous component encompasses a very large percentage of the entire muscle length [Table 1].<sup>83</sup> To what extent the length of the biarticular muscle is interwoven with tendon tissue, differs per muscle. When taking into account the proximal and distal tendon representatives, relative to the entire muscle length, the  $BF_{LH}$  consists for 120% of tendon tissue (i.e. the accumulative percentage). This is 87% for the  $ST$  and 133% for the  $SM$  [Table 1].

**Table 1 Tendon and Myotendinous Junction (MTJ) lengths of the hamstring muscles as a proportion of muscle length.**

		<u>Approximate Percentage (%) of Muscle Length</u>			
		<u>BF<sub>SH</sub></u>	<u>BF<sub>LH</sub></u>	<u>ST</u>	<u>SM</u>
<b>Proximal Tendon</b>	Free tendon (%)	NA	15	3	25
	MTJ (%)	NA	45	27	48
<b>Distal Tendon</b>	Free tendon (%)	2	20	25	15
	MTJ (%)	36	40	32	45

*Data adapted from Woodley and Mercer displaying approximate percentages.*

*NA=not applicable (as lacks a proximal tendon of insertion)<sup>82</sup>; %, Percentage; MTJ, Myotendinous Junction*

As presented in table 1, the SM has the largest tendon component of all three biarticular muscles. The BF<sub>LH</sub> has a very similar muscle/tendon ratio whereas the ST consists of considerably less tendon tissue. This difference in muscle architecture between the BF<sub>LH</sub> and ST is remarkable, as it is generally known that function follows form and vice versa. This indicates that, although sharing a proximal insertion and being interwoven throughout their proximal myotendinous junction, the BF<sub>LH</sub> and ST are designed to serve different purposes. The relatively short proximal free tendon of the ST (compared to the BF<sub>LH</sub> and SM) and its substantial tendon-free muscle fiber portion most probably make this lean muscle more compliant and more suited for force production throughout the entire range of motion with a smaller tendency to tighten or become stiffer due to repeated loading. On the contrary, containing more tendon tissue, the BF<sub>LH</sub> (and SM) can probably rely on a larger additional passive force output and should be capable of storing larger amounts of elastic energy during eccentric contraction. Nonetheless, these relatively viscous tissue characteristics (compared to the ST) might also cause the BF<sub>LH</sub> and SM to stiffen more rapidly, certainly taking into account the massive amounts of eccentric work they have to engage in.

Next to topography and muscle/tendon relations, fascicle length, pennation angle and physiological cross sectional area (PCSA) are key determinants in elongation - and force production capacity of muscle tissue, and thus the amount of load the muscles are able to bear. Therefore, respective features have important implications in terms of muscle function and injury vulnerability as well.<sup>80, 82</sup> As a

whole, the hamstring muscle complex has been described as being morphologically quite lean and consisting of fairly long muscle fibers with a rather small PCSA, indicating that this muscle unit is meant to be active throughout relatively long excursions. Next to their supposed functionality over extensive ranges of motion, this type of configuration is also associated with the capacity to withstand considerable amounts of stretch (which explains their predominant function in energy absorption through negative work in high speed running). However, in considering the morphometric characteristics of the different muscle bellies separately, it has been established that the four hamstring muscle bellies differ considerably in terms of pennation angle, fibre length and PCSA [Table 2].<sup>82</sup> The muscle fibres and fascicles of the BF<sub>LH</sub> and SM are relatively short in length, have a fairly large PCSA and considerable pennation angles (both uni- and bipennate muscle trajectories). This in contrast to the BF<sub>SH</sub> and ST, which are more lean and consist of longer fascicles with a smaller volume and no bipennate junctions, implicating that these muscles have to deal with smaller amounts of intramuscular shear forces during contraction and elongation than their more voluptuous neighbours (BF<sub>LH</sub> and SM). These discrete intermuscular variations in muscle morphology, suggest that the BF<sub>LH</sub> and SM are primarily suited for explosive force production in the midrange of motion, and are, because of their muscle fibre properties and substantial tendinous component, more prone to overuse and strain injuries. On the other hand, the BF<sub>SH</sub> and ST ought to be more stretch tolerant and best suited for moderate force production throughout a more extended range of motion.

	Mean Fascicle Number	Mean Fascicular Length (cm)	Mean Fascicular Volume (ml)	Mean Fascicular PCSA (cm <sup>2</sup> )	Mean Total Compartmental PCSA (cm <sup>2</sup> )
<b>BF<sub>SH</sub></b>	12	12.4	3.6	0.29	2.98
<b>BF<sub>LH</sub></b>	22	7.0	3.4	0.49	10.06
<b>ST</b>	27	9.0	2.7	0.27	8.08
<b>SM</b>	28	5.0	2.9	0.58	15.75

*BF<sub>SH</sub>*, Biceps Femoris Short Head; *BF<sub>LH</sub>*, Biceps Femoris Long Head, *ST*, Semitendinosus; *SM*, Semimembranosus; *cm*, centimeter; *ml*, millimeter; *cm<sup>2</sup>*, square centimeter

Aside from anatomy and morphology, their dual innervation also increases the risk of hamstring strain injury. The entire hamstring unit is neurologically guided by the sciatic nerve, which is composed by the radices leaving the spinal cord between the 4<sup>th</sup> lumbar and the 2<sup>nd</sup> sacral vertebrae to proceed their peripheral trajectory. However, depending on the level at which it branches into the tibial and common fibular nerve divisions, the biarticular muscles are innervated by the sciatic and the tibial nerve whereas the BF<sub>SH</sub> is guided by the fibular (and sciatic) nerve. Certainly taking into account the large range of anatomical variations, the variety in neural guidance within the hamstring complex might cause asynchronous motor unit excitation and asynchronous muscle contraction, inducing excessive muscle load and shear stresses in certain muscle–tendon regions.

In these terms, the anatomo-morphological profile of the hamstring muscles (biarticular trajectory, dual innervation, considerable muscle/tendon ratio) and in particular the inter-muscular differences, certainly provide a partial explanation for the high injury vulnerability of this muscle group. It also somewhat elucidates the particular injury vulnerability of the BF<sub>LH</sub> muscle, which is probably challenged most during explosive running and kicking activities as it

1. Consists of fairly long proximal and distal free tendon- and MTJ components and voluptuous muscle fibers, which make it less stretch tolerant
2. Is designed to produce higher amounts of muscle force (morphometry), which increases the imposed loads and intramuscular shear stresses
3. Shares a proximal tendon with the ST and a distal tendon with the BF<sub>SH</sub>, which, certainly acknowledging the different innervation of the BF<sub>SH</sub>, increases the risk of excessive intramuscular shear stress (more so in case of asynchronous contraction and deficiencies in synergistic coordination)
4. Has more multi-directional connective tissue connections with adjacent structures than its neighbours: sacrotuberous ligament, ST muscle fibers, fibular head, collateral lateral ligament, knee joint capsule, lateral tibia, iliotibial tract (via BF<sub>SH</sub>); which increases shear stress and tissue loading

5. Consists of a distal myotendinous junction in which both the homonymous fibres as well as the fibers of the BF<sub>SH</sub> insert under a 45° pennation angle, which potentially causes excessive, misdirected muscle-tendon stress in case of asynchronous muscle contraction with regard to both muscle bellies (which is plausible given the difference in neural guidance)
6. Undergoes the highest amount of stretch throughout the front swing phase of running<sup>19</sup>
7. Has a type II (fast twitch) fibre dominance which makes it prone to acidification and fatigue quite early (as is the case for the entire hamstring unit)<sup>32</sup>

Although the muscle architecture most probably holds a constitutional susceptibility to strain and this cannot be remediated, it also puts emphasis on the inherent differences in muscle function and loading characteristics. Being designed to serve varying purposes and to meet different (mechanical) demands, the quality of intra-muscular coordination and interplay between the biarticular hamstring muscle bellies is most probably essential with regard to individual load bearing capacity and tissue homeostasis of the separate muscle bellies. Bearing in mind that the BF<sub>LH</sub> and ST share a proximal tendon and (as such) have to withstand similar mechanical loads imposed on the proximal myotendinous junction, the nature and quality of intramuscular cooperation within this particular functional muscle entity is most probably imperative in the running related hamstring injury risk. Quite interestingly, exactly these two muscles are prone to the explosive running type of hamstring injuries (the BF<sub>LH</sub> being remarkably more involved).<sup>6</sup>

### **Rehabilitation and prevention**

To accurately prevent a(ny) sports injury, it is essential to deal with its cause, which mostly comprises of the injury mechanism and the intrinsic risk factors that made that particular athlete susceptible to injury under the given playing circumstances. However, certainly in rehabilitation (secondary injury prevention), the therapeutic policy is still primarily based on symptomatic management, with dominant focus on restoring local tissue homeostasis and isolated muscle function. This merely comes down to normalizing the patients clinical presentation, which is characterized by pain on palpation,

muscle elongation and resisted contraction (differential diagnosis of muscle – tendon injuries). Apart from this symptomatic treatment (which is a vital first step in secondary rehabilitation), the search for the exact cause of the injury is tended to be neglected.



When wanting to encounter these potential causative factors in (secondary) prevention, their possible involvement in hamstring injury susceptibility needs to be brought to the evidence and that is where the shoe pinches. Due to the lack of prospective research, the only factors of which the association with an increased hamstring injury risk have been brought to evidence are age, injury history and muscle strength.<sup>19</sup> When looking at this evidence, it seems that in terms of this muscle strength, only Quadriceps peak torque has been identified as a valid risk estimate of hamstring injury susceptibility. Likewise, the role of hamstring flexibility or stretch tolerance in injury risk reduction is still under discussion (although always considered to be essential in hamstring injury prevention, certainly acknowledging the injury mechanism and the vital capacity of producing strength in lengthened state

conditions as is the case in high speed running).<sup>19, 76</sup> Involvement of other potential risk associates has been explored throughout the years, but due to limitations in study design and conflicting results in between studies, the current evidence for the intrinsic hamstring injury risk profile has remained limited. In an attempt to increase insights in the high hamstring injury risk in football, multiple studies with varying methodological designs have already been conducted. Approximately, those studies can be categorized into four groups: (1) observational and describing research, (2) retrospective research, (3) prospective research and (4) interventional research. Although observational and retrospective studies might contribute to better understanding as regards the pathomechanics and underlying intrinsic risk factors, actual scientific evidence for the role of certain features in hamstring injury occurrence can only be gathered by pooling the results of prospective and interventional research. Unfortunately, respective studies come with methodological challenges (time management, financial burden, prone to bias, statistical power, etc.) that frequently incline the researcher to opt for more feasible designs. Nonetheless, a limited amount of prospective (3) and interventional (4) studies has assessed the causal effect of clinical or functional features on hamstring injury occurrence (3) and the effect of particular rehabilitation regimens on time to return to play (RTP) and risk of recurrence (4). Factors that demonstrated to have a significant influence on future hamstring injury occurrence are: previous hamstring injury,<sup>9, 19</sup> bilateral eccentric strength imbalances,<sup>9, 19, 21</sup> deficits in conventional and functional (mixed) isokinetic antagonist strength ratios,<sup>69</sup> deficits in muscle flexibility<sup>80</sup> and weaker performance on the Single Leg Hamstring Bridge (SLHB) test.<sup>29</sup> Intervention studies, looking at the protective effect of including certain exercises in (secondary) prevention protocols, assessed the relevance of implementing the Nordic Hamstring exercise,<sup>2</sup> early stage lengthened state strength training,<sup>8, 73</sup> additional core-stability and agility training,<sup>66</sup> and correcting for pre-seasonal strength imbalances,<sup>21</sup> amongst others. Unfortunately, most of the results deducted from respective prospective research have been contradicted by similar studies<sup>19</sup> and the interventional studies do not sufficiently allow risk appraisal because they only encounter time to RTP and hamstring injury recurrence in their prediction models, without checking the underlying effect of the intervention. The actual factor, responsible for the development of or protection against injury, is generally not identified (apart from the studies adjusting isokinetic strength deficits and verifying associated effects).<sup>21</sup> Therefore, at



present, we can only be certain of the detrimental involvement of eccentric hamstring deficits (relative to other side or quadriceps strength) and hamstring injury history.<sup>19</sup>

In terms of retrospective research results (2), it has been demonstrated that hamstring injuries might lead to morphological changes,<sup>44, 67</sup> neuromuscular inhibition,<sup>31</sup> strength<sup>44, 47, 72</sup> and flexibility<sup>47</sup> deficits, as well as alterations in running biomechanics.<sup>11, 44, 63</sup> Whether these dysfunctions really increase the risk of future injury or reinjury, and can thus be defined as both consequence and potential cause of hamstring injury, cannot be stated based on the available evidence.

Lastly, in terms of pathomechanism, existing observational studies concluded that the terminal swing and initial stance phases of high speed running most probably hold the primary injury mechanism because mechanical loads on the hamstring muscle-tendon continuum reach their maximum within that timeframe.<sup>18, 20, 63</sup> Because of the mechanical properties of connective tissue, we can indeed assume that repeated strain, induced by intense negative work in the distal range of motion, causes the hamstring muscle-tendon unit to fail when mechanical stress is the highest (inciting event). To confirm this pathogenic model prospectively, one would have to submit a football player to a monstrous high speed running protocol to exertion, after a period of voluminous and high intensity training exposure and check whether the voluntary participant would actually injure his hamstrings due to excessive strain in terminal front swing. Evidently, this would be quite unethical and methodologically impossible to verify. Related biomechanical research also suggested that proximal muscle activity (muscles within pelvis and trunk unit) has the capacity to increase and decrease hamstring muscle loading throughout running,<sup>19</sup> which appeared to be the case as well for kinematic running features like the amount of forward trunk lean.<sup>39</sup> Likewise, although making perfect sense in theory, these features cannot be defined as actual risk factors for hamstring strain injury, without confirming evidence through injury risk prediction in prospective research approaches.

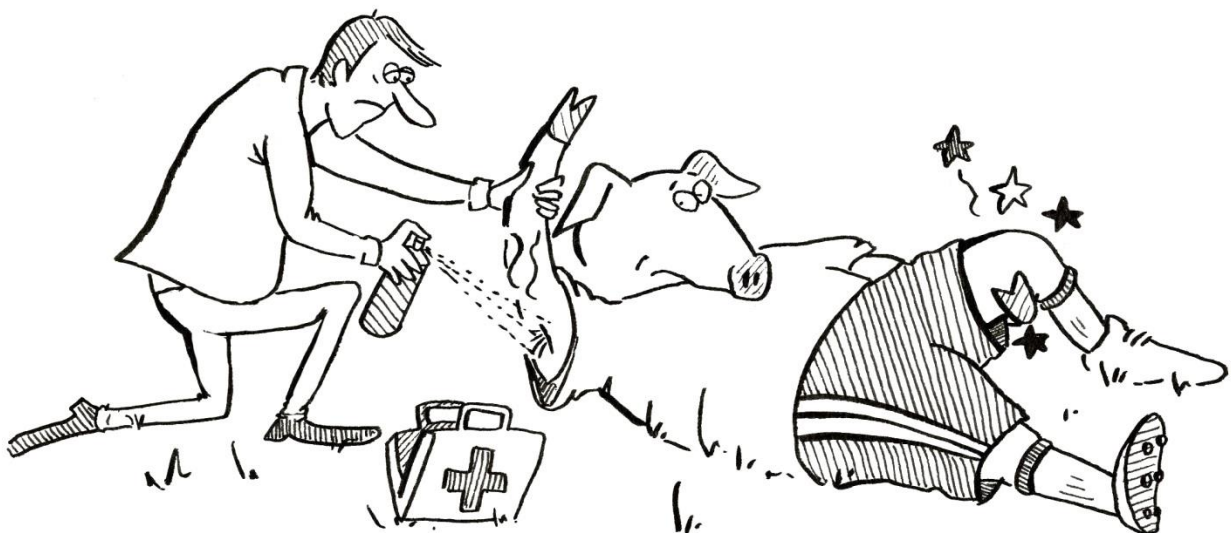
This means that when assessing and addressing the relative risk to hamstring injury in a football player, the practitioner is largely given the brush-off as concerns valid clinical risk estimates for hamstring injury risk appraisal and sufficient causal (secondary) prevention. Rehabilitation regimens

commonly consist of manual therapy, stretching and strengthening exercises, with a varying level of intensity and pace of progression, in function of the location and the extent/severity of the lesion. Essentially, these treatment strategies come down to symptom relief as the dysfunctions identified in the clinical examination (pain on palpation, stretch intolerance and bilateral strength deficits) are being addressed without further ado. Due to lack of supporting evidence, the detrimental intrinsic risk profile cannot be remediated appropriately. It is therefore not incomprehensible, that hamstring injuries tend to (re)occur this extensively.<sup>8, 67</sup> The essential search for comorbidities, associated complaints/dysfunctions and underlying risk factors within the patients locomotor system is left out. Rehabilitation and secondary prevention are still mainly symptom-contingent, and primarily (or solely) based on the structural characteristics of the lesion and the patient's clinical presentation. The fact that (secondary) hamstring injury prevention generally comprises of flexibility and strength training (and this has been demonstrated not to be very successful), points out that the hamstring injury risk is definitely not primarily based on these local muscle characteristics, but that much more needs to be explored. Research urgently needs to invest in prospective studies, in which both primary<sub>1</sub> and secondary<sub>2</sub> hamstring injury risk is investigated. This preferably by using first<sub>1</sub> and repeated<sub>2</sub> hamstring injury occurrence as primary dependent outcome measures, in association with comprehensive screening or intervention protocols.

Although former research was not able to validly amplify the intrinsic risk profile with some sports- and injury-mechanism-related risk estimates to implement in rehabilitation and prevention, it certainly made a deserving attempt to do so. By exploring possible involvement of running biomechanics<sup>19, 39, 44</sup> and neuromuscular inhibition<sup>31</sup> after injury and their potential influence on reinjury susceptibility, and the beneficial influence of incorporating core stability and agility exercises in rehabilitation regimens,<sup>29, 66</sup> fellow researchers already put emphasis on the need for investigation of intra- and intermuscular neuromuscular coordination in hamstring injury risk prediction (and reduction). However, to date, no studies have been conducted trying to verify the influence of neuromuscular coordination on hamstring injury susceptibility using prospective methodological designs. Therefore, the studies embedded within this doctoral dissertation, wanted to take the first steps in the right

direction. In this doctoral dissertation, we decided to explore the possible role of coordination in the intrinsic hamstring injury risk profile because:

- monitoring for local features of muscle function and load bearing capacity (adequate hamstring strength and flexibility) clearly does not suffice to weapon the football player against injury.
- intramuscular variations in anatomy and morphology suggest discrete differences in functional purposes in between the different hamstring bellis, which stresses out the necessity of solid **intramuscular coordination**.
- the football game consists of a variety of highly complex and explosive movement patterns that come with substantial biomechanical and metabolic demands on every link in the athlete's kinetic chain, certainly as regards the hamstrings.<sup>69</sup> These complex biomechanical conditions demand an optimal technical and physical performance capacity, which can only be achieved when all links within the kinetic chain engage in adequate **intermuscular coordination**.



## Summary

To summarize the state of the art with regard to hamstring injuries in male football, it can be stated that male football players continue to present themselves relatively susceptible to (re)injury due to

- the large volumes of repeated explosive running efforts during football exposure
- the architectural characteristics of the hamstrings (and the inter-muscular differences)
- lacking evidence concerning the underlying intrinsic risk factors, disabling the development of effective prevention strategies and making the individual athlete prone to injury during explosive running

One needs to bear in mind that all sports that involve sprinting and explosive changes in running pace and running direction, hold a relative risk of hamstring injury due to (1) the mechanical loads involved and (2) the anatomy and morphometry of the hamstrings. Therefore, it is essential that maximal effort is being invested in unraveling the complex intrinsic risk profile in an attempt to rescue the hamstrings out of this precarious situation.

## Aim of the PhD research

### Research content

The aim of this research project was to verify

- (1) what makes the BF<sub>LH</sub> more vulnerable to strain injury than its medial opponents, other than muscle anatomy and amount of stretch during the front swing phase of running, and
- (2) whether the quality of neuromuscular coordination within and beyond the hamstring muscle unit is associated with hamstring injury
- (3) which biomechanical characteristics during explosive running might be detrimental and potentially harmful, predisposing a certain football player to a hamstring injury.

Attempting to solve respective questions and to provide the stakeholder with useful guidelines for assessment, rehabilitation and prevention, this work primarily aimed to identify significant (modifiable) intrinsic risk factors for hamstring injuries in male football players. As mentioned earlier, current research and clinical practice have been focusing on local hamstring muscle features and function. Nonetheless, addressing the entire ‘kinetic chain’ is increasingly becoming standard in general (sports) injury prevention.<sup>1, 3, 53, 55, 61, 77</sup> In line with this contemporary evolution and acknowledging the structural (and presumably according functional) particularities of the BF<sub>LH</sub>-ST unit, this dissertation goes more deeply into the relevance of investigating features of neuromuscular coordination within the hamstring muscle unit and in adjacent kinetic chain regions, for the purpose of hamstring injury risk prediction.

More specifically, the following items were thoroughly depicted on association with elevated hamstring injury risk:

- (1) Exercise related hamstring muscle metabolism and **intramuscular** coordination
- (2) Posterior chain muscle functioning and quality of the **intermuscular** coordination
- (3) **Core – and thigh muscle activation patterns** as well as **lower limb and trunk kinematics** during high speed running

These topics are tackled in Chapters I to III. In the first chapter, the role of metabolic muscle functioning (*intramuscular coordination*) in hamstring injury vulnerability is investigated by assessing the metabolic hamstring response to exercise. In looking at the individual activations features of the different hamstring muscle bellies and the characteristics of inter-muscular coordination within the entire muscle unit, we wish to investigate the functional differences between the hamstring muscle bellies (in particular as concerns the BF<sub>LH</sub> and ST) and the associated location-specific injury vulnerability. To do so, muscle functional magnetic resonance imaging was used. By assembling the T2 map of the acquired T2 weighted Magnetic Resonance (MR) image and repeating this before and after exercise, we could establish which muscle fibers were activated most and whether variability in this muscle recruitment pattern could be associated with elevated hamstring injury vulnerability.

Although this technique has already been used to examine hamstring muscle function in previous research, this has never been done in direct association with the hamstring injury risk. Nonetheless, respective studies did attempt to make a contribution to better injury prevention, as those mfMRI protocols were conducted to select exercises to predominantly address the most frequently injured BF<sub>LH</sub>, assuming that selectively addressing this muscle would make it less vulnerable for strain injury (relative to its neighbours).<sup>49, 51-52</sup> These studies never verified to what extent the exercises they elected had any effect on BF recruitment or strength using an interventional approach, nor did they search for an association with hamstring injury occurrence. Therefore, the studies embedded within Chapter I, were the first ones to investigate the clinical relevance of investigating intramuscular activation features (coordination) in relation to hamstring injury susceptibility in football players.

Chapter II explores the *intermuscular coordination* features and discusses the utility of the Prone Hip Extension exercise to assess neuro-muscular coordination deficiencies in the posterior chain continuum (lower back muscles – gluteal muscles – hamstrings) and respective association with hamstring injuries. Inspired by similar research in the domain of chronic low back pain and sacro-iliac joint dysfunctions,<sup>4, 33, 49, 69, 78</sup> the second chapter describes the investigation of the muscle recruitment pattern during a simple prone hip extension task, and verifies if certain muscle recruitment features are possibly detrimental in terms of hamstring injury predisposition. In adopting his PHE test, existing research has primarily been focusing on:

- the absolute timing of muscle activity in each of the investigated muscle groups,
- the relative timing of those muscles with respect to the activity onset of one another (the activation sequence) and
- the amount of muscle activity displayed by each muscle group.

This has mostly been done to assess the quality of motor control in the lumbo-pelvic-hip complex with respect to low back (or sacro-iliac joint) complaints.<sup>3, 13, 17, 40-42, 45, 57, 59, 61-62, 74</sup> Those studies checked whether the above mentioned outcome measures differed in function of the presence of low back complaints, and mostly concluded low back dysfunctions to be associated with a delay in activity

onset of the Gluteus Maximus, rather than with particular alterations in the relative activation sequence or the amount of muscle activity presented by each of the intended muscles.<sup>3, 13, 17, 40, 45, 62</sup> Only one study examined these features in relation to the presence of a hamstring injury history.<sup>26</sup> These authors only assessed the amount of muscle activity and not the timing of muscle activation within the posterior chain. Their retrospective analysis revealed that subjects with a hamstring injury history demonstrated higher amounts of normalized muscle activity in the medial hamstrings and the Gluteus Maximus compared to those without a history of hamstring injury, most probably due to neuromuscular compensation strategies caused by the injury. Only one other study examined the timing of muscle activity during the PHE test with respect to lower limb injuries. Similar to what has been established in motor control research in the context of low back pain, those study results revealed a delay in Gluteus Maximus activity in subjects with a history of lateral ankle sprain compared to their healthy controls.<sup>14</sup> In the second chapter we wanted to verify the importance of muscle activation features during this PHE in determining the hamstring injury risk in football players, primarily focusing on the timing of muscle activity. This because previous research and theoretical frameworks have pointed out the importance of adequate lumbo-pelvic control in protecting the hamstrings against overload as well, mostly identifying the activity onset of the gluteus maximus as the essential outcome measure.<sup>41, 61, 57</sup>

Finally, Chapter III adopts an even broader perspective and explores the causal association between **sprinting biomechanics** and hamstring injury risk. This was done by assessing whether *lower-limb and core kinematics* as well as *muscle activation patterns* during the critical phases of the running cycle, are able to predict hamstring injury occurrence. Previous observational research already adopted similar methodological approaches to gather insights in mechanical loading of the hamstrings throughout the gait cycle in high speed running and the possible effects of muscle activity and kinematics in the lumbo-pelvic region on these hamstring mechanics.<sup>18-20, 43</sup> However, this has never been done in prospective study approaches actually allowing identification of a possible causal relationship between muscle activation or kinematic features during sprinting and the likelihood of

hamstring injury occurrence during post hoc monitoring for injury registry. Chapter III attempted to fill this gap.

For each of the studies embedded within these three chapters, a homogeneous sample of amateur football players was recruited (1<sup>st</sup> and 2<sup>nd</sup> provincial series – Oost-Vlaanderen, Belgium). Screening and assessment of the above mentioned risk estimates was conducted during the 2013 off-season period, after which the participants were monitored for hamstring injury occurrence until the 2014-2015 winter break. Hereafter, all data were sorted and submitted to statistical analysis for injury risk prediction. The results of the separate studies are comprehensively documented in Chapters I, II and III.

### Research approach

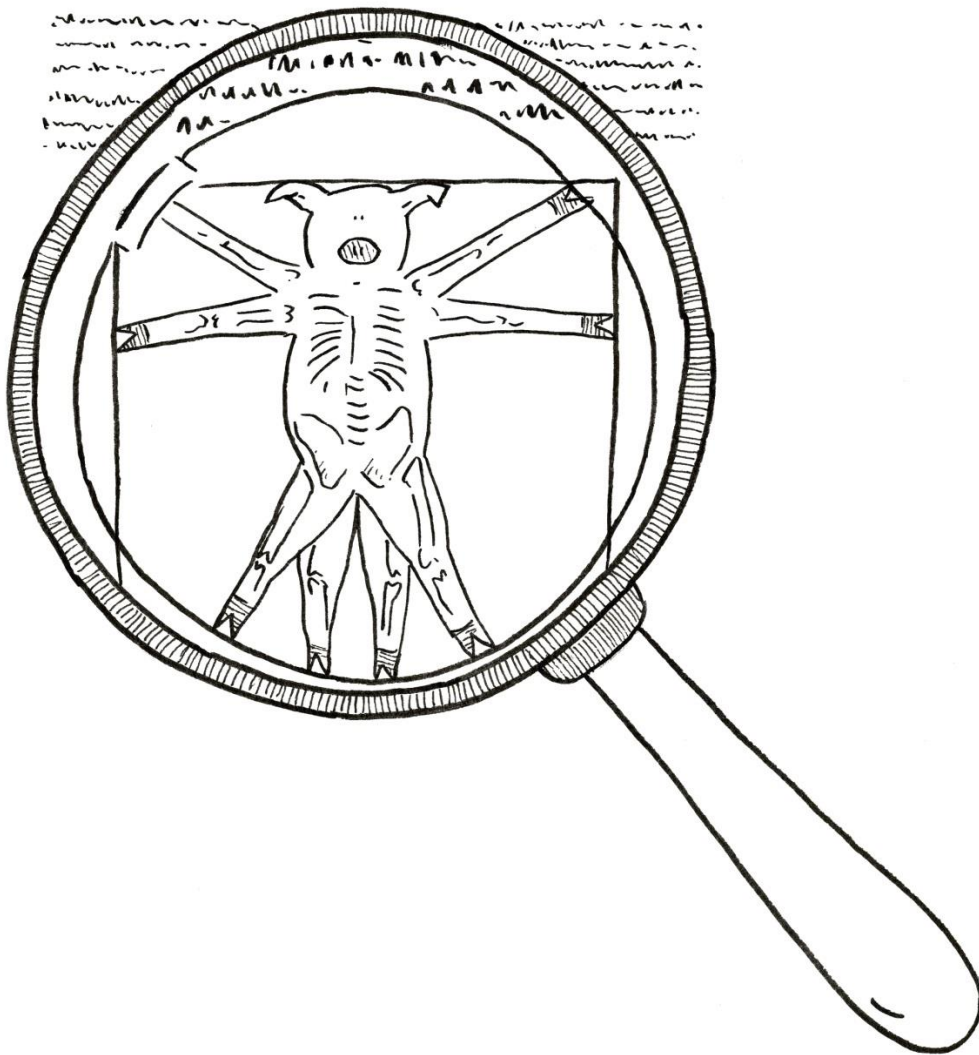
To enhance the reader's understanding of the methodological approaches adopted within this work, the following concluding paragraph will succinctly run through the different techniques and their individual particularities, used to map the neuromuscular coordination features within and beyond the hamstrings.

Each of the chapters included in this dissertation, discusses the investigation of neuromuscular coordination features: starting within the hamstring unit and progressively encountering for the synergist and antagonist muscles in functional and injury-mechanism-related setting as well. To serve these purposes, different methodological approaches were used, depending on the main research question that was posed in the build-up of every study. In the first chapter, muscle functional Magnetic Resonance Imaging (mfMRI) was attributed because this technique provides the best spatial resolution and allows to differentiate activity differences **within the hamstring muscle unit**. Although this imaging technique does not allow to assess innervation behavior of the muscle or timing of muscle activity (unlike surface electromyography recording (sEMG)), it was best suited to verify the metabolic activity demonstrated by each hamstring muscle and therefore also the extent of



(dis)similarity between respective muscles. Muscle functional MRI provides the opportunity to accurately quantify the amount of metabolic activity exerted by the intended muscle (unit) in comparing the muscle tissue signal intensity in a T2 weighted image before and after exercise. By contrast with T1 weighted images, that are used to assess anatomy with the best accuracy, T2 weighted images are more sensitive for (pathological or functional) changes in the content of tissue water (as is the case for the presence of edema or osmotic fluid shifts related to muscle metabolism). Comparing the T2 relaxation time, demonstrated by each hamstring muscle separately, before and after exercise, enabled us to verify which hamstring muscle had been activated the most and whether this activation pattern had any effect on hamstring injury predisposition within our sample of football players. When using the term muscular ‘activation pattern’ throughout the papers embedded within the first chapter, we refer to the extent of motor unit recruitment and associated metabolic activity demonstrated within respective muscle (bellies). As such, the terms ‘activation pattern’, ‘muscle recruitment’ and ‘metabolic activity’ are to be interpreted identically. In the second chapter, the activation sequence within the posterior sling (including the hamstrings, gluteus maximus and lumbar erector spinae) was our topic of interest. Next to amount of muscle activity (the amount of motor units recruited to participate in contraction), the capacity to generate muscle activity (and strength) rapidly or precisely in function of time (depending on the biomechanical conditions of the movement task), is essential for effective and safe functioning. Because the hamstrings, hip and back muscles are part of a synergistic extension unit and have to work together in a well-balanced manner both as regards amount and timing of muscle activity, we wanted to verify whether this **intermuscular** coordination pattern could be involved in hamstring injury vulnerability as well. The main outcome variables within the electrical signal acquired by means of sEMG are (1) amplitude and (2) firing frequency: (1) indicating the amount of motor units participating in electrical discharge (depolarization) and (2) indicating the frequency with which the motor neurons provide the underlying muscle fibers with these electrical impulses. As such, the rise of the amplitude of the sEMG signal or more specifically, the time the intended motor units needed to present an activity amplitude that significantly rose above baseline, was the variable of interest in Chapter II. Chapter III wanted to investigate the importance of intermuscular and kinematic coordination during sprinting (because this activity holds the primary

injury mechanism). This was assessed by submitting the participants to a comprehensive **multi-muscle sEMG analysis** (to assess the innervation behavior of the hamstrings and core muscles) and a **three-dimensional motion analysis** (to assess the segment and joint excursions in core and lower limb) during sprint acceleration. Although quality and quantity of movement and muscle activity are supposed to be interrelated, movement outcome can be mediated by an infinite spectrum of neuromuscular coordination strategies,<sup>80</sup> which makes it difficult and incorrect to draw conclusions regarding running coordination and hamstring injury susceptibility by solely assessing the sEMG signals or kinematic curves throughout the gait cycle in sprinting. Therefore, both methodological approaches were attributed in the third and final chapter.



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# **Chapter I**

## Intramuscular coordination in hamstring injury susceptibility



# CHAPTER I – PART I

Biceps femoris and semitendinosus – team mates or competitors?

*New insights into hamstring injury mechanisms in male football players: a muscle functional MRI stu*



## CHAPTER I – PART I

### **Biceps femoris and semitendinosus – team mates or competitors? New insights into hamstring injury mechanisms in male football players: a muscle functional MRI study**

Joke Schuermans, MS,<sup>1</sup> Damien Van Tiggelen, PhD,<sup>1</sup> Lieven Danneels, PhD,<sup>1</sup> and Erik Witvrouw, PhD<sup>1,2</sup>

<sup>1</sup> Department of Rehabilitation Sciences and Physiotherapy Ghent, Ghent University, Ghent, Belgium

<sup>2</sup> Department of Physiotherapy, Aspetar, Doha, Qatar

Correspondence to Schuermans Joke, Department of Rehabilitation Sciences and Physiotherapy, Ghent University, De Pintelaan 185, 3B3, –Ghent 9000, Belgium; Joke.schuermans@ugent.be

**Accepted 7 October 2014**

**Schuermans J, et al. Br J Sports Med 2014;48:1599–1606. doi:10.1136/bjsports-2014-094017**

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#### **Abstract**

**Background** The hamstring injury mechanism was assessed by investigating the exercise-related metabolic activity characteristics of the hamstring muscles using muscle functional MRI (mfMRI).

**Methods** 27 healthy male football players and 27 football players with a history of hamstring injuries (recovered and playing fully) underwent standardized mfMR Imaging. The mfMRI protocol consisted of a resting scan, a strenuous bilateral eccentric hamstring exercise and a postexercise scan. The exercise-related T2 increase or the signal intensity shift between both scans was used to detect differences in metabolic



activation characteristics between (1) the different hamstring muscle bellies and (2) the injury group and the control group.

**Results** A more symmetrical muscle recruitment pattern corresponding to a less economic hamstring muscle activation was demonstrated in the formerly injured group ( $p < 0.05$ ). The injured group also demonstrated a significantly lower strength endurance capacity during the eccentric hamstring exercise.

**Conclusions** These findings suggest that the vulnerability of the hamstring muscles to football-related injury is related to the complexity and close coherence in the synergistic muscle recruitment of the biceps femoris and the semitendinosus. Discrete differences in neuromuscular coordination and activity distribution, with the biceps femoris partly having to compensate for the lack of endurance capacity of the semitendinosus, probably increase the hamstring injury risk.

**Key words** Eccentric; Football; Hamstring; Injury; MRI

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## Introduction

Hamstring injuries are the most common muscle injuries in male football players and are associated with significant time loss.<sup>1</sup> Given the significant reinjury rates and the high costs involved, adequate prevention and rehabilitation strategies, as well as valid return to play criteria, are of major importance.<sup>2-7</sup> The predominant hamstring injury mechanism in football occurs during high-speed running or acceleration efforts.<sup>8-9</sup> The muscle-tendon junction of the long head of the biceps femoris (BF) is most commonly injured.<sup>10-11</sup> Despite the growing insights into the injury mechanism and risk factors of hamstring strain injuries, a full understanding of the underlying epidemiology is lacking, which is confirmed by the high injury incidence and recurrence rates.<sup>12-14</sup> Biomechanical and kinematic studies have demonstrated that the BF is subject to the highest levels of muscle-tendon unit stretch throughout the crucial terminal (front) swing phase in (high speed) running.<sup>9, 15-17</sup> This could

possibly explain why this muscle belly is injured the most. In addition to stretch, other differences in functional muscle features between the biarticular hamstring bellies might be involved as well. Both the semitendinosus (ST) and the BF engage in maximal eccentric activation throughout the swing phase of running (middle swing to initial stance phase). These synergists work alternately in complex neuromuscular coordination patterns,<sup>15, 18-19</sup> where the BF is predominantly activated prior to and immediately after touch down and the ST is the leading player during mid- and late front swing.<sup>18,</sup>

<sup>20</sup> This stresses the importance of sufficient neuromuscular and intramuscular coordination between those two muscle bellies. Altered muscle activation patterns have been associated with prior hamstring injuries and an increased risk of reinjury.<sup>4, 20-21</sup> Intramuscular synergistic recruitment patterns and the quality and quantity of co-operation between the BF, ST and semimembranosus (SM) have not been investigated. Electromyography (EMG) assessment has been used as a gold standard in the evaluation of muscle recruitment and activation patterns. Owing to its poor spatial resolution and the presence of crosstalk in the observed muscle signals, this method is not ideally suited for the evaluation of muscle recruitment patterns within the hamstring muscle complex. Functional MRI (fMRI) can map the intramuscular and intermuscular recruitment patterns with a very high spatial accuracy<sup>22-25</sup>; however, unlike EMG, it cannot provide any real-time information about the amount and timing of the underlying muscle activity. Nonetheless, fMRI has the ability to detect and evaluate the magnitude of metabolic activity in muscle tissue. Since this technique is non-invasive and has high sensitivity and specificity, it has been used to detect exercise-related muscle activation patterns in various muscle groups (cervical flexor muscles, back extensor muscles, quadriceps, hamstrings and adductor muscles)<sup>26-29</sup> and pathology-related compensatory muscle recruitment patterns (patellofemoral pain syndrome, chronic low back pain).<sup>30-31</sup> Studies using fMRI have also evaluated muscle activity in hamstring muscle bellies during various exercises to identify the most effective exercise for injury prevention.<sup>18, 32</sup> However, this technique has not been used to assess the intramuscular activity proportions (and underlying neuromuscular coordination patterns) in an athletic population at risk. This study aimed to assess how the different hamstring muscle bellies work together in synergistic coordination patterns and whether changes in neuromuscular coordination patterns are associated with hamstring injuries.

## Methods

### Participants

Throughout the spring of 2013 (March – May), male football players were addressed via contact with the club trainer, coach, physiotherapist or sports physician. Initially, 75 male football players from seven clubs in Oost-Vlaanderen, Belgium (recreational football competition) agreed to participate.

Potential participants were excluded from this study if they reported:

- having a history of severe knee or hip injury;
- having a history of lower back complaints/lower back complaints at present;
- having electronic implants or foreign (ferromagnetic) bodies close to the thigh region, or were suffering from claustrophobia, which made them unsuitable for MRI evaluation;
- having less than 5 years of competitive football experience.

Only players aged between 18 and 35 years were included in the study to rule out age-related pathologies. All participants were completely free from injury and ready to play at the moment of testing. Ultimately, fifty-four players participated in this study: 27 football players without a history of hamstring injuries and 27 football players with a recent (within the last 2 seasons) history of at least one hamstring injury (one reported injury episode). A hamstring injury was defined as a football-related injury in the hamstring muscle region, preventing the player from participating in training or competition for at least 1 week. The majority of injuries within the injury group were diagnosed clinically, with or without accompanying medical imaging. The recruitment and inclusion of injured participants was based on self-report, as we were not able to contact all physicians and physiotherapists involved in the original diagnosis and rehabilitation. At the time of testing, none of the players experienced any pain or discomfort in the hamstring region during football participation or during the muscle fMRI (mfMRI) protocol in this study.

## Testing procedure

Participants were instructed not to engage in intensive training or football competition 48 h prior to testing to ensure a valid measure of the exercise-related 'T2 increase' or 'signal intensity shift'. The testing protocol consisted of two scanning sequences with a strenuous hamstring exercise between both scans. The difference in the transverse relaxation time of the separate hamstring muscle bellies before and after exercise (T2 increase or signal intensity shift) indicated the magnitude of underlying metabolic muscle activity.<sup>22</sup> After completing the MRI safety checklist and signing the informed consent, the participants were familiarized with the scanning sequence and the hamstring exercise. The entire testing procedure was performed by the same researcher (JS), which minimized the risk of intertester bias. This study was approved by the Ethics Committee of the Ghent University Hospital (number of approval: EC/2013/118).

## Muscle fMRI

A 3 T scanner (Siemens Trio Tim, Erlangen, Germany) was used for the mfMRI protocol. The participants were positioned supine on the scanning table, which was supplied with a spine coil, with both legs extended and their feet close to the magnet. A flexible body matrix was placed on the anterior thigh area and carefully aligned with the centre of the field of view. Plastic tubes filled with sodium chloride solution were used for accurate localization and determination of the centre of the field of view (the intended slice position) (figure 1). The centre of the body matrix was aligned with the thigh level on which the plastic tubes were fixed. Coloured tape was used to indicate this centre of image acquisition, relative to the scanning table, so that the participant's position before and after exercise was exactly the same, and the second sagittal localizing sequence after exercise was not needed. Each participant underwent the following scanning sequences: one localizing sequence, one Spin Echo T1 sequence, one CPMG (Carr Purcell Meiboom Gill) sequence before exercise and the same CPMG sequence after exercise. The CPMG scanning sequence is the main functional scanning sequence that allowed the calculation of a T2 map after scanning. This T2 map gives an indication of

the metabolic status of the muscle tissue, depending on the signal intensity or the magnitude of the T2 relaxation parameter (T2 time constant of muscle water). The localizing sequence was performed only once to minimize the time span between the end of the exercise session and the second CPMG image acquisition. As the T2 shift half-life is only 7 minutes (min.),<sup>22 33</sup> running a second localizer after exercise may have resulted in an underestimation of the exercise-induced metabolic changes within the hamstring muscles. Due to the lower fairly low contrast in T2 weighted MR images, a Spin Echo T1 (SET1) sequence was added to the functional scanning protocol for more accurate region of interest (ROI) identification and selection in the post hoc analysis. The contrast of a T1 scan is substantially higher than the contrast within a T2 image, so the T1 image made it possible to discriminate the different hamstring muscle bellies from one another in the T2 map more accurately (Table 1).



**Figure 1.** Position of the middle slice (centre of the field of view) for the T1 and both CPMG (Carr Purcell Meiboom Gill) scanning sequences.

<b>Scan Position and Acquisition Parameters</b>	<b>Spin Echo T1</b>	<b>CPMG</b>
<i>Number of slices</i>	6	5
<i>Slice Thickness (mm)</i>	4	5
<i>Field of View (mm)</i>	340	380
<i>Middle Slice Location</i>	Upper border distal third upper leg (ASIS – lateral epicondyle femur)	Upper border distal third upper leg (ASIS – lateral epicondyle femur)
<i>Repetition Time (ms)</i>	550	1500
<i>Echo Time (ms)</i>	9	10.5 - 168
<i>Number of Echoes</i>	1	16
<i>Voxel Size (mm)</i>	0.9 x 0.9 x 0.4	1.5 x 1.5 x 5.0

*CPMG, Carr Purcell Meiboom Gill; Mm, millimeters; ms, milliseconds; ASIS, anterior superior iliac spine*

The middle slice (or the centre between both middle slices for the SET1 sequence) was located on the upper border of the distal third of the thigh, which was marked using the fluid filled tubes (figure 1). This field of view centre was chosen because this specific upper thigh region consists of the highest muscle tissue/connective and tendon tissue ratio. Imaging parameters were identical for both the CPMG sequence before and after exercise.

### **Hamstring exercise**

Participants performed a prone leg curl exercise between both functional CPMG sequences. They were positioned prone on a 60° inclined exercise table to induce hip flexion and were instructed to flex and extend both knees alternately from 90° of knee flexion to full extension with a weight of 5 kg attached to each foot. Participants were instructed to flex and extend both knees at a constant 90 rpm (repetitions per minute) pace, monitored by a metronome. This exercise was chosen to mimic the hamstring mechanics in running (hip flexion and knee extension that had to be controlled and decelerated against gravity) while also providing a fairly high muscle loading to induce a sufficient metabolic activation response (there is a linear relationship between exercise intensity and magnitude of T2 increase). Participants completed the exercise to exhaustion (corresponding to a score of 20 on

the Borg Ratings Scale of Perceived Exertion) because this guaranteed a sufficient metabolic muscle response and because fatigue has already repeatedly been identified as an important actor within the hamstring injury risk.<sup>2 4 34 35</sup> Hip and knee joint deviations in the frontal (abduction—adduction) and transverse (internal—external rotation) planes were prohibited because this would influence the muscle activation patterns (figure 2). When the participants indicated having reached exhaustion and the exercise could no longer be performed with quality, they were submitted to the second CPMG sequence within 1 min. The time to exhaustion was recorded.

### Data analysis

Acquired images were converted into T2 maps (i.e. filtering out the T1 effect) for calculation of the mean transverse relaxation times in the different ROIs using the T2Processor software (copyright P. Vandemaele, Engineer, GIFMI UZ Gent). Afterwards, the T2 value was calculated via the formula:  $S_n = S_0 \times \exp(-TE/T2)$ , where  $S_n$  represents the signal intensity, expressed in milliseconds, at a given TE within the scanner's original signal intensity  $S_0$ .



**Figure 2.** Prone leg curling exercise in between both CPMG scanning sequences of the testing procedure.

For the functional CPMG sequence, five slices were taken at the upper border of the distal third of the thigh in both legs before and after exercise (with an interslice distance (“slice gap”; SG) of 2 mm). In

each of the 10 acquired images (10 slices), 6 ROIs were selected for (T2) relaxation time analysis, representing the BF, ST and SM in both the right and the left leg. Muscle bellies were systematically selected as ROI, with strict inclusion of muscle fibre tissue and exclusion of fatty tissue, neurovascular structures and connective tissue (figures 3 and 4). The slices were taken at the proximal limit of the distal third of the upper leg, which included the entire BF as well as a sufficient diameter of the ST and SM muscle bellies (figure 1). After selecting the ROIs and adjusting the threshold in the T2 map to ensure that only muscle tissue was included, the T2 relaxation time was calculated for each ROI in every slice, using the T2Processor software. The final T2 relaxation time of each muscle before and after exercise was the mean T2 value, retained out of the five slices, respectively CPMG images. Intratester reliability was assessed using the contralateral leg transverse relaxation times of each one of the hamstring muscle bellies before and after exercise in the control group. The relative T2 shift (normalized to the baseline T2 value), rather than the absolute T2 shift, was used for statistical analysis as this out ruled potential bias caused by between-participant differences in baseline metabolic muscle features/activity ( $T2\ shift = \frac{T2\ postexercise\ value - T2\ pre-exercise\ value}{T2\ pre-exercise\ value}$ ).

### Statistical analysis

To compare the formerly injured leg of the injury group with a healthy leg of the control group without having to deal with the factor ‘leg dominance’ as a confounder, we recorded the ratio dominant/non-dominant leg involvement in the injury group and applied this ratio in the control group so that the same subdivision could be made randomly. In this way, an equal dominance/ non-dominance ratio was achieved in both groups. In the injury group, 17 (63%) players sustained their latest hamstring strain injury in their dominant leg. In the control group, the same number of dominant legs (and non-dominant legs) was included for analysis. We evaluated the normality of the data distribution for the different variables using the Shapiro-Wilk test. To check for confounders, we evaluated the similarity of anthropometric features as well as data on exposure and playing position in



both groups, using multivariate analysis of variance (MANOVA) and  $\chi^2$  hypothesis testing. Mixed model analysis was performed to check for significant differences in baseline transverse relaxation time and the activity-related T2 increase between (1) the different hamstring muscle bellies and (2) both groups, taking into account the between-participant variability (random variable 'playerID'). MANOVA and independent Student t tests were used to evaluate possible between-group differences for the separate hamstring muscle bellies. We also used an independent samples Student t test to check for differences in the hamstring muscle load bearing capacity by comparing the duration of the prone knee bending exercise between the injury group and the control group ('time to exertion'). Finally, associations between the mfMRI measures were evaluated with the Pearson and Spearman correlation coefficients. Data analysis was done with the SPSS V.21 Statistical Software package (IBM Corp., New York, USA), and the level of significance was set at  $\alpha=0.05$ .

## **Results**

### **Anthropometrics and injury characteristics**

There were no differences in anthropometrics between both groups (table 2). The injury group sustained their last hamstring injury between 21 months and 1 month before testing (mean (SD) 6 (4) months). The duration of the rehabilitation period following their latest hamstring injury varied from 7 to 84 days, with a mean time loss of  $28\pm 22$  days, indicating that players with both grade 1 and grade 2 muscle strain injuries were included. All players were treated conservatively by a sports physiotherapist.

**Table 2 Participant Information**

	<i>N</i>	<i>Weight (kgs)</i>	<i>Height (m)</i>	<i>BMI (kg/m<sup>2</sup>)</i>	<i>Age (years)</i>	<i>Time since last hamstring injury (months)</i>	<i>Rehab time associated with last hamstring injury (days)</i>
<b>Control</b>	27	71 ± 7	1.80 ± 0.05	21.87 ± 1.72	23 ± 5	/	/
<b>Injury</b>	27	74 ± 7	1.79 ± 0.06	22.99 ± 2.02	24 ± 4	6 ± 4	28 ± 22 (range 7 – 84)

*kgs, kilograms; m, meters*

### Exercise-related T2 increase

The intraclass correlation coefficient (ICC) for the baseline measurements were 0.925, 0.724 and 0.737 for the BF, the ST and the SM, respectively. The ICC for the postexercise measurements were 0.892, 0.801 and 0.856 for the BF, the ST and the SM, respectively.

The overall exercise-related metabolic response was significantly higher in the injury group. There was a significant difference in the amount of metabolic activity in the entire hamstring muscle of 4.8% ( $p < 0.027$ ), with a mean T2 increase of  $18.20 \pm 10.03\%$  in the control group and a mean T2 increase of  $22.87 \pm 9.29\%$  in the injury group (table 3).

Aside from the between-group difference in the mean T2 increase of the entire hamstring muscle, the individual hamstring muscle bellies of the formerly injured players presented a higher metabolic response after exercise (figure 5).

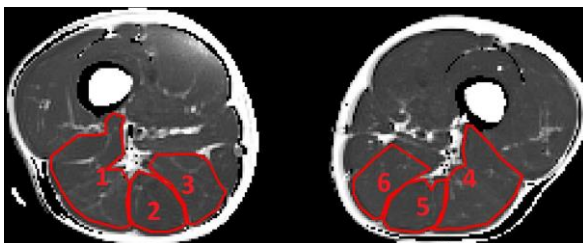
There were significant differences in the magnitude of metabolic activity between the three hamstring muscle bellies within the injury and control groups, with the ST presenting significantly higher levels of metabolic activity compared to its medial and lateral counterparts ( $p < 0.0001$ ). This within-group activity divergence between the separate muscle bellies appeared to be similar in both groups (Figure 5).

The synergistic role of the different muscle bellies and their individual contribution to the exercise-related T2 increase were assessed by the ratio of the individual activity of the BF, the ST and the SM, respectively, to the summated T2 increase of the entire hamstring portion (*share individual muscle = (amount of individual T2 increase) / (summated T2 increase of the entire hamstring muscle)*).

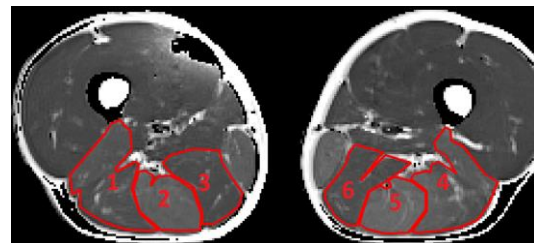
In this way, a different percentage was attributed to the T2 increase in each muscle belly, relative to

the total hamstring activity (equalized with 1 or 100%). There were differences in the individual activity shares between the homonymous hamstring muscle bellies in both groups. The ST demonstrated a 14.4% higher metabolic activation than the BF ( $p<0.001$ ) and a 19.7% higher activation than the SM ( $p<0.001$ ). The BF, in its turn, demonstrated 5.2% more metabolic changes than the SM ( $p=0.015$ ). This supports the finding that the ST has an important share in the metabolic provision (figure 6). We also found that the discrepancy between these relative percentages were significantly smaller in the injury group, with the BF and the SM presenting slightly more metabolic changes, and the ST presenting slightly less metabolic changes within the total T2 increase after exercise.

The magnitude of intramuscular activity imbalance was evaluated by looking at the total difference in metabolic muscle activity between the separate hamstring muscle bellies (the magnitude of intramuscular activity variability), which was significantly lower in the injury group (mean difference=3.47%;  $p=0.039$ ). In this group, the percentage of intramuscular activity variability was  $10.23\pm 3.2\%$ . The control group displayed more intramuscular differences in metabolic activity between the BF, the ST and the SM, with a mean magnitude of intramuscular activity variability of  $14\pm 7.5\%$ . Furthermore, this magnitude of intramuscular activity variability was strongly negatively correlated with the average exercise-related T2 increase (Pearson correlation coefficient=-0.651;  $p<0.001$ ; figure 7).



**Figure 3.** Region of interest selection in the T2-weighted (T2 map) image before exercise. (1) R BF, (2) R ST, (3) R SM, (4) L BF, (5) L ST and (6) L SM (BF, biceps femoris; L, left; R, right; SM, semimembranosus; ST, semitendinosus).

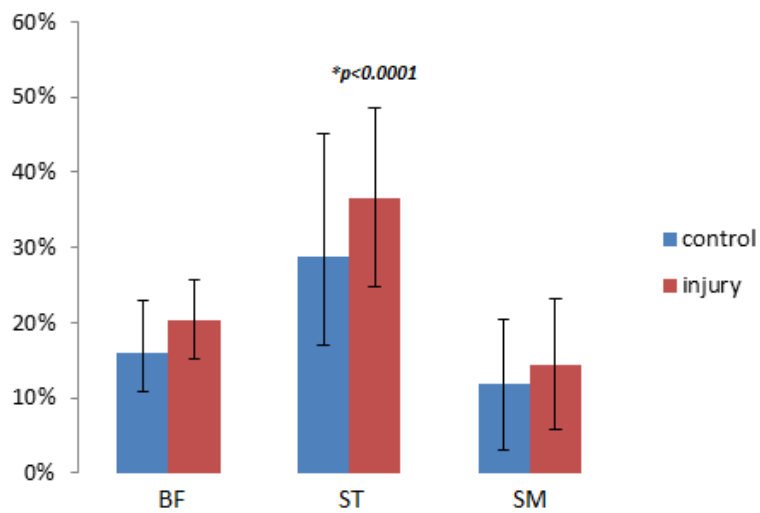


**Figure 4.** Region of interest selection in the T2-weighted image (T2 map) after exercise. (1) R BF, (2) R ST, (3) R SM, (4) L BF, (5) L ST and (6) L SM (BF, biceps femoris; L, left; R, right; SM, semimembranosus; ST, semitendinosus).

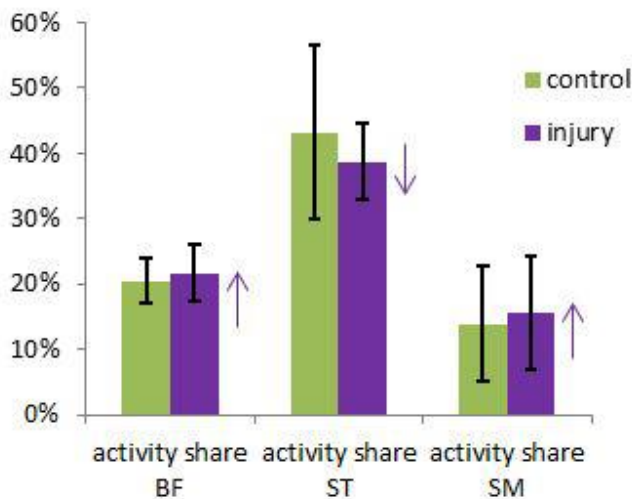
...metabolic

dependent on the baseline T2 value (resting state metabolic status), possible differences in baseline T2

between the injury group and the control group would have biased our results.<sup>24 36 37</sup> Multivariate analysis (general linear model) compared the resting state T2 values for the different muscle bellies between both groups, and revealed no influence of the factor ‘injury’ on the resting state T2 values: p values of 0.881, 0.728, 0.581 and 0.968 for the BF, the ST, the SM and the entire hamstring muscle portion, respectively (cf. table 3).



**Figure 5.** Exercise-related increase in transverse relaxation time of muscle water representing the magnitude of the metabolic muscle activity in the separate muscle bellies (BF, biceps femoris; ST, semitendinosus; SM, semimembranosus).



**Figure 6.** The individual share/portion of each individual muscle belly within the summated T2 increase (metabolic muscle response) for the hamstring muscles in the control group and the injury group (BF, biceps femoris; SM, semimembranosus; ST, semitendinosus).

**Table 3** The average T2 relaxation times of the individual muscle bellies gathered before (T2 pre) and after (T2 post) exercise, the relative increase (%) of the individual muscle bellies (relative to the resting state T2 relaxation time and corresponding metabolic status) and their combined average

	Control			Injury		
	T2 pre (ms)	T2 post (ms)	T2 increase (%)	T2 pre (ms)	T2 post (ms)	T2 increase (%)
BF	40.99 ± 2.38	47.45 ± 4.00	16.09 ± 11.50	40.89 ± 2.96	49.26 ± 4.98	20.36 ± 10.92
ST	38.81 ± 2.28	49.92 ± 4.52	28.89 ± 12.30	39.02 ± 2.11	53.10 ± 4.61	36.64 ± 11.81
SM	41.44 ± 2.37	46.20 ± 3.32	11.78 ± 2.71	41.06 ± 2.71	46.57 ± 3.29	14.44 ± 8.68
mean	40.75 ± 2.15	47.75 ± 10.03	18.20 ± 10.03	40.60 ± 2.24	49.57 ± 3.91	22.87 ± 9.29

\*mean difference of 4.8%,  $p < 0.027$

BF, biceps femoris; SM, semimembranosus; ST, semitendinosus

### Time to exertion

The mean time to exertion in the injury group was significantly lower compared to the control group: 219s (04'07") ± 151s and 292s (05'26") ± 109s, respectively, with a mean difference of 72.9 s (01'13"),  $p = 0.045$ .

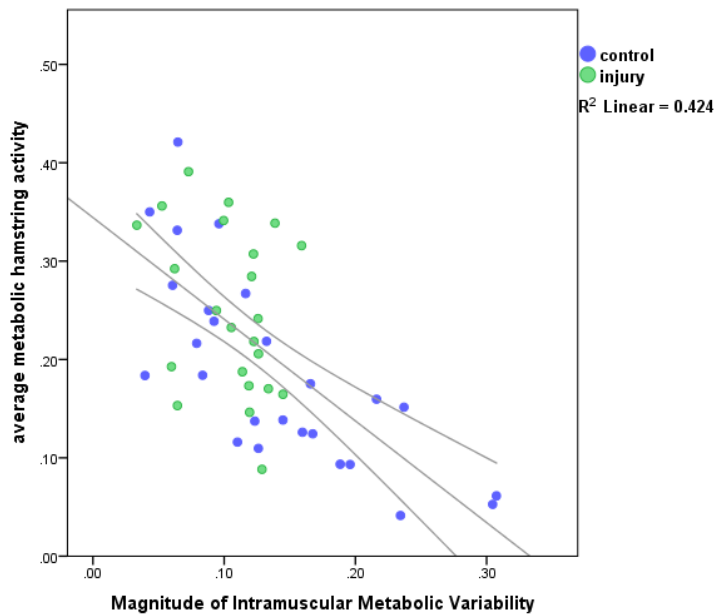
### Time elapsed since the last injury and injury severity

The time elapsed since the last hamstring injury and the duration of the corresponding rehabilitation period (time loss period) were not associated with the magnitude of the exercise-related metabolic muscle response or with the magnitude of intramuscular activity variability (table 4).

**Table 4** Spearman correlations between the injury-mfMRI time interval and the rehabilitation duration of the last hamstring injury and the mfMRI outcome measures

		Mean exercise-related T2 increase in the entire hamstring muscle	Magnitude of intramuscular activity variability
Time elapsed since the last injury (months)	Spearman's rho	-0.114	0.114
	P value	0.588	0.586
Rehabilitation period since the last injury (days)	Spearman's rho	0.209	0.157
	P value	0.295	0.434

mfMRI, muscle functional MRI



**Figure 7.** Scatter-dot diagram of the negative linear relation between the magnitude of the metabolic muscle response due to exercise and the magnitude of the intramuscular activity variability: the higher the variability, the lower the T2 increase and vice versa.

## Discussion

This study demonstrated significantly more symmetrical activation patterns between the BF, ST and SM in the injury group compared to the control group. The prominent role of the ST was evident in both groups. However, in the injury group, the activity of the ST was partly traded in for more involvement of its synergists. The ST seems to be activated most during the prone leg curling exercise. Previous research reported that the ST had the highest muscle activity and was recruited more than both the BF and the SM in strength exercises and in locomotion.<sup>15, 38-42</sup> This activation pattern appears to be the result of sophisticated, complex neuromuscular coordination within the hamstring muscle complex, which possibly provides the most efficient muscle functioning and most economic force production. Previous research demonstrated that the ST has the highest levels of muscle activity during the front swing phase (whereas the BF is predominantly active prior to and after touch down),<sup>15,18, 20</sup> where the hamstring muscle group has to withstand the highest levels of muscle tendon

stretch and negative work. This supports our hypothesis and suggests that under intense eccentric loading conditions, the ST has a prominent role in producing and controlling the torques around both hip and knee joints. We also found a high correlation between the magnitude of intramuscular activity variability and the mean exercise-related T2 increase, with higher exercise-related signal intensity shifts in the presence of a more balanced muscle recruitment pattern. This finding suggests that the more symmetrical and less dissociated the hamstring muscles work together, the higher the physiological changes will be inside the recruited muscle fibres. More intramuscular variability can thus be associated with a lower metabolic turnover and (probably) more economic muscle functioning. More symmetrical muscle activation (lower level of intramuscular dissociation) might imply compensatory and (mal)adaptive neuromuscular coordination patterns, causing the hamstring muscle bellies to contract less efficiently, with earlier onset of pH changes and muscle fatigue. These aberrant muscle recruitment patterns may contribute to an elevated risk of hamstring injury under high loading circumstances, as seen in track and field sports. Interestingly, the BF and the ST are most frequently injured in running-related hamstring strains. The complex inter-relationship, synergistic activation and fibre recruitment patterns between the BF and the ST (which share a proximal tendon) indicate that both muscle bellies are highly interdependent in terms of the magnitude of tissue loading and the adequacy of muscle functioning.<sup>18-20, 41, 42</sup> When one muscle displays an aberrant recruitment pattern (both in timing as in spatial distribution of fibre recruitment), excessive load would be placed on its neighbour which would also induce excessive tensile shear stresses close to the proximal myotendinous aponeurosis of both muscle bellies. Bourne et al<sup>43</sup> published a cross-sectional study in which they observed the mfMRI activation patterns of the different hamstring muscles during a specific sprinting task. They evaluated the differences in recruitment patterns between the formerly injured and the healthy hamstrings in five track or field athletes after sprinting. Contrary to our findings, they reported a decrease in T2 shift and hence lower levels of underlying metabolic activity in the formerly injured hamstring muscle belly, compared to the homonymous hamstring muscle in the contralateral leg. Given that the T2 increase represents the magnitude of the underlying metabolic changes in the recruited muscle fibres, a higher T2 increase and a lower exercise capacity (duration to exhaustion) in our findings would demonstrate a less effective and less economic recruitment pattern

in the hamstring muscle, which has a lower strength endurance and loading capacity. The exercise-related T2 increase or signal intensity shift indicates physiological changes within the muscle fibre, which are caused by osmotic changes in intracellular fluid volumes and pH, in turn triggered by the accumulation of metabolites. Therefore, this outcome measure gives an indication of the efficiency of muscle recruitment and the muscle fibre endurance capacity. Why the above mentioned study demonstrated opposite results, might be explained by the differences in study population and sample size, as well as the possibly longer time span between the sprinting task and the second functional scanning sequence. The similarity in baseline T2 values in our study sample, demonstrates no between-group difference in metabolic fibre characteristics. Since the exercise-related signal intensity shift did differ between the injury group and the control group, it is likely that the formerly injured hamstrings have a lower loading capacity and display less efficient recruitment patterns, as the injured group also scored significantly lower in terms of strength endurance (lower time to exertion). These compensatory recruitment patterns could possibly make the homonymous muscle more prone to future injury. Indeed, biomechanical and isokinetic testing after clinically and functionally recovered and rehabilitated hamstring strain injuries have shown that eccentric strength deficits as well as altered running kinematics, with a decreased stride length, smaller knee extension and hip flexion angles, are present at time to return to play.<sup>44</sup> Our study outcome supports the finding that predominantly the BF and secondly the ST are prone to injury in high-speed running (heavy eccentric loading). When the ST cannot keep up with its former predominant role in force production and negative work delivery (due to injury) under high eccentric loading circumstances, the BF will compensate for this functional deficit. Owing to the smaller fascicular length of the BF muscle, compared to the ST,<sup>45</sup> it is less stretch tolerant and less suited to contribute to energy storage through negative work and to control the hip and knee torques in its distal range of motion in this crucial terminal phase of running. As a consequence, even minor deficits in ST functioning or coordination within the synergistic interplay of the BF and the ST would cause one or both muscles to fail. In line with our findings, we suggest that injury to the BF and/or the ST most probably occurs because the BF is not optimally suited for force production in the distal range of motion and the ST probably is more prone to premature acidification and the onset of fatigue.



There were some limitations to this study. We chose the prone leg curling exercise with free weights in order to simulate the hamstring loading characteristics in running and to provide an adequate exercise intensity. We are aware that hamstring loading in the prone leg curling exercise is very different from hamstring loading in high-speed running, so the muscle recruitment patterns could differ substantially. Owing to the exercise intensity-dependency and the short half-life of the activity-related T2 signal intensity increase, we chose not to include a sprinting protocol in our study. As we found substantial differences between the injury group and the control group, we believe that these differences are attributable to prior hamstring injuries, even though the exercise could not mimic the biomechanics and kinematics of sprinting. Exercise related T2 increase has a very high spatial specificity, and may have been different had we decided to make axial slides at another level or at multiple levels of the thigh. The influence of the location of the hamstring injury (involvement of the BF or the ST as well as the proximodistal location of the lesion within the tendon–muscle–tendon continuum) was not known. Since we did not have medical imaging of the hamstring injury of all participants in the injury group, and since an extra subdivision within the injury group, based on injury location, would consequentially lower the power of this study, we chose to keep the injury group together. Finally, although there was no association between the (1) time elapsed since the last injury and the injury severity (duration of the last rehabilitation period) and (2) the intramuscular activity variability or the magnitude of the exercise-related metabolic muscle response, this might have been due to the small sample size. Therefore, no conclusions or assumptions should be made about mfMRI in establishing injury severity and readiness for return to play.

## **Conclusion**

This study evaluated the magnitude and the distribution of the metabolic changes within the hamstring muscles after a strenuous eccentric hamstring exercise. A more symmetrical muscle recruitment pattern in the formerly injured group of male football players was found, corresponding to higher

levels of metabolic activation within the entire hamstring muscle. The injury group had a lower exercise capacity, suggesting that hamstring injuries in football are associated with compensatory neuromuscular activation and recruitment patterns in heavy eccentric loading, causing the hamstring muscle to acidify and fatigue prematurely and to a greater extent. This may explain the high reinjury rate in male football competition. Since the control group presented a higher magnitude of dissociation and variability in hamstring muscle recruitment, we suggest that the exact quality and quantity of hamstring muscle recruitment and the underlying neuromuscular coordination mechanisms are critical in the hamstring injury mechanism and injury risk. mfMRI has proven to be a valid and reliable technique to monitor this complex synergist interplay. Clinicians should account for complex neuromuscular mechanisms within the hamstring muscle unit, especially for the BF and the ST. Instead of focusing on the BF, which gets injured most frequently, attention must be paid to training and strengthening both the BF and the ST. The function of the ST is critical in injury prevention and performance progression and deserves the same (if not more) attention as the function of the BF.

What is already known on this topic?	What this study adds
<ul style="list-style-type: none"> <li>▶ Running-related hamstring strain injury location can partly be explained by the high levels of muscle-tendon unit stretch and elongation seen in the long head of the biceps femoris.</li> <li>▶ Muscle functional MRI is being used to assess (compensatory) muscular recruitment patterns within and between adjacent muscles in association with pathology or after specific exercises.</li> <li>▶ In running and analytical exercises, the biceps femoris, semitendinosus and semimembranosus work together as synergists in complex neuromuscular recruitment patterns. The exact quality of this recruitment in terms of timing and magnitude has not been identified to date.</li> </ul>	<ul style="list-style-type: none"> <li>▶ Football players with a history of hamstring injury present increased, more symmetrical metabolic activity levels within their hamstrings and a lower hamstring muscle loading tolerance, possibly indicating inadequate rehabilitation and an increased risk of re-injury.</li> <li>▶ The biceps femoris and semitendinosus engage in complex synergistic activation patterns during heavy eccentric loading, in which the semitendinosus has a predominant function and elicits the highest metabolic muscle activity. Compensatory and less dissociative hamstring muscle activation patterns might be related to the risk of hamstring injuries in football players.</li> </ul>

### Acknowledgements

The authors gratefully acknowledge the assistance of P Vandemaele, Engineer of the Ghent University Hospital (GIFMI-UZ Gent), for his assistance in the MR scanning and data processing series. Furthermore, they would like to thank their colleagues at the Department for Rehabilitation Sciences and Physiotherapy for their kind support, as well as the participants of this study, without whom this paper could not have been accomplished. For their financial support, the authors' gratitude goes out to

the Agency for Innovation by Science and Technology in Flanders (IWT—Brussels, Belgium), who made this MRI— research possible.

### **Contributors**

EW customized the study design, guided the statistical analysis and the writing process. DVT provided valuable assistance during the testing procedures and gave constructive feedback during the data analysis. LD was involved in the preparation of the scanning sequences and data analysis. JS was in charge of the participant recruitment, testing procedure and data analysis, and wrote this manuscript.

### **Competing interests**

None.

Patient consent Obtained.

Ethics approval The University Hospital of Ghent.

Provenance and peer review

Not commissioned; externally peer reviewed.

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# Chapter I – Part II

Susceptibility to hamstring injuries in soccer

*A prospective study using muscle functional  
Magnetic Resonance Imaging*



## CHAPTER I - PART II

### **Susceptibility to Hamstring Injuries in Soccer A Prospective Study Using Muscle Functional Magnetic Resonance Imaging**

Joke Schuermans, MS,<sup>1</sup> Damien Van Tiggelen, PhD,<sup>1</sup> Lieven Danneels, PhD,<sup>1</sup> and Erik Witvrouw, PhD<sup>1,2</sup>

Investigation performed at the Department of Rehabilitation Sciences and Physiotherapy Ghent, Ghent University, Ghent, Belgium

<sup>1</sup> Department of Rehabilitation Sciences and Physiotherapy Ghent, Ghent University, Ghent, Belgium

<sup>2</sup> Department of Physiotherapy, Aspetar, Doha, Qatar

Correspondence to Schuermans Joke, Department of Rehabilitation Sciences and Physiotherapy, Ghent University, De Pintelaan 185, 3B3, –Ghent 9000, Belgium; [Joke.schuermans@ugent.be](mailto:Joke.schuermans@ugent.be)

**Am J Sports Med published online February 24, DOI: 10.1177/0363546515626538**

**The American Journal of Sports Medicine 2016 May;44(5):1276-85.Vol.**

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#### **Abstract**

##### **Background**

Running-related hamstring strain injuries remain a delicate issue in several sports such as soccer. Their unremittingly high incidence and recurrence rates indicate that the underlying risk has not yet been fully identified. Among other factors, the importance of neuromuscular coordination and the quality of interplay between the different hamstring muscle bellies is thought to be a key determinant within the intrinsic injury risk. Muscle functional magnetic resonance imaging (mfMRI) is one of the tools that has proven to be valid for evaluating intermuscular coordination.

<b>Purpose</b>	To investigate the risk of sustaining an index or recurring soccer-related hamstring injury by exploring metabolic muscle characteristics using mfMRI.
<b>Study Design</b>	Cohort study; Level of evidence, 2.
<b>Methods</b>	A total of 27 healthy male soccer players and 27 soccer players with a history of hamstring injuries underwent standardized mfMRI. The mfMRI protocol consisted of a resting scan, a strenuous bilateral eccentric hamstring exercise, and a postexercise scan. The exercise-related T2 change, or the signal intensity shift between both scans, was used to detect differences in metabolic characteristics between (1) the different hamstring muscle bellies and (2) the prospective cohorts based on the (re)occurrence of hamstring injuries during a follow-up period of 1.5 seasons.
<b>Results</b>	The risk of sustaining a first hamstring injury was associated with alterations in the intermuscular hierarchy in terms of the magnitude of the metabolic response after a heavy eccentric effort, with the dominant role of the semitendinosus set aside for a higher contribution of the biceps femoris ( $P = .017$ ). Receiver operating characteristic (ROC) curve analysis demonstrated that this variable was significantly able to predict the occurrence of index injuries with a sensitivity of 100% and a specificity of 70% when the metabolic activity of the biceps femoris exceeded 10%. The risk of sustaining a reinjury was associated with a substantial deficit in hamstring strength endurance ( $P = 0.031$ ). Soccer players who sustained a reinjury were only able to perform prone leg curls for a mean duration of $146.50 \pm 76.16$ seconds, whereas those with an injury history but no recurrence during follow-up were able to continue for a mean of $237.45 \pm 110.76$ seconds (95% CI, 11.9-230.5 seconds; $P = 0.031$ ).

**Conclusion**

This was the first study to assess the causal relation between the intramuscular recruitment pattern and the risk of sustaining an index or secondary hamstring strain. Changes in intermuscular interplay seem to significantly increase the risk of sustaining index hamstring injuries in male amateur soccer players. Inadequate eccentric muscle endurance could be associated with an increased risk of sustaining a recurring hamstring injury.

**Keywords**

hamstring strain injury; etiology; soccer; magnetic resonance imaging

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**Introduction**

Hamstring strain injuries are the single most common sports injuries in male soccer players. Given the associated time loss and the substantial recurrence rates, these injuries have been the subject of research within sports medicine for many years.<sup>11, 20, 34, 44</sup> In soccer, most commonly the biceps femoris (BF) (and to a lesser extent, the semitendinosus [ST]) is subject to structural or functional lesions.<sup>34, 44</sup> These muscles are most likely to sustain injuries during explosive running accelerations and kicking activities because of the high biomechanical loads placed on the muscle-tendon unit throughout the front swing phases in running and kicking.<sup>3, 6</sup> Next to extensive muscle stretch and heavy eccentric loading, the importance of intermuscular coordination and cooperation between the 3 major biarticular hamstring muscle bellies during these eccentric muscle efforts is increasingly being explored in current research.<sup>21-23, 25, 37, 40</sup> The predominant vulnerability of the BF could possibly be related to its morphological characteristics,<sup>24</sup> the substantial amount of stretch and eccentric loading it is prone to throughout the front swing phase of running,<sup>6, 21</sup> and the efficiency of intermuscular coordination.<sup>21, 37</sup> Bearing in mind that the hamstring muscle unit presents a considerable vulnerability for both structural and (to an even higher extent) functional injuries,<sup>10</sup> exploring the role of neuromuscular coordination in injury susceptibility seems essential. Previous research has already demonstrated that the BF, ST, and semimembranosus (SM) are activated in a specific sequence and with a diverging intensity of contraction throughout the front swing phase in running.<sup>21-23</sup> When the 3 muscle bellies are not capable

of engaging in synergistically adequate and economic contractions, this may cause one of the muscles to fatigue prematurely, ultimately resulting in a functional and/or structural injury.<sup>37</sup> The exact quantity (spatial distribution of muscle work) and quality (temporal activation characteristics) of intermuscular interplay within the hamstring unit are suggested to be of great importance in hamstring muscle load-bearing capacity and injury vulnerability.<sup>37</sup> In a previous study, we already pointed out the value of muscle functional magnetic resonance imaging (mfMRI) in assessing intermuscular coordination and the interplay features within the posterior thigh unit.<sup>37</sup> In the prior study,<sup>37</sup> mfMRI analysis revealed that exercise-induced metabolic activity and the exact intermuscular interplay differed significantly between soccer players with a (recent) history of hamstring injuries and their matched controls. Although surface electromyography (EMG) is a valuable tool to measure muscle activity as well, it is less suited to distinguish muscle activity within the same muscle group,<sup>32-33</sup> as it is inevitably subject to cross-talk (in which neighboring muscles produce a significant amount of the EMG signal that is detected by the local electrode site, challenging correct evaluation of the isolated activity of each one of the hamstring muscle bellies).<sup>11-13, 15-17</sup> More so, even though EMG measures the amplitude and frequency of the real-time motor unit discharges within the underlying muscle tissue, it is not capable of evaluating the metabolic efficacy with which the muscle is able to perform its imposed task. This is where mfMRI provides an interesting advantage. The T2 relaxation time constant of muscle water, represented by the signal intensity of the muscle tissue captured in T2 weighted MRI scans, gives an indication of the metabolic status of the muscle fibers.<sup>5, 30</sup> Comparing the signal intensity or the magnitude of the T2 relaxation time constant of the muscle tissue in a scan before and after exercise allows clinicians and researchers to evaluate to what extent the intended muscle has been activated during that specific exercise. The higher the osmotic and pH changes within the loaded muscle unit, the bigger the increase in signal intensity or the more extensive the T2 shift. These physiological processes within the muscle tissue are directly related to the amount of muscle work, so the higher the T2 shift, the higher the metabolic muscle activity. As the most important risk factor for sustaining a hamstring strain injury is presence of an injury history, adequate primary prevention is essential.<sup>34, 44</sup> However, considering that the risk of sustaining a secondary hamstring injury is more than twice as high as the risk of sustaining a first injury,<sup>12</sup> accurate comprehension and

acknowledgment of the reinjury risk and its implications are even more important. In our previous study,<sup>37</sup> soccer players with a history of hamstring injuries demonstrated an aberrant and less economic muscle activation pattern in which the BF partly compensated for the lack of activation (corresponding with less metabolic changes) of the (originally eccentrically more capable) ST. This pattern was associated with weaker strength performance, possibly indicating an increased risk of sustaining a subsequent injury. Although we already assessed the retrospective relationship between the intermuscular coordination characteristics and soccer-related hamstring injuries, no research has attempted to unravel the potential causal association between the quality and quantity of exercise-induced metabolic changes in the BF, ST, and SM and the risk of sustaining a future injury. In addition, the existing literature has never explored the nature of the reinjury risk profile and its possible disparities with the risk of sustaining a first hamstring injury.

Therefore, this prospective study intended to explore the relevance of mfMRI for the purpose of identifying the future injury risk in male soccer players, making a distinction between the occurrences of first and secondary hamstring strain injuries. In line with the results of previous research,<sup>37</sup> it was our hypothesis that the risk of hamstring injuries is associated with an altered pattern of intermuscular cooperation between the medial and lateral hamstring muscle bellies, with the BF exhibiting more and the ST exhibiting too little effort compared with what they are supposed to produce. The decision to solely include male soccer players was made deliberately, certainly taking into account the recurrence rates which indicate that hamstring injuries are still the single most common type of injury within this sport and the financial, personal, and performance-related stakes are considerable.<sup>44</sup>

## Methods

### Subjects

This study was approved by the ethics committee of the Ghent University Hospital (approval no. EC/2013/118). From March to May 2013, soccer players from 7 recreational regional soccer clubs (Oost-Vlaanderen, Belgium; community level) were addressed for participation in this study by contacting respective trainers, coaches, physical therapists, or sports physicians. Potential candidates were excluded from the study if they had

- a history of severe knee or hip injuries (eg, anterior cruciate ligament or medial collateral ligament ruptures, femoroacetabular impingement, or athletic groin injuries requiring surgery);
- a history of lower back complaints or current lower back complaints;
- less than 5 years of competitive soccer experience; or
- electronic implants, foreign (ferromagnetic) bodies close to the thigh region, or claustrophobia, which made them unsuitable for MRI evaluation.

To rule out (subclinical) age-related degenerative changes (confounders), only soccer players between the age limits of 18 and 35 years were considered for inclusion. All participants were required to be completely free from injuries and ready to play at the moment of testing.

Ultimately, 27 male soccer players with a recent history of hamstring injuries (within the last 2 seasons) and 27 matched controls underwent a standardized mfMRI protocol during the between-season period of July 2013. Soccer players in the injury history group had to be recovered completely and have returned to competition. Participant characteristics of the formerly injured players and the matched controls are presented in Table 1. Participants were instructed not to engage in intensive training or soccer competition 48 hours before testing to ensure a valid measure of the exercise-related “T2 increase” or “signal intensity shift”.



<b>Table 1 Participant Information<sup>a</sup></b>	<b>Control Group (n = 27)</b>	<b>Injury History Group (n = 27)</b>
<b>Weight, kg</b>	71 ± 7	74 ± 7
<b>Height, m</b>	1.80 ± 0.05	1.79 ± 0.06
<b>Body mass index, kg/m<sup>2</sup></b>	21.87 ± 1.72	22.99 ± 2.02
<b>Age, y</b>	23 ± 5	24 ± 4
<b>Time since last injury, mo</b>	/	6 ± 4
<b>Rehabilitation period of last injury, d</b>	/	28 ± 22 (range, 7 – 84)

<sup>a</sup>Data are reported as mean ± SD.

kg, kilograms; m, meter; y, years; mo, months; d, days

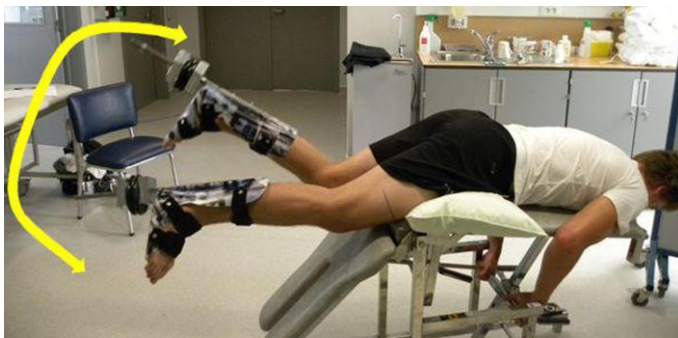
### mfMRI protocol

The testing protocol consisted of 2 Carr-Purcell-Meiboom-Gill echo train acquisition T2 scanning sequences (Table 2) with a strenuous eccentric hamstring exercise between scans (prone leg curls with 5-kg free weights in the distal range of motion until exhaustion) (Figure 1). The difference in the transverse relaxation time of the separate hamstring muscle bellies before and after exercise (T2 increase or signal intensity shift) indicated the magnitude of the underlying metabolic muscle activity.<sup>13,18</sup> After completing the MRI safety checklist and signing the informed consent form, the participants were familiarized with the scanning sequence and the hamstring exercise. The entire testing procedure was performed by the same researcher (J.S.), which minimized the risk of intertester bias. For more details on participant recruitment, the scanning procedure and attributed scanning sequences, eccentric hamstring exercise between scans, and data analysis, the reader is referred to earlier work.<sup>36</sup>

**Table 2 Carr-Purcell-Meiboom-Gill T2 Slice Positioning and Image Acquisition Parameters for Scanning Sequences Before and After Exercise**

<b>No. of slices</b>	5
<b>Slice thickness, mm</b>	5
<b>Field of view, mm</b>	380
<b>Middle slice location</b>	Upper border distal third upper leg (ASIS – lateral epicondyle femur)
<b>Repetition time, ms</b>	1500
<b>Echo time, ms</b>	10.5 - 168
<b>No. of Echoes</b>	16
<b>Voxel size, mm</b>	1.5 x 1.5 x 5.0

*mm, millimeters; ms, milliseconds; ASIS, anterior superior iliac spine*



**Figure 1.** Prone leg curls performed to exertion between the 2 Carr-Purcell-Meiboom-Gill magnetic resonance imaging scanning sequences of the testing procedure.

### Prospective monitoring of hamstring injury occurrence

Differently from what has been conducted before,<sup>37</sup> the present study consisted of a prospective follow-up for the registration of hamstring injuries. After the scanning session, participants were asked to complete an online diary for their weekly exposure (match and training) and the incidence or presence of soccer-related injuries and complaints (<http://www.hsi.ugent.be>). If the hamstring injury occurred for the first time in the respective leg, it was defined as a primary injury. If the reported injury was a sequel of the injury for which the participant was originally recruited into the injury history group (same leg and location), it was considered to be a recurring injury.

The participants were asked to complete this survey every Monday throughout the entire 2013-2014 season as well as the first half of the 2014-2015 season, resulting in a follow-up period of 1 and a half seasons. Participants' compliance to this online survey was verified on a weekly basis. Submission of the entire cohort was verified on Tuesday morning, after which the players who did not yet complete their survey were notified by email. The end of follow-up was set at the 2014-2015 winter break, during which period all participants were contacted again for a final injury inquiry.

### Data Analysis

After gathering the injury data during follow-up, the resulting cohort was subdivided into 4 categories based on the injury incidence during follow-up and injury history:

- healthy controls,
- players with an injury history but no recurring injury during follow-up,
- players who sustained an index injury during follow-up, and
- players who sustained a reinjury during follow-up.

Analysis of the T2 relaxation times in both the resting and postexercise scans was performed using T2Processor software (copyright P. Vandemaele, engineer; Ghent Institute for Functional and Metabolic Imaging, Ghent University Hospital) in Matlab (R2014a; The MathWorks Inc). Hereafter, exercise-induced T2 shifts were determined manually for the BF, ST, and SM of both legs in each participant<sup>36</sup> (Figures 2 and 3) using the following formula:

$$T2\ shift = \frac{T2\ postexercise\ value - T2\ pre-exercise\ value}{T2\ pre-exercise\ value}.$$

The relative T2 shift (normalized to the baseline T2 value), rather than the absolute T2 shift, was used for statistical analysis as this out ruled potential bias caused by between-participant differences in baseline metabolic muscle features/activity.

## Statistical Analysis

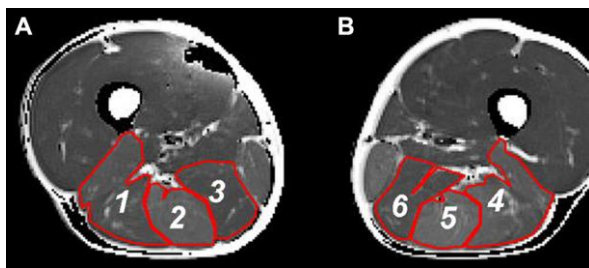
The following variables were subjected to statistical analysis:

1. The T2 shift within each muscle belly, representing the amount of metabolic muscle activity between scans ( $T2\ shift = \frac{T2\ post - T2\ pre}{T2\ pre}$ )<sup>37</sup>
2. The proportional activity shares of the hamstring bellies (BF, ST, and SM) within the entire hamstring–T2 shift, for which the T2 shift per muscle belly was normalized to the summated shifts of all muscle bellies (proportional activity =  $\frac{T2\ shift\ (BF\ or\ ST\ or\ SM)}{T2\ shift\ (BF+ST+SM)}$ ).<sup>37</sup>
3. The hamstring strength endurance (time to exertion on eccentric prone leg curls between both scans in seconds).

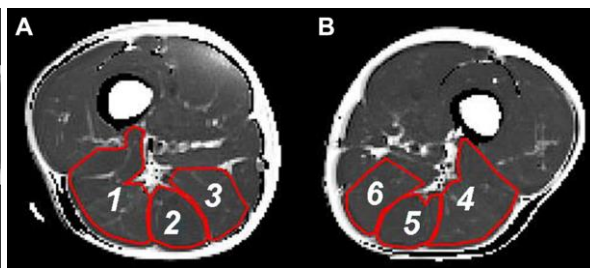
After assessing the normality of the data distribution for the different outcome variables, Mann-Whitney U tests and independent samples t tests were used to compare differences in metabolic hamstring activation between groups (index injury vs control, and no reinjury during follow-up vs reinjury during follow-up, respectively). Variables for which the mean values differed significantly between groups were submitted for logistic regression analysis to verify to what extent the evaluated parameters were able to predict the (re)occurrence of hamstring injuries during follow-up. Additional receiver operating characteristic (ROC) curve analyses were performed if relevant. Statistical analysis was conducted using SPSS 22 Statistical Software package (IBM Corp);  $\alpha$  was set at 0.05.

## Results

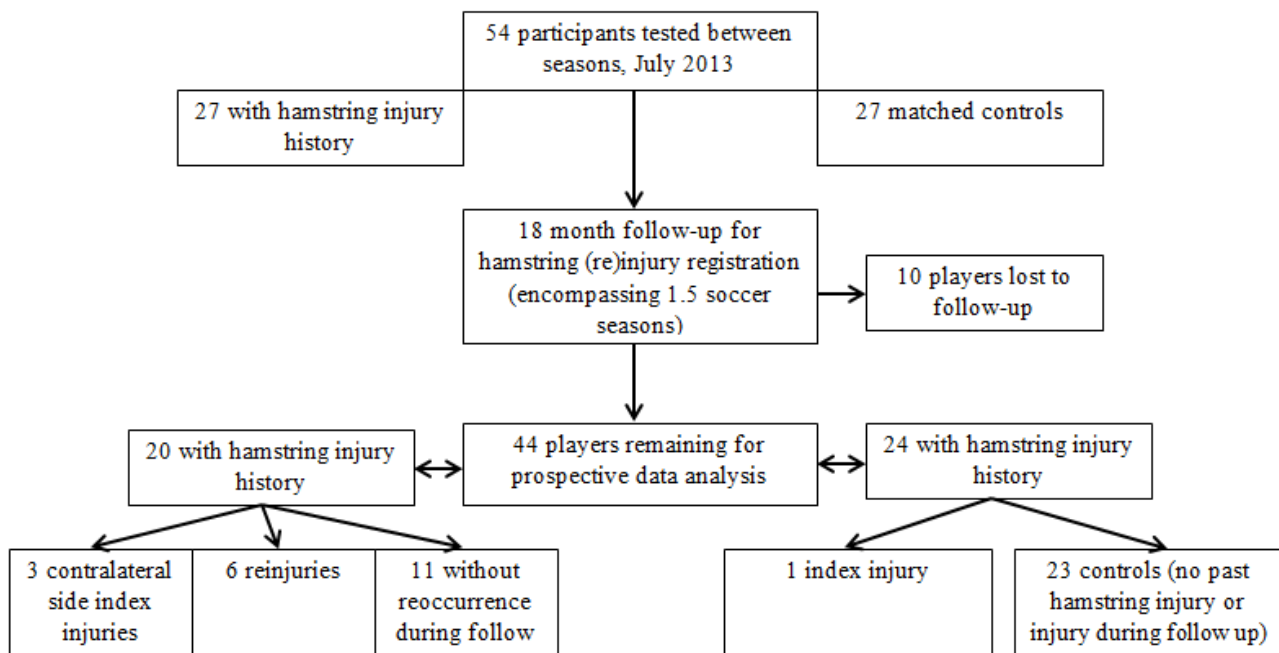
Of the 54 soccer players who underwent the mfMRI procedure in July 2013, 2 sustained a severe knee injury and had to end their soccer career, 2 stopped playing because of academic priorities, and 6 were lost to follow-up. Ultimately, MRI data of 44 participants could be obtained for prospective analysis: 24 controls and 20 with an injury history. A flowchart with details regarding the composition of the cohort throughout testing and follow-up is provided in Figure 4.



**Figure 2.** Region of interest selection in the T2 map acquired before exercise. (A) Right side: biceps femoris, 1; semitendinosus, 2; and semimembranosus, 3. (B) Left side: biceps femoris, 4; semitendinosus, 5; and semimembranosus, 6.



**Figure 3.** Region of interest selection in the T2 map acquired after exercise. (A) Right side: biceps femoris, 1; semitendinosus, 2; and semimembranosus, 3. (B) Left side: biceps femoris, 4; semitendinosus, 5; and semimembranosus, 6.



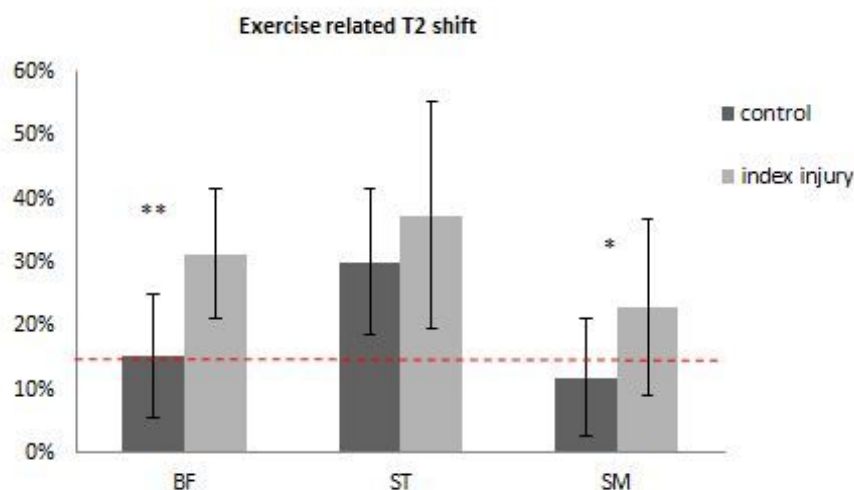
**Figure 4.** Flowchart of study design.

Four of 44 players sustained a first-time hamstring injury during follow-up (3 players in the injury history group sustained a first time hamstring injury in the opposite leg and were counted as part of the index injury group), resulting in an index hamstring incidence of 15%. Six of 20 players sustained a recurrent hamstring injury, generating a recurrence rate of 29% within our cohort. As it was the intention to associate metabolic activation patterns and their mediolateral (a)symmetry with the occurrence of hamstring (re)injuries during follow-up, the exercise-related T2 shifts were evaluated and compared between (1) a control group (n = 23) and an index injury group (n = 4) and (2) a group with a history of hamstring injuries but no recurrence during follow-up (n = 11) and a reinjury group (n = 6). This design would enable us to evaluate to what extent the metabolic muscle activation patterns of participants who sustained a first or recurring injury during follow-up differed from those of healthy controls or participants with a history of hamstring injuries but no reinjuries during follow-up, respectively.

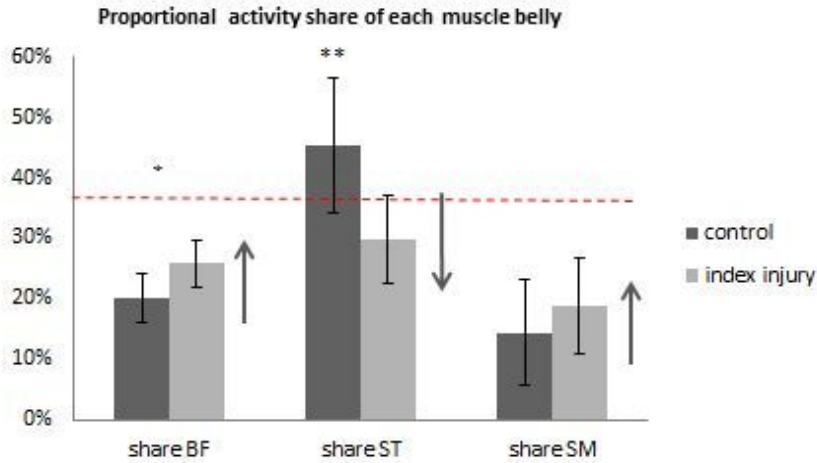
### **Index Injury During Follow-up**

Comparing the exercise-related T2 shifts between the index injury group (n = 4) and the control group (n = 23), the index injury group presented a significantly higher T2 shift in the BF (mean difference, 16.1%; 95% CI, 5.2%-26.9%; P = .005) (Figure 5) and the SM (mean difference, 11.1%; 95% CI, 0.0003%-22.2%; P = 0.050). No significant difference could be observed for the ST (mean difference, 7.3%; P = 0.285) (Figure 5). Logistic regression revealed that only the exercise-related metabolic activity characteristics of the BF were significantly able to predict a first-time injury within our cohort, with the chance of sustaining a first-time injury increasing exponentially with an increased the T2 shift of the BF (P = 0.028;  $R^2 = 0.402$ ). More specifically, ROC curve analysis demonstrated that this variable was significantly able to predict the occurrence of index injuries with a sensitivity of 100% and a specificity of 70% when the metabolic activity of the BF exceeded 10%. For the evaluation of the symmetry between the different hamstring muscle bellies in terms of exercise-induced changes in metabolic muscle fiber characteristics, we assessed the T2 shift for each muscle belly relative to the

total T2 shift, which was set at 100%. Considering this intramuscular activation symmetry within both groups, a significant between-group difference could be demonstrated for the relative contribution of both the BF and ST in which the BF showed a significantly higher contribution in the exercise-induced T2 shift (mean difference, 5.5%; 95% CI, 1.1%-10.0%;  $P = 0.017$ ), whereas the ST contributed significantly less (mean difference, 15.6%; 95% CI, 3.4%- 27.7%;  $P = 0.014$ ) in the index injury group compared to the healthy controls (Figure 6). Logistic regression revealed that only the proportional activity share of the ST was significantly able to predict a first-time hamstring injury, with the risk of sustaining an index injury increasing significantly when the ST demonstrated less contribution to the total metabolic activity, demonstrated by the hamstring muscle unit after the prone leg curls. More specifically, ROC curve analysis demonstrated that this variable was significantly able to predict the occurrence of index injuries with a sensitivity of 100% and a specificity of 61% when the ST contributed less than 34% to the summated T2 shift of the entire hamstring portion. Activity shares of the SM did not differ significantly between groups (mean difference, 4.4%;  $P = 0.350$ ), nor did logistic regression analysis reveal a meaningful association between the contribution of the SM and the occurrence of index injuries during follow-up ( $P = 0.340$ ).



**Figure 5.** Exercise-related T2 shift in each muscle belly ( $[T2 \text{ postexercise} - T2 \text{ pre-exercise}] / T2 \text{ pre-exercise}$ ). The T2 shift of the biceps femoris (BF) was significantly higher in the index injury group (\*\* $P = 0.005$ ). The semimembranosus (SM) tended to be activated to a higher extent in the index injury group as well (\* $P = 0.050$ ). The primary injury risk reached a maximum when the BF activity exceeded 14%. The dotted line indicates the crucial cut-off level of absolute metabolic BF activity, as from where metabolic activity increments increase the risk of injury significantly (ROC curve outcome measure). ST, semitendinosus.



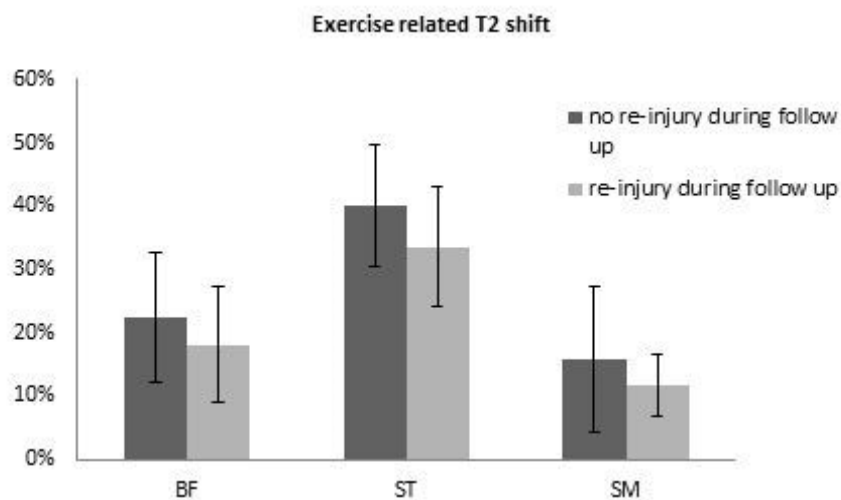
**Figure 6.** Individual share of each hamstring muscle belly in the total T2 shift for the entire hamstring group (portion of 100%). The share of the biceps femoris (BF) was significantly higher in the index injury group (\* $P = 0.017$ ), while the share of the semitendinosus (ST) was significantly lower (\*\* $P = 0.014$ ). The primary injury risk reached a maximum when the share of the ST was less than 37%. The dotted line indicates the crucial cutoff level of metabolic muscle activity, as from where decreases in relative activity of the ST increase the risk of injury during follow-up (ROC curve outcome measure). SM, semimembranosus.

### Recurring Injury During Follow-up

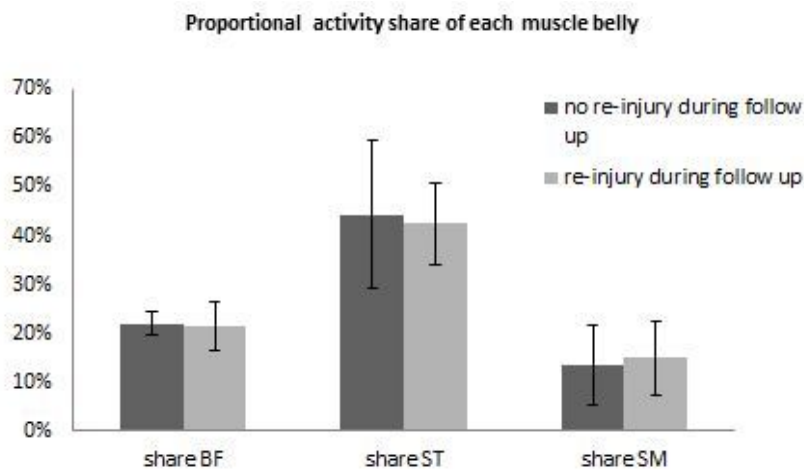
The possible association between the metabolic hamstring features and the risk of sustaining a recurring hamstring injury was assessed by comparing the exercise-related metabolic activation patterns of the participants who sustained a reinjury during follow-up ( $n = 6$ ) with those of the participants with a history of hamstring injuries but no reinjury during follow-up ( $n = 11$ ). No significant differences in the T2 shift could be demonstrated between groups (Figure 7). Furthermore, the relative contribution of each muscle belly in the total hamstring T2 shift was almost identical in both groups (Figure 8). Logistic regression revealed no meaningful relation between the amount of metabolic changes and their distribution within the hamstring unit and the risk of sustaining a reinjury during the subsequent season. For a very comparable metabolic activity profile, however, the reinjury group demonstrated significantly poorer strength endurance, shown by the time to exertion on the eccentric hamstring exercise between scans (Figure 9). The reinjury group was only able to perform prone leg curls for a mean duration of  $146.50 \pm 76.16$  seconds, whereas the participants with an injury history but no recurrences during follow-up were able to persevere for a mean of  $237.45 \pm 110.76$  seconds (95% CI, 11.9-230.5 seconds;  $P = 0.031$ ). More so, ROC curve analysis revealed that the



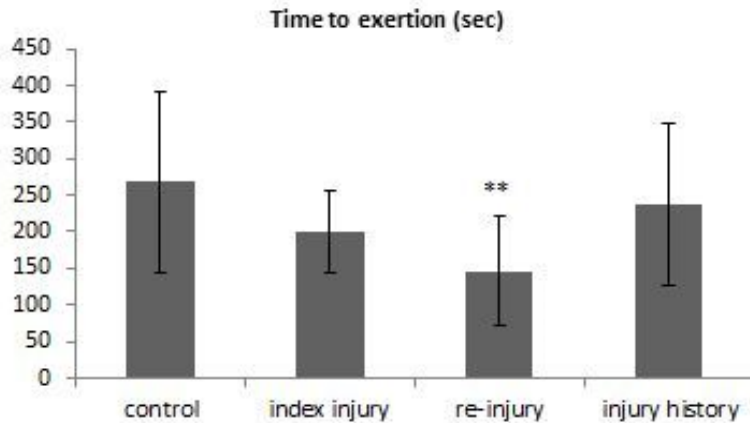
eccentric (strength) endurance capacity on the prone leg curl was significantly able to predict recurring hamstring injuries during follow-up ( $P = 0.031$ ) with a sensitivity of 100% and a specificity of 52% if the time to exertion was  $\leq 256$  seconds.



**Figure 7.** Exercise-related T2 shift in each muscle belly ( $[T2 \text{ postexercise} - T2 \text{ pre-exercise}] / T2 \text{ pre-exercise}$ ) for the injury history group and the reinjury group. BF, biceps femoris; SM, semimembranosus; ST, semitendinosus.



**Figure 8.** Individual share of each hamstring muscle belly in the total T2 shift for the entire hamstring group (portion of 100%) for the injury history group and the reinjury group. BF, biceps femoris; SM, semimembranosus; ST, semitendinosus.



**Figure 9.** Time to exertion on the loaded prone leg curl between both T2 scans. The index injury, reinjury, and injury history groups performed less compared with the control group; only the performance of the group that sustained a reinjury during follow-up was significantly weaker compared with controls (\*\* $P = .014$ ).

## Discussion

The results of this innovative, prospective mfMRI study demonstrate that hamstring injuries in soccer are most probably associated with alterations in neuromuscular coordination within the biarticular muscle unit. The risk of sustaining a first hamstring injury was strongly related to elevated levels of metabolic changes in the BF after eccentric exercise and a significant decrease in assistance of the ST. This study could not associate the risk of sustaining a reinjury with the same divergent recruitment pattern during eccentric exercise. However, the players who sustained a recurring injury during follow-up presented a significantly inadequate deficit in hamstring strength endurance. Taking together the results of the present study and a prior study,<sup>37</sup> we are inclined to believe that the lacking strength endurance could possibly be related to aberrant intermuscular interplay.

## Index Injury Risk

The results of this study demonstrated that the risk of sustaining a first-time hamstring injury increased significantly if the BF was activated beyond 10% of its metabolic resting state or if the ST did not participate sufficiently (relative contribution < 34% threshold) during the prone leg curls. The metabolic hierarchy of the control group differed substantially and clearly indicated an exercise-related metabolic dominance of the ST, which is in agreement with former findings<sup>37</sup> and indicates the existence of a causal association between intermuscular interplay (or task distribution) and the vulnerability for hamstring injuries. In the existing literature, prospective research identifying functional/dynamic risk factors for first-time hamstring injuries is lacking. Because of the limitations of the design (need for large cohorts to encounter sufficient incidence rates as well as potential dropouts and adequate monitoring), such studies have predominantly investigated the influence of injury history, ethnicity, and anthropometric features as well as musculoskeletal characteristics or features of functional performance on the susceptibility to subsequent hamstring injuries in soccer.<sup>3, 12, 16, 18, 19, 34, 42</sup> Likewise, isokinetic strength profiles with a particular focus on bilateral balances and inadequate antagonist ratios have been implemented in prospective designs repeatedly.<sup>4, 9, 45</sup> In terms of neuromuscular coordination and interplay between the different hamstring muscle bellies, there are no prospective studies available. Some studies have investigated the differences in BF and ST activities during exercise and running, but only in healthy controls or in retrospective designs.<sup>21-23, 25, 28, 38</sup> Likewise, the mfMRI technique has predominantly been used in a healthy population, mostly to identify the most suitable exercises for rehabilitation.<sup>20-31</sup> As a consequence, the role of the exact mediolateral interplay in the susceptibility to hamstring injuries used to be part of the frontiers of knowledge. In a fairly recent review, however, the role of neuromuscular inhibition in the recurrence of hamstring injuries has been discussed.<sup>15</sup> Although the authors did not mention intermuscular balance nor the potential association with the primary injury risk (because of the lack of available prospective research), they concluded that hamstring strain injuries result in neuromuscular adaptations, among which are selective eccentric weakness and selective atrophy of the long head of the BF. Interestingly, the present study could also associate recurring injuries with lacking strength

endurance during prone leg curls. Moreover, the selective atrophy of the BF might ultimately result in a higher metabolic response after exercise, as the remaining fibers will inevitably be subject to overloading. If, in addition, the ST would not be able to take the lead (as it most probably is designed to do during eccentric work), the (next) injury might be just around the corner.

In our previous work,<sup>37</sup> we stated that the natural hierarchy in the activity distribution within the hamstring muscle unit probably relates with the differences in muscle fiber typology and functional purposes of both the medial and lateral muscle bellies. We believe that because of its fairly short, voluminous muscle fibers and considerable pennation angle, the BF is better suited for concentric and isometric muscle work (stance and backswing phases), whereas the longer, thin, and fairly straightly aligned muscle fibers of the ST should be more capable of engaging in eccentric actions (front swing phase).<sup>25</sup> This presumption could explain our findings (leading role of the ST in eccentric muscle effort) and could account for the particular injury vulnerability of the BF in running and kicking. In agreement with this hypothesis, Higashihara and colleagues<sup>21</sup> reported a discrepancy between the onset of peak muscle stretch and peak EMG activity in the hamstring muscle unit throughout the explosive front swing phase in sprinting, with the BF reaching peak EMG activity after the onset of peak muscle stretch. The ST, on the other hand, presented peak EMG activity before peak stretch. These findings support our train of thought, as they indicate that the ST is perfectly able to engage in rapid eccentric contractions, effectively controlling flexion and extension torque generated around the hip and knee joints, whereas the BF does not seem to be. Therefore, the alterations in absolute and relative metabolic activity within the hamstring muscle unit due to eccentric exercise are most probably partly responsible for an increased risk of sustaining a functional or structural injury.

### **Recurring Injury Risk**

In contrast with our original hypothesis, we were not able to associate this divergent muscle recruitment pattern with the risk of sustaining a recurring hamstring injury. Interestingly and in line with what has previously been stated,<sup>8, 15, 41</sup> the reinjury group performed strikingly weak on the prone

leg curling exercise, indicating an insufficient hamstring load-bearing capacity and (probably) an unjustified return to play. ROC curve analysis demonstrated that the time to exertion on the prone leg curls, a parameter for hamstring muscle strength-endurance, was able to predict the recurrence of hamstring injuries within our cohort. This study could not demonstrate that the intramuscular recruitment pattern and interplay are related to the risk of sustaining a recurring hamstring injury, as the metabolic activation pattern of the participants with a recurring injury during follow-up did not differ from those with a history but no recurrence during follow-up. Because the cohort in which this pattern was assessed in relation to the reinjury risk was small ( $n = 17$ ), these results must be interpreted carefully, as lacking power might have influenced the outcome. However, in accordance with the results of the present study, predominantly, the functional muscle output and strength capacity seem to be key for secondary prevention.

### **Association Between Metabolic Muscle Features and Strength Endurance**

In agreement with previous research,<sup>37</sup> this study revealed substantially lower strength endurance in both the index and reinjury groups, corresponding with a higher and a similar metabolic expense, respectively. This finding once again indicates that the hamstring muscles of the players who sustained a first or recurring injury function less effectively (probably because of the divergent intermuscular interplay), which causes them to acidify more easily and probably makes them more prone to functional and structural injuries.<sup>10, 37</sup> Next to this potentially locally mediated decrease in fatigue tolerance (deviated intermuscular hierarchy and muscle recruitment), central fatigue mechanisms altering peripheral motor output characteristics might play a role as well. It has been demonstrated repeatedly that muscle injuries tend to occur more frequently toward the end of the season or the end of a match.<sup>10-12, 35</sup> Aside from peripheral fatigue mechanisms due to metabolic changes in muscle and cardiorespiratory systems, centrally mediated fatigue, caused by changes in the central nervous system (mostly by alterations in autonomic and hormonal balances), will also cause the muscle to contract in a less coordinated manner, making it more susceptible to functional and/or structural injuries.<sup>27, 29, 36, 39</sup> As we evaluated local strength endurance by means of a prone leg curl to exertion, we believe that we

predominantly verified the characteristics of local metabolic muscle functioning rather than the fatigue tolerance and load-bearing capacity of the central nervous system. Consequently, we cannot discuss the possible influence of centrally mediated fatigue (tolerance) in the reinjury risk based on the present results. If we had intended to monitor central fatigue and its association with hamstring (re)injuries during follow-up, we should have included outcome measures to assess possible overreaching/overtraining,<sup>29,36</sup> as well as hormonal or autonomic nervous system homeostasis, with additional functional exercise capacity screens (peak VO<sub>2</sub> estimation, heart rate at maximum running speed or maximum aerobic speed,<sup>18,43</sup> yo-yo intermittent test,<sup>26</sup> etc). We specifically chose to verify the role of local metabolic muscle function characteristics and their intermuscular coordination in the risk of hamstring injuries in soccer, so the influence of centrally mediated fatigability of the participants in terms of their injury vulnerability was beyond the scope of this study. On the basis of what has been demonstrated in this study as well as the results from previous research assessing peripheral/local and central fatigability,<sup>27,29,36,39</sup> we believe that the latter is a considerable risk factor for both primary and secondary muscle injuries, whereas local fatigability probably predominantly deteriorates in the presence of a history of muscle injuries because of morphological and functional changes in the previously injured muscle unit.<sup>15,37</sup> Therefore, the evaluation of local muscle strength endurance (preferably with mfMRI quantification) seems to be ideally suited for investigating deviating muscle function (coordination) after an injury and to verify the risk of recurrence.

### **Clinical Message**

Based on the present results, we suggest that the hierarchic shift in the metabolic activity contribution is most probably (partly) responsible for the first hamstring strain injury and that this altered pattern of muscle activation is associated with poorer strength endurance.<sup>37</sup> Bearing this in mind and presuming that a deviated activation pattern could be both a cause and consequence of hamstring strain injuries in soccer, the quality of the recruitment pattern should be acknowledged in preventing first and recurring hamstring injuries. The findings of this prospective study indicate that a perfectly and functionally

balanced out BF-ST unit appears to be of major importance in the prevention of hamstring (re)injuries and, most probably, in the athlete's performance as well. In attempting to protect the BF against structural or functional damage, the clinician should bear in mind this natural intramuscular hamstring hierarchy and effectively train both the BF and ST plyometrically, dominantly addressing the ST during heavy eccentric loading in the distal range of motion. Furthermore, prone leg curls with eccentric overloading could be implemented as an exercise and a test for the purpose of rehabilitation and determining the readiness for return to play in community-level soccer players, with a cutoff value of 4 minutes and 30 seconds.

### **Limitations**

For the limitations to this study, we partly refer the reader to the previous work.<sup>36</sup> Because of the prospective design, the distinction between index and recurring injuries, and the high costs of the mfMRI protocol, the sample sizes for between-group comparison were small. This lowers the power of this study considerably, which must be acknowledged when drawing conclusions. Future largescale prospective research using mfMRI for the assessment of the importance of intermuscular interplay/coordination in the risk of hamstring (re)injuries is needed to be able to affirm or refute the results of this preliminary study. However, this is the very first prospective mfMRI study to assess metabolic hamstring characteristics and intramuscular activation features for the purpose of identifying the risk of index injuries and reinjuries in soccer.

### **Conclusion**

This is the first prospective study using mfMRI to assess the influence of metabolic muscle functioning and intramuscular coordination in the context of identifying the risk of hamstring injuries. The present results indicated that the occurrence of index hamstring injuries could be associated with a hierarchical change in the metabolic activity distribution within the hamstring muscle complex after

eccentric work in which the ST is most probably meant to take the leading part, followed by the BF and SM. When the BF increases its contribution and is activated to a proportionally higher extent, the risk of sustaining an index hamstring injury might increase substantially. This study is also the first to assess the risk factors for index and recurring injuries, considering both injury entities separately but acknowledging their similarity and interdependence. Subjects with reinjuries within our cohort presented a particularly weak performance capacity on the prone leg curling exercise. This type of heavy eccentric loading might be suitable to determine the athlete's readiness to return to play. The athlete should be able to perform the standardized prone leg curls with 5 kg attached to each foot, at a standardized pace of 90 rpm for at least 4 minutes and 30 seconds, before safely returning to competition.

### **Acknowledgements**

The authors gratefully acknowledge the assistance of P. Vandemaele, engineer at Ghent University Hospital, for his assistance in MRI scanning and data processing. Furthermore, we thank Steven Heyndrickx, a highly appreciated former colleague at the Department of Rehabilitation Sciences and Physiotherapy, for the assembly of the online diary for injury registration during follow-up. Last but not least, the authors thank the participants of this study, without whom this prospective study could have never been completed successfully. For their financial support, the authors' gratitude goes out to the IWT (Agency for Innovation by Science and Technology in Flanders; Brussels, Belgium), who made this MRI research possible.



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# **Chapter II**

Intermuscular coordination in  
hamstring injury susceptibility



Prone Hip Extension muscle recruitment is associated with hamstring injury risk in amateur soccer





## CHAPTER II

### **Prone Hip Extension muscle recruitment is associated with hamstring injury risk in amateur soccer**

Joke Schuermans, PT,<sup>1</sup> Damien Van Tiggelen, PT, PhD,<sup>1</sup> Erik Witvrouw, PT, PhD<sup>1,2</sup>

<sup>1</sup> Department of Rehabilitation Sciences and Physiotherapy Ghent, Ghent University, Ghent, Belgium

<sup>2</sup> Department of Physiotherapy, Aspetar, Doha, Qatar

Correspondence to Schuermans Joke, Department of Rehabilitation Sciences and Physiotherapy, Ghent University, De Pintelaan 185, 3B3, –Ghent 9000, Belgium; [Joke.schuermans@ugent.be](mailto:Joke.schuermans@ugent.be)

**Submitted in the International Journal of Sports Medicine (third round of revision)**

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#### **Abstract**

**Background** ‘Core stability’ is considered essential in rehabilitation and prevention. Particularly in preventing hamstring injuries, assessment and training of lumbo-pelvic control is thought to be key. However, supporting scientific evidence is lacking. To explore the importance of proximal neuromuscular function with regards to hamstring injury susceptibility, this study investigated the association between the Prone Hip Extension (PHE) muscle activation pattern and hamstring injury incidence in amateur soccer players.

**Methods** 60 healthy male soccer players underwent a comprehensive clinical examination, comprising of range of motion assessments, and the investigation of the posterior chain muscle activation pattern during PHE. Subsequently, the hamstring injury incidence was recorded prospectively throughout a 1.5 season monitoring period.

**Results** Players that got injured presented a PHE activation pattern that differed significantly from those who did not. Opposed to the controls, hamstring activity onset was significantly delayed ( $p = 0.018$ ), resulting in a deviating activation sequence. Players were 8 times more likely to get injured if the hamstring muscles were activated after the lumbar Erector Spinae instead of vice versa ( $p = 0.009$ ).

**Conclusion** Assessment of muscle recruitment during PHE demonstrated to be useful in injury prediction, suggesting that neuromuscular coordination in the posterior chain is of influence in hamstring injury vulnerability.

**Key words** hamstring muscle injury; soccer; physical examination; surface electromyography; risk assessment

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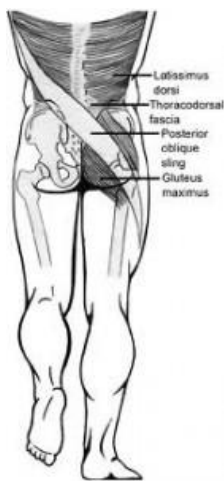
## Introduction

Hamstring injuries are a common and frequently reoccurring problem in several sports.<sup>5, 13, 17, 18, 62</sup> Especially in male soccer, given its high physical demands, this muscle injury remains an obstacle.<sup>3, 6, 29</sup> This type of muscle injury is still the single most common sports injury in soccer (representing approximately 12% of all sports injuries) and is also associated with a considerable risk of recurrence (rates ranging from 12 to 30% after return to play; up to 35% of all recurring muscle injuries involve the hamstrings).<sup>10, 14, 27, 45, 60, 62</sup> Furthermore, although a substantial amount of research already has been (and still is being) conducted aimed at reducing the number and severity of these soccer-related injuries, a recent study has demonstrated that the injury incidence has not decreased, and even presented a slight increase, throughout the last years.<sup>15</sup> The particularly high hamstring injury occurrence in male soccer, is due to the fact that explosive running and kicking (which movement patterns are inherent to soccer play) imposes massive mechanical loads on respective muscle entity. Particularly the front swing phase of sprinting (and kicking) incurs a risk of muscle failure, as the

hamstrings have to engage in intense negative work to control for the strong flexion and extension torques acting upon the hip- and knee joints. Biomechanical research, objectifying hamstring mechanics during sprinting, has suggested that the terminal front swing phase might indeed hold the primary injury mechanism, as muscle-tendon loads are maximized at that moment.<sup>12, 62</sup> Among others, alterations in neuromuscular coordination<sup>51-52</sup> and neuromuscular inhibition<sup>20</sup> are suggested to play a role in hamstring injury vulnerability. Both local<sup>20, 51-52</sup> and more proximally oriented coordination dysfunctions<sup>43, 49</sup> have been associated with hamstring injuries in athletes. To what extent these neuromuscular features are the cause or merely the consequence of hamstring injuries, is not to be deducted as prospective research is lacking.

Neuromuscular coordination, in particular lumbo-pelvic function is suggested to be key in safe hamstring functioning.<sup>43</sup> The hamstrings are primarily responsible for controlling and generating forces around the knee- and the hip joints throughout running. However, in theory, due to their biarticular function and anatomical connections with proximal stabilizing structures, they have the capacity to contribute to stabilizing the pelvis, sacro-iliac joint and lower spine as well.<sup>43-44</sup> Nonetheless, this stabilizing function is only secondary, as the hamstrings are prime mobilizing muscles, morphologically and topographically best suited to generate and control torques around hips and knees.<sup>61</sup> To guard optimal tissue homeostasis and to prevent the hamstrings from overload during running, adequate synergetic functioning in the entire posterior muscle chain is essential. Next to the hamstrings, the gluteal muscles and lumbar erector trunci are suggested to be responsible for effective and safe force transfer from lower limb towards trunk (and vice versa) during locomotion.<sup>9, 31, 36, 44, 53-54</sup> Both the gluteus maximus and the (superficial) lumbar erector spinae too have a dual function. They are designed to create and control extension- and flexion torques, respectively, and to generate sufficient muscle tone for safeguarding the necessary force closure and joint stability within the pelvic girdle. Adequate synergistic interplay and muscle balance within this posterior continuum, has mostly been investigated in terms of lower back complaints.<sup>1, 7, 11, 24, 32-34, 36, 43, 46</sup> However, it seems to us that this feature is essential in hamstring injury prevention as well. The Prone Hip Extension (PHE) test was originally introduced by Janda<sup>30</sup> and has been adopted in multiple studies to investigate

impairments in lumbo-pelvic neuromuscular coordination.<sup>1, 7, 11, 24, 36, 40</sup> By investigating the activation order among the hamstrings, gluteal muscles and lumbar spine muscles, the practitioner intends to gain insights in the synergistic balance and possible dominance / inhibition within the posterior muscle tract (causing relative overload and injury more proximally or distally). Figure 1 illustrates the posterior sling system, with a diagonally directed force vector crossing the lumbo-pelvic girdle from lower limb towards trunk and vice versa.



**Figure 1.** The functional posterior chain unit, consisting of the hip- and contralateral back extensor muscles.

Although mostly suggested to be important in prevention of lower-back and sacro-iliac complaints,<sup>31-34, 36, 40, 46, 49-50, 53</sup> this interplay might have important repercussions for hamstring functioning as well,<sup>42</sup> but this has never been investigated before. Therefore, this study wanted to investigate the influence of neuromuscular coordination in the posterior muscle chain (hamstrings, gluteus maximus and lumbar erector spinae) on hamstring injury vulnerability in a cohort of male amateur soccer players, by assessing PHE muscle recruitment patterns using surface Electromyography (sEMG). Because joint mobility and muscle tightness within and around the lumbo-pelvic-hip complex would evidently effect associated muscle activation characteristics during PHE, respective clinical features were thoroughly examined prior to sEMG analysis.

## Methods

### Participants

Throughout the second half of the 2013 soccer season, male soccer players, active in the same amateur competition series (Oost-Vlaanderen, Belgium), were recruited. Players were excluded if they

- had not fully returned to play (soccer training and matches) after a previous hamstring injury or reported having suffered any functional discomfort in the hamstring region the past 3 months (Cf. reinjury definition by UEFA)<sup>25</sup>
- were still recovering from any injury, which disabled them to fully participate in training and match play
- had a history of severe lower limb injury, lower back complaints / lower back complaints at present, which could have biased clinical outcomes and consequentially, disabled risk estimation

A hamstring injury was defined being an injury in the hamstring muscle region, sustained during soccer training or match play, preventing the player to participate in training or competition for at least one entire week.<sup>25</sup> Although potentially inducing significant inhibition and neuromuscular alterations, we decided not to encounter for less severe hamstring complaints (not preventing the participant from participating in soccer play), to make sure we would not unfoundedly take along the covariate ‘hamstring injury history’ in statistical analysis. Ultimately 60 male soccer players were included for study participation. At the time of testing, all participants were completely injury free and none of them reported any pain or discomfort in the hamstring region during soccer participation or during the assessment protocol in this study.

## Screening protocol

All tests were conducted at the Ghent University Hospital and were performed by the same researcher (JS). Participants were asked not to engage in intensive physical exercise 48 hours prior to testing to rule out fatigue induced bias or a temporal change in tissue homeostasis. After being informed about the purpose and the content of the testing protocol, each participant was asked to affirm his agreement with participation by signing the informed consent and to fill out a short questionnaire to gather data on participant's age, anthropometrics and (hamstring) injury history. This study was approved by the Ethics Committee of the Ghent University Hospital (EC/2013/118) and meets the ethical standards of the International Journal of Sports Medicine.<sup>26</sup>

Evaluating the posterior chain muscle activation order to gather more insights in neuromuscular coordination and potential deficits in lumbo-pelvic control / function, was the main purpose of this research. However, as neuromuscular coordination, assessed by means of the PHE exercise, requires adequate joint mobility and muscle length, those needed to be examined as well in order to correctly estimate the nature of deviating muscle recruitment and thus, possible neuromuscular coordination impairments. Therefore, the protocol consisted of a comprehensive clinical examination, covering Range Of Motion (ROM) assessments throughout the entire lower extremity, as well as surface electromyography (sEMG) recording of the hamstrings, the Gluteus Maximus and the Lumbar Erector Spinae during PHE.

## Range Of Motion (ROM) assessment

After being familiarized with the content of the testing protocol, each subject underwent a standardized 5 minute warm up on a stationary bike. Subsequently, hamstring flexibility (passive knee extension test from a 90° hip- and knee flexion position(Figure 2) (intra-rater ICC > 0.83, inter-rater ICC > 0.93)<sup>19, 21</sup>, Iliopsoas flexibility and Rectus Femoris flexibility were evaluated (modified Thomas

test (Figure 2) (intra-rater ICC > 0.63, inter-rater ICC > 0.90)<sup>2, 16, 19, 21-22</sup> For the hamstring flexibility assessment, passive knee extension capacity was measured from a 90° hip and knee flexion position, as described by Gabbe and colleagues.<sup>22</sup> Contrary to their protocol, knee extension was performed passively. We decided not to perform the passive knee extension test as originally described by Fredriksen (passive knee extension starting from a 120° flexion position in the hip joint),<sup>19</sup> as we felt we could control the hip joint angle better when starting from a 90° hip flexion position and because this position allowed a more reliable measurement of knee extension using a digital inclinometer.



**Figure 2.** Hamstring flexibility – and Hip flexor flexibility assessment quantified by a digital inclinometer by means of passive knee extension and Modified Thomas testing.

Next, hip flexion, internal and external rotation ranges of motion were objectified with the subject adopting a relaxed supine or sitting position, respectively [Figure 3] (intra-rater ICC > 0.83, inter-rater ICC > 0.88)<sup>21, 47</sup>.



**Figure 3.** Mobility assessment of the hip joint using a digital inclinometer by means of flexion, external- and internal rotation range of motion.



All ROM measurements were conducted using a digital inclinometer. Bilateral and unilateral Finger To Floor (FTF) reaching distances<sup>5, 48</sup> [Figure 4] (intra-rater ICC = 0.98, inter-rater ICC = 0.95)<sup>23</sup> were assessed using measuring tape. Lastly, the neuromuscular stretch tolerance of the entire posterior chain was assessed by measuring the knee extension capacity from the Slump-position (active Slump test)<sup>21-22, 56</sup> [Figure 5] (intra-rater ICC > 0.80, inter-rater ICC = 0.92)<sup>21</sup>.



*Figure 4. Bilateral and Unilateral finger to floor reaching test.*



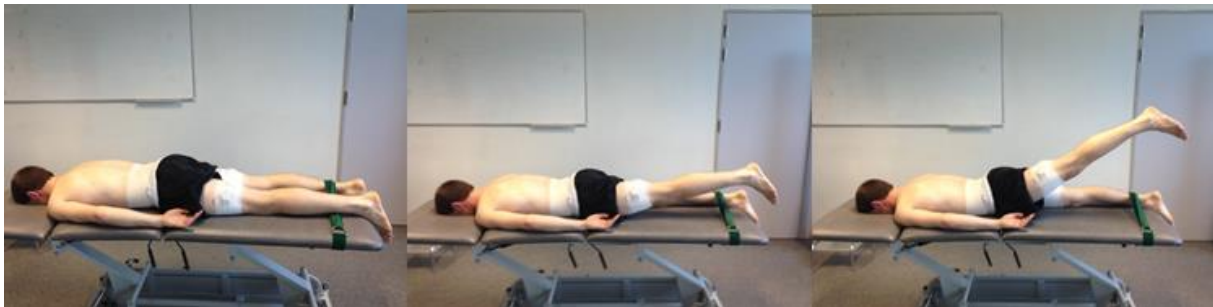
*Figure 5. Active Slump Test; amount of knee extension quantified using a digital inclinometer.*

### **EMG assessment**

For this sEMG analysis, the Noraxon Direct Transmission System (DTS) was utilized (Noraxon U.S.A. Inc., Arizona). After shaving, abrading and cleansing the skin with alcohol, electrodes (Ambu A/S, Denmark) were placed on the Biceps Femoris, the medial hamstrings, Gluteus Maximus and

Lumbar part of the Erector Spinae bilaterally, corresponding the SENIAM guidelines.<sup>28, 38</sup> We chose to primarily take into account the contralateral erector muscle (Contralateral Erector Spinae (CLES)) for final data-analysis, as force transmission across the pelvis occurs cross-coordinated and this crossing posterior muscle chain (hamstrings – gluteus maximus – contralateral paravertebral muscles) is the one working synergistically in daily locomotion as well.<sup>4, 43, 49, 59</sup> After electrode placement, 8 amplifiers, which served to capture and amplify the electric signal prior to forwarding it to the DTS desk receiver, were attached to the skin in the proximity of the measuring site. A tight pair of shorts and a cohesive, stretchable bandage made sure that all electrodes and amplifiers remained firmly attached to the skin during analysis. After checking the quality and validity of the EMG signal in each of the 8 channels (normal baseline voltage, proper zero-offset), 3 maximal voluntary contraction (MVC) trials were acquired per muscle (group), adding up to the registration of 15 MVC trials per participant (3 repetitions for the back muscles, 3 for both the left and right hamstrings and Gluteus Maximus). This procedure was conducted according to the Noraxon guidelines,<sup>35</sup> with the participant adopting a neutral prone position on the examination table. For the lumbar part of the erector spinae, the participants were instructed to perform a back extension, maximally resisting the tester's force applied at level of the shoulder blades, square to the lever of the trunk. For the hamstrings, the participant was instructed to maximally resist a torque towards knee extension from a 30 degree (°) knee flexion position (lower leg and foot supported by the upper leg of the tester). For the gluteus maximus, the participant was asked to extend the hip joint, maximally resisting the tester's torque towards hip flexion. For each of these procedures, the participants was commanded to gradually raise the amount of muscle force, reaching a maximum in approximately 3 seconds. This maximum force output was maintained for 5 seconds, after which the participant was instructed to gradually lower muscle force until full relaxation was reached. For the subsequent PHE EMG signal acquisition, the subject was asked to adopt a neutral prone position again, with the head down straight and both arms positioned next to the trunk, resting on the examination table. Afterwards, each subject was instructed to lift up his leg at a 0.5Hz (Hertz) pace, going into an isolated hip extension with a fully extended knee, without rotating or tilting the pelvis, and to lower it again towards the table hereafter. [Figure 6] This Prone Hip Extension test was repeated 3 times in each leg, starting with the dominant

leg in each subject. The beginning of each hip extension was signalled within the EMG record using a marker, synchronized with the verbal command of the investigator (not the onset of hip extension). The participants were instructed to relax completely in between repetitions, to safeguard a solid baseline resting signal. The main outcome parameter during this PHE study was the time elapsed between the verbal command and the very first burst of muscle activity, so the pre-motor time of each of the included posterior sling muscles (instead of the motor-time, which encompasses the timeframe between activity burst and muscle force development)<sup>37</sup> was the measure of interest. To allow valid interpretation of the possibly differing activation sequence within the posterior muscle chain, average normalized EMG amplitudes during PHE were gathered as well. This was done because information regarding the quantity of muscle fibre recruitment (intensity of muscle contraction relative to the voluntary maximum) within each of the investigated muscles, is essential to make conclusions regarding neuromuscular coordination and consequences as regards injury vulnerability. We used a sampling frequency of 1500 Hz for the assembly of all EMG records. Rotation or any compensation in the frontal and transverse planes was prohibited and carefully monitored by 2 testers.



*Figure 6. Resting-, mid- and end-range position for Prone Hip Extension test.*

### **Prospective recording of injury occurrence**

After testing, the participants were requested to sign up to an online diary for registration of weekly exposure and injury incidence. They were instructed to complete this survey on a weekly basis

[<http://www.hsi.ugent.be>]. The end of this monitoring phase was set at the 2014-2015 winter break (December 2014), during which period all participants were contacted again for final injury enquiry. As we were able to keep in contact with the participants throughout respective period and because adding an additional couple of months of soccer exposure would potentially increase the power of our study, we chose to register injury occurrence throughout one and half a season, instead of just the one after testing. As mentioned previously, a hamstring injury was defined being an injury in the hamstring muscle region, sustained during soccer training or match play, preventing the player to participating in training or competition for at least one entire week. Because the UEFA guidelines state that a reinjury occurs at the exact same location as the prior one, within two months after the final rehabilitation day of the previous injury, all recorded injuries were considered to be index injuries.<sup>25</sup> However, as the presence of in an injury history has demonstrated to increase the risk of a subsequent one,<sup>19</sup> this variable was taken along as a covariate in prospective data analysis.

### Data analysis

All clinical records were organized and catalogued in a central datasheet. The EMG signals of the PHE records were submitted to electrocardiography (ECG) – and high pass (20 Hz) filtering, rectification and smoothing in a 50 milliseconds (msec) window. Additional zero-offsetting of the collected records was not necessary as each one of the signals presented a correct and solid baseline in between the PHE related activity bursts ( $\pm 2 \mu\text{V}$  (microvolt)).

The processed EMG signals of respective records were submitted to a timing analysis algorithm, to evaluate the activation sequence among the hamstrings, gluteus maximus and lumbar erector spinae. Mean onset times were calculated and sorted using a 3 SD (Standard Deviation) threshold within a 0.1 sec time interval, on the basis of which absolute onset times for each muscle (hamstrings, gluteus maximus and lumbar erector spinae; (msec)) could be listed, as well as the relative activity onset of each of those compared to their neighbours (1, 2 or 3). To gather insights as regards the intensity of the muscle contraction (respectively the volume and intensity of motor unit recruitment), Root Mean

Square calculations and post hoc assembly of the average activation patterns and the normalized amount of muscle activity throughout PHE was performed as well. All EMG data-processing was proceeded using the MR3.6 software(Noraxon U.S.A. Inc., Arizona). Based on the ratio [dominant / non-dominant leg involvement] of the recorded hamstring injuries, the same ratio was used in randomly selecting the left or right leg of the non-injured participants, for comparative prospective analysis.

### **Statistical analysis**

After checking the shape of data distribution within all cohorts, each of the intended variables was submitted to

- (1) general linear model repeated measures analyses and post hoc tests (continuous variables),
- (2) as well as binary logistic - and multi-nominal logistic regression analysis (ordinal and nominal variables)

to verify whether a causal association between the clinical and EMG variables on one hand and the hamstring injury risk on the other could be identified, taking injury history along as a confounding covariate. If differing significantly based on injury occurrence, Cohens d values were calculated to quantify the strength of the effect of the muscle activity onset times on the risk of sustaining a hamstring injury. After regression, additional Receiver Operating Characteristic (ROC) curve analysis was performed when indicated. All statistical procedures were conducted in the SPSS 22 Statistical Software Package (IBM Corp. New York, USA). The level of significance was set at  $\alpha = 0.05$ .

Because the BF and MH systematically presented very similar activation features in terms of absolute (individual muscles (msec)) and relative onset times (activation order within the posterior chain (1-4)) (paired samples t = -0.35, p = 0.73; Pearson Correlation = 0.84, p < 0.001), outcome measures of both

were taken together for further analysis. Hence, the onset features of the “Hamstrings” represent the average EMG timing features of the BF and the MH.

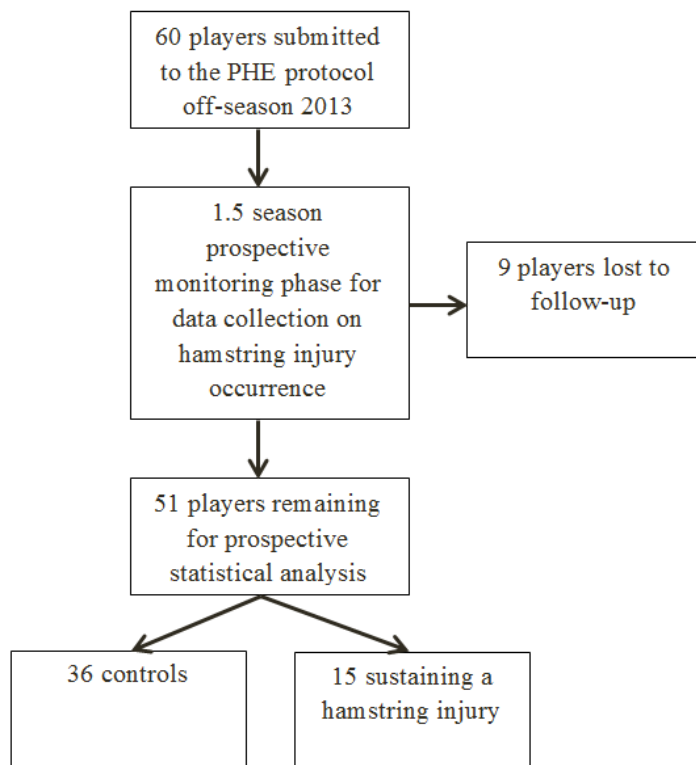
## Results

Of the 60 participants screened in July 2013, 4 stopped playing because of severe injuries (other than hamstring injury) and/or work related priorities, and 5 were lost to follow-up, resulting in a sample size of 51 players for prospective data-analysis. 15 of those sustained a hamstring injury, during the 1.5 season monitoring period (incidence rate of 29%). Average time elapsed between the testing series and injury occurrence was 15 weeks (range [3 – 26] weeks) and the average absence from soccer participation was 3 weeks (range [1 – 6] weeks).

Among the participants that sustained a hamstring injury:

- 8 participants ( $\pm$  50%) sustained a hamstring injury in the dominant (preferred kicking) leg
- 8 participants reported having a laterally oriented pain location, whereas the other 7 indicated that the primary locus of pain was situated rather medially
- only one of the injured participants reported the lesion to be situated rather close to the proximal insertion, whereas the other 14 indicated to have a more central or distal injury location.

Details on participant inclusion throughout the study trajectory can be consulted in figure 7.



**Figure 7.** Flowchart study course.

Anthropometric - and injury related features of the participants are presented in table 1.

<b>Table 1 Demographic results remaining cohort after follow-up</b>		
	<b>Control (n=36)</b>	<b>Injury (n=15)</b>
Body mass (mean $\pm$ SD; kg)	73 $\pm$ 7	73 $\pm$ 5
Height (mean $\pm$ SD; m)	1.80 $\pm$ 0.06	1.81 $\pm$ 0.04
BMI (mean $\pm$ SD; kg/m <sup>2</sup> )	22.41 $\pm$ 1.55	22.50 $\pm$ 1.650
Age ( mean $\pm$ SD; y)	24 $\pm$ 4	24 $\pm$ 3
Time to injury during follow-up (mean [range]; wks)	/	18 [4 – 36]
Absence from sports (mean [range]; days)	/	21 [7 – 56]

*SD, Standard Deviation; kg, kilograms; m, meter; m<sup>2</sup>, square meter; y, years; wks, weeks.*

## ROM measurements and injury occurrence

ROM outcomes, in function of injury incidence during prospective injury registry, are presented in table 2.

	<b>Control (n = 36)</b>	<b>Injury (n = 15)</b>
Hip flexion Mobility (mean $\pm$ SD; $^{\circ}$ )	117.52 $\pm$ 7.89	116.46 $\pm$ 8.01
Iliopsoas Flexibility (mean $\pm$ SD; $^{\circ}$ )	21.77 $\pm$ 8.10	19.04 $\pm$ 9.37
Rectus Femoris Flexibility (mean $\pm$ SD; $^{\circ}$ )	62.13 $\pm$ 13.62	65.21 $\pm$ 12.59
Hip External Rotation Mobility (mean $\pm$ SD; $^{\circ}$ )	37.19 $\pm$ 7.96	36.92 $\pm$ 4.62
Hip Internal Rotation Mobility (mean $\pm$ SD; $^{\circ}$ )	30.33 $\pm$ 5.43	30.61 $\pm$ 5.27
Hamstring Flexibility (PHE) (mean $\pm$ SD; $^{\circ}$ )	131.67 $\pm$ 11.28	132.53 $\pm$ 12.54
Bilateral Finger To Floor (FTF) Reaching Distance (mean $\pm$ SD; cm)	6.19 $\pm$ 6.92	8.73 $\pm$ 7.00
Unilateral FTF Reaching Distance (mean $\pm$ SD; cm)	4.72 $\pm$ 6.28	4.64 $\pm$ 7.06
Knee Extension during Slump (mean $\pm$ SD; $^{\circ}$ )	-26.43 $\pm$ 9.24	-27.51 $\pm$ 6.85

*SD, Standard Deviation;  $^{\circ}$ , number of degrees ; PKE, Passive Knee Extension; cm, centimetre*

No association was found between hamstring injury occurrence and any of the ROM features. As table 2 indicates, ROM measures were nearly identical in both prospective groups.



### Muscle activation during the prone hip extension and injury occurrence

To objectify the posterior chain muscle activation order, timing analysis was performed within the EMG signals of respective muscles of the injured leg in the injury group, and a ‘matched’ leg in the control group, based on the factor leg-dominance. As such, PHE muscle activation signals of the Gluteus Maximus (GM), the Biceps Femoris (BF) and Medial Hamstrings (MH) (taken together and simply referred to as ‘Hamstrings (H)’ in the following sections), and the paravertebral lumbar Erector Spinae at the contralateral side (CLES) were selected for prospective statistical analysis. Based on this selection, 6 possible activation patterns could be retrieved [Table 3].

<b>Table 3 Possible PHE activation sequences</b>				
<b>Order of muscle activity onset</b>				
<b>1</b>	→	<b>2</b>	→	<b>3</b>
a) Contralateral Lumbar Erector Spinae (CLES)		Gluteus Maximus (GM)		Hamstrings (H)
b) Contralateral Lumbar Erector Spinae (CLES)		Hamstrings (H)		Gluteus Maximus (GM)
c) Hamstrings (H)		Contralateral Lumbar Erector Spinae (CLES)		Gluteus Maximus (GM)
d) Hamstrings (H)		Gluteus Maximus (GM)		Contralateral Lumbar Erector Spinae (CLES)
e) Gluteus Maximus (GM)		Contralateral Lumbar Erector Spinae (CLES)		Hamstrings (H)
f) Gluteus Maximus (GM)		Hamstrings (H)		Contralateral Lumbar Erector Spinae (CLES)

*CLES, Contralateral Erector Spinae; GM, Gluteus Maximus; H, Hamstrings*

EMG signal timing analyses and subsequent statistical hypothesis testing revealed the following findings:

First, two distinct recruitment patterns appeared to be most common in the entire cohort (irrespective of injury occurrence), namely

- the sequence in which the hamstrings are activated first, followed by the CLES and lastly, the GM, and

- the sequence in which the CLES demonstrates primary activity, followed by the hamstrings and finally, the GM.

When isolating both recruitment patterns, to exclude the cells with zero counts,  $\chi^2$  testing revealed the in between group difference in recruitment order to be significant ( $\chi^2 = 7.70$ ,  $p = 0.006$ ). In the control group, the most frequently observed activation pattern was the one in which the hamstrings were recruited first, whereas the contralateral erector spinae was solicited first most frequently during PHE in those who got injured [Table 4].

	<b>Control (n = 32)*</b>	<b>Injury (n = 15)</b>
<b>CLES - GM - H</b>	0	1
<b>CLES - H - GM</b>	6	9
<b>H - CLES - GM</b>	15	3
<b>H - GM - CLES</b>	8	0
<b>GM - CLES - H</b>	0	2
<b>GM - H - CLES</b>	3	0

*CLES, Contralateral Lumbar Erector Spinae; GM, Gluteus Maximus; H, Hamstrings.*

*\* The EMG signals of 4 individuals in the control group presented to much noise and were excluded for timing analysis.*

Next to the relative activation times (activation order rather than the exact activity onset times), the absolute activity onset times were thoroughly investigated as well. Table 5 presents the mean (absolute) onset times of all muscles in both the control- and injured groups.

	<b>Control (n = 32)*</b>	<b>Injury (n = 15)</b>
CLES onset time (mean $\pm$ SD ; sec)	0.89 $\pm$ 0.29	0.92 $\pm$ 0.24
H onset time (mean $\pm$ SD ; sec) <sup>(1)</sup>	0.81 $\pm$ 0.24	1.04 $\pm$ 0.38
GM onset time (mean $\pm$ SD ; sec)	1.05 $\pm$ 0.40	1.14 $\pm$ 0.35

*\* The EMG signals of 4 individuals in the control group presented to much noise and were excluded for timing analysis.*

*SD, Standard Deviation ; sec, seconds ; CLES, Contralateral Lumbar Erector Spinae; H, Hamstrings; GM, Gluteus Maximus ; (1) significant difference in onset time between hamstrings and CLES,  $p = 0.001$ ; (2) significant difference in onset time between CLES and GM,  $p = 0.037$ ; (3) significant difference in onset time between the hamstrings and the GM,  $p = 0.003$ ; (4) significant difference in onset time between the CLES and the GM,  $p = 0.004$ .*

Within-group-comparison (General Linear Model – Repeated Measures) revealed that the onset times of these 3 agonist differed significantly from each other in the control group, where the hamstrings were primarily recruited, followed by the erector spinae and lastly, the gluteus maximus ( $p < 0.04$ ). Yet in contrast, this systematic in-between-muscle onset time-difference was not observed in the injury group. In the latter, only erector spinae – and gluteus maximus onset times remained significantly different from one another ( $p = 0.004$ ), but the time differences between the hamstrings and the CLES ( $p = 0.114$ ), and between the hamstrings and the GM ( $p = 0.384$ ), were nullified. Subsequent in-between-group analyses revealed that the primary cause of this shift in onset time-differences within the injured group, was a delay in onset time of the hamstrings. In the injury group, hamstring activity onset presented to be significantly delayed compared to the control group (0.81 msec in the control group, versus 1.04 msec in the injury group;  $p = 0.013$ , Cohen's  $d = 0.76$ ), this was not the case when comparing the activity onset times of the CLES and GM between groups ( $p = 0.667$  and  $p = 0.461$ , respectively).

Binary logistic analysis including both the relative (ordinal variable) and the absolute (scale variable) activity onset times, revealed that the risk of sustaining a hamstring injury increases significantly when the PHE exercise is characterized with

- (1) a delay in hamstring activity onset ( $p = 0.018$ )
- (2) an activation sequence in which the lumbar erector muscles are recruited prior to the hamstrings ( $p = 0.009$ )

Subsequent Receiver Operator Curve Analysis (ROC) revealed that, within our cohort, injury incidence could be estimated with a sensitivity of 0.80 and a specificity of 0.23 ( $p = 0.001$  ; Area Under the Curve (AUC) = 0.80 (95% Confidence Interval (CI) : 0.64 – 0.97)) if the onset time of the hamstrings exceeded 1.04 sec.

Assessing the contraction intensity of each of the intended muscles with respect to injury vulnerability, no significant effect could be established ( $p > 0.38$ ). Average muscle activity (muscle fibre

recruitment) during PHE for the participants that sustained an injury and the healthy controls are demonstrated in table 6.

<b>Table 6 Average EMG amplitude during PHE, normalized to the MVC reference</b>		
	<b>Control</b>	<b>Injury</b>
	<b>(n=36)</b>	<b>(n=15)</b>
<b>CLES (mean ± SD; %)</b>	25,0 ± 30,2	20,4 ± 10,2
<b>GM (mean ± SD; %)</b>	29,7 ± 19,2	24,0 ± 19,0
<b>H (mean ± SD; %)</b>	21,5 ± 10,0	19,0 ± 9,3

*CLES, Contralateral Lumbar Erector Spinae; GM, Gluteus Maximus; H, Hamstrings; SD, Standard Deviation*

## Discussion

The present study demonstrated that the PHE muscle recruitment was significantly associated with injury occurrence during a 1.5 season monitoring period for prospective injury registry. In terms of lumbo-pelvic mobility and flexibility measures, no relation could be established with injury risk.

With regard to the activation order in the posterior muscle chain during PHE, two distinct patterns revealed to be most common in both the control – and the injury group. The sequence in which the hamstrings are activated first, followed by the contralateral erector spinae and lastly the gluteus maximus, was the pattern that was most commonly observed in healthy participants, whereas the pattern in which the contralateral erector spinae takes the lead, followed by the hamstrings and finally, gluteus maximus, was most frequently seen in players who got injured during the period of exposure. Interestingly, subsequent analysis revealed that this altered sequence of posterior chain muscle recruitment is predominantly caused by the delay in onset time of the hamstring muscles, forcing the erector trunci to participate in force production prematurely. Looking at the contraction intensity, no significant in-between-group effect or association with injury occurrence could be established,

indicating that the timing rather than the amount of muscle fibre recruitment is key in muscle injury susceptibility, with respect to neuromuscular coordination and interplay throughout the posterior sling.

Our study was the first to identify a delay in hamstring muscle activity onset during PHE, and it was also the first to prospectively investigate the posterior chain muscle recruitment pattern in a cohort of male soccer players in association with hamstring injury occurrence. In terms of neuromuscular coordination and its possible association with hamstring injuries, and to some extent in agreement with the present findings, the work of Opar and colleagues<sup>41</sup> revealed reduced EMG signals and reduced Rates of Torque Development (RTD) in previously injured hamstrings. Their findings suggested that in participants with a hamstring injury history, respective hamstring muscles present insufficient early torque generation capacity. Although demonstrating reductions in early EMG activity onset, no differences in peak torque could be presented during eccentric isokinetic contraction. The authors suggested that this reduction in ‘early neural drive’ could point out a detrimental prolonged neural / neuromuscular deficit, comprising the rehabilitation process. This relative delay in force production would result in depriving the weakened hamstring from sufficient training stimuli, needed to bring about muscular adaptations such as sufficient hypertrophy and sarcomerogenesis.<sup>41</sup> Although this was assessed retrospectively and by means of synchronized isokinetic dynamometry and sEMG under eccentric loading conditions, we believe that the clinical implications of respective findings are compatible with the ones resulting from our study. The present study also found a delay in hamstring activity onset (albeit during PHE and not during maximal eccentric contractions), which might just as well be caused by inhibited neural drive or alterations within both local and proximal neuromuscular control. These inhibitory mechanisms would result in relative disuse of the entire hamstring unit, leading to decreased neuromuscular control capacity with a higher risk of injury. Our study was a prospective study, in which the presence of a hamstring injury history was taken along as a covariate in statistical analysis. Although injury history appeared to be an independent predictor of hamstring injury, it did not have any influence on the muscle activation features during PHE, nor did it appear to be of significance in the general logistic model, revealing that delay in hamstring recruitment and earlier onset of lumbar muscle activity was significantly able to predict injury occurrence,

independently from injury history. Accordingly, neuromuscular inhibition and imbalances in the synergistic posterior chain interplay, seem to be more than just a consequence of previous injury. Interestingly both in agreement and in contrast with what has been published earlier,<sup>1, 7, 24, 31, 40, 50</sup> the GM activity onset was very similar in both groups and did not present any association with hamstring injury occurrence. Nonetheless, the GM demonstrated to be systematically recruited last, with an onset time being significantly later than the one of the lumbar erector muscles (injury and control group) and the hamstrings (control group). Existing research tends to point out the importance of early activity onset of the GM during the PHE, to adequately stabilize the sacro-iliac joint and allow safe force transmission to the pelvis and lower back throughout PHE.<sup>31, 40, 44, 53</sup> In these terms, the study of Bullock and colleagues (1994) demonstrated that the GM activity onset was significantly delayed in subjects with a history of lateral ankle sprains, compared to healthy matched controls.<sup>8</sup> In accordance with these findings, Bruno and Bagust (2007) found the activity onset of the GM to be delayed as well, when comparing PHE muscle activation patterns between subjects with and without low back pain.<sup>7</sup> This research was inspired by Janda, who originally postulated that the ‘ideal’ muscle recruitment during PHE concerned primary activity of the gluteus maximus, followed by the hamstrings and lastly, the lower back muscles. This pattern was assumed to reflect optimal muscle recruitment during locomotion and was thought to provide the most proximal stability and thus, the safest biomechanical loading conditions. This assumption was merely based on a theoretical biomechanical framework, and not on actual scientific evidence. More recent study findings suggest that this ‘ideal’ recruitment is uncommon in healthy subjects,<sup>36</sup> and that the most frequently observed activation pattern consists of primary activity onset of the hamstrings, followed by the contralateral ES and lastly the GM.<sup>50</sup>

In the injured group the hamstrings were recruited significantly later, suggesting a delay in hamstring recruitment and activity onset. This finding could possibly be interpreted in analogy with the rationale behind the delayed GM activity onset. In the presence of lower back complaints, the phasic GM is believed to be subject to functional inhibition and relative weakness, causing muscle imbalance, deviant neuromuscular coordination and movement impairment throughout the posterior chain.<sup>31</sup> Therefore, it is plausible that the hamstring muscles of the players in our injured cohort are similarly

subject to neuromuscular inhibition (or dominance of the erector trunci, respectively), disabling them to be recruited first throughout respective movement tasks. After all, the ability to produce sufficient muscle force within an optimal time-frame is a general necessity for all (mobilizing, multi-articular) muscles. This feature allows the muscle to provide the best biomechanical conditions for adequate performance and injury prevention.<sup>30</sup> Indeed, research should definitely invest in exploring the importance of timing and coordination in hamstring activity, because deficits in (isokinetic) muscle strength alone cannot explain the unremittingly high hamstring injury occurrence in football.<sup>55, 58</sup> The hamstring muscles are extremely important with regard to efficient running and kicking performance. Engaging in voluminous bouts of intense muscle-tendon loading, their ability to produce a sufficient amount of force, exactly where and when needed (i.e. neuromuscular control) is key. The fact that we found a delay in activity onset during this PHE (both in the BF and the medial hamstrings), which is thought to reflect functional muscle recruitment during locomotion,<sup>33, 36</sup> might point out neuromuscular control deficits and imbalances in the synergistic interplay, causing the hamstring muscles to work less efficient and making them more susceptible to injury.

Although assessing the association between ROM measures and hamstring injury vulnerability was not the main portion of this study, the fact that these clinical features did not present any association with injury occurrence, once again puts emphasis on the complexity of the hamstring injury risk profile in young athletes. Albeit an essential part of pre-participation screening,<sup>4</sup> checking and correcting for flexibility and mobility deficits in the lower back, pelvis and the lower limbs, does not suffice for (adequate) hamstring injury prevention purposes.

This was the first prospective study investigating the relevance of muscle recruitment during PHE in function of hamstring injury susceptibility in male soccer. Even though having generated some renewing insights, this research was not without limitations. First, data collection on injury occurrence was based on participants' self-report, as most of the clubs did not have an associated medical staff. In only taking along hamstring injuries that caused the participant to be out for at least one entire week and by systematically verifying the nature and clinical presentation of the injury by phone, we attempted to minimize the risk of reporting bias, which might have influenced the results. Second, we

did not include kinematic analysis within this testing protocol, as we were primarily interested in muscle activation rather than movement control as such. However, one must bear in mind that both features are highly interdependent. Adding kinematic analysis to verify the quality of movement control during the PHE, in association with the underlying muscle activation features, might have revealed valuable additional insights in posterior chain neuromuscular control and related hamstring injury vulnerability.

Nonetheless, the PHE and the corresponding muscle activation features have shown to be valuable in hamstring injury risk estimation. As the present results suggest that hamstring muscle recruitment preferably proceeds solicitation of the proximal synergists in the posterior extensor continuum during PHE, further research on rehab and injury prevention should determine which functional exercises allow primary recruitment of the hamstrings relative to their agonists, and to what extent these interventions effectively lower the hamstring injury risk in running athletes. By analogy with rehabilitation guidelines for patellofemoral disorders,<sup>39</sup> practitioners could aim to effect rapid hamstring muscle recruitment/contraction (reducing the pre-motor muscle activation time) by using biofeedback training methods.

Although scientific evidence is still scarce, the PHE might be a valuable tool to assess neuromuscular control and the presence of relative dominance, respectively inhibition, within a functional muscle unit. Appearing to have a place in both articular (lower back) and muscular dysfunctions, researchers and practitioners should attempt to formulate guidelines on practical use and clinical interpretation of this simple test in daily practice.



## Conclusion

The results of this study demonstrate that alterations in muscle recruitment during PHE are associated with hamstring injury susceptibility in male soccer players. A delay in hamstring activity onset and primary activation of the lower back muscles was associated with hamstring injury occurrence. The PHE recruitment pattern in which the contralateral lumbar paravertebral muscles were activated first, only secondary followed by the hamstrings and lastly, the gluteus maximus, presented an association with an increased risk of hamstring injury. These posterior chain muscle activation features assessed during the PHE, might reflect the adequacy of neuromuscular control and synergistic muscle balance in the posterior chain continuum and could be important in hamstring injury risk identification. Future research should verify whether injury prevention strategies, focussing on primarily soliciting the hamstrings during functional exercise, are effectively able to reduce hamstring injury susceptibility in soccer players.

## Competing Interests

All authors declare to have no competing interest regarding the (scientific) content of the paper nor regarding the sources of funding.

## Author Contributions

JS carried out the participant recruitment, clinical assessment and sEMG analysis, as well as data collection and statistical analysis. As the principal researcher and author, she was also responsible for statistical analyses and the gathering of the results, as well as for writing this paper. DVT consistently provided his assistance during the clinical assessment prior to follow-up and helped to draft the manuscript. EW assisted with conceiving the study protocol and with drafting the manuscript both content- and format wise. All authors read and approved the final manuscript.

### **Acknowledgements**

The authors gratefully acknowledge the assistance of their colleagues at the department of Rehabilitation Sciences and Physiotherapy in Ghent. In particular Steven Heyndrickx, for the assembly of the online diary for injury registration during follow-up. For their financial support, our gratitude goes out to the Agency for Innovation by Science and Technology in Flanders (IWT – Brussels, Belgium). We would also like to genuinely thank the participants of this study, because their commitment enabled us to deliver the present research findings.

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# **Chapter III**

## Running coordination in hamstring injury susceptibility



# Chapter III – Part I

Proximal neuromuscular control protects against hamstring injury in male soccer players

*A prospective study with EMG time-series analysis during maximal sprinting*



## CHAPTER III – Part I

### **Proximal neuromuscular control protects against hamstring injury in male soccer players: A prospective study with EMG time-series analysis during maximal sprinting.**

Joke Schuermans<sup>1</sup>, Lieven Danneels<sup>1</sup>, Damien Van Tiggelen<sup>1</sup>, Tanneke Palmans<sup>1</sup>, Erik Witvrouw<sup>1</sup>

<sup>1</sup>Department of Rehabilitation Sciences and Physiotherapy Ghent, Ghent University, Ghent, Belgium

Correspondence to Schuermans Joke, Department of Rehabilitation Sciences and Physiotherapy, Ghent University, De Pintelaan 185, 3B3, –Ghent 9000, Belgium; [Joke.schuermans@ugent.be](mailto:Joke.schuermans@ugent.be)

**Accepted in the American Journal of Sports Medicine (October 2016)**

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#### **Abstract**

**Background** With their unremittingly high incidence rate and detrimental functional repercussions, hamstring injuries remain a substantial problem in male soccer. Proximal neuromuscular control ('core stability') is considered to be of key importance in primary and secondary hamstring injury prevention, although scientific evidence and insights on the exact nature of the core-hamstring association are non-existing at present.

**Hypothesis** Departing from a null-hypothesis, this study hypothesized that the muscle activation pattern throughout the running cycle would not differ between participants based on injury occurrence during follow-up.

**Study Design** Prospective cohort study, level of evidence 1b.

**Methods** Throughout the in between seasons period of 2013, 60 amateur soccer players participated in a multi-muscle surface electromyography (sEMG) assessment during maximal acceleration to full speed sprinting. Subsequently, hamstring injury occurrence was registered during a 1.5 season follow-up period. Hamstring-, gluteal and trunk muscle activity time-series during the airborne- and stance phases of acceleration were evaluated and statistically explored on possible causal association with injury occurrence, respectively absence, during follow-up.

**Results** Players that remained spared from hamstring injury during follow-up, presented significantly higher amounts of gluteal muscle activity during the front swing phase ( $p = 0.027$ ), and higher amounts of trunk muscle activity during the backswing phase of sprinting ( $p = 0.042$ ). In particular, the risk of sustaining a hamstring injury during follow-up lowered 20% and 6%, with a 10% increment in normalized muscle activity of the Gluteus Maximus during front swing and the trunk muscles during backswing, respectively ( $p < 0.024$ ).

**Conclusion** Muscle activity of the core unit during explosive running presented to be associated with hamstring injury occurrence in male soccer players. Higher amounts of gluteal – and trunk muscle activity during the airborne phases of sprinting were associated with a lower risk of hamstring injury. Hence, the present results provide a basis for improved, evidence based, rehabilitation and prevention, particularly focusing on increasing neuromuscular control of the gluteal muscles and trunk muscle during sport specific activities (eg. sprint drills, agility drills).

**Key words** hamstring injury; aetiology; soccer; surface electromyography; sprinting acceleration

**Clinical Relevance** Present findings confirm the importance of proximal muscle control in hamstring injury susceptibility, suggesting that functional neuromuscular core training might effectively reduce the risk of hamstring injury. Assessing and correcting (deficient) core control (strength and stability), as well as objectifying the quality of

running kinematics with regard to proximal muscle performance, should be part of hamstring injury prevention and rehabilitation. How the core muscles should be trained optimally in order to maximize their performance during explosive running, is still to be determined.

**What is known about the subject** Hamstring injury rehabilitation incorporating agility and core strengthening exercises are associated with precipitated return to play and decreased recurrence rates. How proximal control or ‘core stability’ and hamstring injury vulnerability are actually related, and whether there is a real causal association between both, is not known.

**What this study adds** This is the first study to elucidate the importance of adequate functional core muscle activity with regards to running related hamstring injuries. In demonstrating the presence of an association between hamstring injury occurrence during follow-up and muscle activity of the core (trunk - and gluteal muscles) throughout the airborne phases of the running cycle, this work supports the argument for adequate (functional) core strengthening in hamstring injury prevention.

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## Introduction

Hamstring injuries are the single most common type of sports injury in male soccer. Functional anatomy, muscle architecture and - morphology, partly explain why in particular this muscle complex presents itself to be this vulnerable for injury.<sup>6, 12, 13, 29, 32</sup> However, the issue of which intrinsic risk factors exactly predispose athletes to a hamstring injury, still raises many questions in research and daily practice. The fact that, despite growing knowledge and increasing efforts as regards evidence based injury prevention strategies, incidence rates do not seem to diminish in both professional<sup>13</sup> and amateur soccer<sup>47</sup>, and even appear to have increased in the UEFA premier league over the last decade,<sup>13</sup> puts emphasis on the lack of evidence regarding the underlying intrinsic risk profile and the questionable adequacy of current prevention strategies. Multiple studies have already tried to



prospectively investigate which factors predispose an athlete to soccer related hamstring injury. Due to limited evidence and because of feasibility considerations, those studies mostly consisted of the assessment of clinical - and strength related risk estimates.<sup>1-2, 5, 10-12, 14, 17, 19, 45, 48, 51</sup> Next to those and because of the emerging evidence in terms of the possible influence of neuromuscular inhibition,<sup>18</sup> research nowadays is focusing on specific hamstring muscle activity features and intramuscular coordination properties within the biarticular hamstring unit as well.<sup>33-34, 42-43</sup> To shed light on the nature of respective hamstring muscle activity, both surface electromyography (sEMG)<sup>15, 18, 27, 33-34,</sup> and muscle functional Magnetic Resonance Imaging (mfMRI)<sup>42-43</sup> procedures have been conducted. Although providing increased insights in hamstring functioning, underlying study designs consisted of rather limited (not sport-specific nor injury-mechanism-related) and local muscle activity assessments.<sup>1-5, 11-12, 14, 16-17, 19, 28, 45, 48, 51</sup> Those studies never looked at muscle function apart from the hamstrings, let alone having done this during high speed running. This limitation causes the research findings to be limited as well, as multiple possibly related parameters are not taken into account. More so, most of the existing research consists of cross-sectional or retrospective study designs, investigating the consequences of prior hamstring injury on muscle mechanics and activation patterns, or observational studies merely describing the nature of those muscle mechanics and activity patterns. Prospective research assessing neuro-muscular hamstring function, in direct association with the proximal muscle activity and the predominant injury mechanism, is non-existent at present. Therefore the aim of the present study was to objectify to what extent the muscle activation patterns of the trunk and gluteal muscles (taken together representing the 'core'), and the hamstrings during the maximal acceleration phase of sprinting, could be linked with hamstring injury vulnerability in male soccer players. As we were unable to predict there to be any effect (nor the direction of the effect) as regards amount of muscle activity during sprinting and subsequent hamstring injury susceptibility due to lack of preliminary research, we adopted a null-hypothesis stating that muscle activation patterns during sprinting would not present an(y) association with hamstring injury occurrence during follow-up. When mentioning to the 'core' (muscles) throughout this work, we are referring to both trunk- and gluteal muscles.

## Methods

### Participants

Throughout the second half of the 2013 soccer season, male soccer players, active in the same amateur competition series (Oost-Vlaanderen, Belgium), were recruited. Players were excluded if they

- had not fully returned to play (soccer training and matches) after a previous hamstring injury or reported having suffered any functional discomfort in the hamstring region the past 3 months (Cf. reinjury definition by UEFA)<sup>20</sup>
- were still recovering from (any) injury, which disabled them to fully participate in training and match play
- had a history of severe lower limb injury, which could have influenced running kinematics and features of neuromuscular recruitment
- had a history of lower back complaints / lower back complaints at present, which could bias the intrinsic risk profile

A hamstring injury was defined being an injury in the hamstring muscle region, sustained during soccer training or match play, preventing the player to participate in training or competition for at least one entire week.<sup>20</sup> Ultimately 60 male soccer players were included for study participation. At the time of testing, all participants were completely injury free and none of them reported any pain or discomfort in the hamstring region during soccer participation or during the running protocol in this study.

### Testing Procedure

The EMG analysis during full sprint took place in Topsporthal Vlaanderen, Zuiderlaan 14, Ghent, Belgium.

In order to get a valid impression of muscle recruitment throughout acceleration towards full speed sprinting, without bias of fatigue or muscle soreness, subjects were instructed not to engage in intensive training or soccer competition 48h prior to testing.

All participants were informed about the content and the purpose of the testing procedure, signed the Informed Consent, and were asked to fill out a short questionnaire to gather data on participant's age, anthropometrics and (hamstring) injury history. Subsequently, they were familiarized with the running protocol and the course of the synchronized 14 channel sEMG-analysis. This information was consistently provided by the same qualified researcher (JS), who was in charge of the entire testing procedure (participant preparation, data assembly and –processing) as well, which minimized the risk of inter-tester bias. This study was approved by the Ethics Committee of the Ghent University Hospital (number of approval: EC/2013/118).

After testing, participants were requested to sign up to an online diary which was put together for the purpose of prospective registry of injury occurrence [<http://www.hsi.ugent.be>]. This online survey contained questions about weekly exposure (match and training) and the incidence/presence of soccer related injuries and complaints. The participants were asked to complete this survey every Monday throughout the entire 2013-2014 season, as well as the first half of the 2014-2015 season, accounting for a follow-up period of one entire and one half of a soccer season.

Follow-up was terminated at the winter break of the 2014-2015 season, during which period all participants were contacted again for final injury inquiry. As we were able to keep in contact with the participants throughout respective period and because adding an additional couple of months of soccer exposure would potentially increase the power of our study, we chose to register injury occurrence throughout one and half a season, instead of just the one after testing. By analogy with what was stated in our original inclusion criteria, a hamstring injury was defined being an injury in the hamstring muscle region, sustained during soccer training or match play, necessitating the player to consult (para)medical care and preventing him to participating in training or competition for at least one entire week. When a hamstring injury or another injury preventing the participant from participating was

reported, the player was contacted by telephone to verify the nature and the localization of the complaint, and to check whether a medical caregiver was consulted.

Because the UEFA guidelines state that a reinjury occurs at the exact same location as the prior one, within two months after the final rehabilitation day of the previous injury, all recorded injuries were considered to be index injuries.<sup>20</sup> However, as the presence of an injury history has been demonstrated to increase the risk of a subsequent one,<sup>12, 14, 16</sup> this variable was taken along as a covariate in the prospective data analysis.

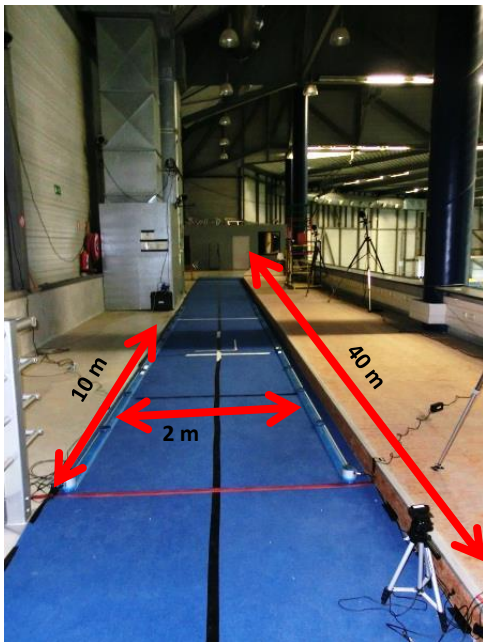
### **sEMG analysis during linear sprint**

The 14 channel EMG analysis during maximal acceleration towards full sprint was conducted on a 40 meter (m) running track, which was flanked by 2 sets of bars of the Optogait system (Microgate, Bolzano-Bozen, Italy). This system was installed between meter 15 and 25 along the 40m running track, and allowed step detection (swing- and stance phase differentiation). We chose to perform sEMG analysis and step-detection within along this part of the track, as this is the distance at which maximal acceleration is achieved in maximal sprinting.<sup>24</sup> [Figure 1] Within this specific measuring volume, EMG signals were captured during one entire stride, such that muscle activation could be objectified in both the stance and swing phases of the running cycle for both legs. Both the Optogait (step detection) and the myoMUSCLE EMG analysis (Noraxon, Scottsdale, USA) software systems were synchronized and incorporated within the Qualisys Track Manager (QTM 2.11) interface (Qualisys Motion Capturing Systems, Ghotenburg, Sweden), to facilitate simultaneous data-acquisition. We deliberately chose to use the Optogait system (Microgate corporation, Bolzano-Bozen, Italy) for step detection instead of using a installing a force plate along the running track because we wanted to perform EMG analyses during one entire stride and the length of a force plate does not allow this.

When indicating having understood the content and course of the testing procedure, participants were instructed to dress down to a pair of tight shorts and indoor soccer shoes. Subsequently, 28 pre-gelled

Ag/AgCl electrodes (Ambu® Bluesensor, P-00-S) and 14 wireless EMG-amplifiers were attached to the skin according to the SENIAM-guidelines,<sup>26,30</sup> in order to capture muscle activity from the external and internal obliques, the thoracic and lumbar erector trunci, the gluteus maximus, the medial hamstrings and the biceps femoris bilaterally (inter-electrode distance of 20 millimetres) [Figure 2]. Elastic fixation bandages (Elastomull® haft, BSN Medical) were used to warrant a stable amplifier position during the subsequent repeated sprinting trials. Muscle activity signals were amplified and transferred to the Noraxon DTS – desk receiver wirelessly, enabling sEMG-analysis during over-ground sprinting (16 channel Desktop Direct Transmission System, Noraxon, Scottsdale, USA). After checking the quality of the EMG signal in each of the 14 channels, participants were instructed to perform a first warm up session consisting of jogging up and down the running track at a comfortable, self-chosen pace. Afterwards, 3 maximal voluntary contraction (MVC) trials were acquired per muscle (group), adding up to the registration of 24 MVC trials per participant. Opposed to what was the case for EMG signal acquisition during full sprint, the MVC signals were captured within the MyoMuscle software interface of Noraxon (MyoResearch 3.4), as this permitted real time evaluation of motor unit signals more easily. MVC data acquisition was conducted according to the Noraxon guidelines,<sup>26</sup> with the participant adopting a neutral prone position on the examination table for the assembly of the MVC trials of the back, gluteal, and hamstring muscles. This was performed starting from a neutral supine position for MVC data collection of the abdominal muscles. For the thoracic and lumbar parts of the erector spinae muscle, the participants were instructed to perform a back extension, maximally resisting the tester's force applied at level of the shoulder blades, square to the lever of the trunk. For the gluteus maximus, the participant was asked to extend the hip joint, maximally resisting the tester's torque towards hip flexion. For the hamstrings, the participant was instructed to maximally resist a torque towards knee extension from a 30 degree (°) knee flexion position (lower leg and foot supported by the upper leg of the tester). The oblique abdominals were tested maximally, having the participant perform an oblique curl-up, which was isometrically resisted in the mid-range of motion (medium trunk flexion and rotation ROM). As such, the right inner and left outer abdominal Obliques were tested during curl-up with trunk rotation towards the right (left shoulder up), and the left inner and right outer abdominal Obliques during a curl up with trunk rotation to the left (right shoulder up).

For each of these procedures, the participants were asked to gradually raise the amount of muscle force, reaching a maximum in approximately 3 seconds. This maximum force output was maintained for 5 seconds, after which the participant was instructed to gradually lower muscle force while returning to the neutral starting position until full relaxation was reached. After MVC recording, the participant was instructed to perform a second 5 minute warm up, running up and down the track at a self-chosen pace once more. Because this second warm up session served to prepare the participant for the repeated maximal sprints, jogging was alternated with short sprint-intervals (as if they would perform starting speed drills).



*Figure 1. 40m sprinting track with 10\*2m 3D measuring volume in between Optogait system.*



*Figure 2. Electrode and amplifier placement for MVC- and sprint trial sEMG data collection.*

Hereafter, each participant was instructed to sprint up the track over a distance of (at least) 30m, trying to reach maximal sprinting speed as quickly as possible. 14 channel EMG signal acquisition and step detection were conducted simultaneously throughout the 10m measuring volume (meter 15 – meter 25) at a sampling frequency of 1500 Hz (Hertz). Every player had to perform 12 maximal sprints, adding up to 6 decently captured right-, and left strides, respectively. A sprinting trial could only be taken along for data analysis if it consisted of three full stance phases (*“touch downs”*, given the *sprinting mode of locomotion*) within the measuring volume.

### **Data analysis**

For each participant, 12 EMG-time series (representing one entire stride each) per muscle were gathered within QTM. First, sprinting trials were divided into swing- and stance phases using 4 events: left toe off, right touch down, right toe off and left touch down in the left stride trials; right toe off, left touch down, left toe off and right touch down in the right stride trials, respectively. These labelled

trials were exported to the C3D format, after which they could be imported in Visual 3D (V3D, C-Motion Inc., USA) to filter (Butterworth High Pass 20 Hertz (Hz)), rectify, smooth (50 milliseconds (msec) window) and normalize the EMG signals. For each phase (front-swing, stance and backswing), EMG data were normalized to 101 data frames, enabling time-dependent in between subject comparison. After all, as we requested maximal acceleration from every participant, running speed could not be standardized inter- nor intra-individually, which lead to the gathering of multiple trials at varying running speeds. Therefore post-hoc time normalization was necessary for in between group comparison of the multi-muscle EMG time-series. This was done normalizing the average data series of each phase, smoothing these series down to 101 data points per muscle, per phase and per participant. Average time-normalized EMG series of each muscle were exported for front swing, stance and backswing phases per participant, after which these time-normalized average activity signals were normalized to MVC voltage. Ultimately, time-dependent, MVC-normalized, EMG-series during maximal acceleration (expressed in %) were categorized per muscle and based on injury incidence during follow-up for the purpose of in between group analysis. Based on their similar time-dependency and synergistic activation characteristics, we clustered time-dependent EMG-series of left and right internal and external oblique abdominal muscles, left and right erector trunci at thoracic and lumbar level into one time-dependent muscle activity vector (trunk-cluster). Because of the specific function of the gluteus maximus, time-dependent activations series of this muscle were investigated separately for both legs. In terms of the hamstrings, time-dependent signals were assessed for the entire hamstring unit, as well as for the biceps femoris and medial hamstrings separately. Ultimately, 5 time-dependent EMG series were analysed in association with hamstring injury vulnerability: **integrated trunk muscle activity, gluteus maximus activity, integrated hamstrings, medial hamstrings activity, biceps femoris activity.**

As we subsequently aimed to investigate if proximal muscle activity would be able to prevent hamstring injury occurrence, our research primarily focussed on protective factors rather than risk factors, opposed to what is done traditionally in injury risk detection research. Originally presuming the muscle activity patterns during sprint not to have an effect on the hamstring injury risk, we asked



ourselves if soccer players that did not sustain a hamstring injury during follow-up presented different muscle activation patterns in the trunk- and lower limb muscles during the running cycle, possibly making them sprint more safely and protecting them against future hamstring injury. Hence, statistical analysis was carried out as such.

### Statistical analysis

The average activation pattern (Root Mean Square (RMS)) within the trunk cluster, the hamstrings and the gluteal muscles were compared between the participants that sustained an injury during follow-up and those who did not, to objectify an association with injury occurrence during follow-up. EMG-series were compared between groups for one entire stride, incorporating front-swing, stance and backswing phases. Comparative Curve analysis (time-dependent pattern of ‘innervation behavior’)<sup>26</sup> was conducted using Statistical Parametric Mapping (SPM), version M.03, in Matlab (R2014a, The Mathworks Inc, Natick, MA). This method conducts statistical inference based on the Random Field Theory. Whilst commonly used for the analysis of functional brain images it is becoming commonplace in biomechanical data analysis.<sup>36-39</sup> Using the mean normalized muscle activity amplitude (per cluster/muscle, group and phase of the running cycle) and corresponding standard deviation at each of the 101 data frames (i.e. the overall activation pattern), it allows statistical comparison of the entire time-dependent EMG signal, instead of the commonly used in between group peak or mean amplitude comparison which only takes into account one or a couple of point estimates, irrespective of time. Another advantage of using SPM and embedded vector-field analysis (multiple time-dependent muscle signals clustered within one vector), is that it provides better control of type I and type II statistical error,<sup>39</sup> enabling more valid risk estimation.

Particularly, multi-muscle EMG series were prospectively compared between groups, using two-tailed SPM vector-field analyses (based on the Hotelling’s  $T^2$  statistic) and SPM two-tailed independent t-tests.<sup>39</sup> A SPM Hotelling’s  $T^2$  test is the vector-field equivalent to a two-sample T-test. The Hotelling’s T was used for cluster comparison (trunk- and hamstring clusters), whereas the SPM two-sample T-

test was used for single vector comparison (gluteus maximus EMG time-series). When indicated, ANOVA tests were implemented in the post-hoc analysis to identify exactly which one of the trunk muscles was responsible for the main effect in the association between cluster-activity and injury during follow-up. For each one of these analyses, the SPM{t} statistic was calculated at each time frame, after which statistical inference was examined based on the behaviour of random curves with the same temporal smoothness. Time-dependent (multi-)muscle EMG-series differed significantly between groups, were then exported to the SPSS 22 Statistical Software package (IBM Corp. New York, USA) for logistic regression and (re-)injury risk prediction taking along data on participant demographics and hamstring injury history as covariates. For both the SPM T-test analysis within Matlab and the statistics within SPSS,  $\alpha$  was set at 0.05 (with correction depending to the number of muscles incorporated into the vector field in case of cluster analyses). All SPM analyses were implemented using the open-source SPM1D code (<http://spm1d.org>) and the SPSS 22 Statistical Software package.

## Results

Of the 60 participants that were screened during the 2013 off season period, 9 were lost to follow-up, resulting in a cohort of 51 players for prospective analysis. 15 of those sustained a hamstring injury during follow-up, whereas 36 remained injury free during the 1.5 season follow-up. An overview of the cohort composition throughout the study period, as well as details on time to injury during follow-up, are provided in table 1 and figure 3.

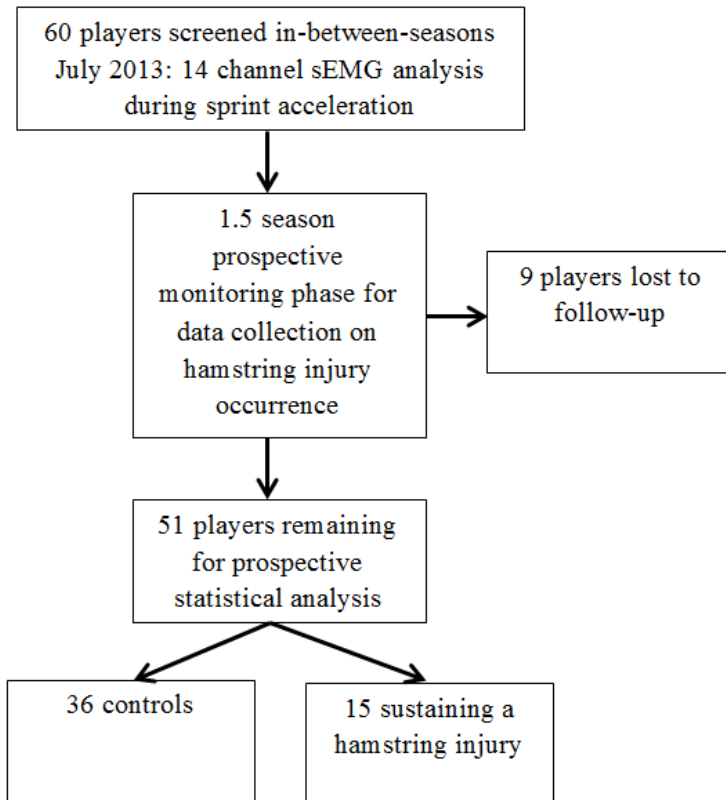


Figure 3. Flow chart study course

Table 1 Participant characteristics after group allocation according to injury occurrence								
	Control group (n = 36 )				Injured group (n = 15)			
Age (years)	24.3 ± 4.4				22.8 ± 2.5			
Weight (kilogram)	75.2 ± 7.3				72.6 ± 5.6			
Height (meter)	1.81 ± 0.06				1.78 ± 0.07			
Playing Position (count)	Attack	Midfield	Defense	Wing	Attack	Midfield	Defense	Wing
	10	14	9	2	6	3	5	2

The average time elapsed between the testing series and injury occurrence was 15 weeks (range [3 – 26] weeks) and the average absence from soccer participation was 3 weeks (range [1 – 6] weeks).

Among the participants that sustained a hamstring injury:

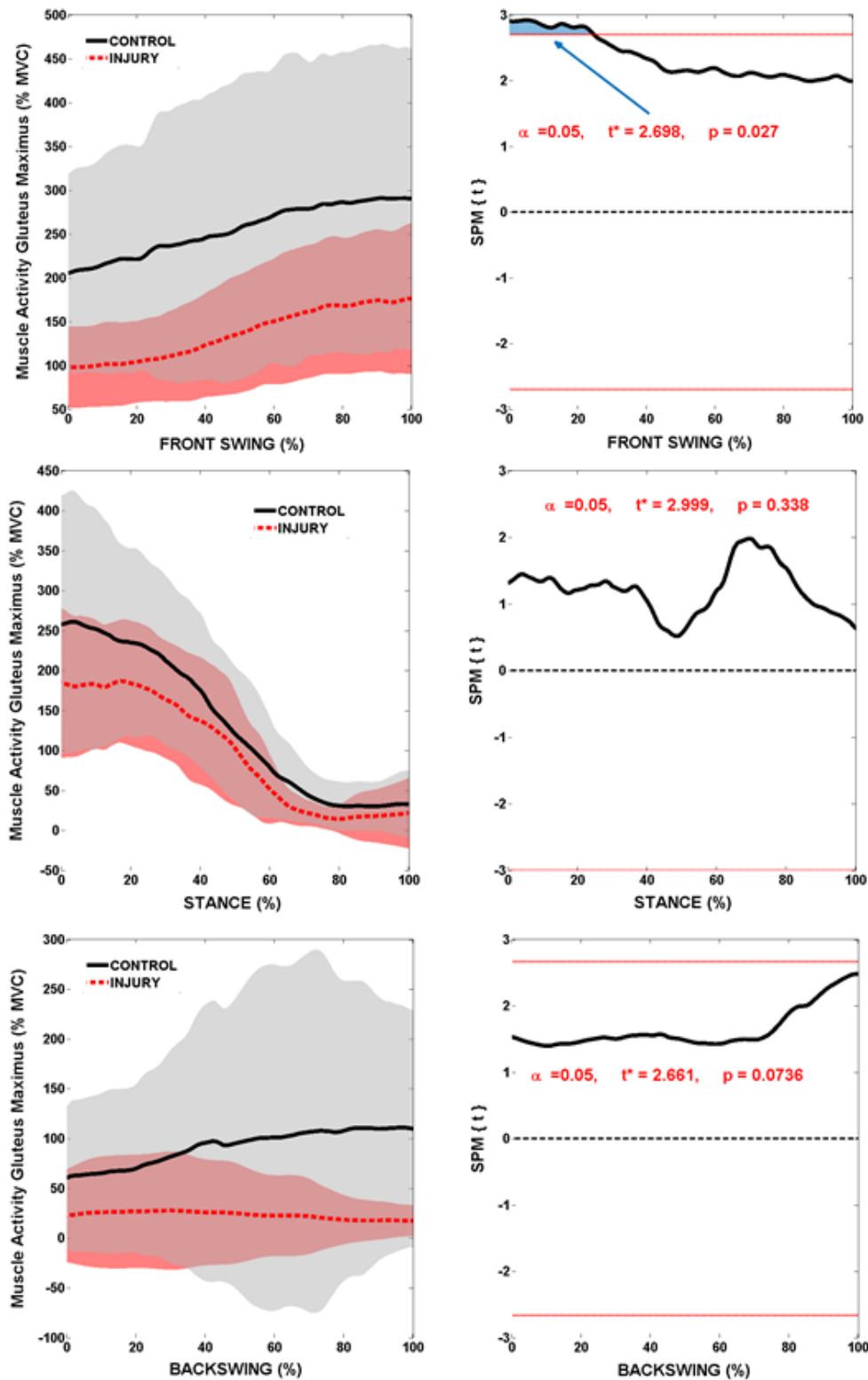
- 8 participants ( $\pm$  50%) sustained a hamstring injury in the dominant (preferred kicking) leg, whereas the other 7 sustained an injury in the non-dominant leg
- 8 participants reported having a laterally oriented pain location, whereas the remaining 7 indicated that the primary locus of pain was situated rather medially
- only one of the injured participants reported the lesion to be oriented rather close to the proximal insertion, whereas the other 14 indicated to have a more central or distal injury location.

Demographic statistical analysis revealed that participant's age, anthropometry or position on the field did not have any effect on injury occurrence within our cohort. All the participants within this study were playing in the same amateur league division (same training and match exposure in terms of volume, frequency and intensity) and none of the players reported to participate in any other sport, so exposure could not have been of any influence.

### **Data on muscle activity during sprint**

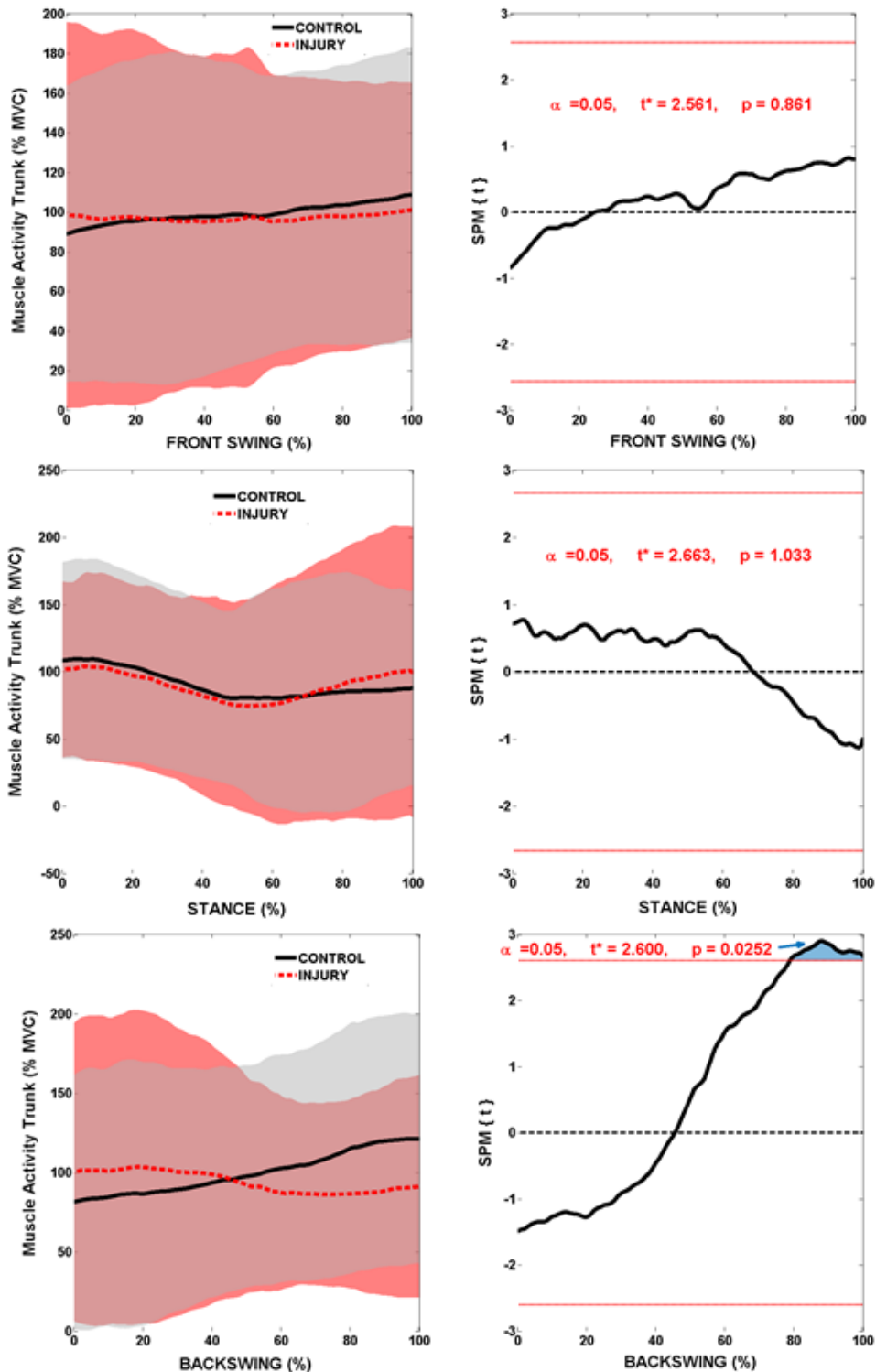
Comparing the lower limb and trunk muscle activation patterns between the players who sustained a hamstring injury during follow-up and those who did not, revealed significant differences in normalized gluteal muscle activity and trunk muscle activity during front- and backswing, respectively. Players that remained injury free during follow-up, presented higher normalized gluteus activity, accentuated near the start of the front swing phase ( $p = 0.027$ ) [Figure 4,6]. In addition, these subjects presented significantly higher levels of trunk muscle activity during terminal backswing ( $p = 0.042$ ) [Figure 5-6]. Subsequent binary logistic regression analysis revealed that the activity of the Gluteus Maximus during initial front swing and the clustered activity of the trunk muscles during terminal backswing, were indeed capable of predicting injury absence during follow-up. In particular, the risk of injury lowered with 20% and 6%, with a 10% increment in normalized muscle activity of the Gluteus Maximus during initial front swing ( $p = 0.023$ ; OR 0.98 ; 95% CI [0.963 – 0.997]) and the

trunk muscles during backswing ( $p = 0.007$ ; OR 0.99 ; 95% CI [0.989 – 0.998], respectively. Accordingly, Receiver Operator Curve (ROC) analysis demonstrated GM activity during initial front swing to be able to predict hamstring injury occurrence with a sensitivity of 82% and a specificity of 74% (AUC = 0.828,  $p = 0.003$ ) with a cut-off value at 145% of normalized activity, as was also the case for clustered trunk muscle activity during terminal backswing, with a sensitivity of 60% and a specificity of 68% (AUC = 0.618,  $p = 0.006$ ) at a 90% of normalized activity cut-off. Subsequent post-hoc analyses, were not able to identify a significant association between the activity of any of the individual trunk muscles (Internal or external oblique abdominals, thoracic or lumbar erector spinae) and hamstring injury occurrence. Gluteus maximus activity during stance and backswing phases presented no significant association with injury occurrence during follow-up, neither did the trunk muscle activity during front swing- and stance phases. Although a history of hamstring injury presented to be a significant predictor of injury during follow-up as well (Odds Ratio (OR): 5.08,  $p = 0.016$ ; 95% CI [1.35 – 19.06]), core muscle activity during front (gluteus maximus) and backswing (trunk) demonstrated to be significant independent predictors of injury occurrence ( $p < 0.024$ ).



**Figure 4.** Normalized muscle activity of the Gluteus Maximus throughout the front swing, stance and backswing phases of sprinting; Gluteus Maximus activity during the initial front swing phase presented a significant association with injury occurrence,  $p = 0.027$

MVC, Maximal Voluntary Contraction; %, percentage; SPM(t), Scalar trajectory variable indicating the magnitude of the in-between-group differences (magnitude of the difference between both curves per time frame throughout respective phase of the running cycle) as demonstrated in the left-hand graphs;  $\alpha$ , level of significance;  $t^*$ , critical  $t$ -value corresponding with the upper limit of the 95% Confidence Interval as defined by  $\alpha$ ;  $p$ , probability with which the magnitude of the in between group difference within the time-frame during which SPM(t) exceeds its critical value could have been produced by a random field process with the same temporal smoothness



**Figure 5.** Integrated Normalized activity of the trunk muscles throughout the front swing, stance and backswing phase of sprinting: Trunk muscle activity during the terminal backswing phase presented a significant association with injury occurrence,  $p = 0.025$

MVC, Maximal Voluntary Contraction; %, percentage; SPM{t}, Scalar trajectory variable indicating the magnitude of the in-between-group differences (magnitude of the difference between both curves per time frame throughout respective phase of the running cycle) as demonstrated in the left-hand graphs;  $\alpha$ , level of significance;  $t^*$ , critical t-value corresponding with the upper limit of the 95% Confidence Interval as defined by  $\alpha$ ;  $p$ , probability with which the magnitude of the in between group difference within the time-frame during which SPM{t} exceeds its critical value could have been produced by a random field process with the same temporal smoothness

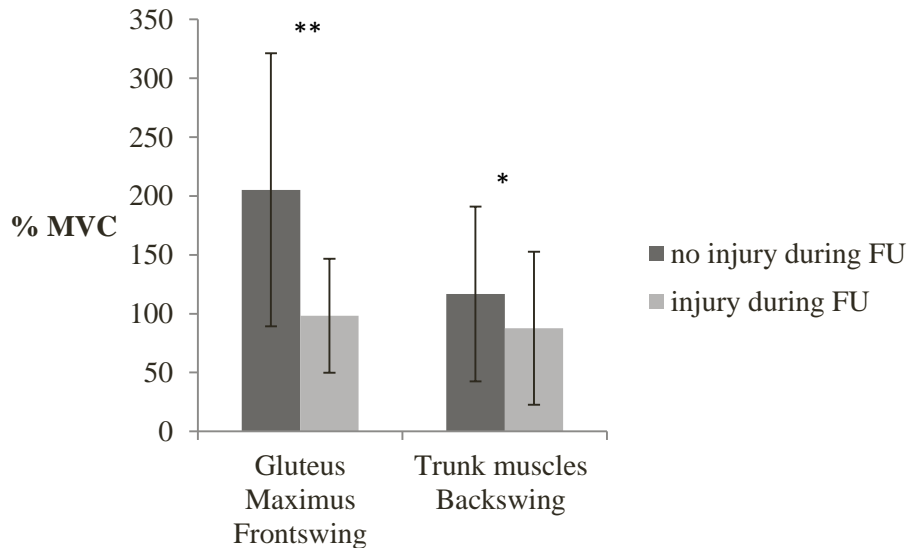


Figure 6: Normalized muscle activity during airborne phases of sprinting based on injury occurrence during follow-up at  $SPM\{t\}_{max}$ ; FU, Follow-Up ; MVC, Maximal Voluntary Contraction;  $SPM\{t\}_{max}$  time-frame within front swing (Gluteus Maximus) and backswing (Trunk Muscles) trajectory at which the in-between-group difference was the highest.

\*\* post-hoc analyses after SPM for logistic regression presented the highest in-between-group difference at the beginning of the front swing phase (1<sup>st</sup> % of the front swing):  $p = 0.002$

\* post-hoc analyses after SPM for logistic regression presented the highest in between group difference at frame 89 of the normalized time-series throughout backswing (at 88% of the backswing phase):  $p = 0.006$

In terms of hamstring activity, no association between the EMG time series biceps femoris and/or medial hamstrings and the occurrence of injury during follow-up were found. Increments in core muscle activity could not be associated with decrements in hamstring activity.



## Discussion

The results of this study demonstrated that higher levels of normalized sEMG activity of the Gluteus Maximus during front swing, and higher levels of normalized sEMG activity of the trunk-cluster (Internal and external Oblique Abdominals, Erector Spinae at the Thoracic and Lumbar level) during backswing, were significantly associated with a lower injury risk during follow-up. As a consequence, time-dependent muscle activity analysis revealed that players appear to be relatively protected against hamstring injury, when the proximal muscles are recruited to a greater extent throughout the airborne phases of sprinting. More specifically, the risk of injury seems to decrease with 20% and 6% with a 10% increase in normalized gluteal and trunk muscle activity throughout the front swing and backswing phases of sprinting, respectively ( $p < 0.024$ ).

Although both researchers and clinicians estimate the influence of the core to be key in (sports) injury vulnerability, scientific evidence has remained forthcoming. The present findings indicate that sufficiently dosed and well-timed neuromuscular control in the core unit (gluteal muscles and trunk), possibly providing adequate stability during locomotion and running, seems important in hamstring injury prevention. Our research findings are somewhat in accordance with previous research results. As such, former EMG research has demonstrated that the use of external pelvic compression (passively increasing sacro-iliac stability and potentially lumbo-pelvic control as well) had a significant effect on electromyographic hamstring function. To what extent this improved force-closure might have a protective effect as regards running related hamstring injuries, could not be determined based on these observational and cross-sectional study results.<sup>3-4</sup> In direct association with hamstring injury susceptibility, previous research has merely been focusing on comparing the functional outcome of hamstring rehabilitation consisting of neuromuscular core training, compared to rather isolated hamstring training.<sup>6, 44, 47</sup> As such, scientific outcome measures have remained limited to injury occurrence and time to return to play up until now. Accordingly, the prospective study of Freckleton and colleagues could demonstrate that Single Leg Hamstring Bridge (SLHB) performance, presuming it to necessitate sufficient neuromuscular control and strength

endurance in both the hamstring and core muscles, was related with hamstring injury vulnerability.<sup>17</sup> In line with these findings, Sherry and Best demonstrated a rehabilitation program consisting of progressive agility and trunk stabilization exercises (PATS program), to be more efficient than a program consisting of hamstrings stretches and strengthening exercises, in terms of secondary injury prevention.<sup>44</sup> de Visser et al. confirmed the effectiveness of agility and stabilization exercises for the purpose of hamstring injury prevention in male soccer players.<sup>12</sup> Unfortunately, these studies do not allow identification of the exact contribution of proximal muscle functioning or 'core-stability' in injury vulnerability and it remains unknown to what extent these interventions improved the functional outcome of hamstring rehabilitation through the acquirement of better core strength and stability. Consequently it could be that the athletes allocated to the PATS program were simply the ones with stronger hamstrings.<sup>44</sup> The same could have been the case for the athletes who did not get injured in the prospective study of Freckleton.<sup>17</sup> Although we did not kinetically measure hamstring strength output, our study did assess the hamstring activation patterns, next to those of the core muscles during sprinting. Because we found the activity of the gluteal and trunk muscles during respective airborne phases to be independent predictors of injury occurrence, without any effect or in between subject difference as regards normalized hamstring muscle activity, this might help us in defining the value of 'core stability' (and its underlying mechanisms) in hamstring injury prevention. As such, the present results suggest that neuromuscular activation characteristics of the core unit are associated with hamstring injury vulnerability in male soccer players.

Next to the above mentioned studies, our results are in agreement with the assumptions of other authors, discussing the possible association between core muscle activity and hamstring loading.<sup>8, 35</sup> Those authors have predominantly been focusing on the anatomical and structural association between the core- and hamstring units, in which adequate proximal control is proposed to be essential for safe hamstring functioning and in preventing the occurrence of excessive strain within this biarticular muscle unit.<sup>35</sup> Based on this line of reasoning, Chumanov et al. performed biomechanical investigations on a study sample consisting of healthy sprinters. In possible compatibility with the present findings, their results revealed that the amount of stretch the biceps femoris needs to withstand

during running, is associated with the amount of activity generated by the pelvic muscles.<sup>8</sup> This association was most significant during the airborne phases and at maximal running speed. In particular, the amount of hip flexor muscle activity was related to significant increments in biceps femoris stretch during front swing, whereas the amount of activity produced by the gluteus maximus and the oblique abdominals were associated with a decrease in the level of biceps femoris stretch during the crucial (front) swing phase. The authors concluded that lumbo-pelvic agonist-antagonist balance during functional activities (e.g. sprinting), should be considered indispensable in hamstring injury prevention.

The fact that we did not find particular effects of muscle activity at terminal swing / initial stance on hamstring injury occurrence but rather during backswing (trunk muscle activity) and the beginning of the front swing phase, emphasizes the importance of both timing and amount of muscle activity during high speed running. If we would not have chosen to use of SPM for the gathering of statistical inference on prospective analyses and just would have looked at the normalized EMG amplitude during terminal swing, where the hamstrings are expected to be loaded the most, we would have come to a completely different conclusion. If we had decided to do so, results would demonstrate that the amount of core muscle activity had no significant effect on hamstring injury occurrence. Statistically assessing the muscle activation pattern throughout the entire stride, revealed significant differences in muscle activity of (1) the gluteal muscles at the beginning of the front swing phase, and (2) the trunk muscles at the end of the backswing phase (which equals the end of the front swing for the opposite leg as well, evidently). These fairly discrete and very time-dependent deficits in normalized muscle activation are, according to us, most probably the cause of (subtle) dysfunctions in neuromuscular coordination in the lumbo-pelvic muscle unit, rather than actual deficits in strength capacity. Therefore, the present findings implicate that (if confirmed by additional prospective research), hamstring injury prevention should not just include strengthening of the core muscles or ‘core stability’ training as it is most often presented in a ‘fitness’ context. It should aim to train the core under functional loading circumstances, trying to facilitate properly timed gluteal and trunk muscle recruitment during explosive running(-like) exercises. In these terms, it seems very plausible that the

hamstrings might be exposed to higher mechanical loading and have to engage in higher metabolic output, when the supporting proximal musculature does not take its responsibility in time. A delay in muscle activity onset has been associated with the hamstring injury risk in former research.<sup>23, 34</sup> As such, the research group of Opar demonstrated that the hamstrings present a delay in rate of torque development after injury, primarily caused by decrements in Biceps Femoris fiber recruitment (as observed by sEMG).<sup>34</sup> Although those findings were most probably the consequence rather than the cause of the injury, they are possibly the cause of deficits in neuromuscular coordination and efferent hamstring muscle guidance and might explain why hamstring injuries tend to reoccur so often. In a completely different study, assessing mechanical hamstring muscle loading and activation properties during over-ground running at maximal intensity,<sup>23</sup> Higashihara and colleagues concluded that the Biceps Femoris only present peak muscle activity after the installation of peak muscle-tendon stretch, whereas the markedly less injured Semitendinosus presents peak EMG activity prior to reaching peak muscle-tendon stretch. To what extent this discrepancy (relative deficit in muscle recruitment as regards timing) has an actual share in the laterally biased hamstring injury vulnerability, cannot be judged based on these observational study findings. Nonetheless, similar to ours and the findings of Opar, they do suggest that timing of (1) (peak) motor unit recruitment and (2) time-dependent magnitude of muscle activity (and possibly torque-output) might be associated with hamstring injuries. Possibly, this might shed a completely different light on the exact nature of functional core stability and the points of particular interest with regard to injury prevention, and, as such, the associated training recommendations and guidelines.

Leaving the particular time-dependency aside, the present study was able to demonstrate that hamstring injury vulnerability presents a direct association with proximal muscle functioning during the airborne phases of sprinting. It hereby provides some rationale for the necessity of neuromuscular control in the core-unit in hamstring injury prevention in soccer. In stating this, we essentially refer to neuromuscular - rather than kinematic proximal control ('core stability'), as this study does not provide the necessary kinematic output to support these findings. As such, this study merely wishes to broaden the clinical perspective of the interplay between neuromuscular input (afferent

proprioception) and output (efferent coordination) in the intrinsic hamstring injury risk profile, without assuming that higher levels of muscle activity might indeed result in less kinematic perturbations and increased postural control (and less mechanical loading of the hamstring unit). So, although this cannot be confirmed biomechanically, our findings suggest that discrete discrepancies in neuromuscular coordination in the proximal core unit, with the gluteal muscles and trunk muscles presenting significantly less muscle activity within very particular periods throughout the front- and backswing phases, increase the risk of hamstring injury. Whether this relative incapability to activate the core muscles with an appropriate intensity (recruiting a sufficient amount of motor units) in function of the contemporary biomechanical demands increases the risk of a hamstring injury due to kine(ma)tic perturbations and whether this increases mechanical hamstring loading, cannot be judged based on the present results. This is exactly what we aim to verify based on the results of a similar study conducted by our research group, this time around primary focusing on running kinematics instead of multi-muscle sEMG. This work is still in the pipeline towards publication. Be that as it may, the present findings do underline the importance of adequate proximal coordination ('neuromuscular core stability') in the context of hamstring injury prevention.

Based on the results of this study, the clinician is recommended to functionally strengthen the core in hamstring rehab and injury prevention, particularly focusing on the gluteus maximus, the oblique abdominals and the erector trunci. Moreover, special focus should be directed to maximal sprint drills and explosive agility exercises, aiming to sufficiently and rapidly address the core-unit, as hamstring demands are the highest under these intense loading conditions and adequate proximal assistance is most required.

This study was not without limitations. First, data collection on injury occurrence was based on participants' self-report, as most of the clubs did not have an associated medical staff and we could not systematically get in touch with the participant's doctor or physiotherapist to check his medical record. In only taking along hamstring injuries that caused the participant to be out for at least one entire week and by systematically verifying the nature and clinical presentation of the injury by phone, we attempted to minimize the risk of reporting bias, which might have influenced the results. Second, we

must acknowledge that the sample size was quite limited, certainly given the prospective nature of this study, which could have led to type 2 statistical error. However, as the statistical procedures (SPM vector field analyses) attributed within this study, strongly control for both type 1 and type 2 errors, the associated risk is limited as well.<sup>39</sup> Second, the results of this study are dependent on the validity and reliability of the MVC data collection procedure, as proposed by the SENIAM guidelines.<sup>26, 30</sup> The ability to analytically recruit a muscle unit, could have varied within our cohort of soccer players, which could have led to over- or underestimation of the functional electromyographic potential of the evaluated muscles. However, this is an important limitation of sEMG analysis in general. As normalization is essential for the purpose of inter-individual comparison, this limitation could not have been overcome in the present study. The strength of this study however, is that it consisted of a very well controlled, multi-muscle sEMG investigation in a context directly related to the most common injury mechanism, with delineated prospective follow-up (which has never been done before). Hence, present findings can contribute to valid implementation of core- and functional chain training in injury prevention, and provide a basis for the discussion concerning the content of return to play screening protocols for better secondary injury prevention.

## **Conclusion**

This is the first study to investigate the exact role of core muscle functioning during high speed running, with regard to the hamstring injury risk in male soccer players. Adequate proximal muscle control was found to be essential during maximal sprinting in order to decrease hamstring injury risk. Indeed, during sprinting, sufficient trunk and gluteal muscles activity seems to be of particular importance during the airborne phases, as the risk of hamstring injury seems to decrease when these muscles are activated to a higher percentage throughout both the back and front swing phases of the running cycle, respectively. As a consequence, our results imply that hamstring injury prevention

should focus on sufficient development and preservation of proximal stability, particularly addressing both trunk- and gluteal muscles.

### **Acknowledgements**

The authors gratefully acknowledge the assistance of their colleagues at the department of Rehabilitation Sciences and Physiotherapy in Ghent (Belgium), as well as the staff members of Bloso, Topsportal Vlaanderen (Belgium). In particular Steven Heyndrickx, for his assistance during the installation of the running track with surrounding measuring systems, as well as for the assembly of the online diary for injury registration during follow-up and the post hoc data processing. Additionally, sincere appreciation goes out to Jos Vanrenterghem (Faculty of Kinesiology and Rehabilitation Sciences, KU Leuven, Leuven, Belgium), Mark Robinson (School of Sport and Exercise Sciences, LJMU, Liverpool, United Kingdom) and Todd Pataky (Shinshu University, Dept. Bioengineering, Matsumoto, Nagano, Japan), for their support during the SPM analyses. The authors would particularly like to thank the participants of this study, without whom this paper could not have been accomplished. For their financial support, our gratitude goes out to the Agency for Innovation by Science and Technology in Flanders (IWT – Brussels, Belgium). All authors declare to have no conflicts of interest regarding the scientific content of the paper nor regarding the sources of funding.

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## Chapter III – Part II

Deviating running kinematics and hamstring injury susceptibility in male soccer players :  
cause or consequence ?



## CHAPTER III - PART II

### Deviating running kinematics and hamstring injury susceptibility in male soccer players: cause or consequence?

Joke Schuermans<sup>1</sup>, Lieven Danneels<sup>1</sup>, Damien Van Tiggelen<sup>1</sup>, Tanneke Palmans<sup>1</sup>, Erik Witvrouw<sup>1</sup>

<sup>1</sup>Department of Rehabilitation Sciences and Physiotherapy Ghent, Ghent University, Ghent, Belgium

Correspondence to Schuermans Joke, Department of Rehabilitation Sciences and Physiotherapy, Ghent University, De Pintelaan 185, 3B3, –Ghent 9000, Belgium; [Joke.schuermans@ugent.be](mailto:Joke.schuermans@ugent.be)

**Submitted in Gait & Posture**

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#### Abstract

**Background** Although the vast majority of hamstring injuries in male soccer are sustained during high speed running, the association between sprinting kinematics and hamstring injury vulnerability has never been investigated prospectively in a cohort at risk.

**Purpose** This study aimed to objectify the importance of lower limb and trunk kinematics during maximal acceleration towards full sprint in hamstring injury susceptibility.

**Study Design** Cohort study; level of evidence, 2.

**Methods** At the end of the 2013 soccer seasons, three-dimensional kinematic data of the lower limb and trunk were collected during sprinting (acceleration) in a cohort consisting of 30 soccer players with a recent history of hamstring injury and 30 matched controls. Subsequently, a 1.5 season follow-up was conducted for (re)injury registry. Ultimately, joint and segment motion patterns were submitted to retro- and prospective statistical curve analyses for injury risk detection and prediction.

**Results** Statistical analysis revealed that index injury occurrence was associated with higher levels of anterior pelvic tilting and thoracic side bending throughout the airborne phases of sprinting, whereas no kinematic differences were found in comparing the running kinematics of players with a recent hamstring injury history with their matched controls.

**Conclusion** Functional deficits in core control, enabling excessive pelvis and trunk motion during swing, probably increases the primary hamstring injury risk. Although sprinting encompasses a relative risk of hamstring muscle failure in every athlete, running coordination demonstrated to be essential in hamstring injury prevention.

**Key Terms** hamstring injury; aetiology; soccer; 3D kinematics; sprinting coordination; acceleration

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## Introduction

Hamstring injuries are the single most frequent non-contact muscle injury in male soccer.<sup>23, 27, 40</sup> The vast majority of those occur during high speed running, where the muscle fails structurally or functionally,<sup>7</sup> due to excessive strain and loading throughout the front- and (early) stance phases of the running cycle.<sup>14, 16-17, 32-33</sup> The posterior thigh unit is at highest risk of injury during explosive acceleration towards full speed sprint. Accelerating induces higher hamstring muscle loading than constant speed sprinting, as the kinetic energy cannot just be recycled throughout absorption and release, but needs to be magnified with every step, through intense and highly efficient plyometric muscle work and optimal intermuscular coordination.<sup>5, 12, 16-17, 26, 32-34</sup> Sufficient acceleration capacity and adequate starting speed are key motor components in soccer performance, for which optimal hamstring functioning is essential. In trying to identify intrinsic risk factors for adequate injury prevention, rehabilitation, and safe return to play, existing research tends to be restricted to the investigation of functional and structural regional neuromuscular characteristics in resting state



conditions.<sup>11-12, 27, 32, 40</sup> Considering the TRIPP (Translating Research into Injury Prevention Practice) frame-work guidelines to be gold standard for evidence based injury prevention,<sup>9</sup> current observational research for risk factor identification seems to be focusing beside the most critical point in injury prevention: the injury mechanism as starting point.<sup>9</sup>

Among others, muscle strength and flexibility, morphological and –metabolic features, as well as neuro-dynamics and stretch tolerance have been investigated in relation to hamstring injury vulnerability.<sup>11, 23, 27, 34, 40</sup> However, these possibly important muscle characteristics have never been examined in coherence with the injury mechanism. In addition, because of the functional integrity of lower limbs and the lumbo-pelvic complex, joint mobility of the spine and lower limb as well as multiple other factors responsible for functional lumbo-pelvic control (postural control, coordination, strength, etc.) are thought to be crucial in rehabilitation and prevention.<sup>2-4, 6, 20, 23, 31, 38</sup> Nonetheless, these potential hamstring injury correlates have only rarely been scrutinized during explosive acceleration for full speed sprinting, during which the hamstring is at highest risk of injury.

High amounts of negative work and tensile strain are inherently present in acceleration and high speed running. Why some players manage to keep their hamstrings in optimal shape and others sustain (recurring) muscle injuries throughout those repeated sprint(-acceleration)s, is a capital question that needs to be resolved in order to adequately and sport specifically prevent these types of high speed running injuries. Besides, although core stability (lumbo-pelvic control) has proven to be key in rehabilitation outcome and secondary injury prevention,<sup>1, 4, 8, 15, 21, 22-24, 35-36, 39</sup> its exact role in primary injury vulnerability and influence on muscle mechanics during running and kicking, remains unclear. Bearing in mind the evidence behind the injury mechanism,<sup>32-33</sup> it would seem merely logical that running technique and the associated biomechanical features within the (high speed) running cycle could be of substantial influence in the risk of sustaining a hamstring injury.

The biomechanics of running have been subject of study repeatedly. Strikingly however, high speed running kinematics have never been investigated in direct association with hamstring injury occurrence. Therefore, this study intended to investigate the association between lower limb and trunk

kinematics throughout maximal acceleration towards full speed sprinting and hamstring injury vulnerability in a sample at risk, consisting of male soccer players. This association was explored both retro- and prospectively, to allow strict differentiation between possible kinematical causes and consequences of hamstring injury.

## Methods

### Participants

Throughout the second half of the 2013 soccer season, 30 soccer players with a recent history (last injury sustained within the past season or the prior one (past 24 months)) and 30 matched controls, all active in the same amateur competition series (Oost-Vlaanderen, Belgium), were recruited. Players were excluded if they had

- a history of severe lower limb injury, which could have influenced kinematics
- a history of lower back complaints / lower back complaints at present, which could bias the intrinsic risk profile
- less than 5 years of competitive soccer experience, as this could induce selection bias

To exclude age related pathologies, soccer players aged beneath 18 or above 35 years were excluded from the study as well. All participants were completely free from injury and ready to play at the moment of testing.

A hamstring injury was defined as a soccer related injury in the hamstring muscle region, preventing the player from participating in training or competition for at least one entire week and necessitating him to consult a (para)medical caregiver.<sup>13</sup> The majority of respective hamstring injuries within the

injury group was diagnosed clinically, with or without enclosed medical imaging (depending on the decision of the medical staff). Actual recruitment and inclusion of formerly injured participants was mainly based on self-report, as we were not able to get in touch with all physicians and physiotherapists involved in prior diagnosis and rehabilitation. At the time of testing, none of the players experienced any pain or discomfort in the hamstring region during soccer participation or during the running protocol in this study.

### **Testing Procedure**

All participants were informed about the content and the purpose of the testing procedure and signed the Informed Consent, after which they were familiarized with the running protocol and the course of the three-dimensional (3D) motion analysis. This information was consistently provided by the same qualified researcher (JS), who was in charge of the entire testing procedure (participant preparation, data assembly and –processing) as well, which minimized the risk of inter-tester bias. This study was approved by the Ethics Committee of the Ghent University Hospital (number of approval: EC/2013/118).

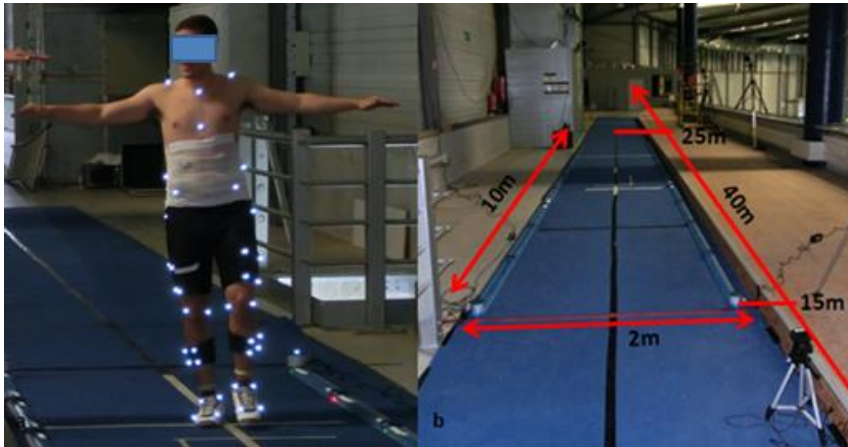
In order to get a valid impression of the running coordination throughout acceleration towards full speed sprinting, without bias of fatigue or muscle soreness, subjects were instructed not to engage in intensive training or soccer competition 48h prior to testing.

After testing, participants were informed about the online diary which was put together for the purpose of injury registration during follow-up (<http://www.hsi.ugent.be>). This online survey contained questions about weekly exposure (match and training) and the incidence/presence of soccer related injuries and complaints. The participants were asked to complete this survey every Monday throughout the entire 2013-2014 season, as well as the first half of the 2014-2015 season, accounting for a follow-up period of one entire and one half of a soccer season.

Follow-up was terminated at the winter break of the 2014-2015 season, during which period all participants were contacted again for final injury inquiry.

### Three-dimensional kinematic testing protocol

When indicating having understood the content and course of the testing procedure, participants were instructed to undress, wearing only a pair of tight shorts and indoor soccer shoes. Afterwards, 40 passive infrared reflective markers (12mm lightweight markers, Qualisys AB, Sweden) were attached in accordance with the LJMU Lower limb and Trunk Model for motion analysis (Van Renterghem J., Liverpool John Moores University), representing respective bony landmarks and segment clusters [Figure 1(a)]. The kinematic analysis of the linear acceleration to full speed sprinting was conducted on a 40 meter (m) running track, which was surrounded by 8 cameras for 3D motion capturing (Oqus, Qualisys AB, Göteborg, Sweden). These cameras were installed along meter 15 and 25 of the running track, resulting in a kinematic measuring volume of  $(10 \times 2) \text{m}^2$ . This camera location enabled to capture running kinematics during full sprinting acceleration, as this is the average distance over which maximal acceleration is achieved in attempting to reach maximal running speed<sup>19</sup> [Figure 1(b)]. All reflective markers were attached to the skin firmly by using double sided carpet tape, to prevent them from coming loose or falling off. The entire 3D data assembly of the acceleration phase in sprinting was carried out by the Qualisys Track Manager hard- and software systems. A 10m Optogait system (Microgate, Bolzano-Bozen, Italy) was used for step detection. Because we wanted to perform kinematic analysis of one entire stride this would have been impossible using a force plate. First, one static trial and 4 functional joint trials (left and right knee and hip joints) were recorded to create a virtual model. Subsequently, 8 markers were removed (left and right acromion, greater Trochanters, left and right medial epicondyles of the knee joint and left and right medial malleolus at ankle level) as these were redundant for motion capture [Figure 1(a)]. Hereafter, the participant was instructed to perform a 5 minute warm up by running up and down the running track at a self-chosen pace, alternated with short sprint-intervals, as if they would perform starting speed drills.



**Figure 1.** (a) Static - and tracking marker placement - Functional joint capture protocol of the left knee ; (b) 40m sprinting track with [10\*2]m 3D measuring volume in between the step detection bars of the Optogait system

After warm up, each participant was instructed to sprint up the track over a distance of (at least) 30m, trying to reach maximal sprinting speed as soon as one could. 3D data collection and step detection were conducted simultaneously throughout the 10m measuring distance (meter 15 – meter 25), as both software systems were synchronised within the QTM interface (Qualisys Track Manager). Every soccer player had to perform 12 maximal sprints, because a minimum of six left – and six right side strides was needed for post hoc data processing and analysis within the Visual 3D interface (Visual 3D v5 Professional, C-Motion Research Biomechanics, Germantown, USA). A sprinting trial could only be taken along for data analysis when it consisted of three full stance phases within the measuring volume.

### Data analysis

For each participant, a virtual model was created according to his specific anthropometric features, on the basis of which 3D segment coordinates and joint angles could be calculated throughout an entire stride. To serve this purpose, the static-, functional joint- and sprinting trials were labelled within the QTM interface (marker identification). Afterwards, sprinting trials were divided into swing- and stance phases using 4 events: left toe off, right touch down, right toe off and left touch down in the left stride trials; right toe off, left touch down, left toe off and right touch down in the right stride trials. Labelled trials were exported to the ‘C3D’ format, after which they could be imported in Visual 3D

(V3D, C-Motion Inc., USA) to quantify joint kinematics in the ankle-, knee- and hip joints, as well as segment kinematics for the pelvis and the thorax. For each phase (front-swing, stance and backswing), kinematic data were time-normalized to 101 data frames, enabling in-between-subject comparison. This time-normalization procedure was necessary as participants were instructed to perform maximal sprinting accelerations (perform at personal best), which lead to the assembly of a collection of sprint-acceleration trials at varying running velocities (both within and between subjects). Ultimately, kinematics were prepared for statistical analysis by subcategorizing all processed data into excel files in function of

- phase: “front swing”, “stance” or “backswing”
- group: “Injury History” or “Control” for the retrospective analysis; “Injury” or “Control” for the prospective analysis
- joint (or segment), and
- plane (Sagittal, X; Coronal, Y; Transverse, Z).

### **Statistical analysis**

For every joint- and segment angle, the entire kinematic curve throughout each of the three phases was submitted to both retro- and prospective in between group comparison based on the presence or absence of injury history on one hand and injury incidence during follow-up on the other. Curve analysis was conducted using Statistical Parametric Mapping (SPM, version M.03) in Matlab (R2014a, The Mathworks Inc, Natick, MA). This method retrieves results on statistical inference, based on the Random Field Theory. Whilst commonly used for the analysis of functional brain images it is becoming commonplace in biomechanical data analysis as well.<sup>28-29</sup> Using the mean joint- or segment angle and its corresponding standard deviation at each of the 101 data frames within one phase, it allows statistical comparison of the entire kinematic profile instead of the commonly used peak - or mean amplitude comparison which only takes into account one or a couple of point estimates, irrespective of time. For more detail on the indications and benefits related to the use of SPM in biomechanical research, we refer the reader to previously published works of reference.<sup>28-29</sup>

Specifically, joint- and segment angle profiles were compared between groups, using SPM two-tailed independent t-tests. Firstly, the SPM{t} statistic was calculated at each data point within a given time frame (front swing, stance or backswing), then statistical inference was examined based on the behaviour of random curves with the same temporal smoothness. Besides taking into account the essential time-dependency of kinematic data behaviour, another advantage of using SPM is that it provides better control of type I and type II statistical error,<sup>30</sup> enabling more valid risk estimation.

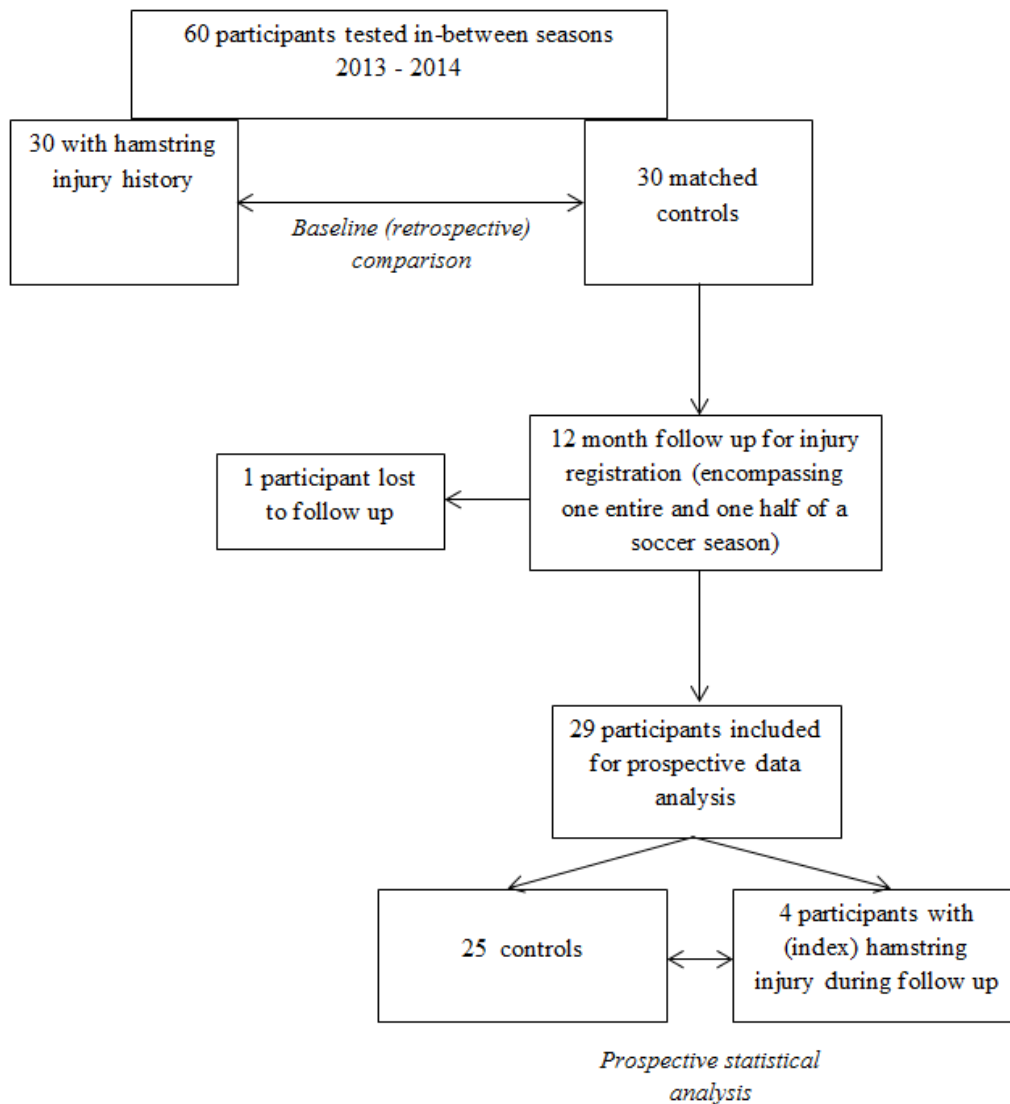
For the SPM analysis within Matlab,  $\alpha$  was set at 0.05. All statistical analyses within the scope of this study were implemented using the open-source SPM1D code (<http://spm1d.org>).

## Results

We assessed the possible association between (deviant) sprinting kinematics and hamstring injury vulnerability with strict differentiation as regards kinematical cause or consequences of increased injury risk. To do so, we performed both baseline statistics within the entire cohort (kinematic consequences of previous hamstring injury?), and prospective statistical analysis within a cohort consisting of only those that reported never having sustained a hamstring injury at initial intake (kinematical cause of hamstring injury?). Average age, height and weight within the group of players with an injury history was 24.7 ( $\pm$  3.4) years, 1.80 ( $\pm$  0.06) meter and 75.2 ( $\pm$  6.8) kilograms. This was 23.7 ( $\pm$  4.5) years, 1.81 ( $\pm$  0.05) meter and 74.4 ( $\pm$  7.1) kilograms within the group of matched controls.

Of the 30 healthy controls submitted to the 3D sprinting analysis, only 1 was lost to follow-up. As mentioned above, mostly to prevent a biasing influence of injury history and to validly verify to what extent running kinematics presented a significant predictive association with hamstring injury

occurrence, only the data of this group (original control group) were included for prospective analysis. Within this original control group (n = 29), 4 players sustained an index injury, resulting in an (index) injury incidence of 13.8% during the 1.5 season follow-up. Details on study course are illustrated in figure 2.



**Figure 2.** Flowchart study trajectory.

Because we wanted to compare the trunk- and lower limb kinematics during full acceleration based on the presence of an injury history or the incidence of a hamstring injury during our 1.5 season follow-up period, without leg dominance being a biasing covariate, we verified the ratio of dominant/non-



dominant leg involvement both retro- and prospectively in the injury groups, and randomly elected the same ratio in the control groups.

### **Baseline comparison**

Comparing the 3D joint angles of the ankle-, knee- and hip complexes (i.e. the angles between adjacent segments) and the pelvis and thorax segment (i.e. the time-dependent 3D position of respective segments in reference to the global laboratory) during front swing-, stance- and backswing phases of maximal sprinting acceleration between the soccer players with a recent hamstring injury history and the healthy controls, no significant in between group differences could be demonstrated. The ankle-, knee-, hip-, pelvis- and thorax kinematics in the coronal, sagittal and transverse planes did not present significant differences based on the presence or absence of a history of hamstring injuries. In other words, the factor ‘hamstring injury history’ did not present to have a significant effect on running kinematics.

### **Prospective analysis: running kinematics and injury susceptibility during follow-up?**

Assessing the kinematic curves of the soccer players that sustained a first time hamstring injury during follow-up (n = 4) in reference to the healthy controls (n = 25), statistical parametric mapping revealed significant differences in pelvis – and thorax motion patterns. In particular, players that sustained a hamstring injury presented substantially more anterior pelvis tilt throughout the entire stride, with a statistically significant difference during the backswing phase (p = 0.0445), compared to the healthy controls [Figures 3,4]. Moreover, the index injury group presented significantly more thoracic side bending throughout the front-swing phase, compared to the healthy controls (p = 0.028) [Figures 3,5]. Additionally, the kinematic curves of the thoraco-pelvic complex in the index injury group presented to be less stable throughout the entire running stride, displaying more fluctuations and variability, compared to the quite neutral thoraco-pelvic motion pattern demonstrated by the healthy controls

[Figure 3]. Mean and standard deviations of these pelvis- and trunk kinematics at  $SPM\{t\}_{max}$  (*point within time frame at which the in-between-group differences are the highest and the probability with which this in between group difference could be attributed to coincidence is the lowest ( $p_{min}$ )*) are presented in table 1.

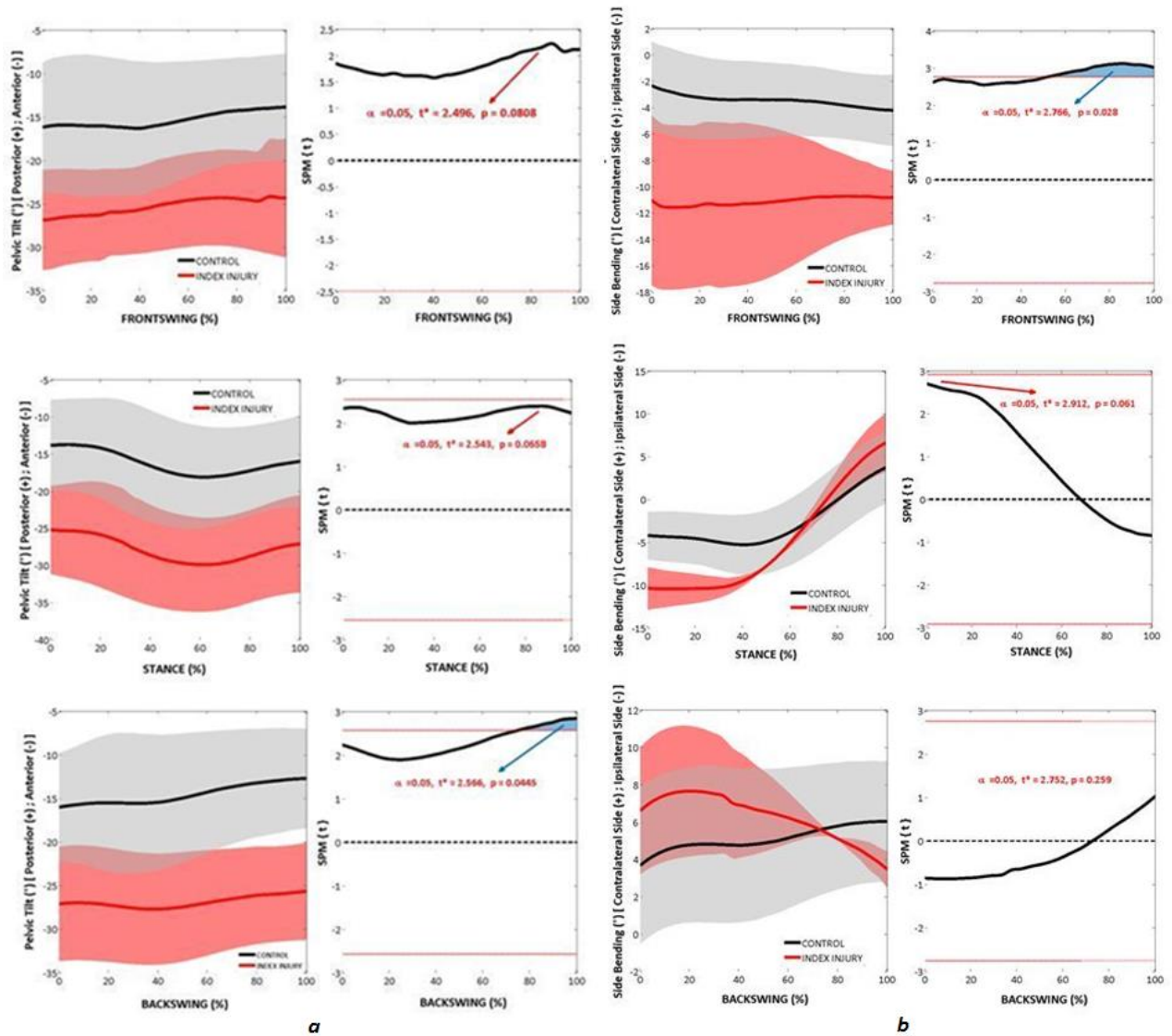


Figure 3. (a) Sagittal plane pelvis kinematics throughout different running phases in maximal sprinting acceleration – Control versus Index Injury, displaying significantly more anterior tilting at the end of backswing,  $p = 0.045$ ; Y-axis presents the degree of Anterior, respectively Posterior Pelvic Tilting throughout the different phases of one stride, X-axis presents the duration of respective phases. (b) Side bending kinematics throughout different running phases in maximal sprinting acceleration – Control versus Index Injury, displaying significantly more side-bending throughout front swing –  $p = 0.028$ ; Y-axis presents the degree of Contralateral (+), respectively Ipsilateral (-) Thoracic Side Bending, X-axis presents the duration of respective phases.

SPM{t}, Scalar trajectory variable indicating the magnitude of the in-between-group differences (magnitude of the difference between both curves per time frame throughout respective phase of the running cycle) as demonstrated in the left-hand graphs;  $\alpha$ , level of significance;  $t^*$ , critical t-value corresponding with the upper limit of the 95% Confidence Interval as defined by  $\alpha$ ;  $p$ , probability with which the magnitude of the in between group difference within the time-frame during which SPM{t} exceeds its critical value could have been produced by a random field process with the same temporal smoothness

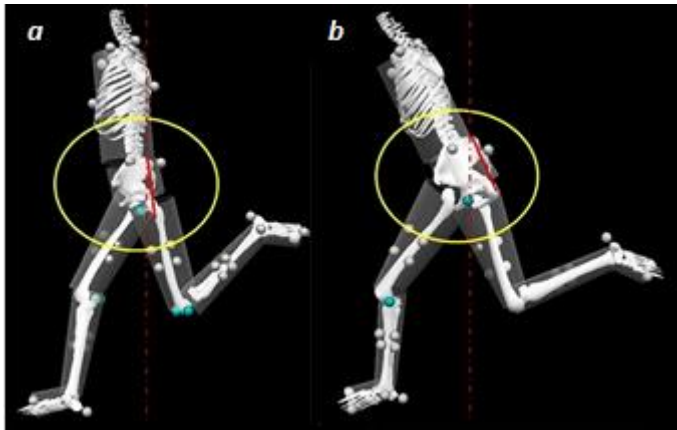


Figure 4. (a) Controls versus (b) Index Injuries: Sagittal plane Pelvis-Lab segment Angle in late Front swing phase (taking into account the backswing of the left leg in the control group, and the right left in the injury group)

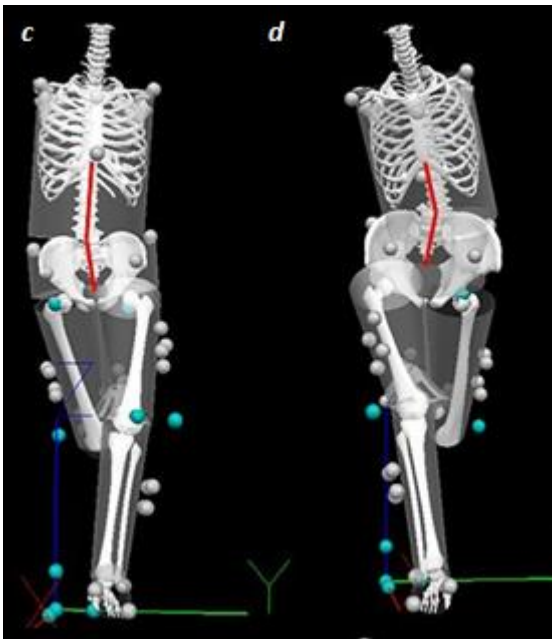


Figure 5. (c) Controls versus (d) Index Injuries: Coronal plane Pelvis-Thorax Angle in late Front swing phase (taking into account the front swing of the left leg in the control group, and the right left in the injury group)

**Table 1 Pelvis and trunk kinematics during crucial\* terminal back- and front swing phases**

	<b>Control (n = 25)</b>	<b>Injury (n = 4)</b>
Amount of (sagittal plane) Pelvis Tilt during terminal backswing (mean $\pm$ SD; $^{\circ}$ )**	12.73 $\pm$ 5.90	25.64 $\pm$ 7.90
Amount of (coronal plane) thoracic side-bending during terminal front swing (mean $\pm$ SD; $^{\circ}$ )**	3.89 $\pm$ 2.68	10.73 $\pm$ 4.30

*SD, Standard Deviation;  $^{\circ}$ , number of degrees; \*at time-frame of highest in-between-group difference as established by SPM analyses; \*\*table demonstrates absolute values (anterior pelvic tilt and ipsilateral side-bending receive a negative sign in Visual 3D). Pelvis tilt and thoracic side-bending demonstrated to have a significant effect on hamstring injury occurrence during follow up ( $p = 0.045$  and  $p = 0.028$ , respectively).*

## Discussion

In this study, the association between lower limb and trunk kinematics during maximal acceleration to full speed sprinting, and hamstring injuries was assessed both retro- and prospectively in male soccer players. Comparison of the running kinematics of the participants with a recent history of hamstring injuries and their matched controls, revealed no in between group differences for any of the joints, planes or phases throughout the captured stride. Assessing the running kinematics in function of hamstring injury risk detection prospectively, however, demonstrated significant biomechanical differences in trunk- and pelvis kinematics between the participants that sustained a (first) hamstring injury during follow-up and those who did not. Index hamstring injury occurrence was associated with significantly more anterior pelvic tilting and thoracic side-bending during the back- and front swing phases of acceleration, respectively. Hip-, knee-, nor ankle kinematics, presented a prospective association with hamstring injury susceptibility.

Quite interestingly, contrary to lower limb motion patterns, in particular trunk and pelvis kinematics, presented to be associated with the risk of sustaining a hamstring injury. As respective increments in sagittal and coronal plane movement of the core-region (trunk and pelvis) were also associated with

more variability within the kinematic trajectory over the course of the airborne phase, our findings might suggest that players appearing to be more vulnerable for hamstring injury, suffer from lacking proximal control and insufficient dissociative capacity within the lumbo-pelvic-hip complex. As such, these kinematic alterations might imply that the kinematic quality of the core and the ability to dissociate lower limb movement (hip-extension and –flexion) from compensatory contribution of the trunk and pelvis, is essential in primary hamstring injury prevention. Certainly given the fact that the increments in anterior tilting were particularly objectified during the backswing phase of running, where pelvic control is challenged the most, as sufficient hip extension is needed for propulsion. Because these kinematical differences in pelvis- and trunk segments were specifically found in the index injury group, we believe that these kinematic characteristics fundamentally contribute to a less safe running pattern, making the running athlete more prone to sustaining hamstring injuries when not recognized and corrected.

Although suggested to be key in sports injury prevention,<sup>1, 4, 8, 15, 21-24, 35-36, 39</sup> the actual scientific background of the functional integrity of the core (trunk and pelvis) has not been objectified in a sport- and injury specific research setting. The present study is the first giving rise to actual scientific evidence concerning the importance of core stability in hamstring injury prevention. Adequate control in the lower back, pelvis and hip joints during the swing phase of running, warranting proper ground contact for forceful propulsion, is of capital importance in running performance.<sup>25-26, 31</sup> Indeed, as functional kinetic chain integrity throughout the swing phases is key for the safety and the adequacy of subsequent touch down and propulsion, poor control in the proximal core might induce both an increased injury risk and poorer acceleration capacity / running economy. Next to possibly exerting excessive tensile strain on the (posterior) thigh muscles,<sup>18</sup> reduced proximal control could also imply raising the metabolic and mechanical demands of the biarticular thigh muscles by means of additional force production, in an attempt to contribute to proximal stability to increase kinematic efficacy throughout both the swing- and stance phases.<sup>2, 3, 20</sup> Interestingly, predominantly the airborne phase was observed to be subject to a lack of proximal control. Certainly in high speed running, where the

airborne phase (flight time) represents up to 80% of the entire stride time,<sup>25-26, 31</sup> adequate core stability would be vital. Several authors have investigated the relation between core stability and hamstring injuries in soccer, however, mainly indirectly and in association with the efficacy of rehabilitation (association between exercise protocol allocation, time to return-to-play (RTP) and subsequent injury recurrence without investigating actual core function).<sup>1, 4, 8, 36-37</sup> Accordingly, Sherry and colleagues compared the effectiveness of a rehabilitation protocol consisting of isolated hamstring stretch and strengthening exercises with the one of integrated kinetic chain training implying core stability and agility exercises.<sup>36</sup> They found the recurrence rates and the time to RTP to be significantly lower in players allocated to the core stability training protocol. Yet, they did not measure core function nor functional coordination so the direct link with hamstring injury susceptibility could not be deducted. In contrast, Silder and colleagues found no significant differences in clinical presentation, functional performance or medical imaging at time to RTP between players allocated to a “Progressive Agility and Trunk Stability” training group and those submitted to a “Progressive Running and eccentric Strength” training group.<sup>37</sup> Unfortunately, this study did not include measures of core muscle strength capacity either nor did they include a control group that did not receive a customized rehabilitation protocol. Assuming them to have a beneficial influence, many other intervention studies incorporated core stability exercises in their (secondary) prevention protocols as well.<sup>1, 4-5, 8, 15, 21-22, 24, 39</sup> Due to poor methodological design and lack of compliance, the exact influence of incorporating functional and isolated core training in (secondary) injury prevention, remains unknown.<sup>1, 4-5, 8, 15, 21, 39</sup> In particular, the evidence to validly link functional core stability with running related hamstring injury susceptibility is non-existing to date. Interestingly, previous research did demonstrate that the magnitude of anterior pelvic tilting is highly correlated with the amount of lumbar lordosis and hip-extension range of motion during backswing.<sup>10</sup> Franz and colleagues suggest that the increase in anterior pelvic tilt with increasing running velocity is predominantly due to increases in lumbar lordosis and trunk kinematics, as they found no statistical differences in hip extension range of motion with increasing running speed. More so, they could demonstrate that running athletes presented higher anterior tilting amplitudes, when hip extension capacity was decreased. Albeit not related to soccer or hamstring injury susceptibility in their observational study, the authors pointed out the importance of

lumbar spine and hip kinematics in lower back and hamstring injury vulnerability. Another study investigated the effects of intentionally inducing forward trunk lean throughout sprinting versus regular sprinting in a sample of eight healthy male sprinters.<sup>18</sup> Their results indicate that both the amount of hamstring muscle stretch and the lengthening velocity significantly increased when adopting a forward lean in running. As intentional forward trunk lean induces more anterior pelvic tilt as well, these could possibly explain why the players presenting an increased pelvic tilt, were subject of hamstring muscle failure during follow-up in our study.

Although repeatedly suggested to be of potential importance for the prevention of lower limb injuries, our findings confirm the association between core kinematics/control and hamstring injury risk. In order to get an even better insight in this interplay, future research should attempt an integrated investigation of lower limb and trunk kinematics, surface electromyography (sEMG) and muscle mechanics.

### **Limitations**

There were some limitations to this study. First, we must bear in mind that the sample size for prospective statistical analysis was small. This might have compromised the potential predictive validity of the kinematic outcome measures. However, as the statistical procedures (Statistical Parametric Mapping) attributed within this study, strongly control for both type 1 and type 2 errors, associated risk is limited as well.<sup>29</sup> Second, we did not have medical records of the injury history of the participants that entered this study, nor did we have any medical documentation on the injuries sustained during follow-up (physician's report, records of medical imaging). Therefore, we were reliant on the participant's reporting and study compliance, which might have induced a certain degree of recall/reporting bias. Moreover and because of the same reason, we decided not to take along information on the exact location of the lesion (muscle belly, distance from the ischial tuberosity and tissue involvement (muscle-tendon ratio)). Adding those covariates to the analysis, might have yielded



towards more detailed and possibly somewhat different insights in the running related hamstring injury risk. The strength of this study is however that it is the first study that investigated the association between running coordination and hamstring injury risk in male soccer players. More so, in performing both retro- and prospective analyses, it enabled differentiation as regards the direction of the association between running kinematics and hamstring injury risk, which appeared to be the cause rather than the consequence of hamstring injury vulnerability in our cohort.

## **Conclusion**

Surprisingly, this was the first study to relate lower limb and trunk kinematics during sprinting to hamstring injury risk. Our findings indicate that running coordination might actually be highly associated with the risk of sustaining a hamstring injury. Lacking control of the lumbo-pelvic unit (insufficient ‘core stability’), presented by excessive pelvis and trunk (range of) motion during the swing phases of running presented to be related to the primary hamstring injury risk. Therefore, assessing and addressing sprinting kinematics / running technique seem to be indispensable in primary hamstring injury prevention. Clinicians should acknowledge the importance of proper running technique in muscle injury rehabilitation and prevention in soccer, in which a bilaterally symmetrical, decently aligned running technique should be aspired, with adequate proximal neuromuscular control.

## **Acknowledgements**

The authors gratefully acknowledge the assistance of their colleagues at the department of Rehabilitation Sciences and Physiotherapy in Ghent (Belgium), as well as the staff members of Bloso, Topsportal Vlaanderen (Belgium). In particular Steven Heyndrickx, for his assistance during the installation of the running track with surrounding measuring systems, as well as for the assembly of the online diary for injury registration during follow-up and the post hoc data processing. Additionally, sincere appreciation goes out to Jos Vanrenterghem (Faculty of Kinesiology and Rehabilitation

Sciences, KU Leuven, Leuven, Belgium), Mark Robinson (School of Sport and Exercise Sciences, LJMU, Liverpool, United Kingdom) and Todd Pataky (Shinshu University, Dept. Bioengineering, Matsumoto, Nagano, Japan), for their support during the SPM analyses. The authors would particularly like to thank the participants of this study, without whom this paper could not have been accomplished. For their financial support, our gratitude goes out to the Agency for Innovation by Science and Technology in Flanders (IWT – Brussels, Belgium). All authors declare to have no conflicts of interest regarding the scientific content of the paper nor regarding the sources of funding.

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# **General Discussion**





## GENERAL DISCUSSION

### Summary

All of the studies embedded within this dissertation have a remarkable common outcome, indicating that the hamstring injury risk presents a significant association with alterations in neuromuscular control within and beyond the hamstring muscle unit. Indeed, according to our original hypothesis, the results of each study indicate that the injury risk is not just to be assessed (nor addressed) locally. Quite the reverse, multiple modifiable factors, not directly related to (isolated) hamstring structure and function, seem to present an association with injury vulnerability. The research findings in Chapter I demonstrated that the risk of sustaining a hamstring injury increases significantly, when the ST does not present sufficient levels of metabolic activity (relative to the BF). This probably necessitates the BF to compensate by contributing more (excessively) to the shared muscle effort required during a heavy load prone leg curling exercise, as we also found a relative increase in BF activity in participants that sustained an injury. Additionally, results indicated that a weaker prone leg curling performance was associated with an elevated risk of sustaining a recurring hamstring injury. The prone leg curling performance appeared to be negatively correlated with (1) the amount of metabolic changes in the hamstring muscle unit and (2) the symmetry of metabolic muscle activation (more BF, less ST activity). Therefore, the results within this chapter suggest that the synergistic hamstring activation pattern in which the ST takes on the majority of effort, and the BF is only activated to a secondary extent, is associated with better performance through more economic and safer hamstring functioning. The 2<sup>nd</sup> chapter revealed that the muscle recruitment pattern amongst the muscles of the posterior chain (lumbar erector spinae, gluteus maximus and hamstrings) was associated with hamstring injury occurrence if this pattern was characterized by a significant delay in hamstring muscle activity onset, with the lumbar muscles presenting activity before activity onset of the hamstrings instead of the other way around (as was the case in the participants that remained injury free during follow-up). The results of this second chapter indicate that, aside from deficits in

intramuscular coordination (interplay between the hamstring muscle bellies, Chapter I), intermuscular coordination properties (interplay between the posterior sling muscles) are significantly associated with hamstring injuries as well. Taking the first two chapters together, it seems that the quality of muscle recruitment within and between the extensor synergists in the posterior chain, is essential for safe hamstring functioning. In these terms we could demonstrate that the ST and BF not only need to make good agreements with regard to the amount of muscle recruitment and force production, but also need to do so meeting particular temporal demands relative to their proximal synergists in the posterior chain, when aiming to perform safe and effective. In the third chapter the results of investigating the injury-mechanism-related coordination features by means of muscle activity and kinematic quality during high speed running were discussed. Respective studies revealed that lacking activity of the core muscles during the airborne phase of sprinting and an inability to control for excessive pelvic and thoracic movements throughout respective open kinetic chain phase, are associated hamstring injury occurrence. Similar to research findings in Chapters I and II, the latter results indicate that the quality of neuromuscular coordination most probably has a substantial influence on the hamstring injury risk but this time with specific focus on core function during explosive, injury mechanism related, loading circumstances. Indeed, since the terminal swing phase of high speed running holds the primary injury mechanism, it can be expected that the quality with which the nervous system guides intentional muscular efforts (neuromuscular coordination) prior to and during these loading conditions, has a substantial impact on hamstring functioning and loading (most probably by altering running kinematics).

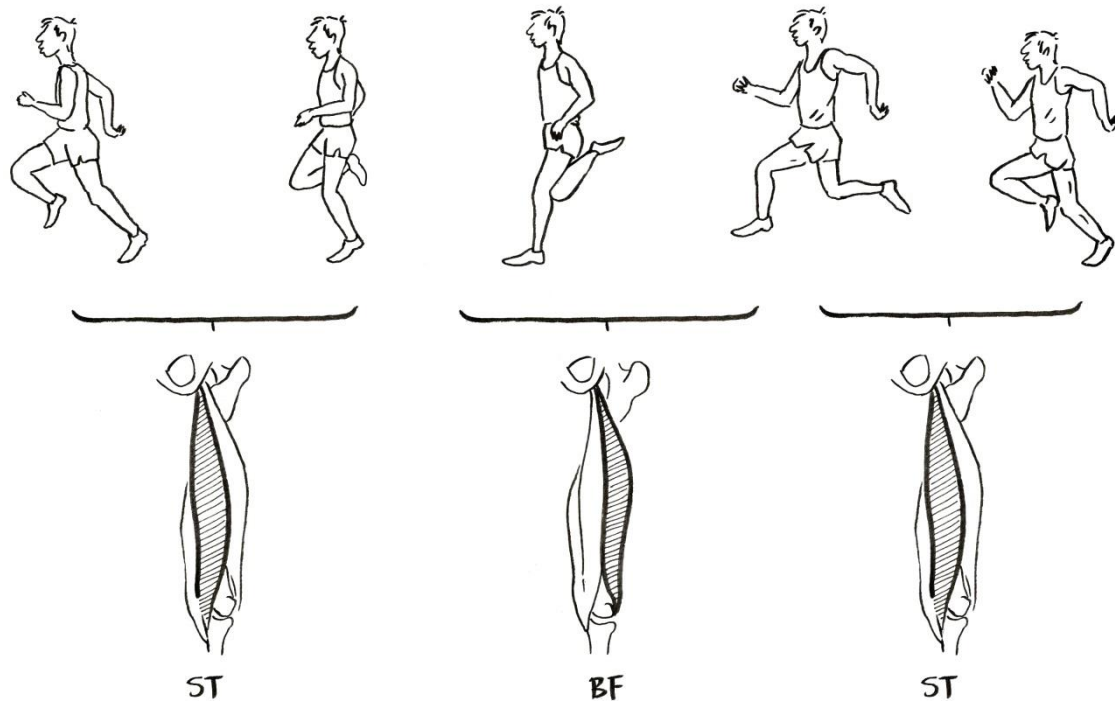
Taken together, the present study results provide a scientific basis for the fact that neuromuscular control and associated muscle activation patterns play a prominent role in hamstring injury predisposition. In these terms, apart from the possible influence of age, injury history, strength and flexibility, muscle activation and interplay within and beyond the hamstring unit seem to be predominant determinants in the football related hamstring injury risk. Hence, the quality and quantity with which the hamstring muscles and their functional agonists and antagonists are activated during running-related efforts, seem to be important determinants in the intrinsic hamstring injury risk profile.

## Discussion

To substantiate the research findings embedded within this dissertation, the general discussion is organized in function of the original hypotheses, attempting to formulate a well-founded and clinically relevant answer to our main research questions. In providing arguments against and in favor of our results, we wish to provide the reader with a broader perspective on hamstring injuries and reinforce the existing evidence regarding the intrinsic risk profile.

### **Do the different hamstring muscle bellies demonstrate significant functional differences and are these related to the hamstring injury risk?**

Inspired by (1) the remarkable differences in muscle architecture, (2) the most common injury location and (3) previous research that indicated that the separate hamstring muscle bellies are loaded differently throughout running,<sup>17, 20</sup> we wanted to assess the possible association between intramuscular activation characteristics and the risk of sustaining a hamstring injury. In line with the particular muscle anatomy and morphometry, these chapters revealed that although sharing a proximal tendon, the BF and ST serve different purposes and are supposed to function accordingly. Specifically, the risk of injury seems to increase when the BF and ST put in a comparable effort, whereas the risk reduces when the ST takes the lead and the BF relatively restricts its contribution during exercise (prone leg curls). These results are in line with the findings regarding muscle activation features during high speed running,<sup>17, 20</sup> which demonstrated that the BF is activated most during late swing and early stance, whereas the ST is overall more active and presents significantly higher EMG activity during mid swing [Figure 4].



*Figure 4. sEMG activity dominance of the BF<sub>LH</sub> and ST throughout the gait cycle in sprinting*

Respective findings are in line with what can be expected when looking at muscle anatomy: The ST consist of uniformly organized and lean muscle fibers with considerably less tendon tissue along its proximo-distal course. The BF has shorter, more voluptuous fibres that are organized both uni- and bipennately and comprises of a much larger tendon representative. These features suggest that the ST is more compliant and better suited to contribute to force output throughout the entire range of motion, whereas the BF will need to appeal to its passive force output more extensively, as it comprises of more tendon tissue and has a smaller angle of peak torque. In these terms, it is merely logical that the BF cannot be activated as extensively as the ST, as it has a lower ability to contribute to active force production (in time as well as in space). The findings in our mfMRI research, confirm this hypothesis, presenting that more pronounced differences between metabolic activation of the ST and BF are associated with more economic and safer hamstring muscle functioning. In short it can be stated that, the higher the contribution of the ST during (intense) hamstring loading, the better for (1) the efficiency of the shared force output as well as (2) the preservation of tissue homeostasis and load

bearing capacity. However, we need to bear in mind that, although demonstrating a significant retrospective association with hamstring injuries, only the players that sustained a first hamstring injury presented respective changes in muscle activation patterns in our prospective study. The participants that had a history of injury and got re-injured during follow-up, did not present an activation pattern that differed significantly from those with an injury history but no recurrence during follow up. Interestingly, details on prospective hamstring injuries registered within this study suggest that the index hamstring injuries were somewhat more severe than the recurring ones: average time-loss in the index injury group was 35 days (range [14 – 56]) , which was 21 (range [7 – 28]) in the recurring injury group [Table 3]. More so, all of the reoccurring hamstring injuries concerned late or even delayed recurrences (within and later than 12 months after previous injury).<sup>12</sup> Given the lower severity and the delayed recurrence associated with the prospective injuries in the reinjury group, and the apparent absence of significant alterations in metabolic activity characteristics within the BF-ST unit (compared to those with an injury history but no (late) recurrences during follow up), we are inclined to believe that the intramuscular coordination features indeed were not (primarily) responsible for the recurring injuries in our study, although they might have been involved in inducing lower endurance capacity, somewhere throughout the hamstring injury history in this cohort. Therefore, as concerns our prospective cohort of male football players, we believe that deviating activation patterns were responsible for lowering the muscle endurance capacity and increasing injury vulnerability of the hamstring in subjects sustaining a first hamstring injury. In the reinjury group, these deviating activation patterns might have initiated a reduction in muscle endurance capacity as well, but this time not in direct association with elevating injury vulnerability. It is very plausible that in this group, multiple other (compensatory) neuromuscular coordination mechanisms are involved in determining the secondary injury risk<sup>7</sup> (by lowering the muscle endurance capacity, amongst others).

**Table 3 Details on hamstring injury (re)occurrences, Chapter I Part II**

	Index Injury during follow-up (n = 4)	Reinjury during follow-up (n = 6)
Time between mfMRI analysis and prospective injury (mean [range], mo)	5 [2 – 9]	4 [2 - 9]
Time in between hamstring injuries (mean [range], mo)	/	10 [5 – 17]
Time-loss prospective injury (mean [range], d)	35 [14 – 56]	21 [7 – 28]

*mo, months; d, days*

In accordance with our findings, previous research assessing the intramuscular activation patterns within the hamstrings during a variety of exercises using similar methods, systematically concluded the ST to be predominantly active. As such, Kuboto and colleagues investigated regional differences in signal intensity shift immediately after and at different time intervals (1 day, 3 days and 7 days after exercise) following an eccentric knee flexion exercise protocol.<sup>27</sup> They reported that the exercise induced T2 increase, was the highest for the ST. More so, the ST seemed to be the only muscle belly in which the elevated T2 value was still present several days after the exercise, indicating the ST was subject to the highest levels of acidification and accumulation of metabolic waste products. This suggests that the ST had been activated more extensively than the BF during respective hamstring exercise. This study included healthy young men (age  $23.7 \pm 1.8$  years; height  $171.8 \pm 4.8$  cm; weight  $66.9 \pm 8.6$  kg), not participating in a particular type of sports. Their preferential ST recruitment could thus not have been biased by sports-induced neuromuscular adaptations and suggests that the preferential solicitation of the ST has a biological (evolutionary) origin. Likewise, Mendiguchia assessed the activity-related T2 shift within the hamstring muscles after a Nordic hamstring exercise protocol.<sup>29</sup> They found significant metabolic changes in both the BF and the ST muscles (opposed to the SM, which did not seem to contribute in eccentric contraction), with the highest prolonged T2 shift in the short head of the BF (BF<sub>SH</sub>). They concluded that, due to the predominantly BF<sub>SH</sub>-oriented prolonged exercise effect of the Nordic hamstring exercise, this exercise particularly requires

metabolic activation and induces muscle damage in the more distal muscle-tendon region. Their findings are evident, as the Nordic hamstring exercise maximizes muscle stress at the distal insertion site, where the lever (and thus, the external load) is maximal. In agreement with our findings, these results indicate that the different hamstring muscle bellies are designed to function differently, most probably allowing each of them to perform at best. These specific intramuscular task differentiation was also demonstrated by Ono and colleagues.<sup>35</sup> Their study consisted of a combined muscle functional MRI protocol and real-time sEMG analysis of the hamstring muscle activity during an isolated hip extension exercise (stiff leg deadlift). They reported that only the SM presented significant **metabolic changes**, whereas both the SM and BF demonstrated similar levels of **EMG activity** during both concentric and eccentric phases of the stiff leg dead lift protocol. These findings suggest that the more voluptuous BF and SM muscles have a predominant role in controlling and generating torques across the hip joint, whereas the ST is possibly predestined to take the lead across the knee. Indeed, more recent research of Mendiguchia<sup>30</sup> indicated that the lean ST muscle takes on the greater part of the effort during eccentric leg curls, compared to the BF, which presented to be dominant during lunge exercises.

Because we wanted to mimic the hamstring muscle mechanics during running, still isolating and primarily addressing the hamstring muscles, our exercise consisted of prone leg curls with free weights from a prone position with the hip joints in 60° of flexion. As is the case in running, this exercise is likely to induce anterior translation of the tibia, that needs to be withstood by the hamstrings, working eccentrically in a more distal range of motion. Besides being more functional and injury-mechanism-related, this exercise does not maximize the load near the knee joint but rather distributes it across its trajectory from sciatic tuberosity towards tibia, as it requires the hamstrings to control for both a proximal and a distal lever (induction of load across hip- and knee joints). By selecting a scanning location in which each one of the hamstring muscle bellies consists of a comparable volume of metabolically active muscle tissue (proximal boarder of the distal third of the upper leg), we could assess the intramuscular coordination features validly and in association with the running related hamstring injury risk. More so, ours was the first study to assess these muscle

functional MRI features in a fairly large homogeneous cohort of football players, with subsequent prospective data analysis.

Our findings are in agreement with those of previous research, indicating that the ST plays a leading role in controlling torques around the knee joint, whereas the more voluptuous and tendinous BF and SM muscles seem to be activated more extensively when (controlling for) additional torque is required around the (proximal) hip joint. In running, both the medial and lateral hamstrings present substantial levels of muscle activity throughout both the stance - and swing phases. However, the lateral hamstrings demonstrate more fluctuation in activity level throughout the running cycle with peak activity during the late swing and initial stance phases of running, whereas the medial hamstrings appear to be more continuously active, presenting a significantly higher EMG signal than the lateral muscle unit during the late stance and initial- to mid-swing phases.<sup>17, 20</sup> Real-time muscle activity evaluation during high speed running, also revealed that the more vulnerable BF<sub>LH</sub> presents peak activity at the moment that peak muscle-tendon stretch occurs, whereas the more constantly active ST presents peak activity prior to reaching maximal muscle-tendon stretch.<sup>18</sup> Linking our findings with previous research results, we suggest that the ST has a morphological advantage over the BF in terms of safe force production and load bearing capacity during high speed running. Because of this relative benefit, the ST should warrant the highest active force production throughout the entire range of motion, whereas the BF is probably essential in additional control of hip- and knee joint torques at more lengthened positions (distal range of motion; both hip flexion and knee extension kinematics), as this muscle is preponderantly designed to absorb and release elastic energy in energy throughout late swing and initial stance phases, respectively. In these terms, the ST needs to be primarily active when energy absorption through tendon tensioning is not possible, whereas the BF has a greater part when the latter is indeed required. Indeed, when this natural function-distribution (essentially determined by morphology and anatomy) gets outbalanced (intramuscular coordination dysfunction), the hamstrings presented to be more susceptible to injury (Chapter I).<sup>45-46</sup>

An important annotation the reader should take along in interpreting these results, is that the exercise related T2 shift the muscle tissue demonstrates after being activated, will differ based on the fibre



distribution and – dominance in respective muscle. The fact that slow twitch muscle fibres appeal on oxidative metabolic processes to gather the necessary energy for contraction, while the fast twitch fibers function anaerobically, has important consequences for their presentation (T2 relaxation time / signal intensity) in the acquired mfMRI images. Due to their aerobic metabolism, slow twitch fibres have a higher resting state T2 signal intensity compared to fast twitch fibres.<sup>2, 38-39</sup> This difference is mostly mediated by the higher intracellular concentration of protein components involved in the oxidative processes (mitochondria, myoglobin molecules) as well as the better circulatory provision (blood flow) the slow twitch fibers receive, giving rise to larger intracellular water volumes, compared to their faster counterparts. In these terms, based on differing metabolic characteristics, the baseline T2 value will differ as well according to the baseline metabolism of respective muscle fibres. When looking at the exercise related increase in T2 signal intensity in both muscle fibre types, this difference in metabolic characteristics presents itself otherwise.<sup>39</sup> Slow twitch fibres will be able to appeal on less energy for muscle contraction per time unit than is the case for fast twitch fibres, which also means that the intensity of muscle contraction and amount of force production will be much lower and their metabolism during activity will not differ substantially from the baseline situation. In fast twitch fibers however, the intracellular homeostasis will radically change from the very beginning of muscle fibre recruitment and contraction, because all fibres will contract explosively and intensively, giving rise to extensive accumulation of lactate and other residual osmolites derived from anaerobic force production. This intracellular acidification will cause the muscle water to migrate towards the intracellular environment (osmosis), which can be appreciated very clearly on mfMRI images due to an intense increase in T2 signal intensity in the muscle tissue that had been activated in between the resting and the post-exercise scan. Due to lack recent (in vivo) histochemical studies assessing the fiber distribution (and its possible association with muscle injury risk) in the hamstring unit, we are still under the assumption that the 4 muscle bellies have a same fiber distribution, implying a slight dominance of the fast twitch type.<sup>14, 25</sup> Nonetheless, this might just as well not be entirely correct and subtle differences in fibre type distribution in between muscle bellies might make the importance of adequate intramuscular coordination even more important, as this would directly imply a higher risk of overload as well (due to increments in intramuscular strain caused by asynchronous muscle fibre

contraction). We found the ST to present the highest amount of metabolic activity during the prone leg curls in the entire study sample (Chapter I Parts I and II). Nonetheless, the ST systematically presented a slightly lower baseline T2 value as well, which might co-explain its particularly high activity during respective exercise. This paragraph is of course rather speculative and should be interpreted with a pinch of salt until this matter is reaffirmed by future research.

### **Might muscle recruitment in the posterior muscle chain and, in particular, hamstring activity onset, detect an athlete at risk of hamstring injury?**

In Chapter II, the neuromuscular coordination features were observed from a broader perspective, taking into account the agonist muscles in the posterior muscle chain. In existing literature, the Prone Hip Extension test (PHE) is mostly adopted in the context of lumbar or sacro-iliac dysfunctions, in which a lack of neuromuscular coordination/control on account of the local stabilizing muscles (lumbar extensor spinae (LES) and (mostly) gluteus maximus (GM)) is thought to be the cause of functional (and structural) stability deficits and associated complaints. In these terms, Janda, Sahrman and many other authors suggested the PHE exercise/test to be a valuable tool for assessment and correction of deficiencies in proximal neuromuscular coordination.<sup>24, 45</sup> In their theoretical framework, they propose early and substantial GM activation during PHE to be key, as this muscle needs to warrant sufficient pelvic stability and sacro-iliac force closure for safe force transmission from the lower limb towards the trunk. This hypothesis has been investigated multiple times over the last decade, yet study results have shown to be conflicting. When assessing the recruitment sequence and intensity during PHE, some studies found no consistent recruitment pattern,<sup>28</sup> whereas others did find one recruitment pattern to be most common, namely the one that appeared to be most common in our healthy cohort as well [Chapter II].<sup>15, 41</sup> Next to the discussion regarding the existence of a particular activation sequence by contrast with the PHE soliciting the posterior chain muscles merely at random,<sup>28</sup> none of the available original research actually confirmed that initial activity onset of the

GM could be associated with optimal proximal control, as this pattern has only been documented rarely. Nonetheless, many studies did confirm that lower back and other musculoskeletal complaints present an association with a significant delay in GM activity onset. Although the GM always seems to be activated last (relative to the onset times of the hamstrings and the lumbar muscles),<sup>3, 5, 15, 23, 26, 42</sup> it presented to be activated significantly later in subjects with lower back dysfunction<sup>26</sup> and a history of ankle sprain,<sup>4</sup> compared to the healthy controls. However, this could not systematically be confirmed by similar studies.<sup>15, 47</sup>

Interestingly and more within the scope our research, Chance-Larsen and colleagues hypothesized that the timing dissimilarities between the GM and the BF, in which the GM presents a relative delay in onset time, might put the hamstrings at risk of overload and injury.<sup>5</sup> This due to lacking contribution and insufficient guard of proximal stability by the GM, necessitating the BF to raise its stakes. The authors investigated whether this relative timing difference could be remediated via the implementation of proximal control exercises consisting of lower abdominal hollowing and anticipatory isometric GM activation prior to exercise. They concluded that proximal control and dissociation exercise might be useful in amplifying and advancing GM recruitment during prone hip extension, possibly reducing the load imposed on the vulnerable BF muscle. Due to a very small sample size and the absence of an ‘injury’-variable within their study, the exact value of relative delay in GM onset or the relevance of implementing respective exercise protocol for the benefit of hamstring injury prevention, cannot be pronounced either.

As it appears, delays in GM onset times might be associated with lower back complaints (possibly due to lacking pelvic- and sacro-iliac stability during force transfer from the lower limb towards the trunk) as well as injuries in the lower limb, which indicates that this muscle entity is essential for safe and controlled force transfer between trunk and lower limb, both for local tissue homeostasis and load bearing capacity, as well as remote musculoskeletal functioning. Unfortunately, this association has only been made retrospectively to date, which renders it difficult to pronounce upon the causality within the objectified interdependence between differences in muscle recruitment and injury vulnerability. Taking all of the existing evidence into account, it seems that the outcome of the PHE

test in terms of muscle activity onset and the sequence of recruitment among the posterior sling muscles, must be interpreted with caution. Nonetheless, in an attempt to round out the knowledge with regards to the hamstring injury risk in male football, our PHE study did venture prospective analysis in investigating the association between the muscle activation pattern in the posterior chain and the risk of sustaining a hamstring injury (Chapter II). In accordance with previous research, the football players within our cohort, systematically presented a relative delay in GM onset time as well, compared to the onset of the hamstrings and LES, irrespective of hamstring injury occurrence during follow-up. On the contrary, hamstring injury occurrence did present a significant association with a delay in hamstring activity onset, which occurred after LES onset, in the players that sustained an injury instead of the other way around. These findings suggest that, as concerns hamstring injury vulnerability in football, the activity onset of the hamstrings, relative to the other posterior sling muscles seems essential (rather than the early recruitment of the GM). This seems very plausible, taking into account the fact that multiple researchers before us did not find an association between GM activity onset and injury neither,<sup>15, 42, 47</sup> and that the timing properties of hamstring muscle activity have demonstrated to be essential in terms of the efficiency and safety of their function during high speed running.<sup>6, 13, 17, 18, 44</sup>

As such, Opar and colleagues found a significant decrease in early rate of torque development throughout eccentric contraction in subjects with a history of hamstring injury, and stated that this inhibited neural drive, might predispose the hamstrings to reinjury as this would make the muscle insufficiently able to safely anticipate for high muscle-tendon stress and strain throughout the rapid swing phase of the running cycle.<sup>36</sup> As hamstring strain injury is most commonly located in the BF, and because recent research demonstrated that this muscle belly presents a delay in peak activity, relative to the onset of peak stretch and to peak activity of the ST throughout the critical front swing in running,<sup>19</sup> our findings might concur with the theory of Opar. The BF differs substantially from the ST with regard to muscle morphology and functionality (Cf. General Introduction ; Chapter I) and most probably runs an elevated injury risk when both muscles do not live up to their predestined functions sufficiently. As such, additional deficits in neuromuscular coordination within the broader posterior

chain (significantly delayed activity onset), might effectively compromise safe hamstring functioning and increase the risk of injury. As the hamstrings (neurologically guided by the large sciatic nerve) are anatomically and biomechanically directly linked to the pelvis (and lumbar spine), proximal control should be a basic requirement for safe hamstring loading and hamstring functioning should have a direct impact on the load imposed on the lumbo-pelvic structures. Whether and exactly how (the hypothesis behind) this sufficient neuromuscular control/coordination can be objectified by assessing the recruitment sequence in the posterior chain, still needs to be brought to the evidence. Nonetheless, with regard to hamstring injury susceptibility in athletes, the necessity of properly dosed hamstring activity, carefully weighted up in time (Chapter II) and space (Chapter I) is beyond dispute. Indeed, when the hamstring muscles presented a delay in pre-motor activity onset time, they appeared to be more likely to get injured.

### **Could running analysis hold the solution?**

The hamstrings are at highest risk of injury throughout the terminal swing and initial stance phases of high speed running, when the mechanical load and associated demands imposed upon this muscle unit are maximized. During this explosive activity, not only the hamstrings, but the entire kinetic chain is being challenged to the utmost, both metabolically and mechanically. Certainly throughout the acceleration and deceleration phases, where kinetic energy, giving rise to generation of constant horizontal velocity, cannot just be recycled but needs to be magnified or reduced to increase or decrease horizontal force production (velocity), high-quality whole body coordination and interplay between each link in the kinetic chain is vital. Therefore, not only neuromuscular coordination within the hamstring muscle unit is essential when unraveling the risk of sustaining a running related hamstring injury. Quite the contrary, every musculoskeletal unit that contributes to horizontal force production, has the ability to increase or decrease mechanical loads or metabolic demands, imposed on or required by the hamstring muscles.<sup>6</sup> Although it has been demonstrated that the hamstrings have the highest responsibility in horizontal force and velocity production in running accelerations,<sup>29</sup> the other

lower limb and trunk muscles are activated to substantial extents as well, to guide and control the kinetic energy throughout the body and to establish a sound running pattern and an efficient movement outcome.<sup>6, 34, 40, 44</sup> Besides their influence on running pattern and – speed, respective lower limb- and trunk muscles have demonstrated to be key in hamstring loading as well. The biomechanical research of Chumanov<sup>6</sup> investigated (using electromyography) the influence of activity of a variety of lower limb and trunk muscles on hamstring muscle mechanics throughout the swing phase of sprinting. They found that the amount of stretch the hamstrings need to withstand is highly dependent on the amount of activity generated by the muscles in the lumbo-pelvic region (in contrast with the muscles acting about the knee and ankle), irrespective of running speed. The muscles that presented to induce increments in hamstring muscle-tendon stretch were the hip flexors, the knee extensors and the erector spinae muscles, whereas the gluteal muscles and the oblique abdominal muscles demonstrated to reduce mechanical hamstring tensioning throughout the swing phase. The authors concluded that the hamstring vulnerability to strain injury during sprinting is the consequence of (1) the large amounts of negative (eccentric) work this muscle unit needs to engage in repeatedly, and most probably also due to (2) perturbations in coordination of the pelvic muscles, inducing excessive hamstring muscle-tendon stretch. Although their rationale seems very plausible, the theory of Chumanov and colleagues cannot be taken for gospel truth without reaffirming prospective research, verifying the presence of an actual causal relation between the quality of lumbo-pelvic coordination and the occurrence of injury.

Similar to this biomechanical research, the group of Higashihara investigated the possible association between disturbances in running kinematics and hamstring loading.<sup>19</sup> They found that deviating trunk kinematics by means of enlarged forward trunk lean, effectively led to significant increments in hamstring muscle stretch and elongation velocity. This was a repeated measures observational study in a healthy sample of 8 male sprinters, so the actual association with hamstring injury vulnerability was not assessed. Therefore, although the results of the biomechanical research of Chumanov<sup>5</sup> and Higashihara<sup>19</sup> suggest that, next to aberrant lumbo-pelvic muscle activity,<sup>6</sup> kinematic deviations in the lumbo-pelvic area<sup>19</sup> magnify hamstring loading, this has never been confirmed with prospective research designs neither to date. In these terms, exploring the actual (potentially causative) association

between lumbo-pelvic coordination (both neuromuscular and kinematic) and hamstring injuries as performed in the present work was quite innovative.

This dissertation contains the very first biomechanical research investigating the association between lumbo-pelvic muscle activity and (most probably associated) – kinematics, or briefly ‘lumbo-pelvic coordination’, and hamstring injuries in a cohort of male football players. In accordance with what has been suggested in prior observational research, we statistically identified perturbations in proximal neuromuscular coordination both by means of muscle activation patterns and kinematics in the lumbo-pelvic-hip complex, in players that sustained an injury. Interestingly, the muscles that have proven to reduce mechanical load on the hamstring muscles in the study of Chumanov,<sup>6</sup> presented to be significantly less active throughout the airborne phases of running in our injured cohort. During respective open kinetic chain phase, sufficient proximal postural muscle control is of the highest importance, as the core and lower limb cannot appeal to a steady foundation (i.e. the ground) to provide a solid basis for the development and transfer of forces / kinetic energy. Under these airborne circumstances, the proximal lumbo-pelvic unit (containing the body center of mass) is the primary region from which the external (gravitational) force will originate. During this open kinetic chain phase, the substantial gravitational and horizontal forces acting upon the center of mass (core), are not counteracted by ground reaction forces as is the case in the contact phases of the gait cycle. Therefore, when being airborne, the core needs to succeed in preserving sufficient stability and postural control, while receiving and counteracting the external forces imposed upon the running body. Only in doing this adequately, the core unit can warrantee safe and sufficient guidance of the front – and hind leg during front- and backswing. This guidance is essential, as the efficiency of strike and subsequent contact for forceful propulsion, depends greatly on the stability and strength provided by the muscles in the lumbo-pelvic-hip complex.<sup>44</sup> The studies embedded in Chapter III reported an increased hamstring injury risk in those football players who presented deficiencies in proximal control, by means of (1) lower activity of the gluteal and trunk muscles and (2) increments in kinematic deviations of the pelvis and trunk throughout the front- and backswing phases of high speed running (sprinting acceleration). Although we were the first to biomechanically assess proximal coordination features

during sprinting in association with hamstring injuries in football, our findings fit in perfectly with the speculative framework that has been drawn up by previous researchers occupied with this topic.<sup>6, 19, 21-22, 32, 37, 44</sup> These have postulated that the hamstring muscles count on a solid and properly controlled core during locomotion and sports, enabling them to primarily engage in their main function: generating horizontal force, without excessively having to account for pelvis stabilization as well. In these terms, respective authors have recommended to systematically assess and address lumbar- and pelvic function, to effectively cure and prevent hamstring injuries. The research findings demonstrated in the last chapter of this dissertation can substantiate this. Players that got injured during follow-up, effectively presented a lesser ability to warrantee core stability throughout the running cycle, most probably due to lack of neuromuscular coordination and adequate and properly timed core muscle activation. As a consequence, the hamstring muscles of the injured players might have been subject to excessive mechanical loading (strain), ultimately resulting in muscle failure during football activity. Indeed, when the proximal core muscles presented to be activated to a lesser extent during the unsteady airborne phases (Chapter III, Part I) and when the lumbo-pelvic region demonstrates increments in 3D kinematics throughout this phase (Chapter III, part II), the risk of sustaining a hamstring injury increased significantly.

### **Hamstring injury susceptibility in football: it's all about team play**

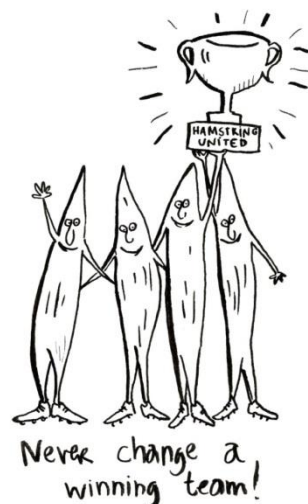
Taking together all research findings within this doctoral dissertation, the hamstring injury risk seems to be mediated by both local and global neuromuscular coordination features. The football player runs a higher risk of injuring his hamstrings when these muscles

- 1) do not perform according to their predestined function
- 2) (re)act to slowly during functional exercise
- 3) cannot count on the support of their agonists



These coordinative deficiencies might put both the BF and the ST at an increased risk of injury: When the ST does not take its responsibility sufficiently as regards amount of muscle fibre recruitment and active force output throughout the running cycle, when the BF has to engage in elevated metabolic efforts, and when they (both) fail to do this in time, they will both end up to be more prone to injury due to repeated functional under- (ST) or overload (BF). About half of the prospectively injured cohort reported perceiving a laterally oriented pain, whilst the other half gave notice of a more medially located lesion. (Chapters II and II(part I)). Although these findings are merely based on participant's self-report and should be taken with a pinch of salt, former epidemiological research reported the same findings. In their prospective study, Woods et al.<sup>48</sup> found that, although the BF was subject of injury in the majority of the cases, a substantial amount of football players also demonstrated having injured the ST in high speed running. These results do support our hypothesis, stating that both the BF and ST muscles might be at risk of sustaining a running related injury in football when subject to/of coordination deficits.

Irrespective of BF of ST involvement, a good result in football essentially depends on efficient team play and team integrity. This appears to be key in hamstring load bearing capacity as well. The better the hamstrings work together, the better they communicate with another and their neighbors, and the more they are able to count on their functional agonists- and antagonists throughout the kinetic chain, the more efficiently they will function and the higher the loads they will be able to bear – *ultimately making them less susceptible to injury.*

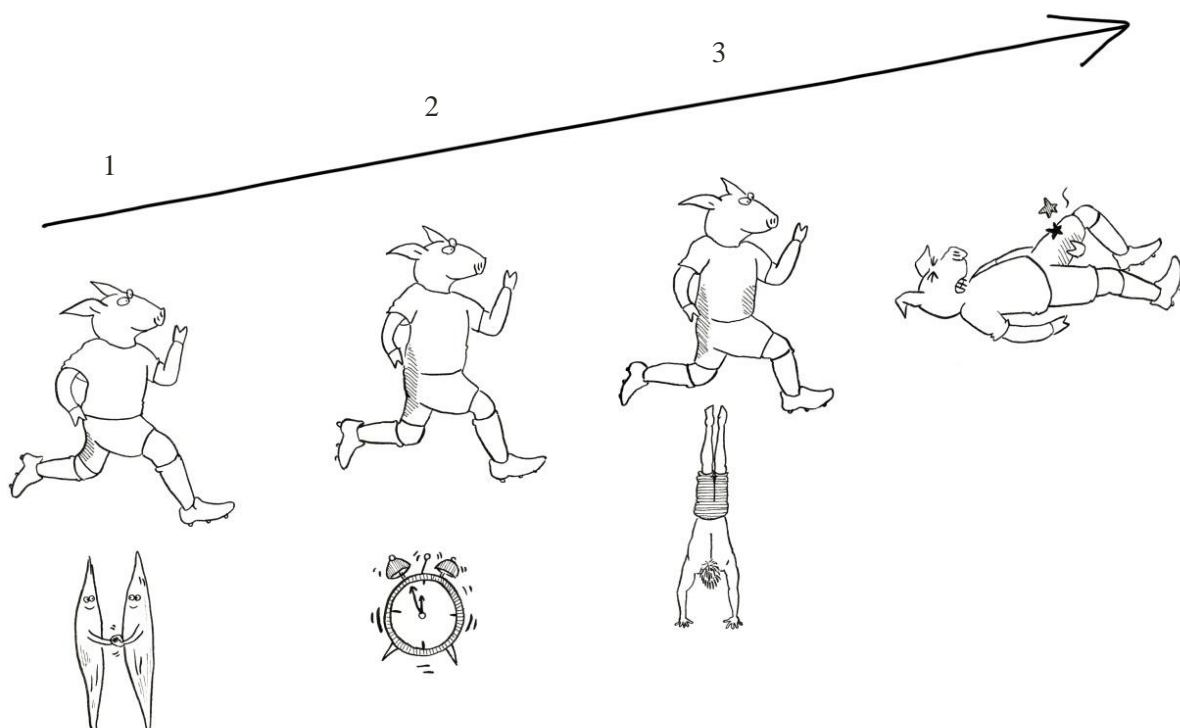


Time to switch glasses and broaden our clinical perspective, it is about time the hamstrings experience a successful game season.

### Why does the football player injure his hamstrings during sprinting ?

Assembling the main findings of this doctoral thesis, it seems that the football player is predisposed to sustain a hamstring injury during high speed running when because:

- 1) The ST does not generate sufficient force output during the mid-swing phase of the gait cycle in running, necessitating the BF to contribute more than it is supposed to do during respective phase
- 2) The entire hamstring unit is solicited too late, allowing excessive muscle-tendon stretch at crucial terminal swing, which should be most detrimental for the BF because this muscle might be covering for the lack of ST contribution
- 3) The core does not succeed in providing the necessary proximal stability, imposing even more metabolic and mechanical load on the hamstring muscles



These conditions cause the hamstrings to be subject to substantial mechanical and metabolic loading demands, with the ultimate consequence of strain injury.

## Clinical Implications

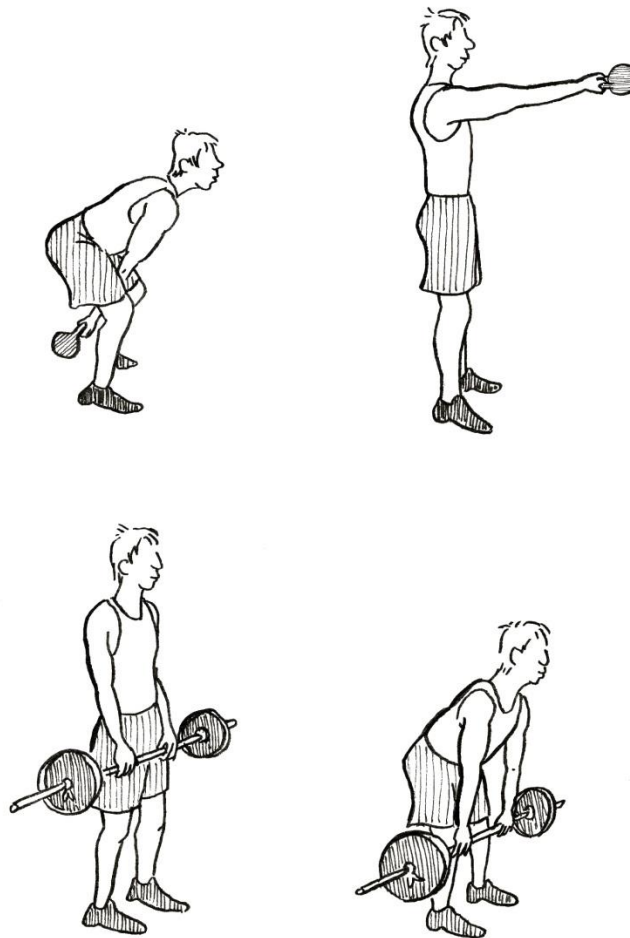
*“ Bene diagnosticur, bene curatur ”*

The key message distilled out this dissertation, is that muscle injuries (and most likely all non-contact sports injuries, for that matter) are not to be cured nor prevented by regionally assessing muscle function and load bearing capacity only. The present study results demonstrated that the hamstrings are more susceptible to sustain an injury, because of subtle changes in neuromuscular coordination within and far beyond the hamstring muscle unit. This might be caused by incomplete recovery from previous injury (any injury), or strength- and flexibility deficiencies/imbances somewhere within the kinetic chain, leading to aberrant proprioception and coordination/guidance. As such, the basis of (secondary) hamstring injury prevention consists of exploring the kinetic chain for functional deficits in neuromuscular coordination/control, to identify the exact cause of respective dysfunctions in motor output.

Therefore, in order to accurately cure and prevent hamstring injuries:

- (1) One must bear in mind the constitutional vulnerability to strain (injury), that is inherently present in the hamstring muscle unit (in particular, the biceps femoris).
- (2) The hamstring unit needs to be trained sufficiently both in terms of (1) coordination and (2) strength and flexibility. Due to its inherent injury vulnerability and the high demands in load bearing capacity, the hamstring muscle needs to be conditioned intensely, with focus on functional hamstring eccentrics and plyometrics.

- (3) The core needs to be able to warrant a solid basis from which the hamstring muscles can operate safely during functional activities like running and kicking. This can only be guaranteed by verifying and maintaining sufficient proximal control in the athletic population and providing the patient with additional core coordination and strengthening exercises whilst training the hamstrings (explosively) dynamically.
- (4) Particular focus should be directed towards conditioning the ST, to restore intramuscular hierarchy and biological functionality. Being far more stretch tolerant, the ST is designed to take on the greater part of active torque production during running - particularly throughout front swing. The BF on the other hand is stiffer and contributes to counteracting the momentum towards knee extension during that crucial phase more passively. If we want to minimize the risk of excessive strain and associated injury in the BF, we need to train the ST additionally, to increase its active contribution to the total amount of negative work throughout eccentric muscle contraction of the entire hamstring muscle unit. Hamstring exercises that dominantly solicit the Medial Hamstrings over the BF have demonstrated to be the Kettlebell Swing [Figure 5] and the Romanian Deadlift [Figure 6].<sup>49</sup> Although these exercises do not have the potential to train the ST task specifically (negative work throughout rapid front swing in high speed running), they provide the ST with an intense eccentric loading stimulus, as the external momentum they have to control for (counteract) is much larger than during running. Performing those exercises does certainly not suffice when attempting to make the hamstring unit reach optimal load bearing – and performance capacity. They should be implemented within a comprehensive and diverse prevention/rehabilitation protocol, consisting of training the entire kinetic chain on endurance, strength, flexibility and speed. With respect to rehabilitation, we rigorously recommend to integrate the exercises from the ‘lengthening protocol’ (‘L-protocol’), proposed by Askling and colleagues as well, as this protocol has proven to have good functional outcomes.<sup>1</sup>

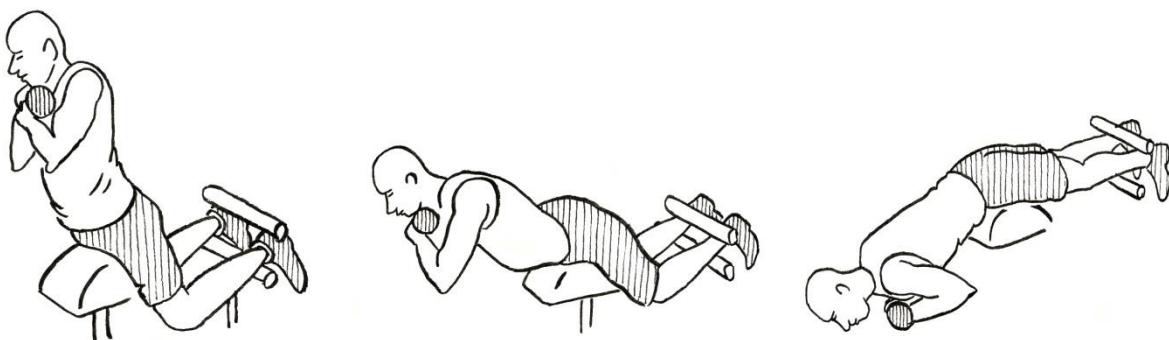


*Figure 5. Starting and end position of the Kettlebell Swing exercise (upper image) and the Romanian deadlift exercise (lower image)*

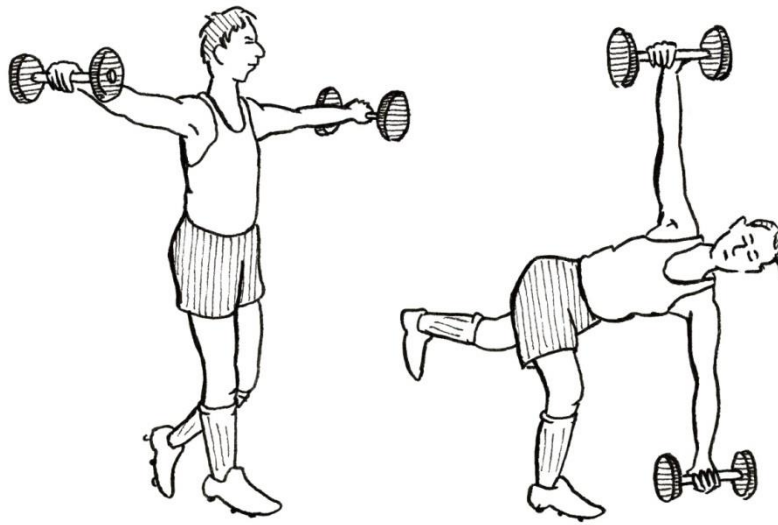
(5) The hamstring muscles should be trained explosively, as the timing of hamstring activity seems to be of capital importance as well (Chapter II). They need to be exposed to exercises that oblige them to take on the lead in terms of muscle activity onset (with respect to other (ant)agonists responsible for the given motion task). Which exercises are best suited to serve this purpose, needs to be depicted in future research. Be that as it may, such exercises should also consist of providing an accurate stimulus to the trunk and pelvis as well, as precisely these muscles need to be coordinated with the highest accuracy, to allow safe and economic hamstring functioning and sports performance. In these terms, it would be very useful to determine which exercises integrate both hamstring muscle and core muscle

activation/stimulation, allowing the hamstring muscles to be recruited first. By analogy with rehabilitation guidelines for patellofemoral disorders which use biofeedback training to primarily solicit the Vastus Medialis Obliquus (VMO) during quadriceps contractions,<sup>32</sup> the authors suggest to explore the value of this real time biofeedback in eliciting rapid hamstring muscle recruitment/contraction (reducing the pre-motor muscle activation time). Besides being useful in trying to evoke early hamstring muscle recruitment, this feedback application might also allow to train the medial and lateral hamstrings more individually and thus, with higher efficiency. As such, it could provide the clinician with a tool to restore the natural functional hierarchy within the hamstring unit, and considerably reduce the risk of overload and injury.

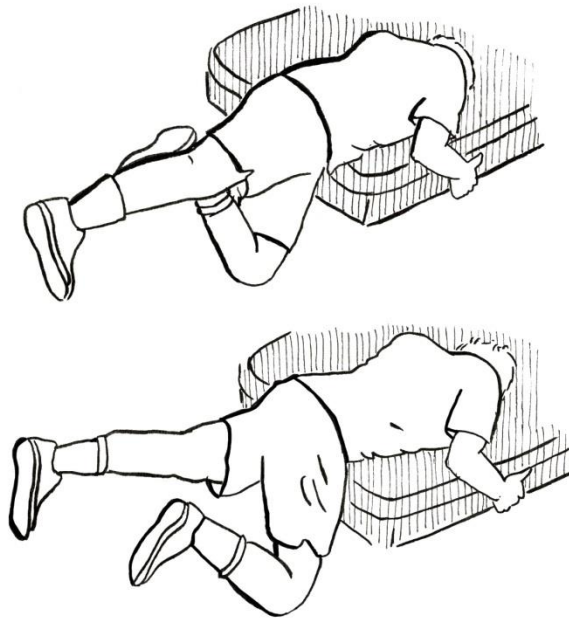
Next the possible application of hamstring biofeedback training, we propose the following hamstring exercises might be useful for training the core functionally and meeting the above mentioned loading demands (based on the present and prior study findings<sup>1, 11, 16, 30</sup> and the currently existing assembly of exercises most commonly used in fitness and rehabilitation): Nordic Hamstrings and Glute-Ham Raises [Figure 5], Good Morning exercises, Supine Pelvic Lift variations, Bulgarian Split Squats, Diver exercise, Single Leg Hamstring Bridges, Single Leg Deadlifts, Supine and Prone Lengthened State Hamstring Curls, Single Leg Windmills [Figure 6], Prone Running [Figure 7], Wall Sprints (if desired with additional resistance using Kinetic Bands), Weighted Sled Sprint Drills [Figure 8], (Starting Speed) Acceleration Drills, etc.



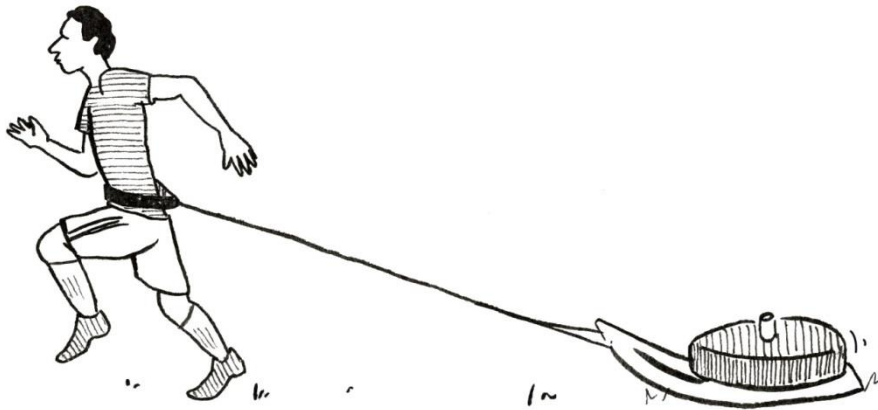
*Figure 5. Glute-Ham Raise exercise*



*Figure 6. Single Leg Windmills*



*Figure 7. Prone Running*



*Figure 8. Weighted Sled Sprint Drills*

To conclude this section, I would like to stress the importance of causal differential diagnosis and correction of underlying risk factors in the management of hamstring injuries and hampering chronic hamstring syndromes (frequently caused by recurring hamstring injury). Only by tackling the underlying problem we can prevent the athlete's hamstrings to become subject to repetitive overload and ultimately, injury, even before the player's injury risk increases significantly. Certainly given the loading intensity and volume the hamstrings have to deal with in football, and their inherent vulnerability to strain, this muscle unit deserves the clinician's undivided attention, even in case of a blank injury history. Next to injury history, hamstring strength and flexibility, the practitioner is stimulated to investigate and correct running kinematics, by amplifying proximal control and functional strength. Besides, the present findings suggest that the intra-muscular interplay and the timing of muscle recruitment are probably essential. However, more research needs to be conducted to establish how these issues can be investigated and remediated validly.



## Strengths and Limitations

However the main research findings look promising and potentially open doors towards increasing efficiency in hamstring rehabilitation and injury prevention, one must bear in mind that one swallow does not make a summer. Certainly given the fact that, the studies embedded in this dissertation were not without limitations. In these terms, the sample sizes of each of these studies were fairly small, implicating a relative risk of type 2 statistical error. This could have implications for the statistical power with which the present conclusions are drawn. Nonetheless, because of the strictness and comprehensiveness with which the (prospective) data were gathered and (statistically) processed (e.g. benefits of Statistical Parametric Mapping (Chapter 3 – Parts 1 and 2)), we believe we were able to validly control for those types of statistical errors for the greater part. In order to verify the strength of evidence of the outcome of each of the studies embedded within this dissertation (and to provide future researchers with some methodological guidelines), additional analysis was performed:

- 1) As concerns the effect of metabolic hamstring activity on hamstring injury history and prospective hamstring injury susceptibility described in Chapter I Parts I and II, respectively, power and sample size calculations revealed that the power of the statistical analyses giving rise to the results for retrospective analysis (Part I) was 100% as regards the primary outcome measure (intramuscular activity variability or shift in natural recruitment hierarchy), which was 94% (95 CI for  $\beta$  : 6.64% - 23.36%) for Part II (index injury risk estimation). Although this enforces the importance of respective findings, future largescale prospective research using mfMRI for the assessment of the importance of intermuscular interplay/coordination in the risk of hamstring (re)injuries is needed to be able to affirm (or refute) the results of this preliminary study. Based on power calculations, fellow researchers are advised to select a sample size of at least 30, to successfully demonstrate a significant effect of 10% at a statistical power level of 80% ( $\alpha = 0.05$ ) as regards the amount of metabolic activity relative to baseline by means of magnitude of T2 increase. Of course, this suggestion is only made departing from the assumption that the demonstrated significant effect is of clinical relevance.

It could also be that a smaller effect would be of considerable clinical importance as well. Therefore, in order to be able to make any steady conclusions as regards the clinical importance of the intramuscular activation pattern in the athlete's hamstring injury susceptibility, more related research is essential. Be that as it may, Chapter I Part II provides a valuable basis for future initiatives, being the very first prospective mfMRI study to assess metabolic hamstring characteristics and intramuscular activation features for the purpose of identifying the risk of index injuries and reinjuries in football.

- 2) In the second chapter, the hamstring activity onset time was the primary outcome variable of interest. Ad hoc effect size analysis demonstrated a Cohen's  $d$  of 0.76, which indicates a large effect and suggests clinical relevance.<sup>43</sup> Post hoc analysis of the statistical power with which the predictive value of a delay in hamstring activity onset on hamstring injury susceptibility was determined, revealed a statistical power of 73%. This indicates that, departing from a similar effect size and using a sample size of 51, the chance of unjustified acceptance of the null hypothesis ( $OR = 1$ ; type II error) may amount to 27%. In order to be able to demonstrate a significant effect of hamstring activity onset time during PHE on subsequent hamstring injury risk with a statistical power of 80%, a minimal sample size of 60 is needed. However, due to the large effect-size for this outcome parameter within our somewhat smaller remaining cohort for prospective analysis ( $n = 51$ ), we were sufficiently able to reject the null-hypothesis just as well.
- 3) Power calculations based on the methodological features and (descriptive) statistics in the first part of Chapter III, revealed that the predictive effect of Gluteus Maximus and trunk muscle activity was demonstrated with a statistical power of 93% within the logistic model that we used. This speaks highly in favor of the strength of evidence with which associated conclusions were drawn and enforces the clinical relevance of core-muscle sEMG analysis during high speed running in hamstring injury risk prediction.
- 4) In the second part of the third chapter, sample size was too small to compose a valid prediction model ( $n = 29$ ; event rate = 0.13), so only kinematic-curve analysis and in between group comparison was done based on the occurrence of first time injuries within a cohort with

a blank injury history (SPM(t) analysis). (the statistical power was too low to allow valid estimation of the OR). Nonetheless, the Cohen's d values for the amount of pelvic tilt during terminal backswing and the amount of thoracic side-bending during terminal front swing were 1.87 and 1.96 respectively, both indicating a very large effect size for both outcome measures.<sup>40</sup> Moreover, the Minimal Detectable Change (MDC) values were 12.58° for the in-between-group difference in pelvic tilt, and 6.10° for the difference in thoracic side-bending, which implies that the effect-sizes demonstrated within our study (12.92° and 6.84°, respectively), were of valid statistical significance. The fact that these MDC values, which indicate to what extent the mean group averages need to differ to be of statistical significance without a potentially biasing influence of the Standard Error (SE) around respective effect size, were lower than the differences retrieved in our kinematic study, again speaks in favor of the relevance of our findings. Evidently, future prospective research verifying the importance of running kinematics in a large cohort is necessary to reinforce these preliminary conclusions.

Based on these arguments we can conclude that the strength of evidence of the general conclusion and take home message derived from the studies embedded in this thesis is high, although statistical power might have been questioned departing from the rather small sample sizes involved.

Another common limitation of the studies within this dissertation is that we were reliant on participant's self-report regarding the gathering of injury related data for both retrospective and prospective research purposes. We defined a hamstring injury as an injury occurring in the posterior thigh area during football, preventing the athlete to participate in training or match for at least one entire week. By systematically verifying the nature and severity of the complaint by phone and checking whether medical care was consulted, we hope we were able to prevent allocation bias in prospective analyses. However, we have no objective data on exact injury location within the hamstring muscle unit nor could we make judgements concerning the structural extent of the injury as we were not able to appeal on medical (imaging) records. Likewise, in terms of injury history, we were dependent on the accuracy of participant recall as well, which could have influenced the intrinsic risk and injury vulnerability of the included participants and as such, our results. Nonetheless, to our

opinion, it is mainly the functional burden and the time-loss associated with a hamstring injury that need to be addressed and prevented in male football, rather than details on injury location and severity. Therefore, we believe this dissertation makes a valuable contribution to improve our insights in the hamstring injury susceptibility in football and lightens the pathway to more efficient and comprehensive management and prevention strategies. Next to these limitations, mostly with regard to data collection and statistical analysis, the strengths of the research within this dissertation are worth mentioning as well. Unlike what has been conducted in former research, the present studies took up the challenge of assessing fairly complex features related to hamstring muscle functioning, adopting prospective analysis methods. This implicates that substantial amounts of complex data needed to be collected, processed and submitted to laborious statistical analysis methods, requiring a lot of time and undivided focus of the researchers involved. However, it did enable us to make a valid differentiation with regards to whether alternations in neuromuscular control are to be considered the cause rather than the consequence of hamstring injuries. Another strength of this work, is that it made a clear differentiation between the primary and secondary hamstring injury risk, by (1) assessing players that got injured for the first or second time separately, (2) systematically taking the presence of a (recent) hamstring injury history along as a covariate in statistical analyses or (3) excluding participants with a recent hamstring injury history in the prospective data analysis. This allowed us to be even more certain of what causes or is merely just a consequence of a hamstring injury in male football, enabling more accurate and specific interpretation of primary and secondary prevention. Last but not least, the use of Statistical Parametric Mapping (SPM) for the statistical analysis of both the (essentially time-dependent) electromyography - and the kinematic data in the last two chapters turned out to be a major advantage. Taking into account each and every data frame within the time period during which the biomechanical data were explored and statistically inquired (eg. front swing-, stance- or backswing phase, as elected within this work) and correcting the level of significance accordingly (depending on the number of variables involved), this technique does not only strictly control for type 1 and 2 statistical errors, but it also sheds a very broad and refreshing light on biomechanical data analysis. Concretely, it frees the researcher from its restricting tunnel vision that constrains him/her to look at one or two certain variables at one moment in the acquired data series (or one average/integral

calculated over the entire period of data acquisition). If we had solely taken into account muscle joint angles and muscle activity at touch down, or the peak or average value during front swing, for example (as generally has been done in previous research), we would never have been able to demonstrate respective effect of proximal (core) coordination features (kinematics and amount of muscle activity) on the like probability of sustaining a hamstring injury during follow-up.

Both a strength and limitation related to the final strength of evidence derived from this thesis, is the methodological variety used to assess features of neuromuscular coordination. Each of the adopted screening protocols provided an essential advantage in addressing the different research questions embedded in this work. However, in an ideal research setting, free from financial, ethical and organizational restrictions, the importance of neuromuscular coordination in the intrinsic hamstring injury risk ought to be investigated by simultaneously measuring

- multi-muscle metabolic activity features (mfMRI),
- multi-muscle innervation behavior patterns (sEMG),
- full body kinematics (3D motion capture)
- **and** kinetics (groundreaction forces, joint torques and muscle-tendon mechanics; implementing a force plate)

during the activity that holds the highest injury risk: maximal sprinting.

## Future Perspectives

As the studies imbedded in this dissertation are the first to explore respective outcome measures prospectively in a study sample at actual risk of injury, additional research is definitely needed to reaffirm the present findings. More so, when confirmed by other researchers, these findings should be translated into specific rehabilitation and prevention strategies, to find out (1) if correction of deviated local and global neuromuscular coordination features is possible, (2) whether these adjustments

effectively have the capacity to reduce the hamstring injury risk, and (3) how this should be done preferably (type of exercise, frequency, volume, intensity, implementation within seasonal training schedule, etc.). Specifically, one should verify whether alternations in local (Chapter I), regional (Chapter II) and global (Chapter III) neuromuscular coordination are associated with a higher hamstring injury risk and whether correction of those factors prevents (re)injury. Particularly, As already mentioned in the beginning of the discussion, the possibility that the hamstring muscles bellies slightly differ in fibre type dominance is quite plausible, certainly bearing in mind their anatomical and functional differences. This would definitely partly explain their remarkable injury vulnerability and should definitely be investigated more thoroughly in future research.

More so, it would be useful to assess to what extent these findings present an association with hamstring injury vulnerability in other sports populations like track and field, running, rugby, American football, Australian rules football, hockey, etc. In doing so, it is evident that previous research findings and associated best practices in terms of rehabilitation and prevention strategies should be respected and integrated. In addition, as recent research has demonstrated that the occurrence of hamstring injuries during football training (contrary to what has been established during match play) presented a significant increase over the years,<sup>10</sup> researchers should identify the reason for this detrimental trend and attempt to reverse it. The main reason for this increase is undoubtedly the increasing intensity and explosiveness of the football game over the last decades.<sup>3, 8-9</sup> In aspiring to raise the stakes during the game, it is merely logical that training sessions are being adjusted correspondingly as well. The balance between optimal training load and overload is precarious, and this is certainly the case for hamstring loading in male football.

In particular, next to the confirmation of the present research findings, future work should focus on finding parallels and correlations between the investigation methods adopted in our research and more easy-to-administer, less time- and money consuming assessment tools, examining the same outcome parameters. As such, one could verify whether deficiencies in intramuscular interplay (BF versus ST) can be detected through (manual) strength testing or particular motion analysis. The same is true for the activation sequence in the posterior chain, where the ability to manually or visually identify muscle

recruitment patterns could be verified. With regard to running kinematics, it would be worthwhile to check whether lacking control in the lumbo-pelvic unit could be detected using simple one- or two-dimensional motion analyses, and to what extent real time video-imaging and correction (kinematic biofeedback) could possibly reduce injury susceptibility.



Lastly, although we gathered quite a few renewing findings within this doctoral dissertation, these issues most probably will not suffice to fully weapon the football player against hamstring injuries. Given the complexity of the biomechanical demands imposed upon the hamstrings in football, the associated complexity as regards the underlying intrinsic risk profile and trends in contemporary sports medicine, future research should definitely invest in investigating and mapping the

- (1) interdependency in between intrinsic risk factors,
- (2) the differences and parallels between the risk of running a first hamstring injury and a recurring one (as there are the share of post injury compensations / adaptations and the influence of rehabilitation, to name a few)<sup>7</sup>,

- (3) the influence of centrally mediated fatigue, overtraining, autonomic dysfunctions, illness and deconditioning in (hamstring) injury susceptibility, and last but not least
- (4) the influence of the central nervous system and possible relations with central sensitization processes and neuroplasticity.

By attempting to consider all these features and gathering the evidence that is available to date, we might just get really close to finally unraveling the mystery behind the hamstring injury risk in football.

## General Conclusion

The research findings within this PhD thesis demonstrate that the hamstring injury risk comprises of much more than just local features of muscle functioning as there are strength and flexibility. The hamstrings seem to be subject to overload and increasing injury risk when

- (1) the ST is not recruited sufficiently (compared to the effort of the BF) during eccentric hamstring loading;
- (2) the hamstrings present an activation delay (relative to the proximal back extensor muscles) during the Prone Hip Extension Exercise;
- (3) the core unit lacks coordination and control, resulting in insufficient core muscle activation during the unstable airborne phase of high speed running and in deviating pelvis – and trunk kinematics

In brief, our study findings suggest that the hamstrings are dependent on adequate neuromuscular guidance as concerns the functional interplay between the (1) separate hamstring bellies, (2) the synergists within the posterior sling, (3) the qualitative (timing of activity) and quantitative (amount of



activity) cooperation with the core (gluteal – and trunk muscles) and (4) associated running technique/coordination (particularly during the airborne phase). Thus, the results of this dissertation identify a football player to be at increased risk of sustaining a running related hamstring injury when he presents obvious imbalances in medio-lateral hamstring muscle recruitment, a deficiency to contract the hamstring muscle unit rapidly and a lack of core-control / excessive pelvis and trunk motion during high speed running.

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# Epilogue

*“Vulneratus nes victus “*







## Epilogue

When aiming to take into account these features in future research and clinical practice, a massive amount of work still needs to be covered. However, there is definitely no need for doom-mongering. Although hamstring injury incidence during training presented a subtle increase over the last decade, the incidence during matches remained status quo.<sup>4</sup> On the contrary, football play did change substantially over the years. In particular the running distance at high speed and the number of sprints have increased significantly during match play<sup>1-3</sup>. The average number of sprints performed during a European Premier League football match, for instance, has **doubled** when comparing the season of 2002 with the one of 2009.<sup>2</sup> As a consequence, the demands in terms of power and speed have increased substantially, and will most probably continue to do so. As the hamstring muscle is one of the most, if not the most important, prime mover in linear sprinting tasks,<sup>5</sup> the loads imposed upon this unit and the associated demands in terms of coordination, strength and flexibility, have exponentially increased over the years as well. Therefore, we should consider it to be a victory rather than a defeat, that we managed to keep the incidence rates during competition more or less stable throughout the years.

Nonetheless, stagnation means decline. If demands in football performance will keep on increasing, we must arm our athletes accordingly. **Indeed, because the game keeps on getting “harder, better, faster and stronger”, so must our (secondary) prevention strategies.**



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# Summary



## Summary

The research embedded within this doctoral thesis focused on the intrinsic hamstring injury risk profile in male football players. In spite of the substantial amount of effort that is being invested in the implementation of best practices as concerns (secondary) prevention of hamstring injuries to date, these muscle injuries present the tendency to occur more frequently as the time goes on. Because of the high reoccurrence risk, the detrimental influence on sports performance and mental health, as well as the high financial costs involved, this work attempted to contribute to a better understanding of the complexity of the football related hamstring injury risk, and hence, enable reduction of occurrence.

The first chapter consists of both a retro- and a prospective study, investigating the role of metabolic muscle function and intermuscular interplay between the hamstring muscle bellies in the detection of (1) injury history and (2) future injury vulnerability. Both studies demonstrated that the quantitative cooperation features (spatial muscle fibre recruitment pattern) between the different hamstring muscle bellies, in particular the BF and ST, are of key importance as regards hamstring injury susceptibility. The risk of sustaining an injury demonstrated to be significantly higher, when the medially oriented Semitendinosus muscle (ST) was activated to a lesser extent during prone leg curls, as this most probably obliged the laterally oriented, and most frequently effected, long head of the Biceps Femoris muscle (BF<sub>LH</sub>) to make an additional (possible excessive) effort during these types of exercise. By analogy with what muscle architecture has us believe, the ST and BF<sub>LH</sub> demonstrate to have individually differing functional purposes, which appeared to increase the risk of injury when not respected accordingly.

In the second chapter, we adopted a slightly wider scope of interest in assessing the intermuscular interplay characteristics within the posterior sling muscle continuum (back muscle, gluteal muscles and hamstrings). In particular, we investigated whether the order of muscle activation during the Prone Hip Extension test (PHE), could be associated with the risk of sustaining a hamstring injury in conducting a prospective cohort study. We elected this exercise in the hamstring injury risk study

context, as we wanted to examine the influence of neuromuscular coordination properties both within (Chapter I) as well as between the hamstring muscle bellies and their most important synergists in the human body as regards gait and running: the posterior sling muscles (Chapter II). Previous studies suggested that a delayed onset of the gluteal muscles, relative to the activity onset of the back – and hamstring muscles, would be detrimental for lumbo-pelvic function and arthrokinematics of the lower back, which might possibly endanger this region of becoming subject to mechanical overload and associated degenerative changes and complaints. With respect to the hamstring injury risk in football, our study demonstrated that the hamstring muscles of the subjects that got injured during the follow-up period presented a significant delay in activity onset, being solicited after recruitment of the lower back muscles, instead of the other way around as seen in the healthy subjects of our cohort. These findings lead to the conclusion that the quality of intermuscular cooperation and in particular, the relative timing of muscle activity within the posterior sling continuum during respective Prone Hip Extension test, is an important feature to take along in assessing and addressing the hamstring injury risk. Similar to the functional imbalances between the BF and the ST found in Chapter I, the temporal delay in activity onset refers to deficits in neuromuscular guidance of the hamstring muscle unit, making it function less economic and less safe than it ought to do for efficient football performance. Indeed, as the efficacy of eccentric and concentric hamstring strength production during running and kicking activities in football, is highly dependent on (1) the timing of muscle activity and (2) the intermuscular task distribution, the study findings gathered in Chapters 1 and 2 are in accordance with previous findings and should be encountered for in performance enhancement, prevention and rehabilitation.

Both prospective studies embedded in the concluding chapter (III) underline the absolute necessity of adequate neuromuscular coordination and sufficient, optimally timed muscle activity with regards to sound hamstring functioning as well. Concretely, respective study results revealed that a football player runs a higher risk of getting injured in the hamstring area, when the core muscles present lower activity levels and when the pelvis and trunk display more inconsistency (more anterior tilting of the pelvis and side bending of the trunk) throughout the airborne phase of sprinting (front-and backswing

phases). The latter indicates that, for the hamstrings to be sufficiently protected against overload and injury, not only the amount and (relative) timing of hamstring (belly-specific) activity is essential (Chapters I and II), but the conditional status and the functional performance capacity of the proximal lumbo-pelvic - or 'core' unit is absolutely vital as well.

In the end, this dissertation attempted to enrich the (understanding as regards the) hamstring injury risk profile in male football play by demonstrating **that efficient and safe hamstring functioning is most probably dependent on the quality of neuromuscular control and guidance within (1) the hamstring muscle unit, (2) the synergistic entity of the posterior sling and (3) the proximal lumbo-pelvic - or 'core' unit. Only in adequately bundling their forces (intramuscularly as well as with their proximal team mates (core)), the hamstring muscles provide themselves with the opportunity to experience a successful season.**

# **Nederlandstalige samenvatting**





## Nederlandstalige samenvatting

De onderzoeksactiviteiten binnen dit doctoraal proefschrift, namen het intrinsiek risicoprofiel voor het oplopen van hamstringblessures onder de loep binnen een homogene steekproef van mannelijke voetballers. Voormalig wetenschappelijk onderzoek leverde reeds aanzienlijke inspanningen in een poging het intrinsiek risico op het oplopen van een hamstringblessure te ontrafelen. Echter, gezien we moeten vaststellen dat dit type sportblessure tot op de dag van vandaag het frequentst voorkomt in het mannelijke voetbalcircuit, kan gesteld worden dat de therapeutische en preventieve maatregelen wat betreft hamstringblessure-management ontoereikend zijn de dag van vandaag. Omdat hamstringblessures naast hoge incidentiecijfers ook zeer frequent recidiveren en daar ze zodoende een zeer nefaste invloed hebben op het prestatievermogen en psychosociaal welbevinden van de voetballer, en niet in het minst de sociale gezondheidskas of de portefeuille van de club/speler, had dit doctoraatsproject tot hoofddoel het intrinsiek risicoprofiel diepgaander te gaan identificeren en te definiëren.

Het eerste hoofdstuk bespreekt de resultaten van een retro- en een prospectieve studie, waarin het mogelijke verband tussen de intramusculaire spierfunctie (coördinatie) en het hamstringblessurerisico onderzocht werd. Beide studies toonden aan dat het kwantitatieve samenwerkingsverband tussen de biarticulaire spierbuiken, in het bijzonder de Biceps Femoris (BF) en de Semitendinosus (ST), een significante invloed heeft op de hamstringblessurepredispositie. Het hamstringblessurerisico bleek veel groter te zijn voor spelers die tijdens de 'prone leg curling' oefening een relatieve activatietoename in de BF vertoonden, en een relatieve activatieafname in de ST, wanneer deze activiteit vergeleken werd met hun gepaarde controles. Naar analogie met hetgeen de intramusculaire verschillen in spierstructuur tussen BF en ST suggereren, hebben beide, anatomisch zeer nauw verbonden spieren, verschillende functionele doeleinden en lijkt het risico op een spierblessure groter te zijn wanneer de functioneel anatomische taakdifferentiatie niet gerespecteerd wordt.

In hoofdstuk 2 namen we afstand van de hamstrings als geïsoleerde functionele eenheid en werd onderzocht in welke mate de kwaliteit van neuromusculaire coördinatie tussen de verschillende spieren van de posterieure keten (lumbale erector spinae, gluteus maximus en hamstrings) in verband gebracht kan worden met hamstringblessuregevoeligheid. In dit verband werd de activatiesequentie in de posterieure musculaire keten tijdens de 'Prone Hip Extension' test (PHE) in kaart gebracht. Na het doorlopen van de onderzoeksactiviteiten in het eerste hoofdstuk, werd in functie van verdere risicodetectie, voor dit PHE protocol gekozen, om te verifiëren of naast de intramusculaire coördinatie, mogelijks ook intermusculaire coördinatie karakteristieken van belang zijn binnen risicodetectie (en zo ook blessurepreventie). Daar de synergie tussen bovenvermelde posterieure ketenspieren van cruciaal belang is tijdens functionele activiteit, werd de activatie volgorde bestudeerd in functie van prospectieve letselgevoeligheid. Voorgaand onderzoek aangaande de rekruteringsvolgorde tijdens de PHE, vertrok vanuit de veronderstelling dat laattijdige activatie van de gluteus maximus (ten opzichte van het solliciteren van de lumbale musculatuur en de hamstrings), nefast en mogelijks schadelijk zou zijn voor de lage rug en de sacro-iliacale gewrichten, daar hierdoor onvoldoende stabiliteit zou kunnen worden gevrijwaard bij disto-proximale krachtoverdracht. In hoofdstuk 2 werd gekeken naar de activatiesequentie in posterieure keten in functie van hamstring blessurepredispositie. Onze studieresultaten toonden aan dat de spelers die een hamstringblessure opliepen tijdens de prospectieve opvolgperiode, een significante laattijdigheid in hamstringactivatie vertoonden tijdens de PHE, in vergelijking met de gezonde controles. Op basis van deze bevindingen werd in dit hoofdstuk geconcludeerd dat de kwaliteit van intermusculaire coördinatie binnen de posterieure keten en in het bijzonder, de (relatieve) timing van hamstring spierrekrutering tijdens de PHE test, een belangrijke determinant is binnen het intrinsiek hamstring blessure risicoprofiel. In lijn met het belang van intramusculair functioneren binnen de hamstring eenheid zoals aangetoond in het eerste hoofdstuk, wijzen de resultaten in hoofdstuk 2 op het belang van neuromusculaire coördinatie, echter dit keer op intermusculair niveau. In dit verband blijkt dus dat zowel het exacte samenspel tussen BF en ST, als ook de timing van hun rekrutering ten opzichte van hun proximale synergisten een prominente rol spelen in het belang van veilige en efficiënte hamstringfunctie. Het dominante letselmechanisme indachtig (terminale zwaafase tijdens de sprint) lijkt het inderdaad heel plausibel dat de efficiëntie van

de excentrische hamstring contractie (tijdens respectievelijke fase) in belangrijke mate afhangt van de kwaliteit van intra- en intermusculaire coördinatie, zowel wat hoeveelheid spieractiviteit als timing van spierrekrutering betreft: Wanneer de ST onvoldoende activiteit vertoont tijdens de zwaafase, zal de BF dit moeten opvangen. Indien dit dan ook nog eens te traag gebeurt, worden deze spieren mogelijks excessief op lengte gebracht tijdens de explosieve voorste zwaafase waardoor het risico op verrekking of ruptuur uiteraard aanzienlijk groter wordt.

In hoofdstuk 3 werd in beide prospectieve studies het belang van adequate neuromusculaire controle in de lumbo-pelvische regio onderzocht. Dit in de veronderstelling dat niet enkel intramusculaire coördinatie en synergie binnen de posterieure keten van belang zijn binnen risicodetectie (en correctie), doch ook looptechniek en neuromusculaire coördinatie karakteristieken binnen de ruimere kinetische keten. Daar loopversnellingen en sprints wel degelijk maximale inzet en samenwerking van het volledige musculoskeletaal apparaat vereisen, werd hier gekeken naar de associatie tussen spieractiviteit en kinematica van romp- en bekken tijdens maximale springt en de prospectieve hamstringblessure incidentie. De resultaten in dit hoofdstuk toonden aan een voetballer een hoger hamstringblessure risico loopt, indien tijdens de zweeffase van de sprintcyclus (1) de romp- en gluteale spieren minder activiteit vertonen en (2) romp en bekken meer kinematische deviaties (minder bewegingscontrole) vertonen. Deze finale onderzoeksbevindingen tonen aan dat, willen de hamstrings degelijk gewapend zijn tegen blessure, niet enkel de (onderlinge) hoeveelheid en timing van hamstringactiviteit essentieel zijn, doch ook de functionele capaciteit van de proximaal stabiliserende musculatuur in romp- en bekken en de hieraan gekoppelde bewegingspatronen tijdens explosieve loopversnellingen.

Deze doctorale dissertatie had tot doel bij te dragen aan het verrijken van de inzichten in het intrinsiek hamstringblessurerisico. In dit verband kon worden aangetoond dat **de efficiëntie en veiligheid waarmee de hamstrings functioneren tijdens loopactiviteiten meer dan waarschijnlijk sterk afhankelijk is van de kwaliteit van neuromusculaire controle (1) binnen de hamstring eenheid, (2) tussen de synergisten van de posterieure keten en (3) binnen de proximaal stabiliserende musculaire eenheid van romp en bekken. Als en slechts als de krachtenkoppels binnen de gehele**

**kinetische keten degelijk gebundeld worden (intra- en intermusculair), kunnen de hamstrings aanspraak maken op een succesvol seizoen, vrij van blessures.**

# **Word of gratitude**



## Word of gratitude

I feel genuinely grateful, being handed the opportunity to write and defend this doctoral thesis.

I have always had a special interest in sports medicine, both as regards prevention and rehabilitation of injuries as well as assessing and optimizing sports performance. When the promotor of this work, Prof. dr. Erik Witvrouw, addressed me after terminating my 5<sup>th</sup> and final university year to verify whether I would be interested in doing doctoral research in the field of hamstring injuries in male football, I enthusiastically confirmed my commitment to get the strongly desired IWT scholarship. Being provided an individual scholarship to conduct ‘strategisch basis onderzoek’ (strategic fundamental research), I was able to mould the study protocols and subsequent data-analysis processes in function of my personal interests, beliefs and aspirations, which made the entire PhD period particularly interesting, challenging, and instructing, as it enabled me to get to know myself more profoundly. 4 Years later, I am pleased with the result and hope this is the case for all the stakeholders involved and evidently, the readers as well. It has definitely not been all roses throughout the PhD trajectory, but I can honestly say that I have never regretted taking the academic path after graduation, instead of the readier clinical one. Although the process of submissions, revisions and, unfortunately many, rejections can be very hard and ungrateful, the joy and satisfaction that come with acquiring and processing data and presenting renewing scientific evidence in the field one is inspired by the most, is irreplaceable. Thanks to this PhD, I have discovered and refined the true orientation of my scope of interest, encompassing sports, biomechanics, research and writing. As it sharpened my (critical) clinical reasoning engine as well, I believe my experiences as a researcher enabled me to become a better clinician/diagnostician just as much.

I would not have been able to present this dissertation in its current form if it wasn't for the guidance and (unconditional) support of my colleagues, family and friends. First, I wish to express my sincere gratitude to promotor Prof. dr. Erik Witvrouw and copromotor Prof. dr. Damien Van Tiggelen. Having supported me throughout the past 4 years, I consider Erik to be the ‘executive trainer’ and Damien to



be physical coach, when continuing to speak in football terms. From the very start, Erik believed in me enough to honour me with the privilege of becoming one of his doctoral students. Although he physically slipped out of the picture to enrich his research experience in the Sports Medical centre of excellence, Aspetar, in Doha, Qatar, I was able to persistently count on him for assistance in work and deed. In particular as concerns writing and (re)submitting the papers included in this thesis, he has been an indispensable moving force. Bursting of enthusiasm and creativity, he has been an infinite source of inspiration and motivation, and most importantly, a very dear friend as well. Next to the physically absent though mentally very present support of Erik, Damien and the members of my guidance committee, Prof. dr. Lieven Danneels and Prof. dr. Dirk De Clercq, have been my towers of strength throughout this dissertation. Whenever in doubt or in need of some ventilation, I was able to appeal on them. Being (experience) experts in the field of biomechanics and highly familiar with the conduct of a PhD, their guidance and support throughout the entire process have been indispensable. In particular Damien, who I could rely on for his personal assistance during the testing series in the hot summer months of 2013 and 2014, particularly deserves an honourable mention. With his ability to take a firm line and to see things in their proper perspective, his amicable manner approach on professional communication and his sense of humor, he made this doctoral experience even more enjoyable. It therefore needs no further ado, that I will definitely miss these dear colleagues and genuinely hope that we will meet again in professional or friendly terms in the future.

Next, I would like to thank all of the colleagues at the Department of Rehabilitation Sciences and Physiotherapy of the Ghent University for their support, pleasant company and friendly distraction during the period of my provision. Every single one of them has a golden heart and a bright, critical mind, which has proven to be a winning combination when considering the increasing number of students enrolling year after year. My particular gratitude goes out to Tanneke Palmans and Steven Heyndrickx. They systematically assisted me throughout the labour-intensive testing series in Topsporthal Vlaanderen and adjusted their own working schedules accordingly. I really could not have wished for better colleagues.

To conclude, my unlimited appreciation goes out to my family and friends, who's loving support and motivation have truly meant the world to me over the course of this PhD. A special thanks goes at to my parents, brother and sister, as well as my friends from Ghent and Destelbergen. They were systematically able to pick me up when I was feeling 'down and out'. In particular, I want to thank my dear friend and engineer Celine Joos. Apart from her mental support, she also assisted me throughout the process of data-analysis. Her higher evolved 'MatLab brain' was my steady 'mesh' throughout my years as a researcher. Last but not least, I wish to thank my partner. He is my beacon and daily inspiration, always motivating me to perform at my best whilst still enjoying every second of every day. Without his unconditional support, I cannot imagine having brought this PhD to a successful and happy ending.

Not to mention, special thanks also goes out to Ms. Lise Vanlerberghe, who created the drawings embedded in the general introduction and general discussion.

# **Curriculum Vitae**



## Curriculum Vitae

# Joke Schuermans

## Curriculum Vitae

### GENERAL INFORMATION

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Name	Joke Schuermans	
Date of Birth	18 – 02 – 1989	
Place of Birth	Ghent, Belgium	
Nationality	Belgian	
Professional Address	Dept. of Rehabilitation Sciences and Physiotherapy Campus Heymans (UZ) 3B3 De Pintelaan 185 B-9000 Ghent Phone: +32 9 332 53 74 Fax: +32 9 332 38 11 joke.schuermans@ugent.be	
Private Address	Vlinderstraat 7 9050 Gentbrugge Belgium Phone: +32 498 65 44 13 schuermansjoke@gmail.com	

### EDUCATION

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2013 – 2017 ( <i>ongoing</i> )	PhD in Health Sciences, Department of Rehabilitation Sciences and Physiotherapy, Faculty of Medicine and Health Sciences, Ghent University
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*“ Hamstring injuries in football: an update on the intrinsic risk profile  
– Because the incidence is crying out for evidence ”*

2012

Master of Health Science in Rehabilitation Sciences and Physiotherapy, degree attained Magna cum Laude Ghent University, Faculty of Medicine and Health Sciences, Department of Rehabilitation Sciences and Physiotherapy

Master Thesis: “ Which factors can predict the functional outcome of conservative management in patients with Patellar Tendinopathy ? “

*This thesis discusses the results of a prospective pilot study, assessing the importance of (baseline) quadriceps strength and flexibility, tendon morphology on ultrasound, as well as deep and superficial patellar tendon flow as regards the functional and clinical outcome of conservative rehabilitation. Based on respective preliminary findings, one could conclude that the functional and clinical success of conservative rehabilitation is dependent on sufficient muscle strength, flexibility and patellar tendon blood flow, which all can be remediated significantly by implementation and eccentric exercise.*

2010

Bachelor in Rehabilitation Sciences and Physiotherapy, degree attained cum laude Ghent University, Faculty of Medicine and Health Sciences, Department of Rehabilitation Sciences and Physiotherapy

*Throughout the 5 year education course, the curriculum handled*

- *Fundamental sciences: (bio)physics, (bio)chemistry, biomechanics, topographic and functional anatomy*
- *Applied (para)medical sciences: clinical assessment and rehabilitation (manual therapy and exercise therapy), orthopedics, neurology, urology, geriatrics, pediatrics, podiatry, internal medicine (metabolic and respiratory dysfunctions), oncology, psychiatry, etc.*
- *Applied sports sciences*
- *Psychosocial and Ethical sciences: psychotherapy, philosophy and deontology, behavioral sciences*
- *Applied financial sciences: health economics, management*

*Bachelor Thesis: “Oculomotor function and neck complaints in computer workers, an observational study”*

*In the master years, the major sports physiotherapy was elected, which particularly focused on injury prevention and rehabilitation in (recreational) athletes.*

## ADDITIONAL COURSES AND TRAINING

### Linguistics

“Le Francais Médical” (2011), Universty Centre of Linguistic Education

## **Society Related**

*“Health Economics” (2011), Faculty of Medicine and Health Sciences, Ghent University*

## **Practical training – Profession Related**

*“Medical Exercise Therapy” (2014), Instituut voor Permanente Vorming, REVAKI, Ghent University*

## **Academic Specialist Courses**

*“Statistics – Introductory Statistics, Basics of Statistical Inference” (2013)  
Doctoral Schools of Life Science and Medicine, Ghent University*

*“Advanced Statistics” (statistische analyse met behulp van SPSS – gevordereden) (2014)  
Doctoral Schools of Life Sciences and Medicine – Cel Biostatistiek Ugent*

*“Statistical analysis in R for health scientists” (2015)  
Doctoral Schools of Life Sciences and Medicine – Cel Biostatistiek Ugent*

*“Statistical Parametric Mapping: a two day basic course” (2013)  
Todd Pataky, Jos Vanrenterghem and Mark Robinson, Liverpool John Moores University*

*“Systematic Review, Parts I and II” (2013)  
Belgian Centre for Evidence Based Medicine (Cebam)*

## **Academic Transferrable Skills Courses**

*“Advance Academic English: Conference Skills – Presentation Skills” (2013)  
Doctoral Schools of Life Sciences and Medicine*

*“Advanced Academic English: Conference Skills – Academic Posters” (2014)  
Doctoral Schools of Life Sciences and Medicine*

*“Advanced Academic English: Writing Skills” (2014)  
Doctoral Schools of Life Sciences and Medicine*

## **PROFESSIONAL EXPERIENCE**

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### **RESEARCH**

2013 – present                      PhD Researcher at the Department of Rehabilitation Sciences and  
Physiotherapy, Faculty of Medicine and Health Sciences, Ghent University

4-year scholarship (*beurs voor strategisch basisonderzoek [sbo]*) provided by the Agency for Innovation by Science and Technology in Flanders (IWT, Brussels, Belgium) (VLAIO at present).

Field of Research: hamstring injuries in football (risk identification)  
Scope of the research activities

- (metabolic) muscle activation properties
- Motion- and running analyses
- Surface Electromyography
- Three dimensional kinematic analysis
- Muscle functional Magnetic Resonance Imaging

## **PUBLICATIONS**

Schuermans J, Van Tiggelen D, Danneels L, Witvrouw E. Biceps femoris and semitendinosus--teammates or competitors? New insights into hamstring injury mechanisms in male football players: a muscle functional MRI study. *Br J Sports Med.* 2014 Dec;48(22):1599-606.

Schuermans J, Van Tiggelen D, Danneels L, Witvrouw E. Susceptibility to Hamstring Injuries in Soccer: A Prospective Study Using Muscle Functional Magnetic Resonance Imaging. *Am J Sports Med.* 2016 May;44(5):1276-85.

Schuermans J, Van Tiggelen D, Danneels L, Palmans T, Witvrouw E. Proximal neuromuscular control protects against hamstring injury in male soccer players: A prospective study with EMG time-series analysis during maximal sprinting. *Am J Sports Med* 2016 [In Press].

## **TEACHING**

- |             |   |
|-------------|---|
| 2014 – 2016 | Teacher at the Department of Rehabilitation Sciences and Physiotherapy, Faculty of Medicine and Health Sciences, Ghent, Belgium   |
|             | (1) Clinical Assessment of the Lower Limb (practical sessions), 1 <sup>st</sup> bachelor  |
|             | (2) Hamstring injuries in sports (lecture), 2 <sup>nd</sup> master  |
|             | (3) Sports Biomechanics (Lecture), 2 <sup>nd</sup> master   |
| 2014 – 2016 | Guest teacher at OPAC (Oost-vlaamse Politie Academie; kandidaten geweldbeheersing met en zonder vuurwapen): Sports traumatology, Anatomy, General Histologie and human physiology |
| 2015        | Guest teacher at the Royal Belgian Football Association (KBVB), within the ‘Trainer A’ curriculum<br>“Biomechanics in football: kinematics, performance and injury prevention”    |



- 2013                      Guest Lecturer at the Seinajoki International Week (University of Applied Sciences, Seinajoki, Finland), master students
- Essentials of sports injury prevention
  - Hamstring strain injury prevention and rehabilitation
  - Biomechanics, prevention and rehabilitation

## CLINICAL EXPERIENCE

- 2012 - present            Sports Physiotherapist at the Sports and Spine Centre, Melle, Belgium
- (sports) rehabilitation
  - Biomechanical analyses and exercise physiology

Since 2016                Physical Coach KAA Ghent Ladies, Premier League

## Miscellany

- 2016                      Training instructor
- 2012                      Assistant at SpartaNova (Company that provides an online injury prevention and performance progression platform, in collaboration with the Ghent University and the University of Brussels) [[www.spartanova.com](http://www.spartanova.com)]
- 2007 – 2014              Waitress in the catering industry
- 2007                      Dance instructor

## SYMPOSIA AND CONGRESSES

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- 2016                      BOLK Congres der Nederlandse Anatomen, Lunteren, the Netherlands  
Speaker "*The value of muscle functional MRI in muscle injury risk prediction*"
- ESSKA Congress Barcelona, Spain (European Society of Sports Traumatology Knee Surgery and Arthroscopy)  
Poster Presentation "*Hamstring injury risk prediction in male football: practice needs science to make perfect*"
- 2015                      European Congress of Sports Medicine, Antwerp, Belgium  
Speaker and Chair "*A step closer to unraveling the hamstring injury risk using muscle functional MRI*"

Brucosport Spring Congress (The shoulder joint in the athlete, new insights),  
Bruges, Belgium

Research Day of the Faculty of Medicine and Health Sciences, Ghent  
University, Ghent, Belgium

Speaker “*Biceps femoris and semitendinosus--teammates or competitors? New insights into hamstring injury mechanisms in male football players: a muscle functional MRI study.*”

2014 7<sup>th</sup> Biennial Congress of the Belgian Back Society (Neck complaints, a 360 view), Ghent, Belgium

2013 SpartaNova Users Meeting: Hamstring injury prevention; Antwerp, Belgium  
Speaker: Lecture on preliminary research findings and clinical implication

Qualisys Users Meeting, Erlangen, Germany

Symposium “Management of acute knee injuries in the athlete”, dept. of  
Orthopaedics, Ghent University Hospital, Ghent, Belgium

2011 Physioclub “Chronic pain and central sensitization, role of the  
physiotherapist”, dept. o Rehabilitation Sciences and Physiotherapy, Ghent  
University, Ghent, Belgium

## MEMBERSHIP AND ASSOCIATIONS

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2014 – present Departmental Assistant Representative in the Faculty Board of Medicine and Health Sciences

2012 – present Member of the Departmental Alumni Association (AlumniRevaki), Dept. Rehabilitation Sciences and Physiotherapy, Fac. Medicine and Health Sciences, Ghent University

2009 – 2012 Member of the Student Advisory Committee, Dept. Rehabilitation Sciences and Physiotherapy, Fac. Medicine and Health Sciences, Ghent University

2005 – 2010 Supervisor in youth association (Chiro Destelbergen)

## Knowledge of languages

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Dutch: native

English: very good

French: basic

German: basic

### **General interests**

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Sports

Reading and writing

Travel

Animal

