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Telma Sagnard, Brice Picot, Nicolas Forestier. Influence of exercise-induced hamstrings fatigue on proprioceptive reweighting strategies and postural performance in bipedal stance in recreational athletes. *Human Movement Science*, 2024, 98, pp.103298. 10.1016/j.humov.2024.103298 . hal-04752387

HAL Id: hal-04752387

<https://hal.science/hal-04752387v1>

Submitted on 24 Oct 2024

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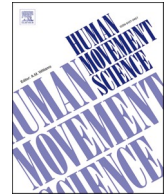
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Influence of exercise-induced hamstrings fatigue on proprioceptive reweighting strategies and postural performance in bipedal stance in recreational athletes

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ARTICLE INFO

Keywords:

Proprioception
Central nervous system
Postural balance
ACL injuries
Vibration

ABSTRACT

Objective: An optimal proprioceptive reweighting strategy is necessary to maintain posture. A suboptimal strategy was associated with injury determinants and whether the strategy can be modified is unknown. Muscle fatigue can be used to investigate proprioceptive reweighting. The aims of this study were to evaluate the effects of local fatigue on proprioceptive reweighting strategies and postural stability as well as relationships between fatigue and these postural parameters.

Design: Fourteen recreational athletes were included. Relative proprioceptive weighting (RPW) was characterized according to the perturbation of the center of pressure (CoP) displacement generated by muscle vibration on a firm and foam surface. RPW evolution <95 % indicated that individuals were able to reweight proprioception from the ankle to lumbar signals according to the surface while evolution >105 % indicated that athletes maintained an ankle-steered strategy. Student's *t*-tests were used to compare RPW evolution, CoP velocity, and root mean square (RMS) before and after exercise-induced hamstring fatigue. Spearman's rank correlation coefficient was used to test the relationship between fatigue variables, RPW evolution, and stability variables.

Results: Hamstring fatigue induced an ankle-steered strategy characterized by an increase in RPW evolution when the surface was changed ($P = 0.002$) and an increase in CoP velocity ($P = 0.045$) and CoP RMS ($P = 0.005$) on firm surface. None of the correlation coefficients testing the relationship between the parameters proved to be significant.

Conclusion: Local fatigue leads to suboptimal proprioceptive reweighting strategies and impaired stability on firm surface. Results suggests that proprioceptive reweighting strategies are modifiable. Whether this predisposes participants to injury remains to be defined.

1. Introduction

Optimal postural control requires the integration of signals originating from various sensory systems (somatosensory/proprioception, visual, and vestibular) as well as the dynamic reweighting of these sensory sources (Peterka, 2018). Sensory reweighting can be defined as the modulation of the weight assigned to a sensory system depending on the environmental conditions and available

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<https://doi.org/10.1016/j.humov.2024.103298>

Received 27 May 2024; Received in revised form 26 September 2024; Accepted 3 October 2024

Available online 21 October 2024

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sensory information to ensure optimal postural control (Assländer & Peterka, 2014). Reweighting may also occur within a single sensory modality, such as proprioceptive signals from a specific anatomical location, which can be weighted according to the reliability in a given environment and internal conditions (Brumagne et al., 2004; Picot et al., 2022). For example, while ankle proprioceptive signals are predominant on firm surfaces to maintain an upright stance, due to the loss of reliability of these signals on unstable surfaces, reliance shifts to lumbar signals (Picot et al., 2022). Adaptability to environmental constraints is essential for maintaining optimal postural control (Peterka, 2018), and depends on the central processing of proprioceptive information (Goossens et al., 2019; Pijnenburg et al., 2014).

Proprioceptive reweighting is heterogeneous among individuals (Brumagne et al., 2004; Mahmoudian et al., 2016; Pinto et al., 2020; Vuillerme et al., 2001). Specific populations demonstrate suboptimal proprioceptive reweighting, such as normal aging (Brumagne et al., 2004), lower-sports-level players (Vuillerme et al., 2001), and individuals with chronic pathologies (Mahmoudian et al., 2016; Pinto et al., 2020). Recently, two opposing behaviors were identified among healthy athletes who demonstrated optimal proprioceptive reweighting on average (Picot et al., 2022). One involved a *flexible* strategy that incorporated proprioceptive reweighting from the ankle to the lumbar signals on the foam surface, and represented two-thirds of the group. Conversely, another involved a *rigid* strategy in which individuals maintained or even increased an ankle-steered strategy, irrespective of balance conditions. While the former is considered optimal, the latter is considered an important risk factor for chronic low back pain (Claeys et al., 2015) and is associated with at-risk determinants of ACL injuries during side-cutting maneuvers (Picot et al., 2024). Persistent inquiry concerning the presence of distinct sensory profiles revolves around the potential for intervention, or whether they represent an immutable characteristic. In other words, is it possible to modify proprioceptive reweighting process among recreational athletes?

Acute muscle fatigue is a common phenomenon experienced while practicing sports, and can be seen as a catalyst for injury risk factors, subsequently causing injury (Benjaminse et al., 2019). It is characterized by a loss of maximal voluntary force and a change in electromyographic activity associated with increased perceived effort to maintain a specific force level (Enoka & Duchateau, 2008). Repetitive knee flexions may induce hamstring muscles fatigue and loss of force (Kanekar et al., 2008; Mezaour et al., 2010). Consequently, postural control can be altered (Kanekar et al., 2008; Mezaour et al., 2010); however, conflicting results exist regarding the effect of local muscle fatigue on postural stability. It could be impaired or maintained (Kanekar et al., 2008; Paillard, 2012). One possible explanation for these discrepancies is the use of sensory-motor compensatory strategies to compensate for the force loss (Mezaour et al., 2010; Paillard, 2012). Muscular fatigue effects on postural control have been mainly evaluated through the prism of the efferent pathway, or the afferent pathway (Paillard, 2012); however, little is known about the effect of fatigue on proprioceptive processing during a functional task. During repetitive muscle contractions, III/IV afferent signals are generated by metabolite accumulation, and thermal and mechanical changes (Laurin et al., 2015). They are integrated at different levels to inform the central nervous system (CNS) about muscle state (Laurin et al., 2015). They can modify afferent signal processing by provoking a central disconnection that prevents muscle spindle discharges from being converted into position sense (Proske, 2019). As a result, Allen et al. (2010) demonstrated that accuracy in position sense and kinesthesia localized in fatigued muscles were altered (Allen et al., 2010). Thus, muscle fatigue modifies central processing of proprioceptive information. Local acute muscle fatigue appears to play a role in proprioceptive weighting abilities by diminishing weight according to fatigued body part (Johanson et al., 2011).

Back-muscles (lumbar multifidus) fatigue has been found to provoke diminished lumbar proprioceptive reweighting on foam support surfaces (Johanson et al., 2011). However, it was not possible to identify whether the reweighting process was suboptimal or whether the CNS adopted an ankle-steering strategy to avoid weighting unreliable signals from the back. To elucidate the mechanism underlying this modification, muscle fatigue should be induced in a group of postural muscles that are not involved in proprioceptive reweighting evaluation. Since muscle fatigue alters the central processing of proprioceptive information, it can be used as an interesting and simple tool for investigating reweighting processing in postural tasks (Monjo et al., 2015).

Therefore, the aims of the present study were to i) evaluate the proprioceptive reweighting process following exercise-induced acute fatigue with the assumption that acute hamstring fatigue would lead to suboptimal reweighting process; ii) evaluate postural stability following exercise-induced acute fatigue hypothesizing that acute hamstring fatigue would lead to impaired stability; and iii) assess the association between the level of fatigue experienced by individuals and the level of degradation of both proprioceptive reweighting process and stability with the hypothesis that modification of reweighting process and stability would not be correlated with the loss of force.

2. Material & method

2.1. Subjects

An a priori calculation of the number of subjects required to obtain a statistical power of 0.90 and a type 1 error of 0.05, showed that at least eight subjects were needed (Johanson et al., 2011). Thirty-one undergraduate students from faculty of sports science practicing at least 4 h/week of sports were recruited.

The exclusion criteria were known neurological disorders, vestibular impairment, and trunk or lower limb injuries within the previous three months. All participants provided written informed consent, which conforms to the Declaration of the World Medical Association. The study protocol was approved by the Ethical Committee of Savoie Mont-Blanc University.

2.2. Experimental procedure

Two test conditions were used to assess the effect of fatigue on proprioceptive reweighting strategies: a pre-fatigued condition

(control condition), followed by a hamstring fatigue condition. To ensure proper reliability, the evaluation was performed as previously described (Kiers et al., 2014; Picot et al., 2022; Picot et al., 2024). The participants stood barefoot in a bipedal stance with their arms relaxed by their sides and their head in a neutral position. Foot position was standardized, and vision was prevented using opaque goggles. The subjects were instructed to stay as still and relax as possible. The task was performed on two surfaces: firm (standing on a force plate) and foam (Physiopad®; 50x41x5cm; 52 kg/m³). Four vibrators (VB115, Techno Concept, France) were placed bilaterally on the triceps surae (TS) and lumbar paravertebral muscles (LPM). For the TS, each vibrator was placed on the Achilles tendon, approximately two fingers above the lateral malleolus, and on the muscle bellies on either side of the lumbar spine between the posterior–superior iliac spines for the LPM (Kiers et al., 2014). For standardized adjustment, the vibrators were tightened and placed by the same experimenter. The vibration frequency was set to 80 Hz with approximately 0.5 mm amplitude to stimulate the muscle spindles. Each trial lasted for 60s. Recordings began 20s prior to vibration (“PRE”), vibration was applied for 20s (“VIB”) and the recording continued for another 20s during the re-stabilization period (“POST”). To avoid any learning effects, computer software automatically and randomly triggered vibrators (Kiers et al., 2014). This also ensured that neither the participant nor experimenter could anticipate the vibration site. Each condition comprised four trials: TS vibration/firm surface, LPM vibration/firm surface, TS vibration/foam surface, and LPM vibration/foam surface.

A force platform (AMTI, model BMS6“0120”, Watertown, MA, 2148 Hz) connected to a measurement card (PCIM-DAS16 card, measurement computing, A/D conversion 16bits) was used to record center of pressure (CoP) displacement during each trial. Signals were stored for subsequent analysis using Dcoll software (GRAMÉ, Laval University, Quebec, Canada). Using MATLAB (The MathWorks Inc, 2022), the data were filtered using a Butterworth low-pass fourth-order filter with a cutoff frequency of 10 Hz. The antero-posterior CoP displacement (dCoP) provoked by vibrations was calculated as the absolute amplitude between the mean CoP position in the PRE period and the mean CoP position in the VIB period (Kiers et al., 2014; Picot et al., 2022). It enabled to determine the proprioceptive weighting ratio (RPW), a reliable indicator of individual proprioceptive strategies (Kiers et al., 2014). RPW is the ratio between the effects of the vibration of the TS and LPM with $RPW = (\text{abs dCoP TS}) / (\text{abs dCoP TS} + \text{abs dCoP LPM})$. RPW of 1 indicated 100 % reliance on ankle afferences, whereas an RPW of 0 indicated 100 % reliance on lumbar afferences. The RPW evolution between the firm and foam surfaces (expressed as a percentage of the RPW on firm support) was used to dichotomize participants according to their ability to reallocate their proprioceptive dominance on each support). An eRPW ≤ 95 % corresponded to the reallocation of signals from the ankle to the lumbar region and reflected a flexible proprioceptive strategy, whereas an eRPW ≥ 105 % indicated a rigid profile associated with a lack of proprioceptive flexibility, resulting in an ankle-steered strategy. Due to the variability of the index, participants with an eRPW between 95 % and 105 % exhibited an unclassified strategy (Kiers et al., 2014; Picot et al., 2024). Only *flexible* individuals in the control condition were finally included and followed the fatigue protocol.

Postural stability was determined by analyzing the CoP velocity (Pinsault & Vuillerme, 2009) and root mean square (RMS) of CoP position (Johanson et al., 2011) in the antero-posterior axis, the most sollicitated axis to control bipedal stance (Federolf et al., 2013), during the PRE period (i.e., no vibration). CoP velocity (in $\text{cm}\cdot\text{s}^{-1}$) was calculated as the total distance covered by the CoP in the antero-posterior direction divided by the duration of the PRE period. It represents a good index of the amount of activity required to maintain stability (Pinsault & Vuillerme, 2009). RMS of the CoP position in the antero-posterior axis was calculated to characterize the baseline variability (Brumagne et al., 2004; Johanson et al., 2011). The data were averaged for trials performed on the same surface (firm and foam) under the same conditions (control and fatigue). An increase in vCoP indicated less efficient postural control (Paillard, 2012) and a higher RMS of CoP position is associated with impaired stability (Brumagne et al., 2004; Johanson et al., 2011). Thus, higher values of these parameters indicate a decrease in postural stability.

2.3. Exercise-induced fatigue protocol

The participants were placed in the prone position, hips tied to the table with a strap (at the maximum with respect to the subject's comfort) with knee joints flexed at 30°, and tibial rotation in a neutral position (Fig. 1) (Beyer et al., 2019). Prior to the fatigue

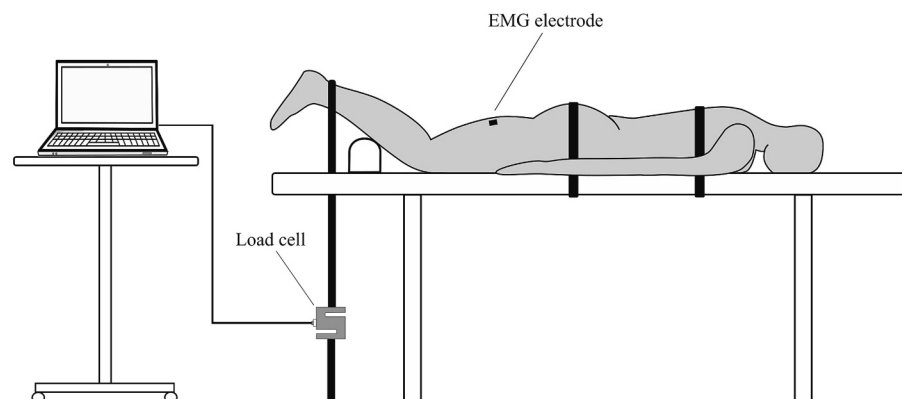


Fig. 1. Position of the exercise-induced hamstring fatigue protocol. EMG, electromyographic.

protocol, the subjects performed a standardized warm-up (10 isometric contractions at 30 %, 10 at 70 %, and 3 at 90 % of their estimated maximal voluntary contraction), followed by three maximal voluntary contractions (MVC) of 3 s duration with 60s rest after each contraction. The fatigue protocol consisted of 25 repetitions of 7 s hamstrings MVC followed by 3 s of relaxation time (Ristanis et al., 2011). In order to specifically target hamstring muscles, participants were instructed to bend their knee without raising hips from the table and to keep the ankles relax. The hips position was secured by a belt tied at a maximum relative to participant discomfort. The same examiner provided verbal encouragement for each contraction. After the fatigue protocol, hamstring MVC was performed to record the force and EMG (fatigue condition). To limit the effect of recovery, participants immediately performed a proprioceptive reweighting evaluation after the fatigue protocol.

Force and electromyographic (EMG) activity were measured during MVC, before and after the fatigue protocol. The signal over the course of the 1 s plateau of the highest MVC (the one with the highest force in the control condition) was analyzed. The force was simultaneously measured for both legs using a load cell (LCM103B-250, Omega product™, 100 Hz) attached to the ground and both legs at the level of the Achilles tendon (Fig. 1). The EMG activity of the biceps femoris and semi-tendinous muscles was recorded (Delsys, Inc., Natick, MA, USA, 2148 Hz) on the dominant limb (the preferred limb to shoot a ball on a target). The skin was shaved, abraded, and cleaned using alcohol. The electrodes were placed over the muscle belly according to the SENIAM recommendations (Hermens et al., 2000). The EMG signal was filtered using a bandpass filter of 20–450 Hz and a 4th order Butterworth filter in MATLAB. The median frequency (MF) of the EMG signal was determined to assess the appearance of fatigue. MF and force decrease in the MVC fatigue condition were indicators of fatigue (Mannion & Dolan, 1994).

2.4. Statistical analysis

Data were checked for normality and homogeneity of variance using Shapiro-Wilk and Levene's tests. Force, median frequency, RPW evolution, CoP velocity, and RMS of CoP positions were then compared between the control and fatigue conditions using a paired sample Student's *t*-test or a Wilcoxon signed-rank tests. Results were given as mean \pm standard deviation (SD) or as median \pm interquartile range (IQR) in case of non-parametric tests. RPW values were compared between the firm and foam surfaces in the control and fatigue conditions using Friedman's test and Conover's post-hoc test when the level of significance was met. The effect sizes (Cohen's *d* or matched-rank biserial correlation) were calculated. The relationship between RPW evolution and fatigue variables, (i.e., eRPW, stability variables and force) were evaluated using Spearman's rank correlation coefficients. The strength of the correlation was

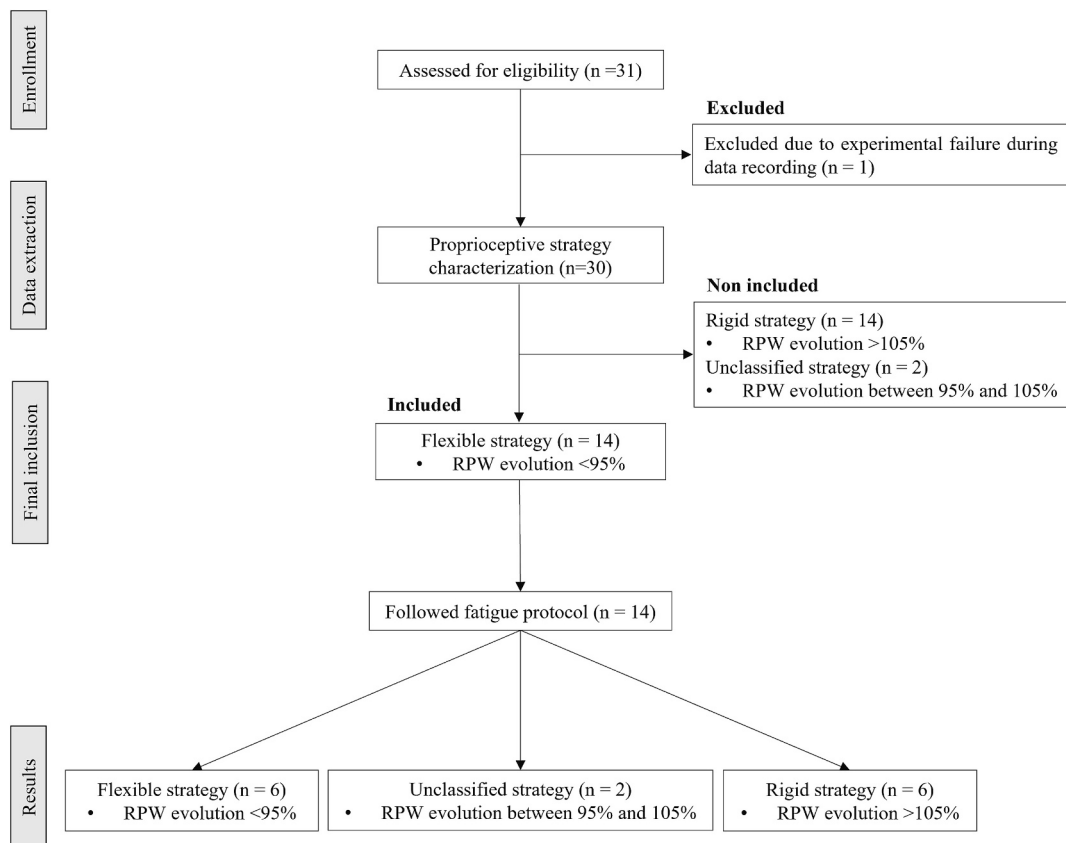


Fig. 2. Flowchart of inclusion, analysis processes and results.

classified as very weak (0.00–0.19), weak (0.20–0.39), moderate (0.40–0.59), strong (0.60–0.79), and very strong (0.80–1.0). The level of significance was set at $P < 0.05$. The statistical analysis was performed using JASP (Amsterdam 0.18.3).

3. Results

Finally, fourteen *flexible* recreational athletes were included in the study (4 females and 10 males, 23.7 ± 2.5 years, 1.79 ± 0.10 m, 76.6 ± 12.9 kg, BMI 23.7 ± 2.4 , RPW evolution 61.2 ± 26.4 %) (Fig. 2). Participants practiced various type of sports (Alpine skiing ($N = 1$), dance ($N = 1$), football ($N = 1$), Nordic skiing ($N = 2$), rugby ($N = 2$), trail running ($N = 4$), triathlon ($N = 1$), volleyball ($N = 2$)) at a recreational level.

3.1. Exercise-induced fatigue

The fatigue protocol induced a decrease in MVC (5.46 ± 1.41 N/kg vs 3.82 ± 1.56 N/kg; $P < 0.001$; $d = -1.75$) and a decrease in the median frequency (MF) in the biceps femoris (89.9 ± 25.5 Hz vs 75.0 ± 17.2 Hz; $P = 0.003$; $d = -0.96$). Only a high tendency of MF decrease was observed for the semi tendinous (80.0 ± 17.8 Hz vs 73.5 ± 16.3 Hz; $P = 0.052$, $d = -0.57$).

3.2. Proprioceptive reweighting

Among the 14 *flexible* participants included, 6 maintained their initial strategy, 2 converted in an unclassified strategy, and 6 converted in a *rigid* strategy following the fatigue protocol (Fig. 2).

Using a Wilcoxon signed-rank test, compared with the control condition, hamstring muscle fatigue induced an increase in RPW evolution (67.2 (26.4) % vs. 102.0 (55.5) %; $P = 0.002$; $d = 0.87$) (Fig. 3A, B). Thirteen participants impaired their reweighting capacity (i.e., increased eRPW) following exercise-induced fatigue, and one participant improved its capacity.

Friedman test performed on RPW values in the four conditions revealed significant differences between conditions (Chi-Squared = 11.55; $P = 0.009$), with higher RPW on the firm than on the foam surface in the control condition (0.70 ± 0.22 vs 0.43 ± 0.24 ; $P = 0.002$) (Fig. 4A), but not following exercise-induced fatigue (0.62 ± 0.24 vs 0.64 ± 0.23 , $P = 0.773$) (Fig. 4B). Compared to the control condition, RPW values in the foam support surface tended to be higher in the hamstring fatigue condition (0.43 ± 0.24 vs 0.64 ± 0.23 ; $P = 0.057$) but not on the firm surface (0.70 ± 0.22 vs 0.62 ± 0.24 ; $P = 0.102$)

3.3. Postural stability

On the firm surface, increased CoP velocity ($P = 0.045$) and RMS of the CoP position ($P = 0.005$) were observed in the fatigue condition (Table 1). On the foam surface, no modification in the CoP velocity or RMS of the CoP position was observed between the control and fatigue conditions.

3.4. Relation between parameters

The modification of RPW evolution induced by the fatigue protocol was not significantly correlated with the level of hamstring muscle fatigue for neither the modification of force, biceps femoris median frequency, or semi-tendinous median frequency (Table 2). There was no significant relationship between the modification of RPW evolution and stability parameters, neither on the firm nor on the foam surface (Table 2) and between force loss and stability parameters (Table 3).

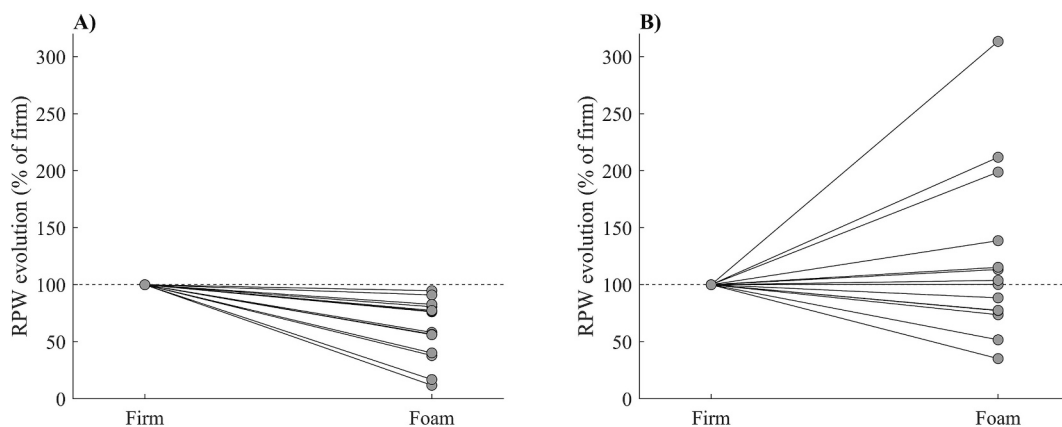


Fig. 3. Individual RPW evolution from the firm to the foam support surface in A) control condition and B) fatigue condition. An evolution <95 % represents a *flexible* strategy, whereas an evolution >105 % represents a *rigid* strategy.

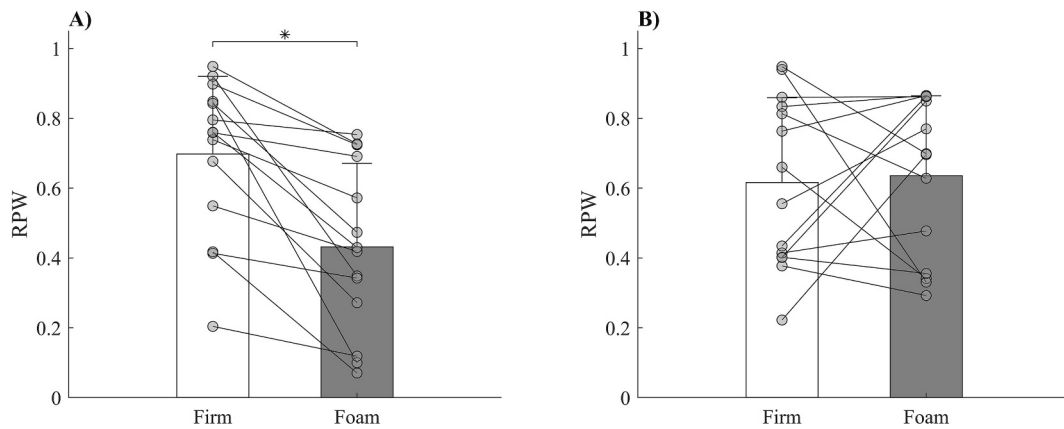


Fig. 4. Mean ± SD and individual RPW values for the firm and foam support surfaces in A) control condition and B) fatigue condition. * $P < 0.01$.

Table 1

Postural stability parameters in the control and fatigue conditions (mean ± SD or median ± IQR for non-parametric tests).

	Control (mean ± SD)	Fatigue (mean ± SD)	P value	Effect size
Firm surface				
CoP velocity ($\text{cm}\cdot\text{s}^{-1}$)	0.91 ± 0.20	1.05 ± 0.28	0.045	0.59
RMS (cm)*	0.50 ± 0.16	0.75 ± 0.27	0.005	0.87
Foam surface				
CoP velocity ($\text{cm}\cdot\text{s}^{-1}$)	1.91 ± 0.50	1.96 ± 0.45	0.646	0.09
RMS (cm)	1.04 ± 0.25	1.09 ± 0.41	0.746	0.04

Note: *, indicates non-parametric test express as median (IQR), CoP, center of pressure; RMS, root mean square; SD, standard deviation.

4. Discussion

This study aimed to i) characterize the proprioceptive reweighting process following acute hamstring muscles fatigue; ii) characterize the effect of acute hamstring muscles fatigue on stability which revealed impaired stability only on a firm surface; and iii) assess whether hamstring muscles fatigue, proprioceptive reweighting and postural stability were related. Results revealed that fatigue led to an inability to adapt proprioceptive weighting when the support surface was changed from firm to foam, as demonstrated by the higher RPW evolution values in the fatigue condition. In addition, stability was only impaired on the firm surface and no relationship between hamstring muscles fatigue, proprioceptive reweighting, and postural stability was observed. These findings suggest that recreational athletes who use a flexible strategy in the non-fatigued condition degrade their proprioceptive reweighting strategy and may adopt a suboptimal strategy (eRPW >105 %) in a hamstrings fatigue state.

4.1. Exercise-induced fatigue

The fatigue protocol provoked a significant decline in force and median frequency in the biceps femoris. Only the median frequency of the semi tendinosus tended to decrease. Therefore, it is reasonable to conclude that this protocol effectively induced hamstring

Table 2

Pairwise correlations between the modification from the control to the fatigue condition of RPW evolution, muscle fatigue variables and stability parameters variables.

	Spearman's rank correlation coefficients [confidence interval]	P value
RPW evolution and fatigue variables		
Force	0.39 [-0.17; 0.77]	0.158
MF BF	0.05 [-0.50; 0.56]	0.880
MF ST	-0.12 [-0.61; 0.44]	0.682
RPW evolution and stability variables		
vCoP on firm surface	0.09 [-0.47; 0.59]	0.773
vCoP on foam surface	-0.32 [-0.73; 0.26]	0.267
CoP RMS on firm surface	0.10 [-0.46; 0.60]	0.739
CoP RMS on foam surface	0.07 [-0.48; 0.60]	0.808

Note: BF, biceps femoris, CoP, center of pressure; MF, median frequency; RMS, root mean square; RPW, relative proprioceptive weighting; ST, semi tendinosus; vCoP, center of pressure velocity.

Table 3

Pairwise correlations between the modification of force (i.e., motor output) and stability parameters in fatigue condition.

	Spearman's rank correlation coefficients [confidence interval]	P value
vCoP on firm surface	-0.04 [-0.56;0.50]	0.881
vCoP on foam surface	0.20 [-0.37; 0.67]	0.502
CoP RMS on firm surface	-0.19 [-0.66; 0.38]	0.501
CoP RMS on foam surface	0.15 [-0.41; 0.63]	0.616

Note: CoP, center of pressure; RMS, root mean square; vCoP, center of pressure velocity.

muscles fatigue in this muscle group.

4.2. Proprioceptive reweighting process

Regarding RPW evolution, an inability to shift proprioceptive weighting when postural conditions changed in the fatigue condition was observed. The participants maintained their ankle reliance on the foam surface under fatigue conditions, whereas they were able to decrease it in the control condition. In the control condition, 14 participants were *flexible*, while in the fatigue condition, 6 became *rigid*, 2 were unclassified, and 6 were still *flexible*.

Impaired proprioceptive reweighting was observed in a study by Johanson et al. (2011) when the back muscles (lumbar multifidus) were fatigued (Johanson et al., 2011). The exact origin of this modification was unclear while it could traduce i) an inability of the CNS to reweigh proprioceptive information or ii) an optimal adaptation to avoid weighing unreliable lumbar signals. Indeed, lumbar muscle fatigue has been linked to decreased proprioceptive acuity (Proske, 2019), which could lead to increased reliance on proprioceptive input from other sources, such as the ankles. Thus, this study provided limited information about the possibility of acting upon the proprioceptive reweighting process because fatigue targeted the lumbar muscles involved in the reweighting process. Results from this study indicate that local fatigue of hamstring muscles leads to a decrease of proprioceptive reweighting ability. Muscular fatigue is thought to modify the afferent signal processing at the central level (Proske, 2019). Liu et al. (2003) used functional magnetic resonance imaging to analyze the human brain activation following an exercise-induced fatigue. They identified an increased activation of the cerebellum following fatigue induced by sustained or intermittent submaximal handgrip contractions (Liu et al., 2003). In the healthy population, increased activation of cerebellar lobule V (left and right) has been associated with increased reliance on ankle signals and a higher RPW (Goossens et al., 2019). Cerebellar lobule V plays a central role in sensorimotor control and motor coordination (Manto et al., 2012). Thus, it can be speculated that hamstring muscles fatigue may provoked central alterations that led to an ankle steered strategy on foam surface, i.e., an impaired proprioceptive reweighting. Nevertheless, altered motor output (i.e., force loss) may not be excluded as a possible reason of impaired postural control. Fatigue of postural muscles is known to induce compensatory sensory-motor strategies that lead to partial or complete preservation of stability (Kanekar et al., 2008; Paillard, 2012). The absence of a relationship between fatigue level indicators (i.e., motor output impairments) and both proprioceptive reweighting evolution and stability variables suggests an impairment of the sensory processing in addition to potential motor output deficits. These findings support the hypothesis that central processing of afferent signals may be compromised by hamstring fatigue, which may account for the observed alterations in proprioceptive reweighting.

4.3. Postural stability

Postural stability was impaired by hamstring muscle fatigue on the firm surface but not on the foam surface. Previous studies have demonstrated that local muscle fatigue of postural muscles could involve the modification of activated muscles, increased joint stiffness, increased rotation of motor units, and increased amplitude of motor reflexes (Paillard, 2012). These modifications in postural regulation can lead to impaired stability, but this is not always the case (Paillard, 2012). On a firm surface, stability is maintained with a high level of soleus and biceps femoris activation (Promsri, 2022). Thus, fatiguing hamstrings may lead to important perturbation which could not be compensated in the regulation of posture then leading to impaired stability on this surface. Hamstring muscles fatigue induced a medium effect on the CoP velocity and a large effect on the CoP RMS, as indicated by Cohen's d. Kanekar et al. (2008) evaluated the effect of hamstring muscles fatigue on postural control (Kanekar et al., 2008). They identified decreased semitendinous preactivity but no modifications in CoP antero-posterior displacement (i.e., conservation of the stability) when testing anticipatory postural adjustments before and after hamstrings fatigue. A similar loss of force was observed in both the study by Kanekar et al. and the present one (-26 % vs. -30 %, respectively). However, further comparison is difficult since they evaluated CoP parameters during short period (between 50 ms and 150 ms). On the foam surface, posture is regulated with more muscles at higher activation levels (Promsri, 2022) thus, fatiguing hamstrings may have a negligible impact on overall posture regulation and stability on an unstable surface. Although the level of stability is maintained on the foam surface, the alteration of proprioceptive reweighting in the fatigue condition suggests proprioceptive processing impairment, less adaptability and over-exposure to injury risk factors in more complex postural situation (Picot et al., 2024). No significant relationship was observed between the degradation of motor output (i.e., force loss) and stability or eRPW on both firm and foam surfaces. These results indicate that postural control impairment following muscle fatigue could results from a complex combination of sensory-motor alterations depending on the individuals and the environment.

4.4. Clinical implications

The results of this study suggest that hamstring muscles fatigue decreases the ability of the central nervous system to perform proprioceptive reweighting when the postural conditions change. Rigid individuals exhibit at-risk determinants of ACL injuries (Picot et al., 2024) and a higher risk of developing low back pain (Claeys et al., 2015). Muscle fatigue dynamically impairs the reweighting process and stability of a firm surface, both of which are associated with injury risk factors (Claeys et al., 2015; Picot et al., 2024). This could explain why an acute spike in workload provoking acute muscle fatigue may serve as a mediator that can lead to injury (Benjaminse et al., 2019). Prospective cohort studies are necessary to provide insight into the interaction between proprioceptive reweighting and injury risk. Proprioceptive reweighting strategy appears to be modifiable and degraded by muscular fatigue. These results are promising because they highlight the possibility of modifying the proprioceptive reweighting profiles. Indeed, the profile may be degraded; thus, further studies should explore whether it is possible to enhance it through specific training and rehabilitation.

4.5. Limitations

The overall proprioceptive reweighting evaluation lasted less than 5 min, so hamstring muscles fatigue might have partially recovered when performing the last postural control trials, explaining the variability observed in proprioceptive reweighting and stability. However, complete recovery was not expected during this time frame (Zhou, 1996). To counteract this effect and the learning effect (Kiers et al., 2014), the trials order was randomized. Regarding the evolution of proprioceptive weighting and the center of pressure root mean square, only one subject did not respond in the same direction as the group. However, we cannot exclude the possibility that the effects of fatigue on proprioceptive reweighting and stability on the firm surface were underestimated or that the potential effect of fatigue on foam surface stability was masked. Effects of fatigue on the motor output and the sensory processing during postural task are difficult to analyze completely independently, however tendinous vibrations act like a probe of the proprioceptive processing (Kiers et al., 2014) and is now the most accessible tool to study proprioceptive processing in functional task. Gastrocnemius and paraspinal muscles activity were not measured in this study. Gastrocnemius activity was limited by instructing participants to keep their ankle relax (avoiding plantarflexion) and paraspinal recruitment was limited by stabilizing hips with a belt. The position used to induce hamstring muscles fatigue is known to engage the hamstring at a high activity level (Beyer et al., 2019; Rutherford et al., 2011), whereas the gastrocnemius plays a minor role in knee flexion (Li et al., 2002). However, the exact level of fatigue experience by the gastrocnemius and lumbar muscles was unknown. Fatigue is a complex phenomenon that leads to various postural control effects (Benjaminse et al., 2019; Paillard, 2012). The response may vary according to subject characteristics (Paillard, 2012); therefore, as a first step in the comprehension of proprioceptive reweighting process modulation with fatigue, only *flexible* individuals were included. This study focused on individuals with an optimal strategy. Since previous work highlights that it is more complicated to improve proprioceptive weighting among individuals who already exhibit an optimal strategy (Pavailler et al., 2016) we therefore hypothesized that it might be more complicated to impair suboptimal strategies. This study only included individuals who exhibited a flexible strategy in the control condition. Therefore, the degradation of the strategy and eRPW induced by the hamstring muscle fatigue may not be transferable to individuals who exhibited a rigid and/or an unclassified strategy in the control condition. To our knowledge, only one study has evaluated the effect of muscle fatigue on proprioceptive reweighting (Johanson et al., 2011); thus, comparisons with literature are limited. However, further studies are required to confirm these results.

5. Conclusion

Acute hamstring fatigue impairs proprioceptive reweighting when the surface constraint is modified. The subjects who were initially *flexible* tended to be more *rigid* in the fatigue condition independently of the level of fatigue. This finding suggests that the proprioceptive reweighting strategy is modifiable. Hamstring fatigue also impairs the stability of participants on a firm surface. Whether these modifications of proprioceptive reweighting and stability in fatigue conditions predispose participants to injuries such as ACL rupture remains to be determined.

Funding statement

This research did not receive any specific grants from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Telma Sagnard: Writing – original draft, Visualization, Software, Methodology, Investigation, Conceptualization. **Brice Picot:** Writing – review & editing, Supervision, Project administration, Data curation, Conceptualization. **Nicolas Forestier:** Writing – review & editing, Visualization, Supervision, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

The authors extend their gratitude to all participants for their valuable contributions to this study. They are also grateful to the reviewer and editor for their valuable feedback, which has contributed to the improvement of the article.

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