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Continuous and discrete electromyographic analysis of trunk and hip extensor musculature during the Biering-Sørensen test in athletes with a history of hamstring strain injury

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ABSTRACT

This study examined electromyography (EMG) responses of trunk and hip extensor muscles during the Biering-Sørensen test in athletes with a history of hamstring strain injury (HSI). 34 athletes with HSI (occurring an average of 6.68 months prior to testing; 28 involving the biceps femoris long head (BFlh), 5 the semitendinosus, and 1 undefined) and 25 uninjured performed the Biering-Sørensen test. EMG signals were recorded from the erector spinae (ES), BFlh, and gluteus maximus (GMax). Group differences in continuous median frequency (MNF) and mean absolute value (MAV) waveforms were analyzed using statistical parametric mapping and slopes and initial values were examined using linear mixed-effects models. The HSI group demonstrated significantly lower endurance scores compared to controls (162.1 ± 64.4 s vs. 192.1 ± 47.4 s; $p = 0.036$). MNF waveforms did not differ between groups ($p > 0.05$). The ES normalized MAV values were significantly higher in the HSI group compared to the uninjured group during the initial and terminal phases of the task ($p < 0.05$). Athletes with HSI exhibited higher initial ES and BFlh MAV than controls as well as a lower GMax MNF slope in the full sample analysis ($p = 0.019$), although this effect was not confirmed in subgroup analyses. The altered EMG patterns in athletes with HSI history likely contribute to reduced endurance and suggest that rehabilitation should prioritize re-establishing balance contribution across the trunk and hip extensors.

1. Introduction

Hamstring strain injuries (HSIs) are among the most prevalent non-contact injuries in athletes, often leading to prolonged recovery and high recurrence rates (Kekelekis et al., 2024). Even after clinical recovery, athletes with prior HSI frequently exhibit persistent neuromuscular deficits, such as reduced eccentric strength and altered activation of both the hamstrings and surrounding musculature (Fyfe et al., 2013). These adaptations extend beyond the injured muscle itself, influencing trunk and hip muscle coordination, which is critical for postural control, load transfer, and high-speed athletic performance (Schuermans et al., 2017b; Schuermans et al., 2017a).

Recent research has identified the importance of exercises of the lumbo-pelvic region for preventing and rehabilitating HSIs (Schuermans et al., 2017a; Higashihara et al., 2022; O'Sullivan et al., 2022). Early research has identified that when performing trunk extension tasks there is considerable simultaneous activation of several muscles of the lumbopelvic region, including the biceps femoris long head (BFlh), gluteus maximus (GMax) and erector spinae (ES) (Moffroid et al., 1994; Plamondon et al., 2004). It is not, therefore, a surprise that these muscles are considered as key contributors to trunk and hip extension during sport-specific tasks (Schuermans et al., 2017a; Higashihara et al., 2022). Following a HSI, compensatory strategies may shift the relative contributions of trunk and hip extensors, potentially reducing lumbopelvic stability and increasing reinjury risk (Schuermans et al., 2017a; Higashihara et al., 2022). Some studies have examined associations between isometric trunk extension measures and hamstring injury risk (Hajek et al., 2024) but evidence on neuromuscular activation patterns of multiple muscles is currently missing.

Evaluating how these muscles respond under fatigue is crucial, as fatigue is known to exacerbate neuromuscular deficits and alter load-sharing patterns of the involved muscles (Kellis and Liassou, 2009).

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The Biering-Sørensen test is widely used for functional assessment of the trunk extensor endurance (Biering-Sørensen, 1984; Coorevits et al., 2008; Shaw et al., 2024). While it has been established that during the test, there is considerable co-activation of the ES, BFlh and GMax (Moffroid et al., 1994; Sparto et al., 1997; Pitcher et al., 2007; Coorevits et al., 2008; Shaw et al., 2024), very little is known about how athletes with a HSI respond during this test. Some have incorporated the Biering-Sørensen test as part of multifactorial screening batteries (Liveris et al., 2025), but this does not provide direct evidence on fatigue responses during isometric trunk extension after HSI. Hence, although control of the lumbo-pelvic region has been implicated in both the etiology and prevention of HSI (Schuermans et al., 2017a; Hajek et al., 2024), the role of isometric trunk fatigability after injury remains unexplored.

Muscle fatigue during sustained contractions is commonly examined through spectral frequency shifts in the EMG signal (Mannion and Dolan, 1994; Dolan et al., 1995; Muceli and Merletti, 2024). In many studies, trunk extensor muscle EMG fatigue responses have been quantified by examining the slope of median frequency (MNF) decline over time, often using linear regression in combination with initial MNF values, to characterize overall fatigue rates (Ng and Richardson, 1996; Sparto et al., 1997; Plamondon et al., 2004). Yet, a review study on ES activation has recommended the use of advanced processing techniques, noting that traditional statistical methods applied to frequency-based indices may fail to identify exactly when critical shifts in muscle recruitment occur during fatiguing tasks (Mohseni Bandpei et al., 2014). To overcome the limitations of the traditional analytical approaches, recent biomechanical research has trended toward the use of one-dimensional statistical parametric mapping (SPM1D) (Pataky, 2012). Rather than reducing EMG signals to discrete summary metrics, SPM1D evaluates the entire EMG waveform, identifying specific temporal "clusters" of significance that might otherwise be masked by averaging (Robinson et al., 2015). In parallel, Linear Mixed-Effects Models (LMM) can be applied to derived summary metrics (e.g., slopes and initial values) to examine coordinated fatigue responses across synergistic muscles while accounting for within-subject variability (Mota, 2023). Accordingly, the combined use of SPM1D and LMM provides complementary perspectives, capturing both the temporal structure of EMG responses and overall fatigue characteristics. Although these approaches have been used in biomechanical and physiological research, their combined application to the analysis of continuous muscle fatigue responses of the lumbo-pelvic and hamstring musculature during the Biering-Sørensen test in athletes with HSI remains scarce. Specifically, it remains unclear whether athletes with a history of HSI exhibit altered time-dependent fatigue behavior in the lumbo-pelvic and hamstring musculature during sustained isometric trunk extension, not only in terms of overall fatigue magnitude but also in the timing and distribution of EMG frequency and amplitude changes across the task. As frequency-derived EMG indices and amplitude measures capture different physiological aspects of neuromuscular fatigue, a combined analytical approach is required: continuous waveform-based methods are needed to identify when fatigue-related changes occur within the contraction, whereas discrete fatigue parameters quantify overall fatigue magnitude across the trial.

The aim of this study was to investigate differences in EMG frequency and amplitude responses of the ES, GMax, and BFlh during the Biering-Sørensen test in athletes with a history of HSI compared to uninjured controls. Studying these differences is important because it can reveal altered fatigue-related neuromuscular strategies in the lumbo-pelvic region, which may inform targeted rehabilitation and injury-prevention strategies. It was hypothesized that athletes with HSI would display a lower Biering-Sørensen test score, a greater EMG signal amplitude of all muscles during the test and an altered EMG frequency response during the test compared to uninjured athletes.

2. Methods

2.1. Participants

An a priori sample size estimation was conducted using GLIMMPSE to determine the minimum number of participants required to detect between-group differences in fatigue-related neuromuscular outcomes within a mixed-model framework (Kreidler et al., 2013). Power calculations were based on a repeated-measures design with one between-subject factor (Group: injured vs. non-injured) and one within-subject factor (Muscle: three levels), assuming a moderate effect size (Cohen's $f = 0.25$) for the Group $\times$ Muscle interaction, an alpha level of 0.05, and statistical power of 0.80. The selected effect size was based on conventional benchmarks proposed by Cohen (1988), while the alpha and power levels reflect commonly accepted standards in biomedical research. These parameters were selected based on commonly accepted conventions in biomedical research in the absence of directly comparable prior data. Conservative assumptions were made regarding within-subject correlations ($\rho = 0.5$) and sphericity. The analysis indicated that a total sample size of approximately 48 participants would be sufficient to detect the targeted effects. To account for unequal group allocation, potential data loss, recruitment targets were increased.

Twenty-five amateur adolescent and adult track and field and soccer athletes (17.6 $\pm$ 3.24 years, 64.12 $\pm$ 10.81 kg, 171.6 $\pm$ 10.19 cm) without a previous HSI and thirty-four athletes (18.74 $\pm$ 3.88 years, 69.04 $\pm$ 14.64 kg, 170.29 $\pm$ 10.22 cm) with a previous HSI participated. Injured players had a grade II hamstring strain (Mueller-Wohlfahrt et al., 2013) during the past year (6.63 $\pm$ 3.38 months, return to sport time after injury 4.08 $\pm$ 1.61 weeks) which was verified by magnetic resonance imaging or ultrasound findings and clinical examination by a qualified medical doctor. Of these, 28 athletes had a BFlh injury, 5 had a semitendinosus injury and in 1 athlete the injury location was not reported. No participant reported bilateral hamstring injuries, and no participants had more than one injury within the past 12 months. The main mechanisms of injury were sprinting (17 athletes), change of direction (6 athletes), landing (4 athletes) and isolated incidents included kicking, contact with another player while in two cases, the mechanisms were not reported. The participants gave their informed written consent, and the protocol was approved by the Institutional Ethics Committee (approval number: 18/2022). The final sample (25 non-injured and 34 injured athletes) exceeded the minimum estimated requirement and was considered adequate to support all planned analyses. The injured limb was identified and recorded for each participant in the HSI group, allowing distinction between injured and non-injured sides in subsequent analyses.

2.2. Experimental protocol

The Biering-Sørensen back extension test was used to assess isometric endurance of the trunk extensor musculature (Biering-Sørensen, 1984). Participants were positioned prone on a physiotherapy bed with the anterior superior iliac spines aligned with the edge of the bed (Fig. 1). The lower extremities and pelvis were secured to the bed using non-elastic belts to minimize movement and stabilize the lower body. The upper trunk, head, and arms were unsupported and extended beyond the edge of the bed. At the start of the test, participants were instructed to maintain the trunk in a horizontal position, aligned with the lower limbs, while keeping the arms crossed over the chest (or hands positioned as specified by the protocol). The test commenced when the participant achieved the correct horizontal position. Participants were encouraged to maintain the position for a maximum duration of 240 s. Test termination criteria included inability to maintain the horizontal posture despite verbal encouragement, excessive trunk flexion, voluntary termination due to inability to maintain the required position, or completion of the 240-s time limit. Time to task failure was recorded as the outcome measure.

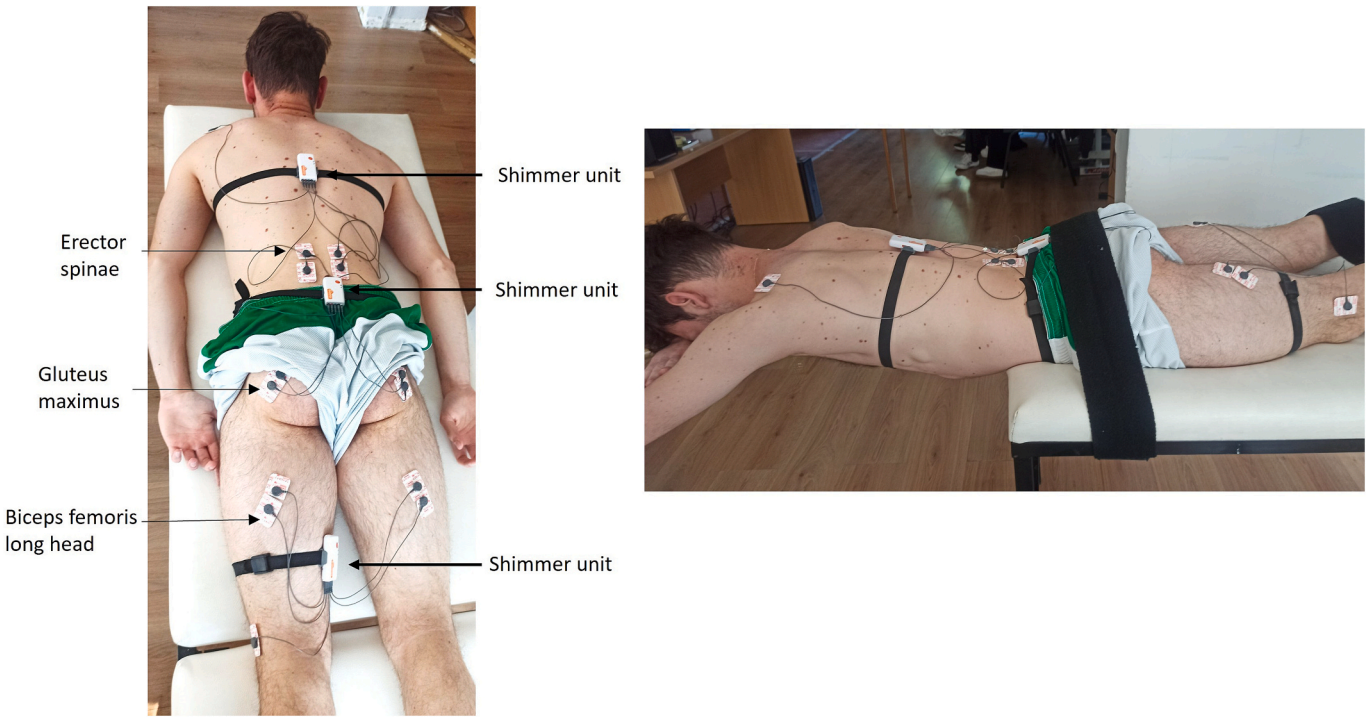

Fig. 1. Illustrations of the experimental set-up. Left: Bipolar surface electromyography electrodes were placed on the erector spinae, gluteus maximus, and biceps femoris long head from each side and interfaced to three wireless Shimmer EMG amplifier units. Right: An illustration of the participant position when performing the Biering-Sørensen test. Straps were used to secure the pelvis and the legs. The participant maintained horizontal position for a maximum duration of 240 s.

Prior to the fatigue tests, the participants performed maximum voluntary contractions (MVCs) against resistance provided by a hand-held dynamometer (Activforce2, San Diego, USA) for EMG amplitude normalization purposes. For each condition, three maximal 5-s contractions were performed, separated by adequate rest periods. For ES, participants were stabilized using straps across the pelvis and lower extremities. The T4 spinous process and posterior superior iliac spines were identified and marked. Participants raised the trunk to approximately 30° above horizontal, with the arms held horizontally (shoulder abduction, elbows flexed to 90°), and exerted maximal effort against the dynamometer. For the GMax, hip extension tests were performed in the prone position, with the pelvis and contralateral limb secured, and the dynamometer positioned 5–7 cm proximal to the knee joint line (Thorborg et al., 2010). Maximal efforts were performed with the hip in neutral alignment and the knee at 90°. For BFlh, knee flexion MVCs were conducted in the prone position at 0° of knee flexion. The dynamometer was placed on the posterior shank at 80% of the distance between the lateral epicondyle and lateral malleolus. During MVC efforts, standardized verbal encouragement was provided to ensure maximal effort. No visual feedback was provided.

2.3. EMG recording

Surface electrodes (Skintact FS50, Leonhard Lang GmbH, Austria) in a bipolar configuration, with an inter-electrode distance of 1.5 cm were used to record the EMG signal using three wireless (via Bluetooth) Shimmer3 EMG units (Shimmer Research Ltd., Dublin, Ireland) (Fig. 1). The EMG signals were digitized through a 24-bit analog-to-digital converter with a gain of 1000 and a sampling frequency of 1024 Hz. The raw signals were processed through a zero-phase fourth-order Butterworth band-pass filter (frequency range of 15 to 450 Hz). EMG recordings were obtained bilaterally. Due to a technical failure of one Shimmer unit during data collection, valid EMG recordings for the GMax were available for a subset of participants ($n = 17$, 9 from the HSI and 8 from the non-injured group), whereas complete datasets were obtained for the ES and BFlh.

Electrode placement followed the SENIAM recommendations (Hermens et al., 2000). For ES, the electrodes were placed on the longissimus lumborum, approximately two fingers width laterally from the spinal process of 1st lumbar ligament (L1). For BFlh, they were placed midway between the ischial tuberosity and the fibular head, aligned with muscle fibers. For the GMax, the position was located at the midpoint between the sacral vertebrae and the greater trochanter, following the line from the posterior superior iliac spine to the posterior mid-thigh. The electrode positions were marked on the skin, the skin was shaved and cleaned with alcohol wipes. Ground electrodes for every shimmer unit were placed on bony landmarks near the measurement location. EMG recordings were limited to the BFlh among the hamstring muscles, as the study specifically aimed to examine its role within the posterior chain during trunk extension tasks, given its documented mechanical linkage with lumbopelvic function (Vleeming et al., 1995).

2.4. Data processing

The EMG data were analyzed in Noraxon MR4 software (v.4.0116, Noraxon Inc. Scottsdale, AZ, USA). For frequency-domain analysis, the Median Frequency (MNF) was computed using a Fast Fourier Transform (FFT) applied to consecutive, non-overlapping 1-s segments of the EMG signal throughout the Biering-Sørensen test. The algorithm implemented in MR4 processes each segment without the application of explicit windowing functions (e.g., Hann or Hamming). FFT computation was performed using a power-of-2 implementation with zero-padding applied where necessary. The use of 1-s non-overlapping segments is consistent with established EMG fatigue analysis procedures for sustained isometric contractions, where short-time quasi-stationarity is assumed and temporal changes in spectral parameters are evaluated using sequential analyses (Bekka and Chikouche, 2003; De la Fuente et al., 2021).

Concurrently, the time-domain amplitude was determined by calculating the Mean Absolute Value (MAV) for each one-second

window. The mean MAV which was calculated using the 2–4 s of the MVC was used to normalize the MAV values during the fatigue test. To facilitate comparisons between subjects with varying endurance capacities, all extracted one-second data points for both frequency and amplitude were time-normalized from 0 to 100% of the total test duration using linear interpolation.

To examine strategies beyond time-specific effects, discrete fatigue-related metrics were derived from the EMG waveforms. For each subject and muscle, left and right sides were averaged to obtain a single representative waveform, as preliminary SPM1D analysis indicated no significant main effects of Side or Group × Side interactions. Linear regression was then applied across the normalized task duration (0–100%) to compute the fatigue slope, representing the rate of change in the EMG parameter (MNF or MAV) over time, and the Initial Value, defined as the EMG value at task onset.

2.5. Statistical analysis

All statistical analyses were performed using Python (version 3.10; (Van Rossum and Drake, 2009), employing the *spm1d (*Pataky, 2012*), statsmodels (*Seabold and Perktold, 2010*),* and *scipy.stats* (Virtanen et al., 2020) libraries. Biering-Sørensen test scores were compared between groups using an independent-samples *t*-test. The magnitude of between-group differences was quantified using Cohen's *d* effect size. Cohen's d effect sizes were interpreted as small (0.2), medium (0.5), and large (0.8), according to conventional thresholds (Cohen, 1988). Time-normalized MNF and MAV signals were analyzed using one-dimensional SPM1D (Pataky, 2012; Robinson et al., 2015). For each muscle, three SPM1D tests were conducted to evaluate the main effects of Group (injured vs. non-injured), Side, and their interaction. Specifically, the main effect of Group was assessed using an independent-samples *t*-test applied to side-averaged waveforms, the main effect of Side was assessed using a paired *t*-test, and the Group × Side interaction was evaluated using an independent-samples *t*-test applied to side-difference waveforms. Statistical inference was performed on the resulting SPM{t} trajectories, with significant supra-threshold clusters identified using Random Field Theory to control the family-wise error rate across the time continuum.

MNF and normalized MAV slopes and initial values were analyzed using LMMs with muscle, group, and their interaction specified as fixed effects, and a random intercept for subject to account for the repeated-measures structure of the three-muscle dataset. Slope and initial value parameters were extracted to provide compact summary descriptors of overall fatigue progression and starting activation levels across the task, as commonly reported in EMG fatigue research. This approach was selected to complement the SPM1D analyses, which separately evaluated the full time-resolved EMG waveforms and localized temporal effects without data reduction. Therefore, the LMM analyses were intended to characterize overall fatigue behavior rather than model the complete temporal structure of the EMG signals. The BFlh data served as the reference level for muscle-related comparisons. LMMs were selected in part due to their ability to accommodate unbalanced datasets, allowing inclusion of all available observations despite missing EMG data for the gluteus maximus in a subset of participants. Statistical significance of fixed effects in the LMM was evaluated using Wald tests (*z*-statistics). When a significant interaction or a strong statistical trend ($p < 0.10$) was observed, simple main effects of Group within each muscle were examined using model-based *t*-tests with estimated degrees of freedom, derived from the LMM. This dual approach ensured that localized neuromuscular changes were identified even if global interaction effects were not observed. The level of significance was set at $a = 0.05$. Values of $0.05 \leq p < 0.10$ were considered indicative of statistical trends and were used to guide exploratory analyses only. Additionally, to assess robustness of findings involving the GMax, subgroup analyses were performed including only participants with complete GMax data.

3. Results

3.1. Biering-Sørensen endurance capacity

A significant difference in endurance duration was observed between groups ($t_{65} = 2.137$, $p = 0.036$). The non-injured group demonstrated a longer time-to-failure (192.1 ± 47.4 s) compared to the HSI group (162.1 ± 64.4 s), corresponding to a medium effect size (Cohen's $d = 0.52$).

3.2. MNF and MAV fatigue curves

Mean group – normalized time curves are presented in Figs. 2 and 3, for MNF and normalized MAV values, respectively. The SPM1D analysis showed non statistically significant Group by Side interaction or main effects for Group or Side on all MNF curves as well as on BFlh and GMax MAV curves ($p > 0.05$). There was, however, a significant main effect of Group on ES MAV. The most prominent difference was identified during the first half of the test (0–52.9% of task duration, $p < 0.001$), characterized by a very large effect size (peak $t = 5.332$, Cohen's $d = 1.38$). Additional significant clusters were identified intermittently throughout the remainder of the test (e.g., 65.2–73.0%, $p = 0.003$; 79.2–83.8%, $p = 0.019$; and 84.3–90.9%, $p = 0.007$), with effect sizes remaining in the medium-to-large range ($d > 0.75$).

3.3. MNF slopes and initial values

The LMM analysis (Table 1) showed that Muscle by Group interaction on MNF slopes did not reach statistical significance ($z = 1.84$, $p = 0.066$). Given the absence of significant interaction, follow-up comparisons were conducted on an exploratory basis to examine potential muscle-specific differences. These indicated that the non-injured group had a significantly steeper GMax MNF slope compared to the HSI group ($t_{57} = -2.64$, $p = 0.019$, $d = 0.69$), while no group differences were found for the ES ($p = 0.882$) or BFlh ($p = 0.063$). A significant main effect of Muscle was observed ($z = -5.65$, $p < 0.001$), indicating that fatigue rates differed across the three muscles regardless of injury history, with the ES exhibiting the steepest slopes (Table 1). Furthermore, for Initial MNF values, there were no significant Muscle by Group interactions, nor any main effects of Muscle or Group ($p > 0.05$). Subgroup analyses including only participants with GMax data indicated that the previously observed GMax difference was not replicated in the reduced sample, whereas ES and BFlh patterns remained broadly similar.

3.4. MAV slopes and initial values

The LMM analysis of MAV Slopes (Table 2) showed non-significant main effect of Group ($z = 0.11$, $p = 0.913$) or Muscle by Group interactions ($p > 0.25$). In contrast, a significant Muscle by Group interaction for initial MAV was found ($z = 9.65$, $p = 0.005$). Post-hoc analysis showed that the HSI group had a significantly higher normalized MAV of the ES ($z = -4.74$, $p < 0.001$, $d = 1.23$) and the BFlh ($z = -2.11$, $p = 0.039$, $d = 0.55$) compared to the non-injured group, while no group difference was observed for the GMax ($p = 0.163$). Finally, a significant main effect for Muscle was observed ($p < 0.001$), with the ES demonstrating higher normalized MAV than the hip extensors. Subgroup analyses for initial MAV values showed attenuated group differences in ES and BFlh, while maintaining the same direction of effects, indicating sensitivity to reduced sample size but overall consistency in pattern.

4. Discussion

The main findings were that athletes with prior HSI showed a lower Biering-Sørensen score, no difference in MNF normalized waveforms, a greater ES normalized MAV during the initial and terminal phases of the task but similar BFlh and GMax MAV waveforms compared to the non-

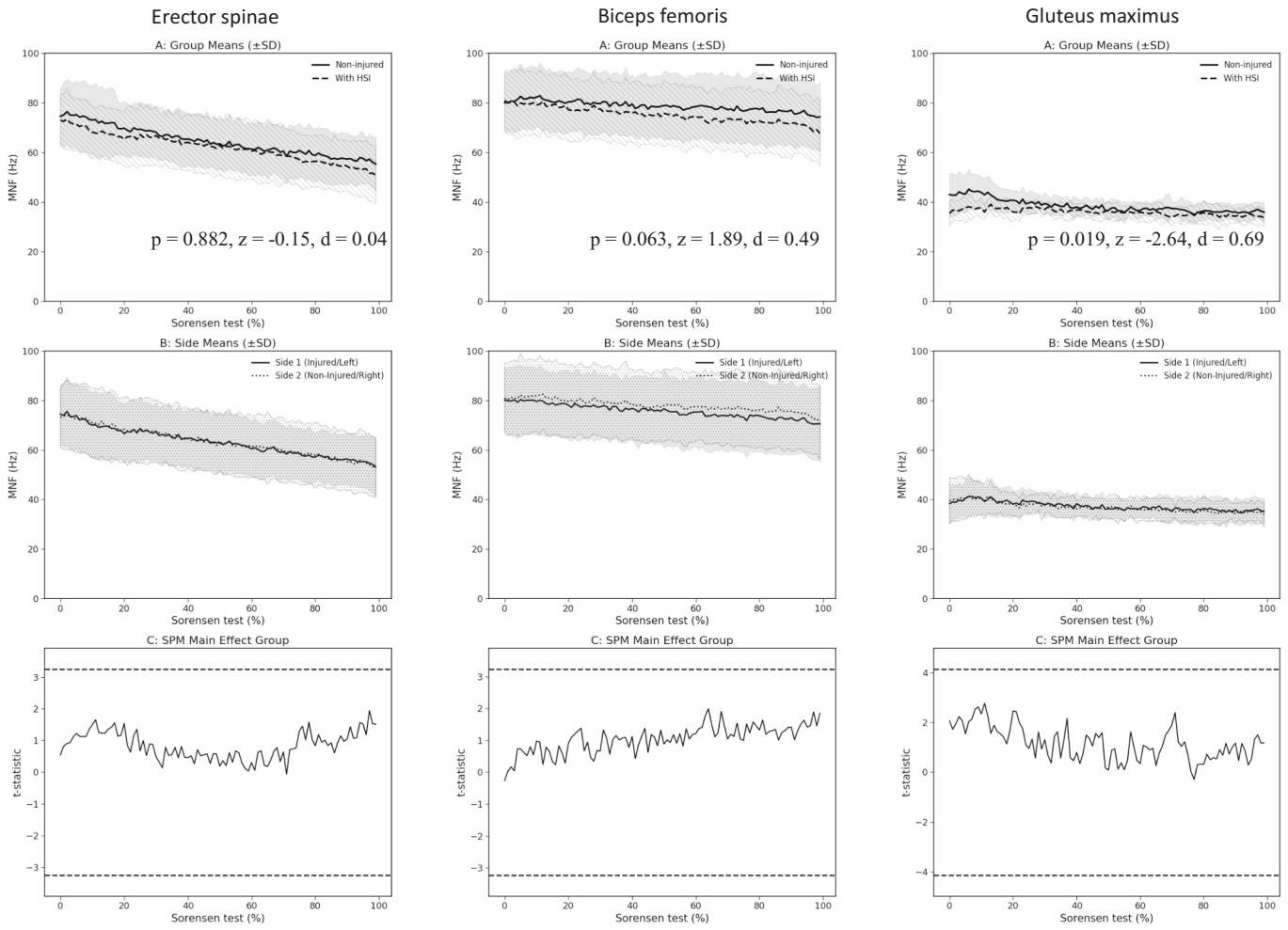

Fig. 2. Mean group median frequency (MNF) – normalized time (0 to 100%) trajectories of each muscle during the Biering-Sørensen test. The upper panel presents the group-level mean (solid, dashed lines) and standard deviation (shaded/hatched areas) for the participants with history of hamstring strain (HSI) and non-injured, with superimposed Linear mixed model (LMM) main effect of Group statistics (p, z, and Cohen's d). The middle panels show the side-level mean and standard deviation (injured for the HSI or non-dominant for the non-injured group vs (non-injured for the HSI or dominant for the non-injured group). The bottom panels illustrate group main effect comparisons using statistics parametric mapping (other effects are not shown). Note: LMM parameters are presented as complementary summary metrics; SPM1D serves as the primary inferential tool as it accounts for the continuous nature of the EMG trajectories rather than discrete summary points.

injured group. Further, higher initial MAV of the ES and BFlh, and a pattern of lower MNF slopes in the GMax in the HSI group in the full sample (not confirmed in subgroup analyses). To our knowledge, no previous study has examined Biering-Sørensen test performance and EMG patterns in athletes with prior HSI.

Contrary to our initial hypothesis, no between-group differences were observed in the continuous MNF waveforms during the Biering-Sørensen test of any monitored muscle (Fig. 3). However, both groups demonstrated a significant decline in EMG MNF, indicating the development of peripheral fatigue (Fig. 3). MNF primarily reflects fatigue-related changes in muscle fiber conduction velocity and action potential characteristics, which are most pronounced during high-intensity isometric contractions (Mannion and Dolan, 1994; Sparto et al., 1997; Shaw et al., 2024; Muceli and Merletti, 2024). During the Biering-Sørensen test, however, the ES and synergistic muscles operate at relatively low force levels and rely heavily on fatigue-resistant motor units and continuous motor unit substitution to maintain posture (Ng et al., 1997; Pitcher et al., 2007; Shaw et al., 2024). As a result, task failure during the Biering-Sørensen test may occur even when MNF continues to decline in a broadly comparable manner across individuals. Importantly, there is evidence that the rate of MNF decline explained approximately 50% of the variability in trunk extensor endurance, with the remaining variance attributed to factors such as discomfort tolerance, neural drive, and coordination strategies (Mannion and Dolan, 1994; Sparto et al., 1997; Ng et al., 1997; Coorevits et al., 2008; Shaw et al., 2024). Therefore, the absence of between-group differences in MNF trajectories in the present study suggests that additional, non-spectral mechanisms contribute to the shorter Biering-Sørensen score observed in the HSI group.

SPM1D analysis showed greater ES activation in the HSI group at both the onset and termination of the task (Fig. 3). Notably, GMax and BFlh MAV waveforms did not differ between groups, even though the HSI group maintained a constantly greater (~10–15%) MAV of both muscles throughout the test (Fig. 3). This suggests that athletes with HSI over-recruited the lumbar extensors to secure lumbopelvic stability immediately upon assuming the unsupported position. The emergence of a second significant cluster at the end of the test likely represents a compensatory "burst" of activity as these athletes raise their effort to maintain the horizontal posture against encroaching volitional failure. Given the shorter Sørensen scores in the HSI group, this increased EMG amplitude may reflect an elevated perceived effort and discomfort, as well as a less optimal distribution of muscle contributions, potentially leading to a faster accumulation of fatigue in specific muscles and contributing to earlier task termination. Alternative explanations should also be considered, including altered motor control strategies, subtle differences in trunk posture, or normalization-related effects (Sole et al.,

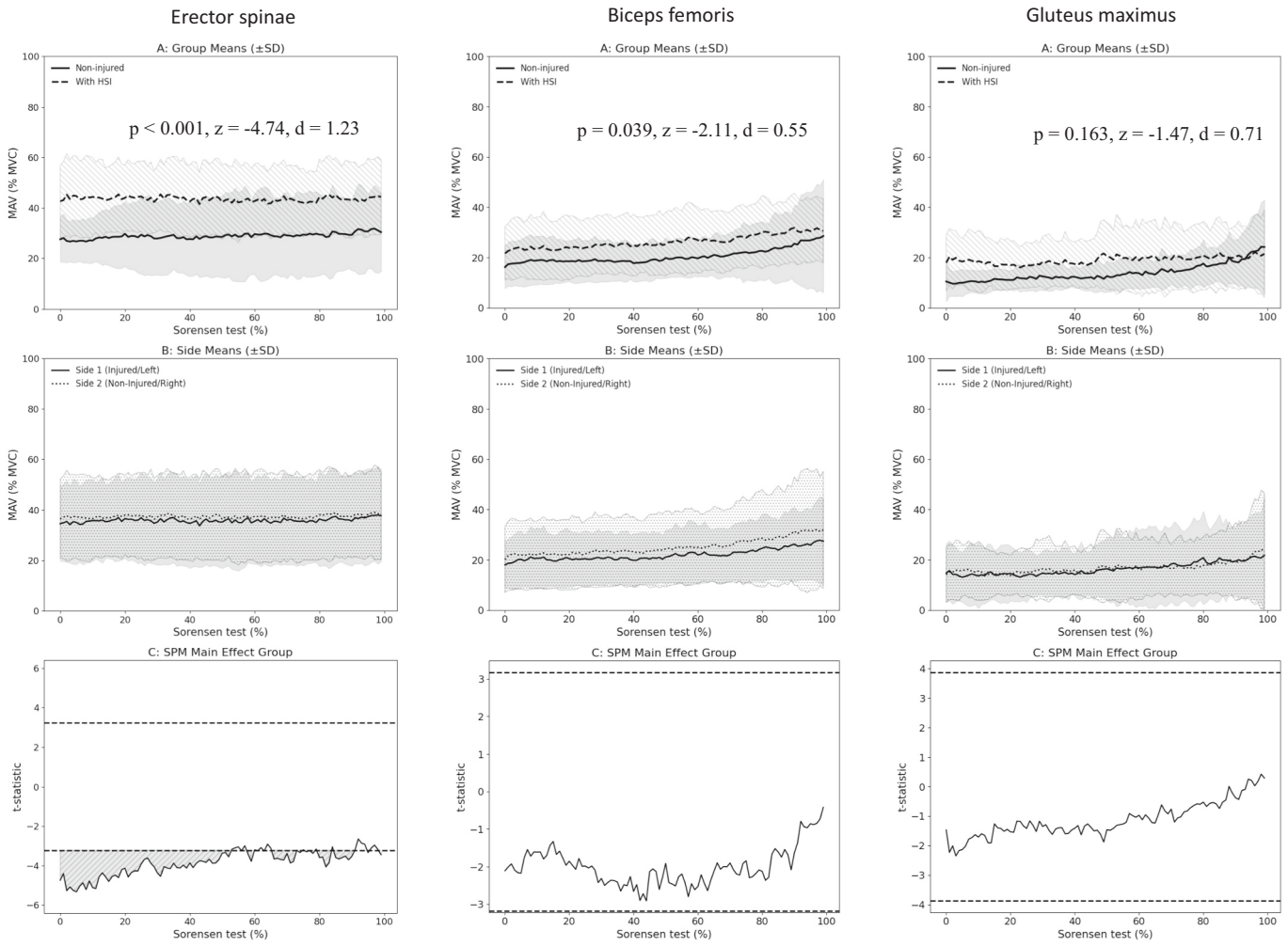

Fig. 3. Mean group Mean Absolute Value (MAV) – normalized time (0 to 100%) trajectories of each muscle during the Biering-Sørensen test. MAV is normalized to maximum voluntary contraction (MVC). The upper panel presents the group-level mean (solid, dashed lines) and standard deviation (shaded/hatched areas) for the participants with history of hamstring strain (HSI) and non-injured, with superimposed Linear mixed model main effect of Group statistics (p, z, and Cohen's d). The middle panels show the side-level mean and standard deviation (injured for the HSI or non-dominant for the non-injured group vs (non-njured for the HSI or dominant for the non-injured group). The bottom panels illustrate group main effect comparisons using statistics parametric mapping (other effects are not shown). Dashewd lines indicate the critical threshold (t) and hatched gray regions denote significant group differences ($p < 0.05$). Note: The LMM summary statistics are included to enhance interpretability of total magnitude; however, the SPM1D analysis remains the primary tool for identifying localized temporal deviations across the task duration.

Table 1
Initial median frequency (MNF) and MNF slope of surface EMG signals recorded from the erector spinae (ES), biceps femoris long head (BFlh), and gluteus maximus (GMax) during the Biering-Sørensen test in athletes with HSI and non-injured participants. Values are presented as mean ± standard deviation (SD). For each muscle, the *t*-test and corresponding *p*-value resulting from the independent samples t-test and conducted as simple main effects following the linear mixed modelling analysis is presented. For each muscle, the t-statistic (t_{57}) and corresponding p-value represent simple main effects of Group, derived from the fixed-effects structure of the linear mixed-effects model. An asterisk (*) denotes a statistically significant between-group difference ($p < 0.05$).

Muscle	Group	Initial MNF (Hz) (Mean ± SD)	t_{57}	p	MNF Slope (Hz/% time) (Mean ± SD)	t_{57}	p
ES	Non-injured	74.60 ± 11.45	0.54	0.589	−0.194 ± 0.128	−0.15	0.882
	HSI	73.03 ± 10.77			−0.189 ± 0.097		
BFlh	Non-injured	80.11 ± 12.36	−0.26	0.794	−0.062 ± 0.077	1.89	0.063
	HSI	80.94 ± 12.03			−0.102 ± 0.087		
GMax	Non-injured	42.99 ± 9.56	02.07	0.57	−0.079 ± 0.040	−2.64	0.019*
	HSI	35.34 ± 5.38			−0.035 ± 0.029		

MNF = median frequency; ES = erector spinae; BFlh = biceps femoris; GMax = gluteus maximus; Hz = hertz; SD = standard deviation; LMM = linear mixed model.

2012). In addition, potential structural or muscle fiber-type adaptations following injury may influence metabolic efficiency and fatigue behavior (Huygaerts et al., 2020).

The above suggestion is enforced by considering the LMM results, which indicated variations (including a limited trend-level effect (BFlh MNF slope, $0.05 \leq p < 0.10$) in MNF (Table 1) and MAV (Table 2) slopes and initial values across the posterior-chain muscles. For the BFlh and ES, normalized MNF slopes did not differ between groups, but when considered relative to shorter endurance time in the HSI group, this implies a faster accumulation of fatigue per unit of absolute time.

Table 2
Initial mean average amplitude (MAV) normalized to maximum voluntary contraction (MVC) and MAV slope of surface EMG signals recorded from the erector spinae (ES), biceps femoris long head (BFlh), and gluteus maximus (GMax) during the Biering-Sørensen test in athletes with HSI and non-injured participants. Values are presented as mean ± standard deviation (SD). Between-group differences for each muscle were examined via post-hoc simple main effects derived from the linear mixed-effects model (LMM) fixed effects and are expressed as Wald z -statistics (z) and corresponding *p*-values. An asterisk (*) denotes a statistically significant between-group difference ($p < 0.05$).

Muscle	Group	Initial MAV (% MVC) (Mean ± SD)	z	p	MAV Slope (%MVC / % time) (Mean ± SD)	z	p
ES	Non-injured	27.59 ± 9.12	−4.74	< 0.001*	0.030 ± 0.133	−0.84	0.403
	HSI	42.65 ± 14.38			−0.008 ± 0.154		
BFlh	Non-injured	16.21 ± 8.57	−2.11	0.039*	0.084 ± 0.145	−0.02	0.981
	HSI	21.62 ± 10.84			0.085 ± 0.116		
GMax	Non-injured	10.49 ± 8.54	−1.47	0.163	0.105 ± 0.090	−1.14	0.254
	HSI	17.95 ± 11.86			0.035 ± 0.109		

MAV = Mean Absolute Value; %MVC = percent of maximal voluntary contraction; ES = erector spinae; BFlh = biceps femoris; GMax = gluteus maximus; SD = standard deviation; LMM = linear mixed model.

Additionally, the higher initial MAV of the ES and BFlh in the HSI group (Table 2), suggests a greater relative demand on these muscles to sustain the task. In the GMax, the HSI group exhibited a flatter MNF slope compared to controls in the full sample (Table 1), however this effect was not replicated in subgroup analyses, indicating sensitivity to sample composition. In contrast, the steeper decline observed in the non-injured group is a well-described fatigue response (Muceli and Merletti, 2024), reflecting metabolic accumulation and slowing of conduction velocity as the GMax contributes to sustained hip extension (Muceli and Merletti, 2024). Taken together, these results indicate that the reduced Biering-Sørensen endurance in athletes with HSI showed an increased reliance on the back and hamstrings, and comparatively less fatigue development in the GMax. This pattern aligns with Schuermans et al. (2017b) who demonstrated reduced gluteal contribution and increased reliance on distal musculature during functional tasks in athletes with prior HSI. Shaw et al. (Shaw et al., 2024) also found that in pain-free individuals, Biering-Sørensen endurance was primarily associated with lumbar paraspinal fatigability, whereas in individuals with a history of low back pain, endurance was more strongly related to hamstring fatigability and the extent of paraspinal activation. In addition, Coorevits et al. (2008) reported smaller MNF slopes in the hip extensors compared with the lumbar extensors in individuals with low back pain. The present results extend this framework to athletes with a history of HSI, indicating that reduced endurance can occur despite comparable peripheral fatigue trajectories of individual muscles when expressed relative to task duration (i.e., time-normalized). In absolute time, however, fatigue develops earlier in the HSI group, likely due to differences in how fatigue-related demands are distributed across the posterior chain. Such altered load distribution may elevate cumulative stress on previously injured musculature, potentially contributing to the higher risk of reinjury observed in this population (Schuermans et al., 2017b; Higashihara et al., 2022).

In addition to neuromuscular and biomechanical factors, pain-related and central mechanisms may also have contributed to the reduced Biering-Sørensen endurance observed in athletes with a recent HSI. Even in the absence of overt symptoms during testing, prior injury may influence motor behavior through altered threat perception, residual discomfort, or heightened vigilance. Pain or the expectation of pain can induce protective adaptations characterized by altered recruitment patterns, reflex inhibition, and redistribution of load away from perceived vulnerable tissues (Hodges, 2011). Such adaptations may persist beyond clinical recovery and could reduce tolerance to sustained loading tasks. Furthermore, central factors such as motivation, perceived exertion, and central fatigue play a substantial role in Biering-Sørensen test performance, which is often limited by discomfort tolerance rather than true contractile failure (Ng et al., 1997; Coorevits et al., 2008). It is therefore plausible that athletes with a recent HSI experienced greater perceived effort or concern about reinjury, leading to earlier voluntary task termination in relation to the same externally imposed task demands and progressive fatigue development over time, rather than reflecting a fundamentally different peripheral fatigue state. While these factors were not directly assessed in the present study, they provide a theoretically grounded explanation for the observed differences between endurance performance and peripheral EMG fatigue indices, particularly given that peripheral fatigue develops progressively over time and may not directly determine the point of task failure in isolation.

From a clinical perspective, these findings suggest that reduced Biering-Sørensen endurance in athletes with HSI reflects a persistent “high-cost” neuromuscular strategy rather than incomplete recovery of muscle strength or fatigue resistance. Rehabilitation programs that focus primarily on isolated hamstring strengthening may therefore fail to address underlying coordination deficits. Targeting gluteal activation, lumbopelvic control, and normalization of load sharing across the posterior chain may be necessary to reduce excessive neural drive to the ES and hamstrings during sustained and dynamic tasks. In particular, interventions could emphasize GMax activation and integration, for example through bridging and hip thrust variations, progressing to loaded hip extension tasks (e.g., Romanian deadlifts) while maintaining lumbopelvic control. In parallel, trunk endurance and control may be addressed using exercises such as Biering-Sørensen holds, bird-dog variations, and side planks, with external feedback to limit excessive lumbar extensor recruitment. Further, to reduce reliance on the hamstrings and lumbar extensors, movement retraining (e.g., hip hinge patterns) may help promote more balanced muscle contributions during functional tasks. Finally, graded exposure to sustained loading may improve tolerance to fatigue and discomfort, potentially reducing protective strategies that contribute to early task termination.

Several limitations should be acknowledged. The cross-sectional design limits interpretation to group differences and does not allow conclusions regarding causality or temporal relationships between neuromuscular patterns and HSI. Surface EMG recordings are susceptible to crosstalk and may not fully capture the behavior of deeper trunk musculature. In addition, EMG amplitudes were normalized to MVC, which may themselves be reduced following injury; therefore, similar relative activation levels could mask differences in absolute muscle activation. GMax data were available for a subset of participants due to measurement constraints, resulting in a smaller sample size for this muscle. To address this, we conducted additional sensitivity analyses restricted to participants with complete GMax data ($n = 17$), applying the same LMM framework for MNF and MAV outcomes. These analyses indicated that GMax-related MNF effects observed in the full sample were not confirmed in the reduced subsample, whereas ES and BFlh patterns remained broadly consistent but were attenuated, suggesting sensitivity to reduced statistical power. MAV slope results were consistent across analyses. The Biering-Sørensen test was selected as a standardized isometric task to assess muscle recruitment and fatigue development across the posterior chain; however, it does not replicate

sport-specific movement demands. Furthermore, EMG data were only obtained from the BFlh and not from other hamstring muscles, limiting insight into potential muscle-specific adaptations within the hamstring group. This is particularly relevant given that different hamstring muscles may be affected depending on injury characteristics. Future studies should consider the influence of hamstring injury severity, recurrence, and muscle-specific involvement (e.g., BFlh vs. semitendinosus), as the present study only assessed the BFlh and did not capture activation patterns across all hamstring muscles. Finally, post-injury rehabilitation history was not controlled and may have influenced neuromuscular function.

In conclusion, athletes with HSI demonstrate reduced trunk extensor endurance during the Biering-Sørensen test despite comparable peripheral fatigue profiles. This performance deficit is characterized by elevated neural drive to the ES and hamstrings alongside reduced fatigue development of the GMax, indicating altered load distribution within the posterior chain. These findings highlight the importance of neuromuscular coordination and tolerance to sustained loading in post-HSI athletes and support rehabilitation approaches that emphasize integrated posterior-chain function rather than isolated muscle endurance.

CRediT authorship contribution statement

Eleftherios Kellis: Writing – review & editing, Writing – original draft, Supervision, Methodology, Data curation, Conceptualization. **Giannis Giakas:** Writing – review & editing, Visualization, Validation, Software, Methodology. **Vasilios Baltzopoulos:** Writing – review & editing, Writing – original draft, Supervision.

Declaration of competing interest

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

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