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Section II – Exercise Physiology and Sports Medicine

Acute Effects of Long and Typical-Duration Static Stretching or Eccentric Exercise on Flexibility and Performance in Young Males with Hamstring Tightness: A Randomized Controlled Trial

by
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Hamstring tightness is a contributing factor to various musculoskeletal health issues across diverse populations. However, the effectiveness of prolonged stretching interventions in enhancing flexibility, as well as the underlying physiological mechanisms remain insufficiently investigated. This study aimed to investigate changes in fascicle length (FL), musculotendinous unit (MTU) stiffness, and muscular performance following a single bout of long-duration static stretching (LS), typical-duration static stretching (SS), or eccentric exercise (ECC) in young men with hamstring tightness. Sixty-eight physically active men (22.0 ± 1.7 years) were randomly assigned to one of the four conditions: LS, SS, ECC, or control. FL, straight leg raise (SLR), MTU stiffness, eccentric torque, and jump height were measured before and immediately after exercise. Immediately following exercise, SLR increased significantly by 11.6% ($d = 1.31$), 4.3% ($d = 0.86$), and 6.9% ($d = 0.99$) for LS, SS, and ECC, respectively (all $p < 0.01$). FL was significantly greater post-exercise in all three intervention groups ($p < 0.05$). MTU stiffness decreased by 11.2% following LS and 13.1% following SS. Additionally, LS resulted in a reduction in peak torque by 23.9% ($d = 1.29$, $p < 0.001$) whereas no changes in jump height were observed in this study. LS did not produce superior acute effects on flexibility improvements, FL changes, or MTU stiffness reduction. Furthermore, LS was associated with an acute reduction in muscle strength. These findings support the use of typical-duration SS or ECC for individuals with tight hamstrings.

Keywords: *musculotendinous mechanical properties; joint extensibility; muscle architecture; peak torque; hamstring shortening*

Introduction

Muscle tightness or shortening is a potential contributing factor to musculoskeletal disorders. Among various muscle groups, the hamstrings are particularly susceptible to tightness, a condition commonly observed in both the general population and athletes (Hamzeh Shalamzari et al., 2022). Additionally, hamstring tightness may arise secondary to muscle or tendon injuries (Courseault et al., 2019). Rehabilitation to restore flexibility is essential during the early stages of recovery to optimize range of motion (ROM), while progressive strength gains can be achieved in the subsequent phases.

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To optimize improvements in ROM, previous research recommends employing stretching protocols that incorporate prolonged stretch duration of 30–60 s combined with high-frequency training (Thomas et al., 2018). A recent meta-analysis suggests that acute improvements in ROM are more likely attributable to changes in overall muscle-tendon unit (MTU) stiffness than to alterations in fascicle length (FL), particularly when static stretching (SS) is performed at moderate-to-high intensity (Ingram et al., 2025a). Additionally, increased stretch tolerance appears to contribute to ROM gains following chronic SS interventions (Magnusson et al., 1997). Many previous studies have suggested the potential effects of long SS on muscle mass and strength, with some of these findings being reported in vitro (Alway, 1994; Frankeny et al., 1983). In human studies, a recent review concluded that performing SS for more than 30 min per exercise session significantly increased muscle mass and peak force production in the plantar flexor muscles (Warneke et al., 2023a). There is also evidence that ROM in the plantar flexor muscles can improve substantially following SS, with a 16.4% increase observed after 60 min of SS, compared with a 6.1% increase found after just 10 min of SS (Warneke et al., 2023c).

Interestingly, research has demonstrated that eccentric (ECC) training not only substantially enhances muscle force production and post-activation performance, particularly when performed with a slow tempo (2 s) during the eccentric phase (Stastny et al., 2024), but also improves ROM (Diong et al., 2022). A recent study found that ECC training acutely improves tissue extensibility to a comparable extent as passive stretching and dynamic stretching in healthy young adults (Aune et al., 2019; Nishida et al., 2018). The underlying mechanisms likely contributing to this effect include a reduction in antagonist co-activation, facilitated by increased voluntary activation of the agonist muscle (Liang et al., 2024). It is also important to note that the increased risk of hamstring strain injury in elite soccer players may be attributable to the shorter long head of biceps femoris fascicles (<10.56 cm) and reduced eccentric knee flexor strength (<337 N) (Timmins et al., 2016). Moreover, delayed onset muscle soreness may occur after an unaccustomed session of ECC, which could be an important factor affecting exercise adherence in some cases.

As mentioned above, long-term stretching studies targeting hamstrings remain limited, particularly with respect to muscle morphology, mechanical properties, and muscular function. Furthermore, hamstring tightness is more commonly observed in males than in females (Yu et al., 2022). This study aimed to investigate the acute changes in joint extensibility, MTU mechanical properties, and muscular force production after long-lasting or typical SS or ECC training in young male individuals exhibiting hamstring tightness. It was hypothesized that long-duration static stretching (LS) would exert a greater effect on joint ROM, FL, MTU stiffness, and muscle strength compared with the other exercises. The results of this study may provide a multidimensional benefit in terms of exercise selection and could recommend programs for individuals with hamstring ROM deficiencies.

Methods

Participants

Sixty-eight healthy and recreationally active young men (aged 18–35 years) were recruited for this study. All participants exhibited hamstring tightness, as determined by a passive straight-leg raise (SLR) angle of less than 80° (Jeong et al., 2022). A priori sample size estimation for the present study was performed using G*Power software, based on a previous study (Warneke et al., 2022). Parameters included a Type I error rate of 0.05, statistical power of 0.80, and an effect size of 0.4. The calculation indicated a minimum requirement of 12 participants per group; after applying a 42% increase to account for potential dropouts, the final sample size was 17 participants per group.

In this study, participants were excluded if they had engaged in routine resistance or stretching exercises, experienced musculoskeletal pain in the lower limbs or the lower back during the preceding six months, had any neurological conditions, regularly used muscle relaxants, or consumed whey protein or collagen supplements. All study procedures adhered to the principles of the Declaration of Helsinki (2013 revision) and were approved by the Ethics Committee of the Research and Innovation Administration Division of the Burapha University, Chonburi, Thailand (protocol code: IRB1-015/2568; approval date: 07

February 2025). Written informed consent was obtained from all participants after they had been provided with detailed information regarding the study procedures.

Participants were randomly assigned to one of the four groups: LS, typical static stretching (SS), eccentric exercise (ECC), and a rest control group (CON). Participants were randomized using sequentially numbered, opaque, and sealed envelopes to ensure allocation concealment. Participants were familiarized with the experimental procedures a few days prior to baseline data collection. To minimize the potential effects of daily activity on study outcomes, all participants were instructed to maintain their usual physical activity levels throughout the study. Additionally, to ensure maximal performance, they were asked to refrain from alcohol, tobacco, and high-intensity exercise for at least 24 hours prior to each testing session.

Measures

All measurements were completed both before and immediately after the exercise intervention, in the specified order, by investigators who were blinded to the group assignment. Owing to time constraints and the reproductive nature of the experimental setting, only the right leg was examined and subjected to exercise in this study. Previous studies have reported the reliability of the measurement variables used in this study (Kamandulis et al., 2024; Namsawang et al., 2024).

Fascicle Length

The FL of the right biceps femoris (BF) and medial gastrocnemius (MG) muscles was measured using ultrasound imaging in B-mode (M5 series, Shenzhen Mindray Bio-Medical, Shenzhen, China) with a linear 4-cm, 7.5-MHz probe (MSK preset). The leg was positioned straight and resting in the prone position during measurements. A transparent pen was used to mark the probe positions, located 15 cm proximal to the popliteal crease for the BF muscle and 10 cm distal to the popliteal crease for the MG muscle. Additional FL at a lengthened position was taken while the SLR was fixed at 60° of hip flexion for the BF muscle in the supine position; passive ankle dorsiflexion was tested at 30° in the prone position for the MG muscle. FL data were analyzed offline using Tracker 6.0.10 software (https://physlets.org/tracker/; accessed on 22 April 2025), with an extrapolated line drawn along the visible fascicle (Miyamoto et al., 2020). The mean FL obtained from the analysis of two images was used for subsequent analyses.

Flexibilities

Passive hamstring flexibility was determined using the SLR test with an inclinometer (ISOMED, Portland, OR, USA). In the supine position, participants were instructed to relax fully. A single investigator then passively flexed the participant's leg with the knee extended until the point of resistance was felt. The measurement procedure was conducted three times, with a 15-s rest interval between trials. The mean of the two closest angles was used for subsequent analysis (Kamandulis et al., 2024). In a slight modification to the previous study (Warneke et al., 2023b), a tape measure was used for the knee-to-wall (KTW) stretch evaluation. Participants were instructed to place the foot on the attached tape measure while the contralateral leg was lifted. During the test, participants were allowed to stabilize their body by placing their hands on a wall. They were then instructed to slowly push the foot backward, keeping the knee against the wall, until the heel of the standing leg began to lift. The farthest distance achieved was recorded in centimeters from the attached measuring tape. The intraclass correlation (ICC) in the present study was 0.905 (0.828–0.970), CV 5%.

Passive Stiffness

Hamstring MTU passive stiffness was assessed by evaluating the tissue mechanical properties using a Biodex System Pro 4 isokinetic dynamometer (Biodex Medical Systems, Shirley, NY, USA). The participant's position was established in accordance with the setup described in a previous study (Muanjai et al., 2017). To ensure a relaxed state during testing, electromyographic activity of the BF and rectus femoris muscles was monitored throughout the procedure. The measurement protocol was consistent with that used in a previous study (Namsawang et al., 2024). Following gravity correction, passive MTU stiffness was determined as the slope of the passive torque-angle curve within 50–80% of the maximum ROM (Cabido et al., 2014).

Eccentric Strength

To assess the impact of the study intervention on strength, maximal eccentric knee flexor torque was measured using a Biodex System Pro 4 computerized dynamometer (Biodex Medical Systems) with a sampling rate of 100 Hz. Details of the knee flexor strength assessment have been described previously (Kamandulis et al., 2024), with testing performed at an angular velocity of $60°·s^{-1}$. The maximum eccentric torque and its corresponding joint angle were analyzed.

Jump Height

The counter movement jump to detect the neuromuscular function was measured with My Jump 3 application while participants wore sport shoes. Beginning from a standing position with the feet shoulder-width apart and hands on the waist, participants were instructed to flex their knees to approximately 110–120° and then jump as high as they could. This was repeated twice, with a two-minute rest interval between each jump. The take-off and landing times were manually identified, and the maximum jump height was analyzed using the in-built software of the application. The maximum jump height achieved was recorded and further analyzed (Jimenez-Olmedo et al., 2022). In the present study, the CV of jump height was 4.9% and the ICC was 0.875 (0.428–0.970).

Design and Procedures

Interventions

According to the intervention protocol, participants positioned the stretched leg against a wall with the knee extended while holding a long towel under the foot in the supine position. The wall stretch was performed to a tolerable angle, avoiding pain in the hamstrings, and was maintained for 60 s by adjusting the hip angle as needed. The movement was repeated 60 times (for total duration of 1 h), with 15 s of rest between each repetition (Warneke et al., 2023b) for the LS group. However, for the SS group, the stretch was held for 30 s, and repeated 6 times with 15 s of rest between each stretch (Muanjai et al., 2022). While standing on the right leg, ECC group participants were instructed to perform the single-leg Romanian deadlift T-drop (Delvaux et al., 2020). The eccentric phase was performed slowly over 2 s, followed by a 1-s return to the standing position on both legs (Stastny et al., 2024). The procedure comprised 6 sets of 30 repetitions performed within 60 s, with 1 min of rest between sets. After the pre-test measurement, the CON group participants were asked to remain in the supine position for 5–10 min.

Statistical Analysis

Normality of all data was assessed using the Shapiro-Wilk test. Descriptive data are presented as mean ± standard deviation (SD). Baseline measurements and participants' characteristics were compared across groups using one-way ANOVA. A mixed ANOVA (two time points × four interventions) was conducted with Tukey post hoc correction applied. Partial eta squared (ηp^2) was used to indicate the effect size for repeated measures, with magnitude interpreted as small (0.01), moderate (0.06), or large (0.14) (Lakens, 2013). Cohen's d values were used to represent the effect size for pairwise comparisons, with thresholds of small (d = 0.2), moderate (d = 0.5), and large (d = 0.8) (Cohen, 1988). For non-parametric data on MTU stiffness, within-group comparisons were analyzed using the Wilcoxon signed-rank test, while between-group comparisons were conducted using the Mann-Whitney U test. Statistical significance was set at α = 0.05. All statistical analyses were conducted using IBM SPSS Statistics for Windows (version 24.0; IBM Corp., Armonk, NY, USA).

Results

Characteristic Variables

Table 1 presents the characteristics of participants. The groups were comparable in terms of demographic characteristics and baseline levels of hamstring tightness.

Flexibilities

Hamstring flexibility, assessed via the SLR test, demonstrated a significant change over time with a time × group interaction effect [$F(3,64) = 8.6$, $p < 0.001$, $\eta p^2 = 0.45$] and a main time effect [$F(1,64) = 48.9$, $p < 0.001$, $\eta p^2 = 0.55$], but no significant main effect of the group. Specifically, the LS, SS, and ECC groups demonstrated average increases in the SLR angle of 11.6%, 4.3%, and 6.9%, respectively, corresponding to large effect sizes (d = 1.31, 0.86, and 0.99; all $p < 0.01$) (Figure 1A). However, post hoc Tukey comparisons among LS, SS, and ECC groups showed no significant differences ($p > 0.05$).

For calf flexibility, measured using the KTW test, a significant main time effect was observed [$F(1,64) = 25.4$, $p < 0.001$, $\eta p^2 = 0.28$], without a significant interaction or group effect. On average, participants demonstrated an increase of 0.78 cm (95% CI: 0.47 to 1.09 cm) in KTW distance following the interventions (Figure 1B).

Fascicle Length

Following a single bout of the intervention, there were significant interaction [$F(3,64) = 3.5$, $p = 0.02$, $\eta p^2 = 0.14$; $F(3,64) = 7.2$, $p < 0.001$, $\eta p^2 = 0.25$] and time [$F(1,64) = 17.9$, $p < 0.001$, $\eta p^2 = 0.22$; $F(1,64) = 37.3$, $p < 0.001$, $\eta p^2 = 0.37$] effects for FL changes measured both at rest and in the stretched position, respectively, with no significant group effect. As illustrated in Figure 1C & D, the CON group did not exhibit any changes in FL for either muscle investigated. In contrast, the BF FL at rest increased by 3.8% in the LS group and by 4.9% in the SS group ($d = 0.78$, 0.95, respectively; both $p < 0.01$). At a stretched position of 60° straight leg raise (SLR60), BF FL increased by 6.4% in the LS group, 3% in the SS group, and 6% in the ECC group ($d = 0.97$, 0.59, and 1.47, respectively; all $p < 0.05$). Similarly, for the MG muscle, FL increased by 3–5% at rest and 5–7% at 30° passive dorsiflexion (DF30) across the LS, SS, and ECC groups, with effect sizes ranging from $d = 0.72$ to 1.10.

Passive Stiffness

The improvement in hamstring flexibility observed in the stretching interventions may be partially explained by changes in MTU stiffness, as indicated by the non-parametric analysis. Specifically, MTU stiffness decreased from a median of 1.02 to 0.89 Nm/deg in the LS group and from 0.95 to 0.77 Nm/deg in the SS group. In contrast, no significant changes in MTU stiffness were observed in the ECC or CON groups. Additionally, no significant differences were observed, as illustrated in Figure 2.

Muscular Functions

In terms of muscular performance changes, there was a significant interaction [$F(3,64) = 7.6$, $p < 0.001$, $\eta p^2 = 0.26$] and time [$F(3,64) = 6.2$, $p = 0.015$, $\eta p^2 = 0.09$] effect for peak eccentric strength, but no group effect. Following a single session of LS, peak eccentric torque decreased significantly by 23.9% ($d = 1.29$, $p < 0.001$), whereas no significant changes in knee flexor strength were observed in the other groups. Moreover, no significant effects were observed for jump height performance (Table 2).

Table 1. Characteristics of participants.

	LS (N = 17)	SS (N = 17)	ECC (N = 17)	CON (N = 17)	*p*-value
Age (years)	20.9 ± 1.1	22.2 ± 4.9	21.9 ± 3.9	21.2 ± 2.6	0.685
Body mass (kg)	65.6 ± 7.8	66.2 ± 10.1	65.1 ± 7.5	66.5 ± 8.6	0.964
Body height (cm)	171.5 ± 6.5	173.5 ± 6.1	173.3 ± 5.5	174.4 ± 7.1	0.582
BMI ($kg \cdot m^{-2}$)	22.3 ± 1.9	21.9 ± 3.1	21.6 ± 2.4	21.9 ± 3.1	0.921
SLR (deg)	68.7 ± 6.9	70.9 ± 5.4	68.4 ± 3.0	71.7 ± 6.5	0.897

Data are mean ± SD. BMI: body mass index; SLR: straight-leg raise; LS: long static stretching; SS: typical static stretching; ECC: eccentric exercise; CON: control

Table 2. Data for muscle performance before and immediately after the interventions (n = 17).

Variables	Time points	LS	SS	ECC	CON
Muscle performance					
KF eccentric torque (Nm)	Pre	126.9 ± 30.9	117.1 ± 28.7	112.2 ± 24.1	106.4 ± 30.3
	Post	98.6 ± 37.9**	110.9 ± 31.9	114.6 ± 24.1	111.3 ± 31.0
	Difference	−28.3 (−39.5, −17.0)	−6.2 (−19.5, 7.2)	+2.4 (−10.1, 15.0)	+4.9 (−3.5, 13.3)
CMJ height (cm)	Pre	29.7 ± 7.5	30.0 ± 6.5	28.7 ± 3.9	27.2 ± 5.7
	Post	30.2 ± 7.3	28.4 ± 7.1	28.6 ± 4.5	26.9 ± 6.6
	Difference	+0.5 (−0.6, 1.5)	−1.6 (−2.9, −0.4)	−0.1 (−1.8, 1.6)	−0.2 (−1.0, 0.3)

*Data are expressed as the mean and SD. KF: knee flexors; CMJ: countermovement jump; LS: long static stretching; SS: typical static stretching; ECC: eccentric exercise; CON: control. Significant changes between pre and immediate post are indicated as ** p < 0.001. No significant group effect was seen in these variables*

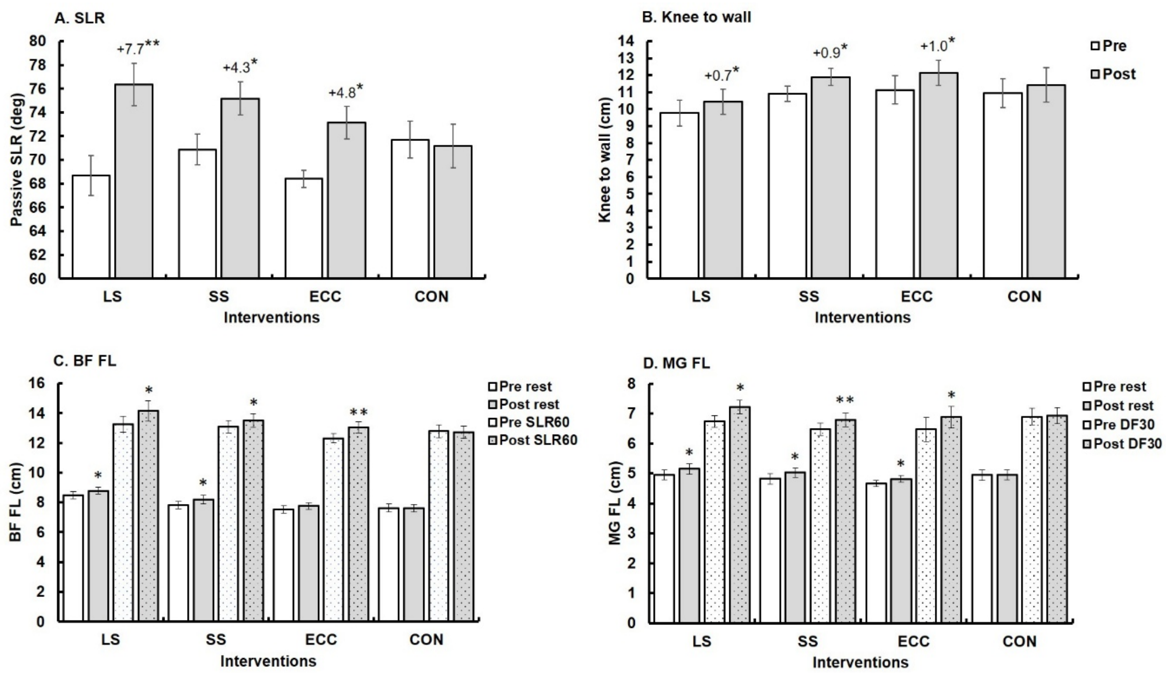

Figure 1. Changes in hamstring flexibility by SLR (A) and calf flexibility by knee-to-wall (B), BF FL (C) and medial gastrocnemius FL (D) immediate after a single bout of the four interventions. Data are presented as mean and SEM (n = 17).
** $p < 0.05$, ** $p < 0.001$: significant difference between pre- and immediate post intervention*

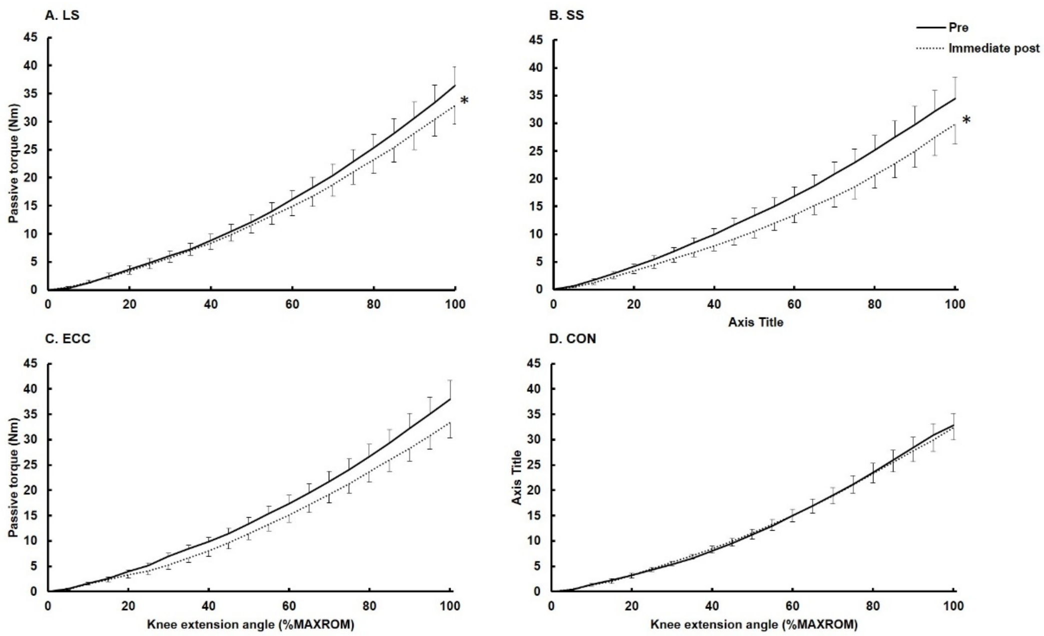

Figure 2. Changes in the passive torque-angle relationship of knee flexor immediate after a single bout of exercise interventions. Data are shown as mean and SEM (n = 17).
** Significant difference between pre- and immediate post intervention*

Discussion

The main finding of this study was that LS did not produce superior acute effects on flexibility, FL, or MTU stiffness compared with other interventions. Additionally, LS was associated with a reduction in strength performance. Given the limited evidence supporting the efficacy of LS, these findings demonstrate—contrary to prior hypotheses—that LS does not offer acute benefits over alternative exercise modalities according to our data.

The mechanisms underlying flexibility improvements observed in this study appear to be primarily attributed to changes in FL and MTU stiffness following stretching exercises. In contrast, the improvement in ROM after a single bout of ECC training might be explained rather by an acute increase in FL. Previous studies have suggested that changes in ROM may be associated with viscoelastic stress relaxation and enhanced stretch tolerance, depending on the type of stretching applied (Nakamura et al., 2021; Opplert and Babault, 2019). The observation in the present study that LS did not produce superior acute improvements in ROM compared with shorter-duration stretching or ECC training contrasts with findings from acute (Warneke et al., 2023c) and chronic (Warneke et al., 2023b) LS training studies. It also has been mentioned on a review that while static stretching can enhance flexibility, no additional benefits were observed beyond a threshold of 4 min per exercise session (Ingram et al., 2025b). Furthermore, the same review emphasized the need for further investigation into high-volume, long-duration static stretching, particularly in relation to its potential to induce morphological adaptations. Such studies are necessary to establish greater confidence in the dose-response relationship for flexibility improvements.

In the present study, a single session of LS resulted in a dramatic reduction of approximately 23.9% in maximal eccentric strength. This decrease is indicative of stretch-induced impairments in strength and/or anaerobic performance, which is consistent with the findings of previous research (Behm et al., 2021; Çabuk et al., 2026; Trajano et al., 2020; Warneke and Lohmann, 2024). The mechanisms underlying this performance deficit remain inconclusive, with several contributing factors proposed in the literature, including neural, morphological, mechanical, and psychological influences (Behm et al., 2021). In contrast, prior research has demonstrated that six weeks of static stretching training, performed for one hour daily and targeting the plantar flexor muscles, led to an increase in maximal strength of approximately 16.8–19.0% (Warneke et al., 2022, 2023b). This strength gain is likely attributed to mechanotransduction processes, through which sustained tension induces muscle hypertrophy in human skeletal muscle (Aguilar-Agon et al., 2019).

Hamstring flexibility is considered an important factor influencing vertical jump performance (Genç and Demircioğlu, 2024). However, in the present study, the improvements in the unilateral SLR angle observed in the experimental groups did not translate into changes in overall jump performance, which is consistent with previous findings (Gesel et al., 2022; Kurt et al., 2024). On the other hand, a decrease in eccentric strength also did not have an impact on jump performance. It is worth mentioning that multiple factors play a role during a vertical jump, which is influenced not only by the strength level, but also by the exercise mode (concentric or eccentric), neuromuscular coordination, skills, and technique (Genç and Demircioğlu, 2024). In addition, during jumping, knee extensors are more important than knee flexors. Furthermore, jumps were performed with two legs, meaning that the non-exercised leg might compensate for deficiencies related to a lack of eccentric hamstring strength. It remains unclear to which extent strength or flexibility of the non-exercised (contralateral) leg may have influenced jump performance because this was not assessed in this study.

A major strength of this study lies in its single-blinded randomized controlled trial design, focusing specifically on the hamstring muscles to examine the acute responses in FL, MTU stiffness, and muscular function following stretching interventions. However, this study presents several limitations. First, the findings are not generalizable to populations of different sexes, older adults, or individuals with varying levels of physical fitness. Previous studies have reported that differences in sex hormones and age can significantly influence tissue stiffness, suggesting that these factors may affect the generalizability of the present results (Alvarez de Sierra Garcia and Expósito Jimenez, 2024; Hirata et al., 2020; Pessali-

Marques et al., 2024). Second, the intensity of stretching may have differed among participants because of subjective perceptions of stretching, particularly during prolonged duration. Third, this study did not assess muscle capacity at higher velocities, and evaluating the functional H/Q ratio may provide additional insight into the influence of antagonist muscle shortening and reciprocal interactions on eccentric strength and injury risk (Stastny et al., 2018). Finally, the chronic effects of long-duration stretching on hamstring muscles warrant further investigation.

Practical Implications

The present study suggests that LS does not provide superior immediate benefits for improving flexibility compared with other methods. Moreover, it may negatively impact muscle performance, particularly by reducing maximal eccentric strength shortly after stretching. Therefore, for athletes or individuals aiming to enhance flexibility, typical-duration static stretching (e.g., ~ 180 s per muscle group) during warm-ups or flexibility routines is recommended. ECC training also emerges as a promising alternative because of its ability to substantially increase ROM without compromising muscle function, and the resulting increase in FL may further reduce the risk of future strain injuries in individuals with hamstring tightness (Timmins et al., 2016). However, delayed onset muscle soreness (DOMS) may occur following the initial training session. This response typically diminishes with subsequent repeated bouts of ECC exercise (Newham and Jones, 2016).

Conclusions

In summary, our findings indicate that LS does not elicit superior acute improvements in flexibility, FL, or MTU stiffness. Moreover, LS was associated with a decline in muscle performance, particularly in maximal eccentric strength. Based on these results, we recommend typical-lasting stretching or ECC exercise as suitable for use in flexibility enhancement programs.

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Informed Consent: Informed consent was obtained from all participants included in the study.

Conflicts of Interest: The authors declare no conflict of interest.

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