

Original Article

Effects of a 6-Week Home-Based High- or Regular-Volume Static Stretching or Hamstring Resistance Exercise in Young Men with Hamstring Tightness

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Abstract

Objectives: This study aimed to examine the effects of unilateral long-duration static stretching (LS) on range of motion (ROM), musculotendinous unit (MTU) stiffness, muscle thickness (MT), strength, and contralateral effects (CE) in young men with hamstring tightness. **Methods:** Sixty-eight young men (22.0 ± 1.7 years) were randomly assigned to one of four groups: LS, typical-duration static stretching (SS), hamstring resistance exercise (HRE), or control. ROM, MTU stiffness, MT, and knee-flexor peak torque were assessed at baseline, after the 6-week intervention, and at the 3-month follow-up. **Results:** ROM improvement after the 6-week was observed across the LS, SS, and HRE groups (all $p < 0.05$). Significant decreases in MTU stiffness were observed, with reductions of 0.13 Nm/deg in the hamstrings for both the stretching groups (all $p < 0.05$). At the 3-month follow-up, reductions in MTU stiffness remained evident in the LS group. A significant time effect was observed for bilateral peak torque without interaction or group effects, while MT showed no changes. **Conclusions:** One hour of hamstring stretching did not result in superior improvements in ROM, MTU stiffness, or morphological and CE adaptations compared to other exercise modalities. Nevertheless, SS remains a time-efficient approach to enhance flexibility and mechanical properties in a home-based setting. **Clinical trial registration:** Thai Clinical Trials Registry (TCTR20250219007).

Keywords: Eccentric Contraction, Leg Flexibility, Mechanical Property, Muscle Mass, Stretching Duration

Introduction

As with many aspects of health-related performance, muscle flexibility plays a fundamental role in facilitating efficient body movement. Insufficient hamstring flexibility has been associated with an increased risk of musculotendinous injuries, poor posture, and lower back

pain^{1,2}. It is well established that stretching-based exercises or interventions can enhance range of motion (ROM). The underlying mechanisms are likely multifactorial, involving alterations in the mechanical properties of the muscle and surrounding soft tissues, increased stretch tolerance, and morphological adaptations³⁻⁵.

A dose-response relationship has been previously reported for stretching interventions aimed at improving flexibility^{6,7}. Additional beneficial effects were observed as collateral outcomes of high-intensity, high-volume stretching training. For example, greater gains in ROM, muscle mass, and force production have been observed following six weeks of long-duration static stretching (LS) of the plantar flexor muscles⁸. An average increase of 27.3% in flexibility and a 15.2% increase in the cross-sectional area of the lateral gastrocnemius muscle were observed following a six-week intervention involving daily

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one-hour static stretching⁹. Moreover, six weeks of daily five-minute static stretching per leg muscle group resulted in a significant average increase of 4.4% in squat isometric strength, regardless of changes in rectus femoris muscle thickness or muscle stiffness¹⁰. Additionally, increases in ROM can also result from strengthening exercises such as eccentric training^{11,12}, which are often accompanied by improvements in muscle strength. However, this modality may initially induce delayed onset muscle soreness (DOMS) during the early stages of training¹³.

Given the observed increases of 2.1% in muscle thickness and 11.4% in dynamic maximal strength of the untrained leg following six weeks of daily static stretching of the calf muscles⁹, a contralateral effect may be present. This stretch-induced strength gain may, in part, be attributed to interlimb transfer mediated by central nervous system adaptations⁹. Exercise-induced hypertrophy may be explained by exercise-induced muscle damage within the muscle fibers¹⁴, a phenomenon observed following high-volume, high-intensity stretching^{9,15} as well as resistance-based exercise¹⁶.

Previous research has demonstrated additional benefits of LS, not only in improving flexibility but also in promoting muscle hypertrophy and strength gains. However, it remains unclear whether these adaptations extend to other muscle groups, such as the hamstrings, which are particularly susceptible to injury and may contribute to low back pain. Moreover, the biarticular calf and hamstring muscles differ substantially not only in size but also in their architecture and function. Specifically, the gastrocnemius is a pennate muscle, whereas the long head of the biceps femoris is a fusiform muscle¹⁷. These architectural distinctions may influence the responsiveness of each muscle group to stretching interventions¹⁸. Therefore, the present study aimed to examine the effects of a six-week, home-based intervention—long- or typical-duration static stretching (SS) or hamstring resistance exercise (HRE) involving an eccentric component—on range of motion, musculotendinous stiffness, muscle thickness, strength, and contralateral adaptations in young men with hamstring tightness. It was hypothesized that LS would produce greater improvements in ROM, MTU stiffness compared to the other interventions, while also eliciting comparable changes in muscle thickness and strength relative to resistance exercise. These results may inform the selection of targeted interventions for individuals in the early phase of rehabilitation or during immobilization.

Materials and Methods

Participants

Sixty-eight healthy young men aged 18–35 years with hamstring tightness were recruited for this study. Hamstring tightness was assessed using the passive straight leg raise (SLR) test, with an inclusion criterion of less than 80° of hip flexion¹⁹. SLR was measured using an inclinometer (ISOMED, Portland, OR, USA), and the maximum hip flexion angle was

defined relative to the horizontal. Exclusion criteria included regular participation in resistance or stretching training; a history of musculoskeletal pain in the lower limbs or lower back within the past six months; the presence of any neuromuscular or skeletal disorders; regular use of muscle relaxants; or consumption of whey protein or collagen supplements.

Participants were randomly assigned to one of four groups—LS, SS, HRE or a physical activity educational control group (CON)—using a method of sequentially numbered, opaque, sealed envelopes. Participants were instructed to maintain their usual physical activity levels throughout the study and to abstain from alcohol consumption, tobacco use, and vigorous physical activity for at least 24 hours prior to each testing session.

Study design

This study was designed as a single-blind, randomized controlled trial. The data presented in this study are part of a larger project titled “Effects of home-based short vs long-lasting static stretching or eccentric exercise on flexibility, muscle size, muscle strength and function in young males with hamstring tightness”. While the study flow CONSORT diagram, methodology, and findings related to flexibility, muscle fascia thickness, and fascicle length have been published previously as part of that project²⁰, the present article focuses on different outcomes, specifically stiffness, MT, muscle strength, and contralateral effects. Outcome measurements were conducted in the following sequence: MT, MTU stiffness, and muscle strength. Assessments were performed by investigators blinded to group allocation on the trained leg at baseline, immediately following the 6-week intervention, and at a 3-month follow-up. To examine potential contralateral effects of stretch-induced hypertrophy, muscle thickness and isometric knee flexor strength were also measured on the non-trained (contralateral) leg. The 6-week training interventions were applied to the dominant leg only, primarily due to the time-intensive nature of the LS protocol. For sessions exercised at home, participants were instructed to record their daily training compliance. Additionally, real-time video calls were conducted once per week to monitor exercise execution and ensure adherence to the protocol. No participants withdrew, and complete data were obtained at all time points throughout the study. The reliability of these measurements has been established in a previous study^{21,22}.

Measurements

Primary outcomes

Range of motion

The maximum ROM of the knee flexors was assessed unilaterally in the dominant (exercised) leg using a Biodex System Pro 4 isokinetic dynamometer (Biodex Medical Systems, Shirley, NY, USA). The test position was standardized according to the procedure described in our

previous study²³, in which electromyographic recordings of the biceps femoris and rectus femoris were used to verify a fully relaxed state. During testing, the dynamometer passively extended the knee at 5°/s until the participant reached maximum discomfort (without pain), and the procedure was repeated three times. The maximum ROM obtained from each trial was recorded and subsequently used in the analysis.

Secondary outcomes

Musculotendinous Unit Stiffness

MTU stiffness of the knee flexors was evaluated using the same procedure, same positioning, and same equipment as described for the ROM assessment. It was challenging for participants to consistently identify a similar endpoint during the session. Hence, the maximum end-ROM was recorded at each time point. The smallest maximum ROM value across the three time points was used to define the endpoint for stiffness calculations. At each time point, the passive trial that achieved the greatest ROM among the three repetitions was used to calculate passive stiffness at this specific end-ROM, determine peak passive resistance torque, and was subsequently used for analysis. After accounting for the gravitational effect of the lower leg, passive stiffness was calculated as the slope of the passive torque–angle curve between 50% and 80% of the maximum ROM, using the least-squares method²⁴.

Muscle thickness

MT of the BF was assessed using B-mode ultrasound imaging (M5 Series, Shenzhen Mindray Bio-Medical, Shenzhen, China) with a 7.5 MHz, 4-cm linear transducer (MSK preset) while participants were in a prone position. Measurements were taken at a standardized location 15 cm proximal to the popliteal crease, using a longitudinal view. Ultrasound gel was applied, and minimal pressure was exerted to avoid tissue compression during image acquisition. MT was measured as the distance between the superficial and deep aponeuroses, and images were analyzed offline using ImageJ software (National Institutes of Health, USA). The average value of two images per muscle was used for statistical analysis. Measurements were performed bilaterally to investigate potential contralateral effects on the untrained limb. A blinded investigator with nine years of experience in ultrasound imaging performed all MT measurements and analyses. In the present study, the ICC for MT of the BF was 0.888 (95% CI: 0.787–0.942), with a CV of 5.4%.

Isometric and eccentric strength

Leg strength was assessed using a Biodex System 4 dynamometer (Biodex Medical Systems, Inc., Shirley, NY, USA). Following a standardized 5-minute warm-up on a cycle ergometer, participants were securely positioned in the dynamometer chair. A familiarization phase consisting

of 2–3 submaximal warm-up contractions at approximately 50% of perceived maximal effort was performed, followed by a 2-minute rest period. Isometric strength testing was conducted first. Participants were positioned with the hip flexed to 85° and the knee flexed to 50°. Participants were instructed to “exert maximal force as hard as possible and hold for 3 seconds.” This was repeated twice with a 1-minute rest interval between trials. Subsequently, eccentric strength testing was performed at an angular velocity of 60°/s. The ROM was set from 110° of knee flexion to 10° of extension (0° representing full extension), with participants positioned at 85° of hip flexion. All exertion tests were performed with standardized verbal encouragement. The highest peak torque value obtained from the two trials was used for analysis.

Exercise Volume, Satisfaction, and Adherence

For all groups, exercise volume was assessed at baseline by self-report of activity from the month preceding study participation, and subsequently monitored throughout the 3-month follow-up period, expressed as the number of minutes per week of any form of exercise.

Following the 6-week intervention period, participants rated their satisfaction with the exercise program using a 7-point Likert scale ranging from +3 to -3, where +3 indicated ‘extremely satisfied’ and -3 denoted ‘very dissatisfied’.

During the 3-month follow-up period, participants in the intervention groups were informed that continuation of the exercise program was voluntary. The number of exercise sessions performed each week was documented to evaluate program adherence.

Interventions

Long-duration static stretching

Participants engaged in a standardized daily hamstring stretching protocol over a six-week period in supine position. The stretch was performed using a long towel positioned beneath the plantar surface of the right foot. With the knee fully extended and the ankle maintained in dorsiflexion, the hip joint was passively flexed and lifted toward the wall until the participant reported maximal muscular tension. The hip angle was then minimally adjusted for each individual as needed to maintain a consistent stretch intensity—defined as the maximal muscular tension experienced without pain perception—throughout the 60-second hold. This stretching exercise was repeated 60 times per session²³, with 15-second rest intervals between repetitions to allow the limb to return to a gravity-dependent position and alleviate any discomfort.

Typical-duration static stretching

Participants in the SS group performed the stretch using a procedure similar to that of the LS group. The protocol consisted of six repetitions of 30-second holds, interspersed with 15-second rest intervals, performed three times per week over a six-week period.

Hamstring resistance exercise

The HRE group performed a single-leg T-drop Romanian deadlift to specifically target the hamstring muscles through eccentric loading²⁴. Participants were instructed to stand on the trained leg with a slight knee flexion of approximately 10–15°, and to slowly flex the trunk forward in a controlled manner until reaching the end range of hip flexion, performing the lowering phase over 2 seconds and returning to the initial position within 1 second, without a prescribed pause between phases. Each session consisted of 6 sets of 30 repetitions, with a 1-minute rest period between sets. This training protocol was conducted three times per week over a six-week period. Exercise intensity was prescribed using the Rating of Perceived Exertion (RPE) scale. During the first two weeks, the target RPE ranged from 6 to 11 (on a 20-point scale), progressing to 12–17 in weeks 3 and 4, and reaching 18–19 in the final two weeks. To achieve higher intensities in the later stages, participants were instructed to add external load to the body.

Control

Participants in the CON group were provided with general physical activity recommendations for young adults, in accordance with the 2022 guidelines of the American College of Sports Medicine (ACSM). No specific exercise or stretching protocols were prescribed for this group.

Statistical Analysis

The sample size for this study was determined using a post-hoc power analysis conducted with G*Power software. The calculation was based on the primary outcome of ROM, with a Type I error rate of 0.05, a statistical power of 0.80, and a moderate effect size of Cohen's $f = 0.2$ for a between-within interaction in a 2-way Analysis of variance (ANOVA; 4 groups X 3 measurements). The analysis indicated a minimum requirement of 16 participants per group. Remaining outcome measures were not individually powered and are therefore considered exploratory.

All data were tested for normality using the Shapiro–Wilk test. Descriptive statistics are presented as mean \pm standard deviation (SD). Absolute differences between time points are reported as mean values with 95% confidence intervals (CIs). Baseline characteristics among groups were compared using one-way ANOVA. To evaluate the effects of the interventions, a mixed-design ANOVA (3 time points \times 4 intervention groups) was conducted, with Tukey's post hoc corrections applied to account for multiple comparisons. Effect sizes for repeated measures were reported as partial eta squared (η^2), interpreted as small (0.01), moderate (0.06), and large (0.14), in accordance with Lakens (2013). For pairwise comparisons, Cohen's d was used, with values interpreted as small (0.2), moderate (0.5), and large (0.8)²⁶.

After testing for normality, MTU knee flexor stiffness data were found to be non-normally distributed. Group

effects were assessed using the Kruskal–Wallis test, while changes over time were initially analyzed with the Friedman test and followed by pairwise comparisons using the Wilcoxon signed-rank test, with effect sizes reported as r . A linear least squares regression analysis was performed to examine the relationships between changes in peak passive torque and MTU hamstring stiffness using pooled data from the LS, SS, and HRE training groups.

Statistical significance was set at an alpha level of 0.05. All analyses were performed using IBM SPSS Statistics for Windows, version 29.0 (IBM Corp., Armonk, NY, USA).

Results

Characteristics, compliance, exercise volume, adverse events, satisfaction and adherence

Table 1 presents the participant characteristics and recorded exercise volume, with no significant differences observed between groups. Additionally, exercise volume remained unchanged across all groups at the 3-month follow-up compared with prior-intervention levels (all $p > 0.05$). Training compliance was excellent across all intervention groups, with all participants completing the prescribed exercise sessions—42 sessions for the LS group (100%) and 18 sessions for both the SS and HRE groups (100%). It was noted that 29.4% of participants in the LS group initially missed sessions by the end of the 6-week intervention; however, all were subsequently completed within a few days, resulting in 100% session completion over an average of 6.5 weeks. At the end of the 6-week home-based intervention period, however, in the HRE group, the home-based exercise intensity unexpectedly failed to reach the targeted level during the final two weeks of the intervention. Although the target RPE was set at 18–19, only two participants reached this level. The reported RPE averaged 14 ± 4 , indicating suboptimal intensity, with an average additional load of only 2.7 kg. No protocol deviations occurred in any of the training interventions.

Mild soreness was subjectively reported in the LS group, averaging 1.6/10 during the first three weeks of training, with no adverse events observed in the SS group. In contrast, the HRE group reported soreness scores of 3.1/10 during the initial three weeks, which increased to an average of 4.1/10 during the subsequent three weeks.

After six weeks of training, the SS group reported the highest satisfaction with the exercise program, with a median score (interquartile range) of 3 (2,3), compared to 2 (0.5,2.0) in the LS group and 2 (0.5,2.0) in the HRE group (all $p < 0.001$). However, this level of satisfaction did not appear to influence the number of continued exercise sessions during the 3-month follow-up period, as no significant group differences were observed in exercise adherence, with a median of zero sessions recorded across all groups.

Table 1. Characteristics of participants.

	LS (N = 17)	SS (N = 17)	HRE (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
BMI (kg·m ⁻²)	22.3 ± 1.9	21.9 ± 3.1	21.6 ± 2.4	21.9 ± 3.1	0.921
Prior-exercise volume (min/wk)	300 (90, 540)	60 (0, 225)	240 (60, 600)	210 (75, 360)	0.121
3 month-exercise volume (min/wk)	260 (57, 308)	154 (15, 234)	180 (102, 317)	218 (120, 352)	0.553

Data are mean ± SD. BMI, body mass index; LS, long-duration static stretching; SS, typical-duration static stretching; HRE, hamstring resistance exercise; CON, control. Exercise volume was calculated from the number of min per week of any exercise, assessed both before study participation (Prior) and after the 3-month follow-up. Weekly exercise volume was not normally distributed; therefore, median values with interquartile ranges are presented, and statistical analyses were conducted using the Kruskal–Wallis test.

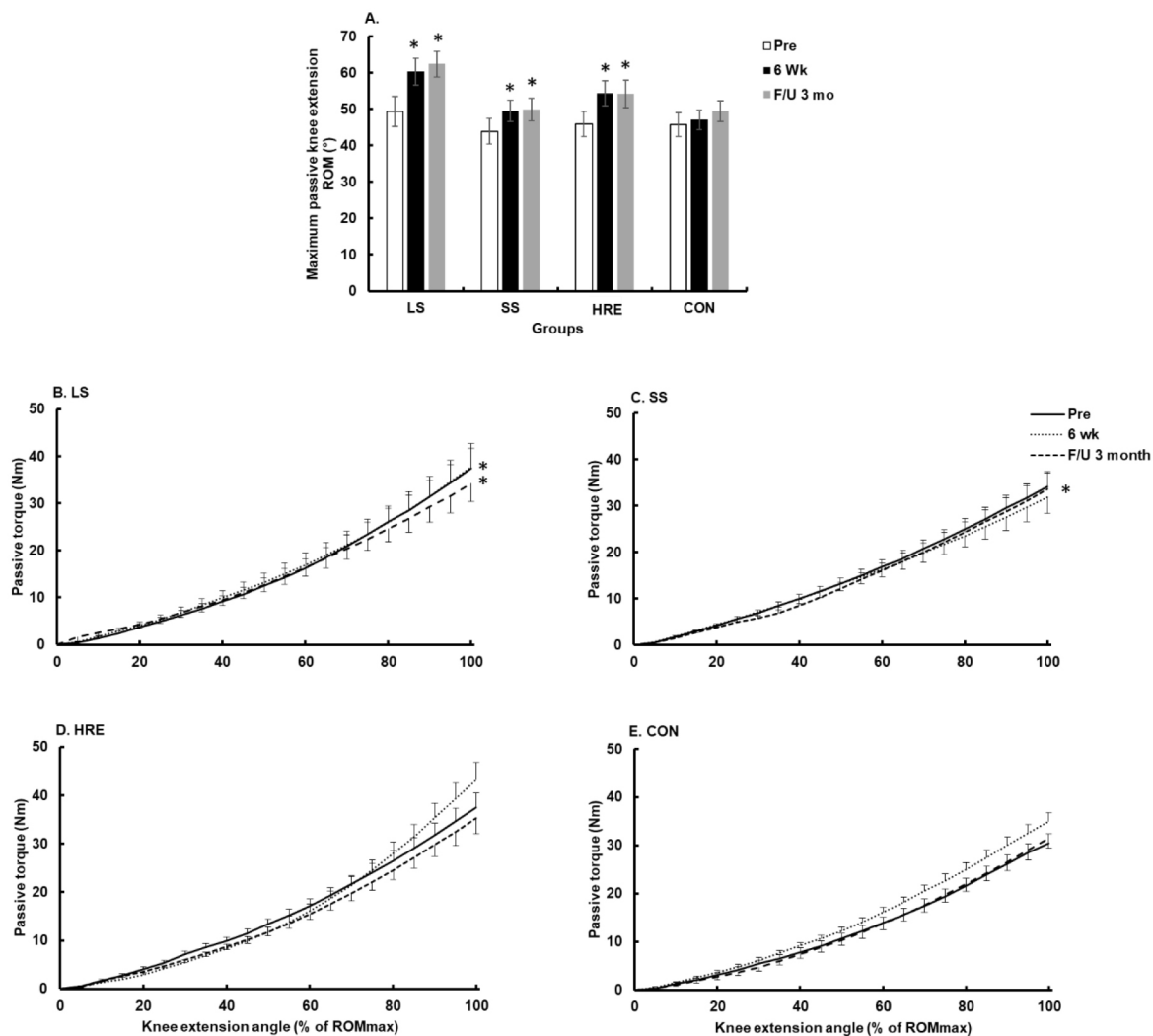


Figure 1. Changes in ROM flexibility and MTU stiffness following the four intervention protocols. A) Maximum passive knee extension ROM. B-E) Hamstrings MTU stiffness. LS, long-duration static stretching; SS, typical-duration static stretching; HRE, hamstring resistance exercise; CON, control group. Statistical significance: $p < 0.05$ (*) compared to pre-test values, (N = 17 per group).

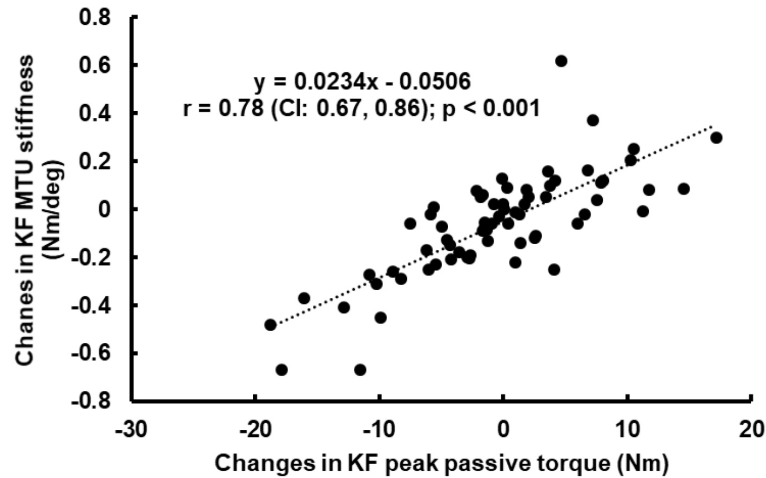


Figure 2. Changes in peak passive torque as a result of 6-week training in relation to the changes in MTU stiffness (N = 51). Data were pooled for the LS, SS, and HRE groups only. KF, knee flexors; MTU, musculotendinous unit.

Table 2. Data for muscle thickness before and after 6-week interventions.

Variables	Time points	LS (N = 17)	SS (N = 17)	HRE (N = 17)	CON (N = 17)
BF MT of stretching side (cm)	Pre	1.19 ± 0.23	1.28 ± 0.27	1.18 ± 0.20	1.27 ± 0.26
	6 wk	1.20 ± 0.26	1.25 ± 0.29	1.21 ± 0.21	1.23 ± 0.25
	F/U 3 month	1.19 ± 0.24	1.25 ± 0.25	1.19 ± 0.24	1.22 ± 0.30
	Interaction effect (p = 0.357); Time effect (p = 0.380); Group effect (p = 0.799)				
BF MT of contralateral side (cm)	Pre	1.16 ± 0.23	1.23 ± 0.24	1.20 ± 0.23	1.22 ± 0.27
	6 wk	1.15 ± 0.19	1.20 ± 0.23	1.17 ± 0.22	1.19 ± 0.27
	F/U 3 month	1.11 ± 0.18	1.18 ± 0.20	1.20 ± 0.22	1.20 ± 0.27
	Interaction effect (p = 0.685); Time effect (p = 0.251); Group effect (p = 0.831)				

Data are expressed as mean and SD. LS, long-duration static stretching; SS, typical-duration static stretching; HRE, hamstring resistance exercise; CON, control group; BF, biceps femoris; MT, muscle thicknes

Primary outcomes

Improvement in hamstring flexibility was defined by the maximum ROM during passive knee extension testing. A significant interaction [F(6,128) = 6.8, p = 0.03, ηp² = 0.18] and time effect [F(2,128) = 21.1, p < 0.001, ηp² = 0.25], but no group effect, was observed for this measure. After 6 weeks of training, ROM increased by an average of 10.9° (95% CI: 2.5–19.3°) [d = 0.67], 5.6° (0.2–11.1°) [d = 0.42], and 8.5° (2.8–14.1°) [d = 0.58] in the LS, SS, and HRE groups, respectively (all p < 0.05) (Figure 1A). Moreover, this improvement persisted at the 3-month follow-up (all p < 0.05), whereas no significant change was observed in the CON group.

Secondary outcomes

Based on non-parametric analysis, no significant group differences were observed in changes in knee flexor MTU stiffness. Initially, the Friedman test revealed statistically significant changes in stiffness within the LS (χ² = 8.3, df = 2, p = 0.016) and SS (χ² = 8.9, df = 2, p = 0.011) groups. Specifically, using the Wilcoxon signed-rank test, increased MTU compliance was observed following the 6-week intervention, with stiffness decreasing from 1.05 to 0.92 Nm/deg (p = 0.031; r = 0.37) in the LS group and from 0.95 to 0.82 Nm/deg (p = 0.035; r = 0.36) in the SS group (Figure 1B–C). Moreover, a sustained reduction in MTU stiffness was noted at the 3-month follow-up in the LS group, with a

Table 3. Normalized muscle strength changes following 6 weeks intervention.

Variables	Time points	LS (N = 17)	SS (N = 17)	HRE (N = 17)	CON (N = 17)
Stretching side					
KF MIVC (Nm/BW)	Pre	1.30 ± 0.36	1.20 ± 0.3	1.36 ± 0.21	1.22 ± 0.21
	6 wk	1.35 ± 0.41*	1.35 ± 0.31*	1.45 ± 0.21*	1.31 ± 0.15*
	F/U 3 month	1.41 ± 0.34*	1.42 ± 0.26*	1.44 ± 0.26*	1.36 ± 0.21*
	Interaction effect (p = 0.536); Time effect (p < 0.001); Group effect (p = 0.542)				
KF Eccentric torque (Nm/BW)	Pre	1.94 ± 0.35	1.65 ± 0.40	1.74 ± 0.42	1.59 ± 0.34
	6 wk	1.89 ± 0.54	1.84 ± 0.41	1.94 ± 0.41	1.72 ± 0.29
	F/U 3 month	1.97 ± 0.43*	1.92 ± 0.4*	1.94 ± 0.49*	1.76 ± 0.32*
	Interaction effect (p = 0.060); Time effect (p < 0.001); Group effect (p = 0.272)				
Contralateral side					
KF MIVC (Nm/BW)	Pre	1.26 ± 0.36	1.22 ± 0.26	1.28 ± 0.23	1.21 ± 0.25
	6 wk	1.35 ± 0.31*	1.28 ± 0.33*	1.36 ± 0.23*	1.26 ± 0.21*
	F/U 3 month	1.35 ± 0.34*	1.35 ± 0.27*	1.34 ± 0.24*	1.31 ± 0.27*
	Interaction effect (p = 0.866); Time effect (p < 0.001); Group effect (p = 0.944)				
<i>Data are expressed as mean and SD. LS, long-duration static stretching; SS, typical-duration static stretching; HRE, hamstring resistance exercise; CON, control group; KF, knee flexors; MIVC, maximal isometric voluntary contraction. *Significant difference compared to baseline.</i>					

value of 0.90 Nm/deg ($p = 0.016$; $r = 0.41$). No significant changes were found in the HRE or CON groups.

When MTU stiffness data were pooled, changes in peak passive torque were strongly associated with alterations in MTU stiffness, accounting for approximately 60% of the variance (Figures 2).

This study was also designed to investigate potential contralateral effects. Regarding changes in muscle thickness, no significant interaction, time, or group effects were observed in either the stretched or contralateral limb (Table 2), suggesting the absence of a contralateral effect on BF MT in this study.

Data on muscle strength are presented in Table 3. Peak torque values were normalized to body weight adjusted for changes over time prior to analysis. The contralateral effect on strength was assessed exclusively through isometric strength measurements of the knee flexor muscles. No significant interaction or group effects were observed for isometric knee flexor strength in either the trained or contralateral leg. A significant time effect was found, with strength increasing by 2.7 (-1.4, 6.9) Nm after six weeks and by 5.6 (1.9, 9.1) Nm after three months in the trained leg [$F(2,128) = 16.4$, $p < 0.001$, $\eta^2 = 0.20$], and by 4.1 (0.2, 7.9) Nm and 5.8 (1.9, 9.7) Nm, respectively, in the contralateral leg. Similarly, for eccentric strength of the knee flexors, only a significant time effect was observed [$F(2,128) = 14.9$, $p < 0.001$, $\eta^2 = 0.19$], with an overall increase of 8.6 (3.7, 13.5) Nm at the 3-month follow-up.

Discussion

High-volume stretching has been associated with several benefits, including greater gains in ROM, muscle hypertrophy, and strength improvements. The present study aimed to investigate how stretching and hamstring resistance exercise involving an eccentric component influence muscle flexibility, morphology and performance, including potential contralateral adaptations in young men with hamstring tightness. Contrary to our initial hypothesis, the results demonstrated that home-based LS did not produce greater improvements in ROM or reductions in MTU stiffness compared to other exercise modalities. Moreover, no changes in MT or contralateral effects for muscle strength gains were observed. The concurrent increase in hamstring muscle strength across all groups suggests a learning effect rather than a training-specific adaptation. From a time-efficiency perspective, the SS program may be considered a practical approach to improving flexibility and mechanical properties in individuals with hamstring tightness.

ROM improvement after the 6-week intervention was observed across all exercise training groups, consistent with previous findings^{11,23,27}, with the greatest gains noted in the LS group; however, these differences did not reach statistical significance between groups. The significant changes in MTU stiffness observed in this study are consistent with previous research on stretching training^{27,28}. It should also be noted that this study incorporated a 15-second rest period between stretching maneuvers.

As a result, the viscoelastic adaptations may differ from those elicited during a continuous, uninterrupted stretching protocol. However, previous evidence has shown that reductions in MTU stiffness do not differ between stretching performed with rest intervals and stretching performed continuously, whereas ROM and peak passive torque exhibit greater changes when rest periods are included²⁹. In contrast, other studies have demonstrated greater reductions in passive muscle stiffness following sustained, continuous stretching^{30,31}. Therefore, the influence of rest periods during extremely prolonged stretching on musculotendinous mechanical properties warrants further investigation.

Moreover, these alterations in mechanical properties persisted for three months following a six-week protocol of daily one-hour unilateral hamstring stretching. Notably, although the LS and SS groups performed the same exercise position, prolonged hamstring stretching may have induced greater tension transmission along the posterior thigh muscle. In contrast, hamstring resistance training involving an eccentric component, using the T-drop exercise, did not alter hamstring MTU stiffness, although it substantially improved ROM. This suggests that the observed ROM improvements in this group may be explained by factors such as increased stretch tolerance. The preservation of MTU stiffness may, in turn, be advantageous for maintaining elastic recoil properties required in power-oriented sports²⁷. Additionally, alterations in peak passive torque measured at the same specific end-ROM accounted for 60% of the variance in MTU stiffness changes. This finding implies that reductions in resistance to passive force at a fixed ROM position may reflect potential structural adaptations²⁸, specifically an increase in the number of sarcomeres in series⁹, which is also associated with improved viscoelastic properties.

Mechanical loading from stretching training not only enhances tissue compliance but may also induce muscle hypertrophy, as evidenced in previous studies reporting increases of 15–23% in muscle cross-sectional area following 6–12 weeks of high-volume, high-intensity stretching^{9,15}. This hypertrophic response is likely attributable to increased protein synthesis triggered by exercise induced damage within the muscle fibers¹⁴. Furthermore, the potential contributions of localized hypoxia or neuromuscular adaptations should also be considered⁸. However, such adaptations were not observed in the present study, which may be due to insufficient loading of the biceps femoris during stretching performed at moderate-to-high intensity, rather than at the higher intensities utilized in prior research. Unexpectedly, greater mechanical stimuli would typically be anticipated to promote muscle hypertrophy following resistance-based interventions, particularly those involving eccentric contractions. Nevertheless, no morphological changes were detected in the HRE group. This absence of change may be attributable to the low-intensity (suboptimal RPE), high-repetition nature of the strength-training protocol, as well as the

limited capacity to progressively increase exercise intensity in an unsupervised, home-based setting. This is consistent with the premise that greater hypertrophic responses are more likely to occur under higher loading conditions³², which plausibly induce greater mechanical tension, muscle damage, or metabolic stress³³. More importantly, the tempo of the eccentric phase is also a key factor influencing muscle hypertrophy. Previous research has shown that a slower tempo—such as a 4-second eccentric contraction—elicits greater hypertrophic responses compared to a faster 1-second eccentric contraction³⁴. Furthermore, previous findings have similarly reported no hypertrophic effects following bodyweight-based resistance training³⁵.

Previous studies have demonstrated that high-volume, high-intensity stretching training can also promote strength gains, potentially through mechanisms involving mechanical tension stimulating the mTOR signaling pathway³⁶ or changes in muscle architecture⁹. Previous research has also demonstrated comparable changes in muscle thickness, isometric strength, and flexibility following a protocol of daily one-hour stretching compared to resistance training performed three times per week for 15 minutes in the plantar flexors²³. However, the present study demonstrated comparable adaptations between stretching and resistance training involving an eccentric component, as no significant interaction effects were detected for peak torque after six weeks. The observed time effect on strength gains across all groups, including the CON group, in both legs may be attributable to changes in habitual activity or the influence of measurement repeatability, rather than a contralateral effect in the non-dominant or untrained leg. This pattern suggests that the gains are more likely attributable to a learning effect rather than a training-specific adaptation, as no interaction effect between time and group was observed for bilateral maximum torque output. Consequently, the strength improvements cannot be clearly attributed to the stretching or resistance training protocols. Moreover, repeated exposure to the dynamometer testing protocol can itself enhance performance, particularly in young, untrained participants. Future studies may therefore benefit from including additional familiarization sessions. Prior findings have reported increases in both muscle thickness and dynamic maximal strength of the untrained limb following six weeks of daily static stretching of the calf muscles⁹. The failure to detect strength adaptations in response to the training protocols may again be explained by the unexpectedly low mechanical loading achieved in this study.

Limitations

This study has several limitations that warrant consideration. First, accurately determining and monitoring exercise intensity in a home-based setting posed a significant challenge, particularly for the HRE condition. Future studies should incorporate more effective strategies for remote supervision³⁷ or improved regulation of high-

intensity exercise, reduce the number of repetitions, or alternatively, confirm these findings under controlled laboratory conditions with direct supervision. Second, the constant-torque technique used in the present study may have influenced the total stretch duration per set; however, the required angle adjustments were infrequent and very brief, making it unlikely that they meaningfully affected the overall stretching stimulus. Third, assessing a single muscle's morphology may not fully represent the adaptations occurring across the entire muscle group. Fourth, the actual training status of participants was uncertain, as it relied on self-reported weekly exercise minutes, which may have contributed to the unexpectedly favorable results. Furthermore, due to random allocation, the LS group had a substantially higher habitual weekly exercise volume at baseline than the SS group, although this difference was not statistically significant. Nevertheless, these data demonstrated extremely high variability, as reflected by a wide interquartile range. Moreover, in a real-world context, it was not feasible to fully control participants' physical activity outside the intervention, which may also have influenced the outcomes. Fifth, a methodological limitation of this study is that the sample size calculation was performed post hoc rather than a priori. The calculation was revised after data collection in order to adjust the effect size, which may reduce the statistical power and precision of the study's estimates compared with a prospectively determined sample size. This limitation should be taken into account when interpreting the findings. Finally, this study investigated the intervention effects only in males; therefore, the findings may not be generalizable to females, as sex-specific physiological adaptations to stretching protocols have been previously reported³⁸. Future research should address these issues to enhance the validity and applicability of the findings.

Clinical applications

A notable strength of the present study is its randomized controlled design, which allowed for the systematic investigation of high-volume unilateral hamstring stretching. The results demonstrated that a relatively low-volume protocol (15 minutes per week; SS) produced a substantial increase in ROM and reductions in MTU stiffness comparable to those observed with a more prolonged daily stretching protocol (420 minutes per week; LS). This finding aligns with recent recommendations suggesting that approximately 10 minutes of stretching per muscle per week may be sufficient to enhance flexibility³⁹. The SS group also reported a high level of satisfaction with the prescribed exercise; however, this did not appear to influence exercise adherence following the intervention period. According to our findings, lower-volume SS may be prioritized when time constraints and adherence are key considerations for individuals with hamstring tightness. These effects may differ in older adults or clinical populations, in whom tissue properties and tolerance to stretching may be altered.

Conclusions

In summary, the findings of this study indicate that one hour of unilateral hamstring stretching did not produce superior improvements in hamstring flexibility or reductions in MTU stiffness compared to other exercise modalities, and no morphological or contralateral strength adaptations were observed. These results suggest that typical-duration static stretching provides a time-efficient strategy to enhance flexibility and mechanical properties in individuals with hamstring tightness in a home-based environment. From a practical perspective, home-based interventions, whether for stretching or strength, should emphasize proper technique, controlled intensity, and maintaining participant motivation, rather than focusing solely on high exercise volume.

Ethics Approval

The study protocol was approved by the Ethics Committee of the Research and Innovation Administration Division, Burapha University (IRB1-015/2568; February 7, 2025), and all procedures conformed to the ethical standards of the Declaration of Helsinki (1964) and its later amendments.

Consent to Participate

All participants provided written informed consent prior to participation after receiving a detailed explanation of study procedures.

Authors' Contributions

PM and SK conceived and designed research. PM, WS, NS and NL conducted experiments. SC, SSU, and SA analyzed data. PM, SK, WS and SC drafted the manuscript. PM, SK, MTU and NL revised the manuscript. All authors read and approved the manuscript.

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