Gulgosteren et al. BMC Sports Science, Medicine and Rehabilitation (2026) 18:6
https://doi.org/10.1186/s13102-025-01435-5

BMC Sports Science, Medicine and Rehabilitation

RESEARCH

Open Access

Persistent neuromuscular deficits in the posterior kinetic chain following hamstring strain injury: EMG insights from nordic hamstring curl, kettlebell swing, and supine sliding leg curl

Erkan Gulgosteren[1], Oguzhan Yuksel[2], Baris Gurol[3], Onur Yildirim[4], Ozdemir Atar[5*], Caglar Soylu[6,7*], Emre Altundag[8] and Gorkem Acar[9]

Abstract

Background Hamstring strain injuries (HSIs) are among the most common non-contact injuries in football, often resulting in prolonged rehabilitation, high recurrence rates, and persistent neuromuscular deficits. Although rehabilitation focuses on restoring strength and flexibility, alterations in posterior chain muscle activation patterns may remain undetected, potentially contributing to reinjury risk. This study aimed to compare posterior chain muscle activation patterns between football players with a history of hamstring injury and healthy controls during three functional exercises: Nordic Hamstring Curl (NHC), Kettlebell Swing (KS), and Sliding Single-Leg Curl (SSLC).

Methods Forty-two male football players (mean age: 23.4 ± 3.1 years; 21 previously injured, 21 healthy controls) participated in the study. Surface electromyography (sEMG) was used to record activation of the biceps femoris long head (BF), gluteus maximus (GM), latissimus dorsi (LD), and iliocostalis lumborum (IL) during each exercise.

Results Mean activation values were Across all exercises, injured players demonstrated significantly lower muscle activation compared with healthy controls. In NHC, BF (−23.9%, $p < 0.001$), GM (−21.3%, $p < 0.001$), LD (−15.4%, $p = 0.005$), and IL (−14.6%, $p = 0.001$) activations were reduced in the injured group. During KS, reductions were observed in BF (−28.7%, $p < 0.001$), GM (−24.3%, $p < 0.001$), LD (−17.3%, $p = 0.008$), and IL (−16.8%, $p = 0.007$). In SSLC, BF (−20.8%, $p < 0.001$), GM (−19.7%, $p < 0.001$), LD (−12.5%, $p = 0.008$), and IL (−15.8%, $p = 0.004$) activations were significantly lower in injured participants.

Conclusion The largest differences were found in BF and GM during hip-dominant exercises, with consistent but smaller deficits in LD and IL, indicating a widespread neuromuscular inhibition beyond the hamstring itself. Conclusions: Football players with a history of hamstring injury present persistent deficits in posterior chain muscle

*Correspondence:
Ozdemir Atar
ozdemir@comu.edu.tr
Caglar Soylu
caglar.soylu@sbu.edu.tr

Full list of author information is available at the end of the article

© The Author(s) 2025. **Open Access** This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by-nc-nd/4.0/.

activation, particularly in BF and GM, even after return to play. These impairments extend to trunk musculature (LD, IL), suggesting that rehabilitation should incorporate multi-segmental posterior chain retraining, especially in hip-dominant tasks, to mitigate reinjury risk.

Clinical trial registration : The clinical trial was registered retrospectively on 09 June 2025 under the identifier NCT07171385.

Keywords Hamstring injury, Posterior chain, Electromyography, Kettlebell swing, Nordic hamstring curl

Introduction

Muscle chains are functional groups of muscles that influence coordinated movement and force generation during exercise. These chains can be classified as synergists, muscle slings, or myofascial chains. Each category is characterized by interconnected anatomical and neural relationships. Muscle slings provide dynamic stability while facilitating multi-joint movement. The myofascial sling system links anatomically distant muscles through passive connective tissue structures, enabling efficient force transmission between the lower and upper extremities via the trunk [1].

Among these slings, the posterior kinetic chain (PKC) comprises the contralateral latissimus dorsi and ipsilateral gluteus maximus, erector spinae, multifidus, and hamstring muscles, interconnected through the thoracolumbar fascia. This system is a critical pathway for transferring force from the lower to the upper body [1]. Within this chain, the hamstring muscles play a pivotal role in high-performance athletic tasks such as sprinting and rapid changes in direction [2]. Hamstring injuries frequently occur during high-speed running—particularly in the terminal swing phase—or during excessive stretching in the mid-stance phase [3, 4]. Alterations in hamstring function during these mechanically demanding phases are key contributors to injury risk [5].

Hamstring strains are among the most prevalent and problematic injuries in sports involving high-speed running. They are defined as excessive stretching or tearing of the posterior thigh muscles—specifically, the biceps femoris, semitendinosus, and semimembranosus—which cross both the hip and knee joints and are essential for walking and running [6–8]. The biceps femoris is the most frequently injured, accounting for approximately 84% of all hamstring injuries [9, 10]. These injuries are especially common in soccer, where they result in more cumulative time lost than all other injury types combined, accounting for up to 25% of all injury-related absences [11–13]. Injury incidence in professional soccer has been reported to range from 1.06 to 5.87 per 1,000 h of training or match play [10, 14–16].

Longitudinal surveillance studies underscore the magnitude of the problem. For example, Ekstrand et al. reported 1,614 hamstring injuries over 13 seasons in 36 elite soccer teams across 12 European countries, with one-third occurring during training and two-thirds during matches [15, 17]. Recurrence rates remain high, ranging from 12% to 33% [6, 18], and reinjury imposes substantial costs on clubs. In one professional UEFA league team, the absence of five key players for 90 days due to injury was estimated to incur a financial loss of approximately €7.5 million [19].

Given these statistics, targeted prevention and rehabilitation strategies are essential. Eccentric hamstring exercises are widely recognized as effective interventions to address deficits in strength and muscle architecture, owing to the biarticular nature of the long hamstring muscles. Rehabilitation protocols often combine hip- and knee-dominant eccentric strengthening exercises to optimize outcomes. Common examples include the Nordic Hamstring Curl (NHC), Supine Sliding Leg Curl (SSLC), Romanian Deadlift (RD), and Kettlebell Swing (KS) [20–23]. Knee-dominant exercises (e.g., NHC, SSLC, prone and supine leg curls, bent-knee bridge) tend to preferentially recruit the medial hamstrings, while hip-dominant exercises (e.g., RD variations, 45° hip extension, kettlebell swing) elicit greater biceps femoris activation [24].

Despite the extensive use of these exercises in both prevention and rehabilitation contexts, no study to date has directly compared the surface electromyographic (sEMG) activity of posterior chain muscles during multiple hamstring-strengthening exercises in athletes with and without a history of hamstring injury. This gap in the literature limits evidence-based decision-making in exercise prescription tailored to athletes' injury histories.

The primary aim of this study is to systematically evaluate and compare sEMG activation patterns of key posterior chain muscles during selected hamstring-strengthening exercises in athletes with and without a history of hamstring strain injury. By analysing activation differences between hip-dominant and knee-dominant exercises, the study seeks to determine which exercise elicits the greatest muscular engagement in each population, thereby providing evidence-based guidance for injury prevention and rehabilitation program design. The findings are expected to have practical implications for athletes, sports medicine professionals, and coaches by informing targeted exercise selection strategies that optimize performance while minimizing the risk of reinjury. It is anticipated that athletes with a previous hamstring

injury will exhibit significantly lower posterior chain muscle activation during these exercises compared with uninjured athletes.

Materials and methods

Study design

This cross-sectional study was designed to compare posterior chain muscle activation during functional strengthening exercises between athletes with and without a history of hamstring injury. All assessments were performed under standardized laboratory conditions within a single visit. To minimize bias, the outcome assessor who processed and analyzed sEMG data was blinded to group allocation throughout data handling and statistical analysis. A priori power analysis was conducted using G*Power (version 3.1) based on sEMG amplitudes reported in a comparable investigation of posterior kinetic chain muscles [25]. Assuming a between-group effect size (Cohen's d) of 1.0, $\alpha = 0.05$, two-tailed independent-samples testing, and statistical power ($1-\beta$) = 0.95, the required sample was ≥ 19 per group; allowing for potential attrition, the final target was 21 per group ($N = 42$) [25, 26]. All participants provided written informed consent prior to enrolment.

Participants

The study enrolled 42 volunteers who met prespecified eligibility criteria. For the hamstring-injured group, participants were 18–30 years of age; had a body mass index (BMI) of 18.5–24.9 kg/m^2; volunteered and were able to perform all tests and exercises; and had a history of unilateral hamstring strain within the previous 6 months. For the healthy control group, participants were 18–30 years; BMI 18.5–24.9 kg/m^2; volunteered and were able to perform all tests and exercises; had no hamstring strain in the past 6 months; and demonstrated a straight-leg raise on the dominant limb < 80° (criterion used to operationalize hamstring flexibility in this protocol). Exclusion criteria for all participants were a lower or upper extremity injury within the previous year; professional sports background; sensory impairments limiting participation; any musculoskeletal, neurological, respiratory, or cardiovascular condition restricting exercise; recent spinal surgery; acute low-back or lower-limb musculoskeletal pain; or a history of malignancy. All participants provided written informed consent. Ethical approval was granted by the Gülhane Clinical Research Ethics Committee, University of Health Sciences, Turkey, on 31/10/2023 (meeting no: 2023/09; decision no: 2023 – 350). The study was conducted in accordance with the Declaration of Helsinki.

Surface electromyographic (sEMG) measurements

Surface kinesiological sEMG recordings were obtained from the latissimus dorsi, biceps femoris long head, gluteus maximus, and iliocostalis lumborum pars lumborum as components of the posterior oblique sling. In the injured group, recordings were taken from the side of the injured extremity; in controls, from the dominant limb. An 8-channel Noraxon Ultium system (Noraxon USA, Inc., Scottsdale, AZ, USA) with Ag/AgCl surface electrodes (1 cm diameter) was used [25]. Skin was prepared per SENIAM recommendations—shaving, light abrasion, and alcohol cleansing—until a light reddish tone indicated low impedance; inter-electrode distance was kept below 2 cm [27]. Electrode placements followed SENIAM landmarks: latissimus dorsi midway between the vertebral column and lateral trunk border, 4 cm below the inferior scapular angle, 25° oblique to fibers; biceps femoris long head at the midpoint between the ischial tuberosity and lateral tibial condyle, parallel to fibers; gluteus maximus along the line from the posterior superior iliac spine to the mid-posterior thigh, parallel to fibers; iliocostalis lumborum at L3, midway between the lateral border of erector spinae and a vertical line through the posterior superior iliac spine, parallel to fibers [27]. A 15-s resting recording verified baseline signal stability; electrodes were re-applied if noise was present. Additionally, the dominant limb of each participant was determined by asking which leg they would use to kick a ball. For the control group, all measurements were performed on the dominant side; for the injured group, on the previously injured side.

To ensure methodological consistency, all electrode placements were performed by the same researcher, who had prior experience with sEMG applications and followed SENIAM recommendations. The accuracy of electrode placement was confirmed through repeated trials, with test–retest reliability (ICC > 0.90) verified in a pilot phase before data collection.

Exercise protocol

After MVIC testing, participants rested for 5 min and then performed three posterior chain exercises—NHC, KS, and SSLC—selected for their capacity to recruit posterior kinetic chain musculature (Fig. 1) [25]. Each repetition comprised concentric, isometric, and eccentric phases of 3 s each, paced with a metronome. A video camera synchronized with sEMG ensured accurate phase identification. Exercises were computer-randomized in order. Joint angles were standardized with a plastic goniometer, and participants received standardized verbal encouragement. Each exercise was performed for three repetitions, with 5 s rest between repetitions and 2 min between exercises.

Signal acquisition, processing, and analysis

Signal acquisition, processing, and analysis were performed using a Noraxon Ultium EMG sensor system

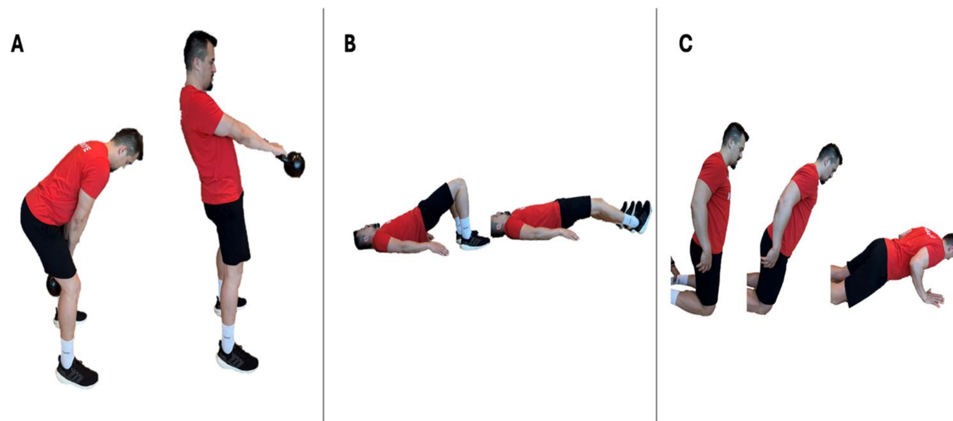

Fig. 1 **A** Kettlebell swing (KS); **B**; Supine sliding leg curl (SSLC); **C** Nordic hamstring curl (NHC)

(Noraxon USA, Inc., Scottsdale, AZ, USA). Signals were differentially amplified (CMRR >100 dB; input impedance >100 mΩ; gain 1000 dB; signal-to-noise ratio ≤ 1 μV RMS) and digitized at 4000 Hz. Two filters were applied: a band-pass 10–500 Hz implemented with a first-order high-pass and fourth-order low-pass Butterworth filter to remove undesirable artefacts, and a 60 Hz notch filter to eliminate mains noise; a cancellation algorithm removed ECG contamination. The root mean square (RMS) amplitude was then calculated. Data were processed in Noraxon MyoResearch XP (version 3.16; Noraxon Inc., Scottsdale, AZ, USA). For each trial, amplitudes were expressed as a percentage of the mean RMS of the MVIC for the corresponding muscle (%MVIC), and the mean %MVIC across three trials was used for analysis [26–29].

Statistical analysis

All data were analyzed using IBM SPSS Statistics version 28.0 (IBM Corp., Armonk, NY, USA). Descriptive statistics were presented as means ± standard deviations (SD) for continuous variables (e.g., muscle activation levels expressed as %MVIC, age, height, weight, and BMI). Homogeneity of variances and normal distribution assumptions were verified using the **Levene's test** and **Shapiro–Wilk test**, respectively. If normality assumptions were met, independent samples t-tests were employed to compare muscle activation levels (%MVIC) between the injured and healthy groups for each muscle (biceps femoris, gluteus maximus, latissimus dorsi, and iliocostalis lumborum) across the three exercises (Nordic hamstring curl, kettlebell swing, and supine sliding leg curl). In cases where normality was violated, non-parametric equivalents such as the Mann-Whitney U test were used as alternatives. Regarding Type I error control in multiple comparisons, no adjustments such as the Bonferroni correction were applied, as the analyses were exploratory and focused on specific a priori hypotheses; however, effect sizes and confidence intervals were reported to aid interpretation and mitigate potential Type I error concerns. Effect sizes were calculated to quantify the magnitude of group differences. Cohen's d was computed for t-test comparisons, with thresholds interpreted as small (0.2), medium (0.5), and large (≥ 0.8). Additionally, eta squared (η^2) was derived from the t-test results to estimate the proportion of variance explained by group membership, with interpretations as small (0.01), medium (0.06), and large (≥ 0.14). For each comparison, 95% confidence intervals (CI) for the mean differences were calculated using the formula: mean difference ± (t-critical value × standard error of the difference), where the t-critical value was based on degrees of freedom (df = 40) and a two-tailed alpha level. The significance level was set at $p < 0.05$ for all tests. No adjustments for multiple comparisons were applied, as the analyses were exploratory and focused on specific a priori hypotheses; however, effect sizes and confidence intervals were reported to aid interpretation and mitigate Type I error concerns. Power analysis conducted a priori using GPower software confirmed that the sample size provided at least 80% power to detect medium-to-large effect sizes at $\alpha = 0.05$. All analyses were performed blinded to group allocation where possible to minimize bias. Graphics and figures were generated using the ggplot2 package in RStudio (R version 4.3.2, RStudio version 2023.12.1).

Results

The study included 42 participants, comprising 21 individuals with hamstring injuries and 21 healthy controls. No statistically significant differences were observed between the groups in demographic or anthropometric characteristics, including age, height, weight, and body mass index (all $p > 0.05$; Table 1).

sEMG analysis revealed that healthy athletes consistently demonstrated greater posterior chain muscle

Table 1 Demographic characteristics of injured and non-injured participants

Variable	Injured Mean (SD)	Non-Injured Mean (SD)	t-statistic	*p*-value
Age (years)	23.29 (2.30)	23.75 (2.54)	−0.61	0.542
Height (cm)	174.46 (4.92)	174.76 (3.56)	−0.23	0.82
Weight (kg)	70.93 (5.69)	74.23 (7.88)	−1.56	0.128
BMI (kg/m^2)	23.37 (2.43)	24.34 (2.87)	−1.19	0.239

Abbreviations: *BMI* Body mass index, *cm* centimeters, *kg* kilograms, *m*^{2} square meters

activation compared to previously injured athletes across all three exercises—NHC, KS, and SSLC (Figs. 2, 3 and 4).

In the NHC (Fig. 2), activations of the biceps femoris (BF), gluteus maximus (GM), latissimus dorsi (LD), and iliocostalis lumborum (IL) were significantly higher in the healthy group (BF: 76.8 ± 11.5 vs. 52.3 ± 12.1%MVIC, $p < 0.001$, d = 2.08; GM: 50.7 ± 9.8 vs. 38.4 ± 10.2%MVIC, $p < 0.001$, d = 1.23; LD: 34.2 ± 7.0 vs. 27.5 ± 7.5%MVIC, $p = 0.005$, d = 0.92; IL: 42.5 ± 8.2 vs. 33.5 ± 8.6%MVIC, $p = 0.001$, d = 1.07).

In the KS (Fig. 3), the same trend was observed, with the healthy group showing markedly greater activation (BF: 82.4 ± 11.2 vs. 58.7 ± 11.8 %MVIC, p < 0.001, d = 2.06; GM: 92.6 ± 12.4 vs. 68.9 ± 13.0 %MVIC, p < 0.001, d = 1.87; LD: 44.5 ± 8.7 vs. 36.8 ± 9.1 %MVIC, p = 0.008, d = 0.86; IL: 52.9 ± 9.9 vs. 44.0 ± 10.3 %MVIC, p = 0.007, d = 0.88).

In the SSLC (Fig. 4), reduced activation in the injured group persisted across all muscles (BF: 70.5 ± 10.3 vs. 48.6 ± 10.9 %MVIC, p < 0.001, d = 2.07; GM: 55.1 ± 9.3 vs. 44.2 ± 9.7 %MVIC, p < 0.001, d = 1.15; LD: 31.6 ± 6.4 vs. 25.9 ± 6.8 %MVIC, p = 0.008, d = 0.86; IL: 39.4 ± 7.7 vs. 32.0 ± 8.1 %MVIC, p = 0.004, d = 0.94). Across all exercises, effect sizes indicated medium-to-large differences, and the 95% confidence intervals confirmed the robustness of these findings.

Discussion

The findings of this study reveal that athletes with a history of hamstring strain injury (HSI) exhibit consistently lower sEMG activation in the BF, GM, LD, and IL during three widely used PKC strengthening exercises—NHC, KS, and SSLC—compared to healthy controls. These deficits persisted across both knee-dominant (NHC, SSLC) and hip-dominant (KS) movement patterns, with large effect sizes, indicating that neuromuscular alterations may remain long after clinical recovery. This agrees with prior evidence showing that post-HSI athletes often demonstrate reduced activation of injured limb musculature, even when standard return-to-play criteria are met [5, 8, 30]. The mechanisms underlying these persistent deficits are likely multifactorial, including arthrogenic muscle inhibition, maladaptive neuromuscular recruitment strategies, and residual deficits in muscle architecture [6, 8, 18, 30].

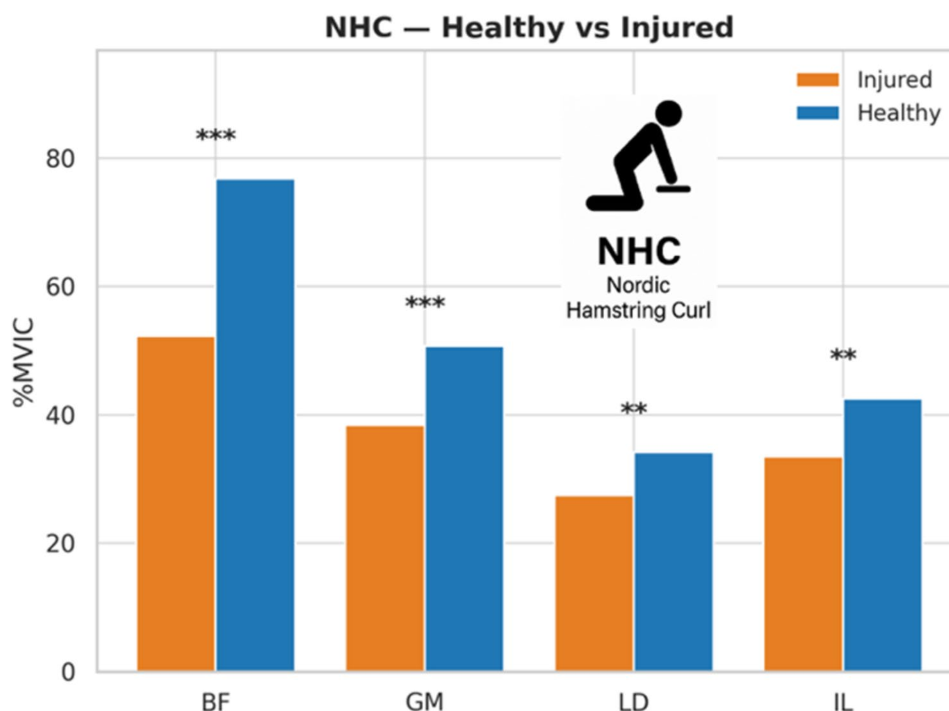

Fig. 2 Nordic Hamstring Curl (NHC). Posterior chain muscle activation (%MVIC) in healthy vs previously injured groups (mean ± SD). Muscles: BF = Biceps Femoris long head, GM = Gluteus Maximus, LD = Latissimus Dorsi, IL = Iliocostalis Lumborum. %MVIC = normalized to maximal voluntary isometric contraction. $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***)

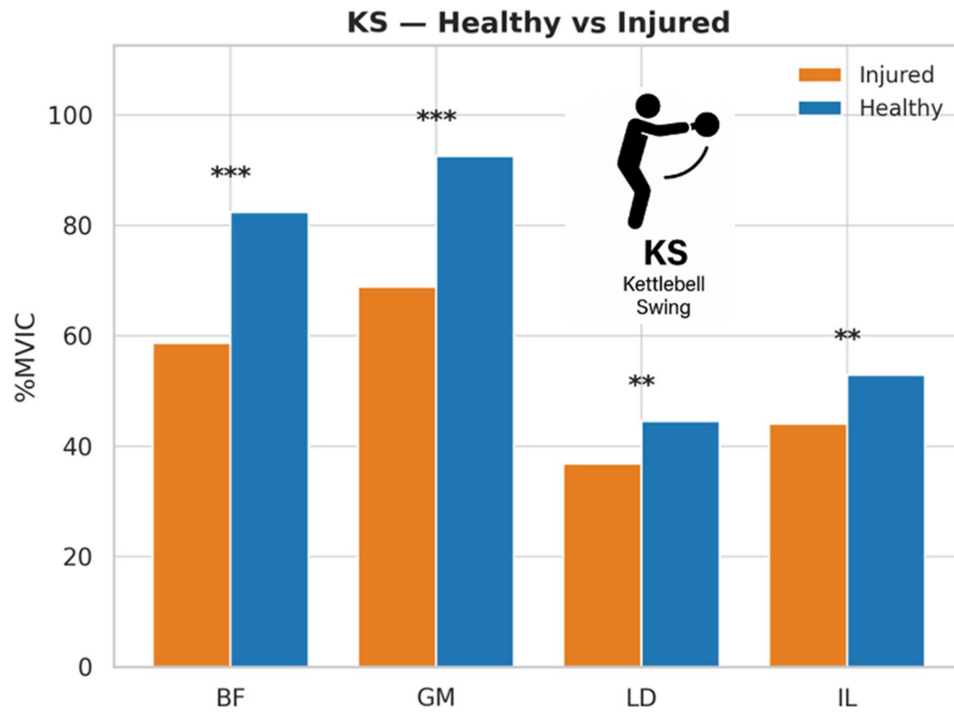

Fig. 3 Kettlebell Swing (KS). Posterior chain muscle activation (%MVIC) in healthy vs previously injured groups (mean ± SD). Muscles: BF = Biceps Femoris long head, GM = Gluteus Maximus, LD = Latissimus Dorsi, IL = Iliocostalis Lumborum. %MVIC = normalized to maximal voluntary isometric contraction. $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***)

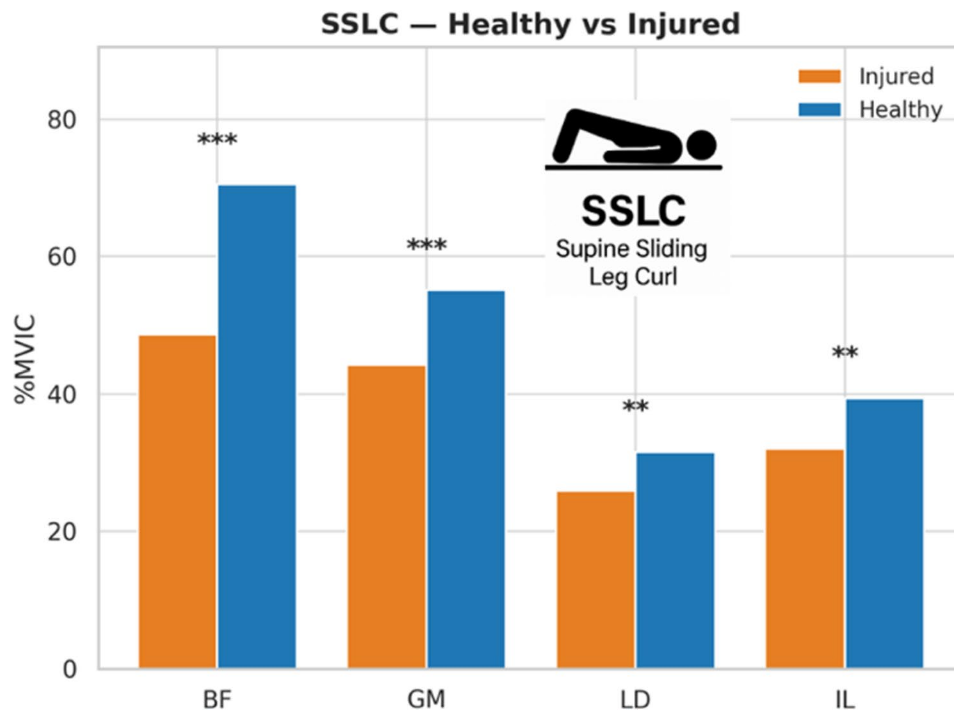

Fig. 4 Supine sliding leg curl (SSLC). Posterior chain muscle activation (%MVIC) in healthy vs previously injured groups (mean ± SD). Muscles: BF = Biceps Femoris long head, GM = Gluteus Maximus, LD = Latissimus Dorsi, IL = Iliocostalis Lumborum. %MVIC = normalized to maximal voluntary isometric contraction. $p < 0.05$ (*), $p < 0.01$ (**), $p < 0.001$ (***)

In the NHC, known for eliciting very high hamstring sEMG activity, especially in the BF and semitendinosus (ST) due to its eccentric knee-dominant nature [20, 24, 31], the healthy group in this study generated markedly greater BF activation (76.8% MVIC) compared to the injured group (52.3% MVIC). The GM, LD, and IL also showed significantly reduced activity in the injured group, suggesting a broader impairment in the posterior oblique sling, that is critical for force transfer between the lower and upper body [1, 25, 31]. These findings mirror those of previous studies demonstrating selective BF weakness and reduced eccentric torque production at longer muscle lengths after HSI [5, 30]. Such deficits have been linked to shortened fascicle length in the BF long head, a known risk factor for reinjury [6, 18]. Given that fascicle length adaptations require several weeks of targeted eccentric loading to normalize [18, 24], reduced BF activation during the NHC may hinder the restoration of this protective adaptation. Moreover, leg positioning in NHC significantly influences sEMG activation [32], and injured athletes may subconsciously adopt positions that unload the BF to avoid discomfort, further reducing stimulus for adaptation.

The KS, a ballistic hip-dominant exercise involving rapid hip extension, produced the highest PKC activation values in healthy athletes (e.g., GM 92.6% MVIC, BF 82.4% MVIC). Its ability to recruit both the hamstrings and gluteals extensively is consistent with previous literature showing that hip-dominant exercises preferentially activate the ST and GM while still heavily engaging the BF [1, 23, 24, 33]. In the injured group, however, activations were 20–29% lower, with the greatest deficits in GM and BF. This aligns with studies suggesting that reduced GM function after HSI may lead to compensatory hamstring overuse during sprinting and cutting maneuvers, thereby elevating reinjury risk [2, 3, 34]. The present results support the recommendation that rehabilitation should include exercises like KS to restore proximal hip extensor contributions, potentially reducing hamstring overload in high-speed running [11, 13, 15]. Furthermore, evidence from kinematic analyses of sprinting indicates that deficits in hip extension power can compromise late swing phase mechanics, where the BF long head undergoes high eccentric loading [3, 6, 34].

The SSLC, a closed-chain knee-dominant movement, elicited moderate BF activation levels (48.6% MVIC injured vs. 70.5% healthy), lower than NHC but still substantial enough for early-phase rehabilitation. This agrees with prior sEMG studies showing that sliding leg curl variations and glider exercises produce high sprint-normalized hamstring activity, making them suitable for safe reintroduction of load during early recovery [25, 35, 36]. The SSLC appears to target BF more than ST, which may be beneficial in correcting the altered BF/ST activation ratio frequently seen post-HSI [5, 24]. However, the persistent deficits found in the injured group indicate that even relatively low-to-moderate intensity exercises cannot fully normalize activation without progressive loading and targeted intervention. Recent research has shown that hamstring exercises differ considerably in BF and ST activation patterns [34], and inadequate exercise selection may perpetuate imbalances.

From a clinical perspective, these findings underscore the importance of targeted, phase-specific rehabilitation and prevention strategies. For example, progression from low-load exercises like SSLC to high-load, eccentric-biased tasks like NHC and KS may help restore both knee- and hip-dominant strength components, addressing deficits across the PKC. Importantly, combining hip- and knee-dominant exercises appears to yield the most comprehensive activation profile [15, 17, 20–23, 31, 35], supporting recommendations for integrated rehabilitation programs. Persistent activation deficits, particularly in BF and GM, suggest that athletes may return to sport with incomplete restoration of neuromuscular capacity, predisposing them to recurrence rates of up to 33% [6, 18]. Therefore, sEMG monitoring during rehabilitation could provide objective benchmarks for readiness to progress loading and eventually return to competition [20–22, 31]. Furthermore, incorporating trunk stabilization exercises—particularly targeting the latissimus dorsi and iliocostalis lumborum—within rehabilitation may improve lumbopelvic stability and enhance kinetic chain efficiency during high-speed locomotion and return-to-play transitions.

The observed reductions in LD and IL activation are particularly noteworthy, as these muscles contribute to the posterior oblique sling and play a key role in lumbopelvic stability [1, 25]. Reduced trunk and spinal extensor activation may reflect protective movement strategies that minimize trunk rotation and extension forces through the injured limb. Such adaptations, while potentially protective in the short term, may compromise kinetic chain efficiency and force transfer during high-speed locomotion. This reinforces the need for trunk-focused interventions within hamstring rehabilitation to optimize whole-chain coordination. Practically, trunk stabilization involving LD and IL can be integrated into rehabilitation protocols through exercises such as prone hip extensions with abdominal drawing-in maneuvers or latissimus dorsi-focused rows combined with gluteal bridges, performed progressively from isometric holds to dynamic multi-joint movements to enhance force transmission and reduce compensatory patterns.

Potential limitations of the present study include its cross-sectional design, which cannot determine whether the observed deficits are a consequence of the injury or a predisposing factor. The relatively small, homogenous

sample of young male athletes limits generalizability to female or elite populations [14, 16]. In addition, only unilateral EMG data were recorded under standardized laboratory conditions, which may not capture real-world variability in muscle recruitment during sport-specific actions [3, 4, 30]. Future studies should adopt longitudinal designs, track adaptations over the course of rehabilitation, and examine how different hamstring exercises influence fascicle length recovery, hip extension torque, and intermuscular coordination. Furthermore, sex-specific analyses and bilateral comparisons may reveal additional nuances in neuromuscular recovery and reinjury mechanisms [9, 10, 34]. Also, future research should aim to incorporate more dynamic, sports-specific tasks—such as sprinting, cutting maneuvers, or agility drills—to better capture the real-world demands of athletic performance and enhance the generalizability of findings beyond controlled laboratory settings.

It should be acknowledged that the present findings are based on a homogeneous sample of young male football players, which may limit their generalizability to female athletes, different age groups, or other sports disciplines. Future research should address these populations to explore potential sex- and sport-specific neuromuscular adaptations.

Moreover, neuromuscular feedback mechanisms may play a critical role in rehabilitation progression. Integrating real-time sEMG feedback into clinical decision-making could allow practitioners to monitor intermuscular coordination and optimize load progression more precisely.

Overall, the present study adds to a growing body of literature emphasizing that neuromuscular deficits persist after apparent clinical recovery from HSI and that these deficits span multiple muscles within the PKC, not just the injured hamstring. Given the critical role of these muscles in sprinting, change-of-direction tasks, and force transfer across the kinetic chain, rehabilitation should prioritize restoring symmetrical activation patterns, integrating both hip- and knee-dominant exercises, and addressing trunk-pelvis coordination. Such an approach may improve functional capacity, reduce reinjury rates, and ultimately enhance athletic performance in high-risk sports [11–13, 15, 17, 20–23, 31, 35, 36].

Conclusions

Athletes with a history of hamstring strain injury exhibit significantly reduced activation of the BF, GM, LD, and IL during both hip- and knee-dominant strengthening exercises compared to healthy controls, indicating persistent neuromuscular deficits that may elevate reinjury risk. The greatest differences were observed in high-demand tasks such as NHC and KS, which are essential for restoring eccentric and hip extension strength. These results highlight the need for comprehensive rehabilitation programs incorporating both exercise types, progressive loading, and trunk-focused interventions, with sEMG-based monitoring to guide return-to-play decisions. A summary of phase-specific recommendations includes integrating low-load SSLC exercises in early rehabilitation phases to safely reintroduce eccentric loading, progressing to higher-demand KS or NHC exercises in later phases to optimize hip- and knee-dominant strength restoration. These findings also highlight the preventive and practical relevance of combined rehabilitation approaches. Specifically, integrating both hip-dominant and knee-dominant exercises within training routines may improve neuromuscular control and reduce reinjury risk in football players and similar high-speed sports. Addressing these deficits may improve kinetic chain efficiency, reduce recurrence rates, and enhance performance in sports requiring high-speed running and rapid directional changes.

Abbreviations

BF	Biceps Femoris long head
BMI	Body Mass Index
CI	Confidence Interval
d	Cohen's d (effect size)
EMG	Electromyography
GM	Gluteus Maximus
HSI	Hamstring Strain Injury
IL	Iliocostalis Lumborum
KS	Kettlebell Swing
LD	Latissimus Dorsi
MVIC	Maximal Voluntary Isometric Contraction
NHC	Nordic Hamstring Curl
PKC	Posterior Kinetic Chain
RMS	Root Mean Square
SD	Standard Deviation
SE	Standard Error
sEMG	Surface Electromyography
SSLC	Supine Sliding Leg Curl
ST	Semitendinosus
η^2	Eta squared (effect size)

Acknowledgements

No.

Authors' contributions

EG performed the formal analysis, conducted the investigation, curated the data, and drafted the original manuscript. OY contributed to the methodology, provided supervision, and prepared the visualizations. BG drafted the original manuscript, contributed to the writing – review and editing, and participated in the investigation, methodology, and supervision. OA contributed to the methodology, provided supervision, and was involved in drafting and revising the manuscript. CS prepared the visualizations, contributed to the methodology, and was involved in drafting and revising the manuscript. EA prepared the visualizations, contributed to the methodology, and was involved in drafting and revising the manuscript. GA prepared the visualizations, contributed to the methodology, and was involved in drafting and revising the manuscript. All authors read and approved the final manuscript.

Funding

This research received no external funding.

Data availability
The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
Ethical approval was granted by the Gülhane Clinical Research Ethics Committee, University of Health Sciences, Turkey, on 31/10/2023 (meeting no: 2023/09; decision no: 2023 – 350). All participants provided written informed consent prior to enrolment.
In addition, written consent was obtained from the individual appearing in Fig. 1 for the use of their image in this publication.

Competing interests
The authors declare no competing interests.

Author details
[1]Faculty of Sport Sciences, Mersin University, Mersin 33150, Türkiye
[2]Faculty of Sport Sciences, Dumlupınar University, Kütahya 43100, Türkiye
[3]Faculty of Sport Sciences, Eskişehir Technical University, Eskişehir 26555, Türkiye
[4]Faculty of Sport Sciences, Istanbul Gelisim University, Istanbul 34310, Türkiye
[5]Faculty of Sports Sciences, Çanakkale Onsekiz Mart University, Çanakkale 17020, Türkiye
[6]Gulhane Faculty of Physiotherapy and Rehabilitation, University of Health Sciences, Ankara 06010, Türkiye
[7]Sports Performance, Recovery, Injury & New Technologies (SPRINT) Research Centre, Australian Catholic University, Melbourne, Australia
[8]Faculty of Sport Sciences, Kütahya Dumlupınar University, Kütahya 43100, Türkiye
[9]Department of Sport Science, Institute of Graduate Education, Manisa Celal Bayar University, Manisa 45040, Türkiye

Received: 28 August 2025 / Accepted: 10 November 2025
Published online: 29 November 2025

References

1. Lee J-K, Lee J-H, Kim K-S, Lee J-H. Effect of abdominal drawing-in maneuver with prone hip extension on muscle activation of posterior oblique sling in normal adults. J Phys Ther Sci. 2020;32(6):401–4.
2. Kellis E. Antagonist muscle architecture and aponeurosis/tendon strain of biceps femoris long head during maximal isometric efforts. Eur J Appl Physiol. 2019;119(1):73–83.
3. Thelen DG, Chumanov ES, Hoerth DM, Best TM, Swanson SC, Li L, et al. Hamstring muscle kinematics during treadmill sprinting. Med Sci Sports Exerc. 2005;37(1):108–14.
4. Thelen DG, Chumanov ES, Best TM, Swanson SC, Heiderscheit BC. Simulation of biceps femoris musculotendon mechanics during the swing phase of sprinting. Med Sci Sports Exerc. 2005;37(11):1931–8.
5. Timmins RG, Opar DA, Williams MD, Schache AG, Dear NM, Shield AJ. Reduced biceps femoris myoelectrical activity influences eccentric knee flexor weakness after repeat sprint running. Scand J Med Sci Sports. 2014;24(4):e299–305.
6. Eirale C, Farooq A, Smiley FA, Tol JL, Chalabi H. Epidemiology of football injuries in Asia: a prospective study in Qatar. J Sci Med Sport. 2013;16(2):113–7.
7. Orchard JW, Seward H, Orchard JJ. Results of 2 decades of injury surveillance and public release of data in the Australian football league. Am J Sports Med. 2013;41(4):734–41.
8. Longo UG, Loppini M, Berton A, Marinozzi A, Maffulli N, Denaro V. The FIFA 11 + program is effective in preventing injuries in elite male basketball players: a cluster randomized controlled trial. Am J Sports Med. 2012;40(5):996–1005.
9. Ekstrand J, Lee JC, Healy JC. MRI findings and return to play in football: a prospective analysis of 255 hamstring injuries in the UEFA elite club injury study. Br J Sports Med. 2016;50(12):738–43.
10. Larruskain J, Lekue JA, Diaz N, Odriozola A, Gil SM. A comparison of injuries in elite male and female football players: A five-season prospective study. Scand J Med Sci Sports. 2018;28(1):237–45.
11. Hickey JT, Timmins RG, Maniar N, Williams MD, Opar DA. Criteria for progressing rehabilitation and determining return-to-play clearance following hamstring strain injury: a systematic review. Sports Med. 2017;47(7):1375–87.
12. Engebretsen AH, Myklebust G, Holme I, Engebretsen L, Bahr R. Prevention of injuries among male soccer players: a prospective, randomized intervention study targeting players with previous injuries or reduced function. Am J Sports Med. 2008;36(6):1052–60.
13. Reurink G, Goudswaard GJ, Moen MH, Weir A, Verhaar JA, Bierma-Zeinstra SM, et al. Rationale, secondary outcome scores and 1-year follow-up of a randomised trial of platelet-rich plasma injections in acute hamstring muscle injury: the Dutch Hamstring Injection Therapy study. Br J Sports Med. 2015;49(18):1206–12.
14. Ekstrand J, Hägglund M, Kristenson K, Magnusson H, Waldén M. Fewer ligament injuries but no preventive effect on muscle injuries and severe injuries: an 11-year follow-up of the UEFA champions league injury study. Br J Sports Med. 2013;47(12):732–7.
15. Ekstrand J, Hägglund M, Waldén M. Epidemiology of muscle injuries in professional football (soccer). Am J Sports Med. 2011;39(6):1226–32.
16. Ekstrand J, Healy JC, Waldén M, Lee JC, English B, Hägglund M. Hamstring muscle injuries in professional football: the correlation of MRI findings with return to play. Br J Sports Med. 2012;46(2):112–7.
17. Ekstrand J, Waldén M, Hägglund M. Hamstring injuries have increased by 4% annually in men's professional football, since 2001: a 13-year longitudinal analysis of the UEFA elite club injury study. Br J Sports Med. 2016;50(12):731–7.
18. Dalton SL, Kerr ZY, Dompier TP. Epidemiology of hamstring strains in 25 NCAA sports in the 2009–2010 to 2013–2014 academic years. Am J Sports Med. 2015;43(11):2671–9.
19. Hägglund M, Waldén M, Bengtsson H, Ekstrand J. Re-injuries in professional football: the UEFA elite club injury study. *Return to play in Football*, theory and practice of return to sport. Cham, Switzerland: Springer; 2017. pp. 953–62. https://doi.org/10.1007/978-3-662-55713-6_74.
20. Bourne MN, Duhig SJ, Timmins RG, Williams MD, Opar DA, Al Najjar A, et al. Impact of the nordic hamstring and hip extension exercises on hamstring architecture and morphology: implications for injury prevention. Br J Sports Med. 2017;51(5):469–77.
21. Duhig SJ, Bourne MN, Buhmann RL, Williams MD, Minett GM, Roberts LA, et al. Effect of concentric and eccentric hamstring training on sprint recovery, strength and muscle architecture in inexperienced athletes. J Sci Med Sport. 2019;22(7):769–74.
22. Cuthbert M, Ripley N, McMahon JJ, Evans M, Haff GG, Comfort P. Corrections to: the effect of nordic hamstring exercise intervention volume on eccentric strength and muscle architecture adaptations: a systematic review and meta-analyses. Sports Med. 2020;50(1):101–2.
23. Askling CM, Tengvar M, Tarassova O, Thorstensson A. Acute hamstring injuries in Swedish elite sprinters and jumpers: a prospective randomised controlled clinical trial comparing two rehabilitation protocols. Br J Sports Med. 2014;48(7):532–9.
24. Bourne MN, Williams MD, Opar DA, Al Najjar A, Kerr GK, Shield AJ. Impact of exercise selection on hamstring muscle activation. Br J Sports Med. 2017;51(13):1021–8.
25. Ferri-Caruana A, Mollà-Casanova S, Baquedano-Moreno M, Serra-Añó P. Electromyographic activity of posterior kinetic chain muscles during hamstring strengthening exercises. Phys Ther Sport. 2022;55:205–10.
26. Faul F, Erdfelder E, Lang A-G, Buchner A. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behav Res Methods. 2007;39(2):175–91.
27. Stegeman D, Hermens H. Standards for surface electromyography: The European project Surface EMG for non-invasive assessment of muscles (SENIAM). Enschede: Roessingh Research and Development; 2007.
28. Halaki M, Ginn K. Normalization of EMG signals: to normalize or not to normalize and what to normalize to. In: Computational Intelligence in Electromyography Analysis—A Perspective on Current Applications and Future Challenges. 2012. p. 175–94.
29. Beaudette SM, Unni R, Brown SH. Electromyographic assessment of isometric and dynamic activation characteristics of the latissimus dorsi muscle. J Electromyogr Kinesiol. 2014;24(3):430–6.

30. Jorge A, et al. Muscle activity and kinematics during three hamstring strengthening exercises compared to sprinting: a cross-sectional study. Int J Sports Phys Ther. 2024;19(5):569–80. https://doi.org/10.26603/001c.116158.
31. Moiroux-Sahraoui A, et al. Comparative electromyographic activity of hamstrings during sprinting versus strengthening exercises: implications for injury prevention. Cureus. 2024;16(8):e66370. https://doi.org/10.7759/cureus.66370.
32. Ferreira RM, et al. The effects of the leg position on the nordic hamstring exercise eccentric force: a randomized cross-over study. Muscles. 2024;3(3):259–70. https://doi.org/10.3390/muscles3030023.
33. Morin T, et al. Robustness of hamstring muscle activation strategies following selective hypertrophy induced by Nordic hamstring curl and stiff-leg deadlift exercises. J Appl Physiol. 2025;139(1):296–307. https://doi.org/10.1152/japplphysiol.00237.2025.
34. Sahinis C, et al. Differences in activation amplitude between semitendinosus and biceps femoris during hamstring exercises: a systematic and critical review with meta-analysis. J Sports Sci. 2025;43(11):1054–69. https://doi.org/10.1080/02640414.2025.2486879.
35. Akyürek TA, Ertan H, Darendeli A. Biceps femoris EMG activity during incline treadmill running and nordic hamstring task. J Strength Cond Res. 2025;39(5):540–6. https://doi.org/10.1519/JSC.0000000000005049.
36. Mao L, et al. Fascicle behavior and muscle activity of the biceps femoris long head during running at increasing speeds. J Sports Sci Med. 2024;23(1):603–10. https://doi.org/10.52082/jssm.2024.603.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.