

# Prone Hip Extension Muscle Recruitment is Associated with Hamstring Injury Risk in Amateur Soccer

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## ABSTRACT

'Core stability' is considered essential in rehabilitation and prevention. Particularly with respect to hamstring injury prevention, 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 regard 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. 60 healthy male soccer players underwent a comprehensive clinical examination, comprising a range of motion assessments and the investigation of the posterior chain muscle activation pattern during PHE. Subsequently, hamstring injury incidence was recorded prospectively throughout a 1.5-season monitoring period. Players who were injured presented a PHE activation pattern that differed significantly from those who did not. Contrary to the controls, hamstring activity onset was significantly delayed ( $p = 0.018$ ), resulting in a shifted 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 ( $p = 0.009$ ). Assessment of muscle recruitment during PHE demonstrated to be useful in injury prediction, suggesting that neuromuscular coordination in the posterior chain influences hamstring injury vulnerability.

## Introduction

Hamstring injuries are a common and frequently reoccurring problem in several sports [5, 13, 17, 18, 57]. Especially in male soccer, given its physical demands, this muscle injury remains an obstacle [3, 6, 28]. 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 as well (rates ranging from 12 to 30% after return to play; up to 35% of all recurring muscle injuries involve the hamstrings) [10, 14, 26, 43, 55, 57]. 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 recent years [15]. 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 the 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 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 [12, 57]. Among others, alterations in neuromuscular coordination [48, 49] and neuromuscular inhibition [20] are proposed to play a role in hamstring injury vulnerability. Both local [20, 48, 49] and more proximally oriented coordination dysfunctions [41, 46] have been associated with hamstring injuries in athletes. To what extent these neuromuscular features are the cause or merely the consequence of hamstring injuries cannot to be deduced as prospective research is lacking.

Neuromuscular coordination, in particular lumbo-pelvic function, is suggested to be key in safe hamstring functioning [41]. The hamstrings are primarily responsible for controlling and generating forces around the knee and hip joints throughout running. However, in theory, due to their bi-articular 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 [41, 42]. 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 [56]. To protect 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 [9, 30, 35, 42, 50, 51]. Both the gluteus maximus and the (superficial) lumbar erector spinae likewise have a dual function because they are designed to create and control extension- and flexion torques, respectively, and in addition generate sufficient muscle tone for safe guarding 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 [1, 7, 11, 23, 31–33, 35, 41, 44]. 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 [30] and has been adopted in multiple studies to investigate impairments in lumbo-pelvic neuromuscular coordination [1, 7, 11, 23, 35, 39]. 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).

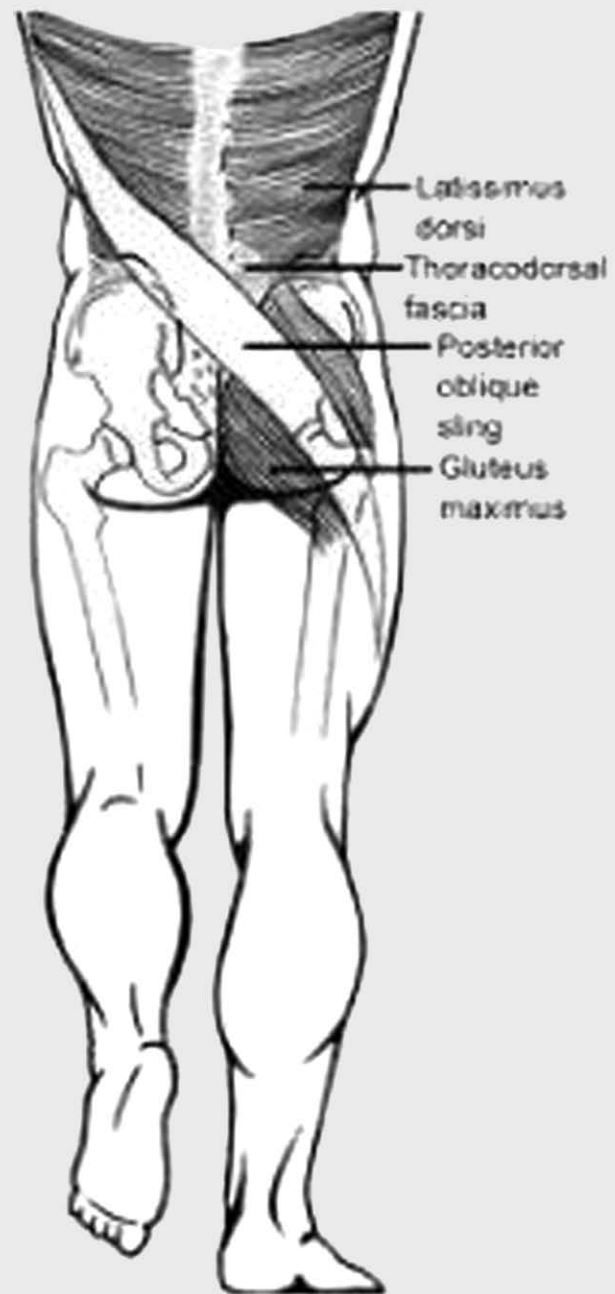
► **Fig. 1** illustrates the posterior sling system, with a diagonally-directed force vector crossing the lumbo-pelvic girdle from lower limb towards trunk and vice versa.

Although mostly suggested to be important in prevention of lower-back and sacro-iliac complaints [30–33, 35, 39, 44, 46, 47, 50], the intermuscular interplay within the posterior sling might have important repercussions on hamstring functioning as well [41], but this has never been investigated before. Therefore, this study will 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 investigating PHE muscle recruitment patterns using surface electromyography (sEMG). Because joint mobility and muscle tightness within and around the lumbo-pelvic-hip complex would evidently affect associated muscle activation characteristics during PHE, respective clinical features were thoroughly examined prior to sEMG analysis.

## Materials and 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. To do so, the management and staff of 7 different clubs were contacted. These clubs were all active in the first (and second) level of the same regional recreational competition series, which unified the volume and intensity of exposure during training and match within the selected study sample (2 training sessions (2 h/training) and one match per week). Players were excluded if they



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

- 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. re-injury definition by UEFA [24])
- 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 participating in training or competition for at least one entire week [24]. Although potentially inducing significant inhibition and neuromuscular alterations, we decided not to account for less severe hamstring complaints (not preventing the participant from participating in soccer play), to make sure we would not erroneously 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 h 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 clinical screening, 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 it meets the ethical standards of the International Journal of Sports Medicine [25].

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 aspects 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 min warm-up on a stationary bike. Subsequently, hamstring flexibility (passive knee extension test from a 90° hip and knee flexion position, ► Fig. 2), iliopsoas flexibility and rectus femoris flexibility were evaluated (modified Thomas test; ► Fig. 2) [2, 16, 19, 22]. 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 [22]. Contrary to their protocol, knee extension was performed passively. We decided not to perform the passive knee extension test as originally described by Fredriksen [19] (passive knee extension starting from a 120° flexion position in the hip joint), 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.

Next, hip flexion, internal and external rotation ranges of motion were obtained with the participant in a relaxed supine or sitting position, respectively (► Fig. 3).

All ROM measurements were conducted using a digital inclinometer. Bilateral and unilateral Finger To Floor (FTF) reaching distances [5, 45] (► Fig. 4) 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 [21, 22, 53]; ► Fig. 5).

## 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 to the SENIAM guidelines [27, 37]. We chose to take into account the contralateral erector muscle, 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 [4, 41, 46, 54]. After electrode placement, 8 amplifiers which served to capture the electric signal and forward 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 of the EMG signal in each of the 8 channels, 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 [34,] 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 level 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 extended the hip joint, maximally resisting the tester's torque towards hip flexion. For each of these procedures, the participants were asked to gradually raise the amount of muscle force, reaching a maximum in approximately 3 s. This maximum force output was maintained for 5 s, after which the participant was instructed to gradually reduce 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 0.5 Hz (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 thereafter (► Fig. 6). This Prone Hip Extension exercise



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



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



► **Fig. 4** Bilateral and unilateral finger to floor reaching 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, thus 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) [36]. To allow valid interpretation of the possibly differing activa-

tion 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.

### Prospective recording of injury occurrence

After testing, the participants were requested to sign on to an online diary for registration of weekly exposure and injury incidence and to complete this survey on a weekly basis [<http://www.hsi.ugent.be>].

The end of this monitoring phase was set at the 2015 winter break (December 2015), 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 as 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 re-injury occurs at the exact same location as the prior one within 2 months after the final rehabilitation day of the previous injury, all recorded injuries were considered to be index injuries [24]. However, as the presence of an injury history has demonstrated to increase the risk of a subsequent one [19], 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 s 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, revealing the average EMG amplitude for every muscle throughout the consecutive hip extension trials were performed as well. These quantitative data were then first normalized relative to the MVC records for subsequent statistical analysis. All EMG data processing was conducted using the MR3.6 software (Noraxon



► Fig. 5 Active slump test; amount of knee extension quantified using a digital inclinometer.



► Fig. 6 Resting-, mid- and end-range position for Prone Hip Extension test.

U.S.A. Inc., Arizona). Based on the ratio [dominant-/non-dominant leg involvement] of the recorded hamstring injuries, the same ratio was utilized 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)

for evaluation of a possible causal association between the clinical and EMG variables on the one hand and the hamstring injury risk on the other, including injury history as a confounding covariate. If differing significantly based on injury occurrence, Cohen's *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

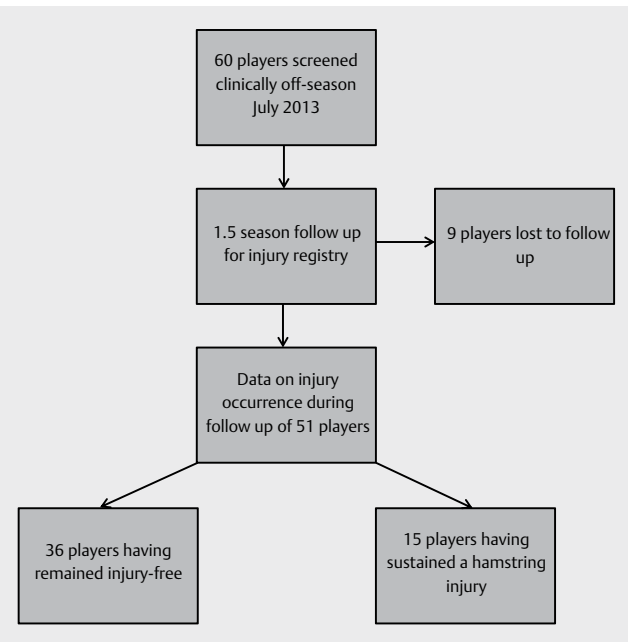
Of the 60 participants screened in July 2013, 4 stopped playing because of severe injuries (other than hamstring injury) and/or work-related priorities, and 5 were lost to follow-up, resulting in a sample size of 51 players for prospective data-analysis. 15 of those sustained a hamstring injury during 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 oriented 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 ► **Fig. 7**.

Anthropometric - and injury-related features of the participants are presented in ► **Table 1**.



► **Fig. 7** Flowchart study course.

### Clinical measures of mobility and flexibility and injury occurrence

Mobility and flexibility outcomes, as a function of injury incidence during prospective injury registry, are presented in ► **Table 2**.

No association was found between hamstring injury occurrence and any of the ROM features. As ► **Table 2** indicates, clinical 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 the 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), 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 obtained (► **Table 3**).

EMG signal timing analyses and subsequent statistical hypothesis testing revealed the following findings: First, 2 distinct recruitment patterns appeared to be most common in the entire cohort, 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 were injured (► **Table 4**).

In addition 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.

Within-group-comparison (General Linear Model – Repeated Measures) revealed that the onset times of these 3 agonists 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, vs. 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 with both the relative and absolute 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 s. The average hamstring activity onset time appeared to be able to predict hamstring injury occurrence with a statistical power of 92% ( $\beta = 0.08$ ).

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**.

## Discussion

The present study demonstrated that 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, 2 distinct patterns revealed to be most common in both the control – as well as the injury group. The sequence in which the hamstrings are activated first, followed by the contralat-

► **Table 1** Demographic results final cohort after prospective injury recording.

	Control (n = 36)	Injury (n = 15)
Body mass (mean ± SD; kg)	73 ± 7	73 ± 5
Height (mean ± SD; m)	1.80 ± 0.06	1.81 ± 0.04
BMI (mean ± SD; kg/m <sup>2</sup> )	22.41 ± 1.55	22.50 ± 1.650
Age (mean ± SD; y)	24 ± 4	24 ± 3
Time to injury during follow-up (mean [range]; wks)	–	18 [4–36]
SD: Standard Deviation; kg: kilograms; m: meter; m <sup>2</sup> : square meter; y: years; wks: weeks		

► **Table 2** Comparison of the clinical features between soccer players who sustained a hamstring injury and those who did not.

	Control (n = 36)	Injury (n = 15)
Hip flexion Mobility (mean ± SD; °)	117.52 ± 7.89	116.46 ± 8.01
Iliopsoas Flexibility* (mean ± SD; °)	21.77 ± 8.10	19.04 ± 9.37
Rectus Femoris Flexibility* (mean ± SD; °)	62.13 ± 13.62	65.21 ± 12.59
Hip External Rotation Mobility (mean ± SD; °)	37.19 ± 7.96	36.92 ± 4.62
Hip Internal Rotation Mobility (mean ± SD; °)	30.33 ± 5.43	30.61 ± 5.27
Hamstring Flexibility* (PKE) (mean ± SD; °)	131.67 ± 11.28	132.53 ± 12.54
Bilateral Finger To Floor (FTF) Reaching Distance (mean ± SD; cm)	6.19 ± 6.92	8.73 ± 7.00
Unilateral FTF Reaching Distance (mean ± SD; cm)	4.72 ± 6.28	4.64 ± 7.06
Knee Extension during Slump (mean ± SD; °)	-26.43 ± 9.24	-27.51 ± 6.85
SD: Standard Deviation; °: number of degrees; PKE: Passive Knee Extension; cm: centimetre		
* Iliopsoas flexibility was objectified by measuring the hip extension ROM in the Modified Thomas testing position; rectus femoris flexibility was objectified by measuring the knee flexion ROM relative to full knee extension in the Modified Thomas testing position; hamstring flexibility measures represent the entire knee extension range of motion (90° of knee extension augmented with the additional ROM capacity during the passive assessment)		

eral 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, further analysis revealed that this altered sequence of posterior chain muscle recruitment is predominantly caused by the delay in onset time of the hamstring muscles, consequentially forcing the erector trunci to participate in force production prematurely. Looking at the contraction intensity, no sig-

► **Table 3** Possible PHE activation sequences.

Order of muscle activity onset		
1	2	3
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)

► **Table 4** Frequency distribution within the different patterns of activation during the prone hip extension exercise for prospective control and injury groups.

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

CLES, Contralateral Lumbar Erector Spinae; GM, Gluteus Maximus; H, Hamstrings. \* The EMG signals of 4 individuals in the control group presented too much noise and were excluded for timing analysis

nificant 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 [40] 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 an insufficient capacity to generate force/torque early. Although demonstrating reductions in early EMG activity onset, no differences in peak torque was present 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

► **Table 5** Average muscle onset times during PHE in players who remained injury free (control) and those who sustained a hamstring injury (injury).

	Control (n = 32) *	Injury (n = 15)
CLES onset time (mean ± SD; sec)	(1) 0.89 ± 0.29	0.92 ± 0.24
H onset time (mean ± SD; sec)	(2) 0.81 ± 0.24	(4) 1.04 ± 0.38
GM onset time (mean ± SD; sec)	(3) 1.05 ± 0.40	1.14 ± 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,  $p = 0.004$ .

► **Table 6** Average EMG amplitude during PHE, normalized to the MVC reference.

	Control (n = 36)	Injury (n = 15)
CLES (mean ± SD; %)	25.0 ± 30.2	20.4 ± 10.2
GM (mean ± SD; %)	29.7 ± 19.2	24.0 ± 19.0
Hamstrings (mean ± SD; %)	21.5 ± 10.0	19.0 ± 9.3

CLES: Contralateral Lumbar Erector Spinae; GM: Gluteus Maximus; SD: Standard Deviation

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 [40]. 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 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 [1, 7, 23, 30, 39, 47],



the GM activity onset was very similar between 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 sufficient 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 [30, 39, 42, 50].

In these terms, the study of Bullock and colleagues (1994) demonstrated that GM activity onset was significantly delayed in subjects with a history of lateral ankle sprains, compared to healthy matched controls [8]. 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 [7]. 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 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 [35], and that the most frequently observed activation pattern is the primary activity onset of the hamstrings, followed by the contralateral ES and lastly the GM [47].

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 analogously to 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 [30]. 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 [29]. Indeed, more and more research puts emphasis on the importance of timing and coordination in hamstring activity, progressively abandoning the predominant role of (isokinetic) muscle strength [52]. 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 the sufficient amount of force exactly 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 [32, 35], might point out neuromuscular control deficits and imbalances in the synergistic interplay, causing the hamstring muscles to work insufficiently and making them more susceptible to injury.

Although assessing the association between analytical mobility and flexibility 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 emphasizes the complexity of the hamstring injury risk profile in young athletes. Albeit an essential part of pre-participation screening [4], 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 new 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. By 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. One must bear in mind that both features are highly interdependent, however. 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 [38], 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 gauge for neuromuscular control and relative dominance or 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 contralateral erector muscle was associated with hamstring injury occurrence. Thus, 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 (addressing all posterior sling muscles and preferably, the entire kinetic chain), would be effectively able to reduce hamstring injury susceptibility in soccer players.

## Author Contributions

JS carried out the participant recruitment, clinical assessment and sEMG analysis, as well as data collection and statistical analysis. Being the principal researcher and author, she was also responsible for statistical analyses and 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.

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## Conflict of interests

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

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