

Article

The Acute Effects of Active, Passive, and Proprioceptive Neuromuscular Facilitation and Dynamic Stretching on Lower-Limb Muscle Stiffness and Range of Motion: A Randomized Crossover Study

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Abstract

Objective: This study comprehensively compared the acute effects of active stretching (AC), passive stretching (PA), proprioceptive neuromuscular facilitation (PNF), and dynamic stretching (DS) on lower-limb muscle stiffness and range of motion (ROM). **Methods:** A randomized crossover repeated-measures design was employed. Data were acquired using MyotonPRO (Myoton AS, Tallinn, Estonia, Software v.5.0.0.257). Twelve physically active male college students participated in the study. Each participant completed all five conditions (CO, AC, PA, PNF, DS) in a randomized order, separated by 48 h washout periods. Muscle stiffness and ROM of the lower-limbs were evaluated before and after each stretching intervention. Muscle stiffness was measured in the following muscles (L = left; R = right): quadriceps: vastus lateralis (Vlt), rectus femoris (RF), vastus medialis (Vm); hamstrings: semitendinosus (Sem), biceps femoris (Bic); gluteus maximus (GM); gastrocnemius: medial (Gcm)/lateral (Gclt). A two-factor repeated-measures analysis of variance (ANOVA) with Bonferroni correction was employed to examine ROM and muscle stiffness under different stretching methods. **Results:** 1. All methods improved ROM (PA 95% CI [2.15, 4.66], $\eta^2 = 0.35$; PNF 95% CI [1.80, 4.32], $\eta^2 = 0.30$; AC 95% CI [1.92, 4.43], $\eta^2 = 0.32$; DS 95% CI [3.50, 6.01], $\eta^2 = 0.51$; $p < 0.05$); 2. PA significantly reduced muscle stiffness in Gcm-L (95% CI [−28.00, −8.74], $\eta^2 = 0.210$), Gclt-L (95% CI [−16.52, −2.18], $\eta^2 = 0.110$)/R (95% CI [−32.75, −8.10], $\eta^2 = 0.167$), and Vm-L (95% CI [−15.73, −6.33], $\eta^2 = 0.079$), but increased RF-L (95% CI [6.16, 21.58], $\eta^2 = 0.191$) stiffness; PNF significantly increased Sem-L (95% CI [2.46, 16.51], $\eta^2 = 0.117$) and Vm-R (95% CI [4.83, 16.21], $\eta^2 = 0.200$) stiffness; AC significantly reduced Sem-R (95% CI [−20.59, −0.83], $\eta^2 = 0.079$) stiffness while increasing GM-R (95% CI [6.34, 17.29], $\eta^2 = 0.254$) stiffness; DS significantly decreased muscle stiffness in Vlt-L (95% CI [−21.23, −5.90], $\eta^2 = 0.186$) and Sem-R (95% CI [−23.09, −3.33], $\eta^2 = 0.115$) ($p < 0.05$). **Conclusions:** DS significantly improved lower limb flexibility and reduced muscle stiffness in selected muscles. AC improved anterior thigh muscle stiffness. PA reduced stiffness in posterior chain muscles. PNF increased stiffness in specific muscles, suggesting caution before explosive activities.

Keywords: stretching; muscle stiffness; active stretching; passive stretching; flexibility



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1. Introduction

Stretching is a fundamental component of exercise and athletic training. Among the various stretching techniques, static stretching can be performed either actively (AC) or passively (PA). In active static stretching, the target muscle is lengthened and held by the contraction of antagonist muscles without external assistance, whereas passive static stretching relies on an external force (e.g., a partner or equipment) to maintain the stretch, requiring no voluntary contraction of the stretched muscle. Dynamic stretching (DS) involves controlled, repetitive movements that progressively increase joint range of motion, while proprioceptive neuromuscular facilitation (PNF) stretching combines passive stretch with an isometric contraction–relaxation cycle to enhance muscle extensibility via autogenic inhibition [1].

The resistance encountered during stretching originates from both the intrinsic mechanical stiffness of anatomical structures (muscle fascicles, tendons, aponeuroses, joint capsules, and ligaments) and neurophysiological reflex activity [2]. The present study specifically examines fascicle-level stiffness, a fundamental biomechanical property reflecting a muscle's resistance to active contraction and passive deformation.

Although numerous studies have examined the acute effects of individual stretching modalities, simultaneous comparisons among active static, passive static, dynamic, and PNF stretching remain limited. Prior investigations have typically compared two or three modalities, often in a single muscle group, and have largely assessed joint range of motion (ROM) or maximal force rather than directly assessing muscle mechanical properties [3–5]. To our knowledge, no study has employed the MyotonPRO device—a validated, non-invasive tool for quantifying muscle stiffness, elasticity, and stress relaxation time [6,7]—to simultaneously evaluate the immediate effects of these four commonly used stretching techniques across multiple lower-limb muscles within a single within-subject experimental design.

A direct comparison of these four modalities is warranted because each engages distinct neuromuscular mechanisms. AC stretching relies on agonist–antagonist coordination and active contraction, PA stretching eliminates voluntary drive, DS involves movement and potential thermal effects, and PNF exploits the contraction–relaxation cycle to induce autogenic inhibition. Despite their widespread use in sports and rehabilitation, their differential impacts on muscle mechanical properties remain unclear, and evidence is needed to guide modality selection for specific goals such as acutely increasing ROM while preserving or modulating stiffness. By using the MyotonPRO to obtain multi-muscle, multi-parameter data within the same participants, the present study may reveal how these divergent mechanisms translate into different patterns of stiffness change, thereby offering insights that isolated or pairwise comparisons cannot provide.

Therefore, the aim of this study was to compare the acute effects of AC, PA, DS, and PNF stretching on ROM and lower-limb muscle stiffness in physically active college students. We hypothesized that all stretching methods would increase ROM, and that PA and DS would reduce muscle stiffness in most muscle groups. A secondary hypothesis was that the magnitude and pattern of stiffness changes would differ among modalities, with AC and PNF producing more variable, muscle-dependent effects.

2. Materials and Methods

2.1. Experimental Design

Before the study began, participants completed two to three familiarization sessions involving all testing procedures and stretching exercises to minimize potential learning and coordination effects on the experimental outcomes.

A randomized crossover repeated-measures design was employed. During the experiment sessions, twelve participants completed ROM and muscle stiffness assessments immediately after a standardized 5 min jog. Following a 1 min rest period, the intervention order was completely randomized for each participant (CO, AC, PA, PNF, DS). Each stretching intervention employed identical hold durations and was separated by 48 h washout periods. The 48 h washout interval was selected based on the findings of Torres et al. [8], who demonstrated that muscle stiffness changes following a single stretching bout showed progressive recovery over time. Post-intervention ROM and muscle stiffness were evaluated immediately after each session. The order of muscle stiffness measurements corresponded to the order of the stretching interventions. The experimental procedure is illustrated in Figure 1.

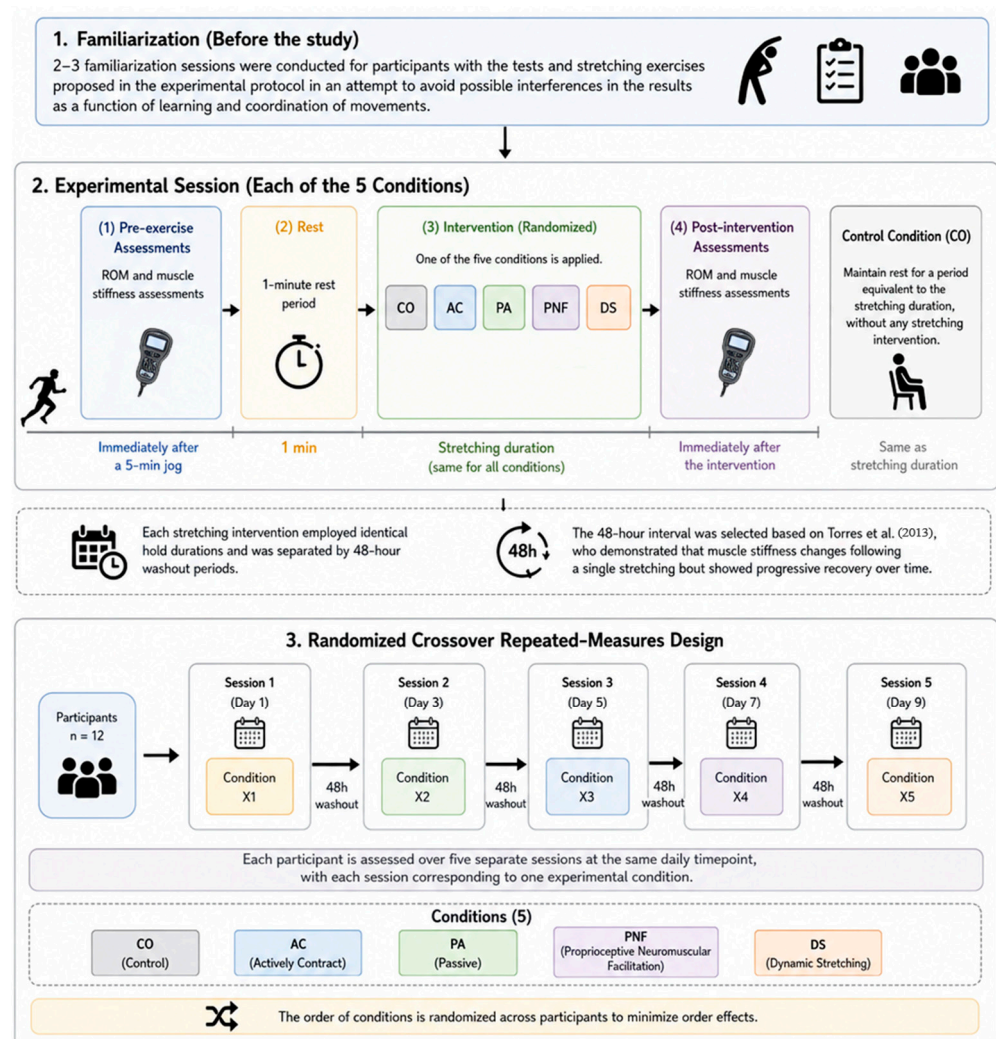


Figure 1. Experimental procedure. Torres et al. [8].

To isolate stretching effects, the CO required participants to remain at rest for a period equivalent to the stretching duration, without any stretching intervention. Each participant was assessed over five separate sessions at the same time of day, with each session corresponding to one experimental condition. Ambient laboratory conditions were maintained, and all participants wore consistent athletic attire. External daily temperatures (recorded by the China Meteorological Administration) were as follows: Day 1: 29 °C, Day 2: 27 °C, Day 3: 29 °C, Day 4: 28 °C, Day 5: 30 °C.

2.2. Participants

Sample size estimation and justification: The sample size required for this study was calculated by G*power3.1. An a priori statistical power analysis was conducted for sample size estimation, using data from Oliveira et al. [9]. The projected sample size required for interaction effects between measurement time and stretching method, with an effect size of 0.25, $\alpha = 0.05$ and power = 0.80, statistical test: ANOVA—repeated measures, within factors, number of groups = 1, number of measurements = 10, correlation among repeated measures = 0.5, non-sphericity correction $\epsilon = 1$, total sample size = 14.

The present study selected 12 male university students (age: 23.42 ± 1.38 years; weight: 67.59 ± 7.81 kg; height: 174.92 ± 4.68 cm) from the School of Physical Education at Ningbo University who engaged in physical training a minimum of three times per week (athletic training duration: 10 h) and had no history of significant lower-limb injuries (within the preceding 12 months). Exclusion criteria were: (1) history of lower-limb surgery or fracture within the previous 12 months; (2) current musculoskeletal injury; (3) regular use of medications affecting muscle function; (4) participation in structured flexibility training programs within the preceding 6 months. Participant recruitment and data collection were conducted from April 2024 to July 2024. Prior to the commencement of the experiment, all participants were informed of the objectives of the study, the protocol to be followed, and the potential risks associated with participation. None of the participants had exhibited any signs of illness or sports-related injuries, and all remained in good health throughout the study. The experimental protocol was approved by the Ethics Committee of the School of Physical Education, Ningbo University, China (Approval No.TY2023036), and conducted in accordance with the principles outlined in the Declaration of Helsinki. Prior to the commencement of the experiment, all participants were thoroughly informed of the testing procedures and precautions. They voluntarily participated in the study and provided written informed consent.

2.3. Procedures

For the ROM test: The subject sat on a cushioned flat surface with legs fully extended, heels together, and the entire plantar surface of both feet firmly positioned against the vertical plate of the testing apparatus. With palms facing downward, arms fully extended, and fingertips aligned, the subject flexed forward steadily at the hips to smoothly advance the Vernier measuring scale (ensuring continuous contact with the track throughout the movement, without sudden tremor) until maximum reach was achieved. The maximal flexion posture was held steadily for 2 s, and the result was documented (in centimeters, recorded to one decimal place; negative values anterior to zero-point, positive values posterior to zero-point). The test was taken three times and the best result was used. Repeated trials were separated by 5–10 s rest intervals. The test–retest reliability of the ROM measurement was assessed using baseline values obtained before each of the five experimental sessions. All measurements were performed by the same examiner using the same testing apparatus and standardized procedures. A two-way mixed-effects model with absolute agreement was used to calculate the intraclass correlation coefficient (ICC). The ROM measurement demonstrated excellent reliability ($ICC(3,1) = 0.91$, 95% CI: 0.81–0.97), with a standard error of measurement (SEM) of 1.76 cm.

For the muscle stiffness test: Subjects were instructed to remain in a supine and prone position on a yoga mat. The probe of the digital palpation device (MyotonPRO, Myoton AS, Tallinn, Estonia, Software v.5.0.0.257) was positioned vertically in alignment with the pre-marked measurement points on the skin surface. Measurement points were located at the muscle belly of each target muscle and marked on the skin using a medical marker pen. The specific anatomical landmarks were as follows: vastus lateralis (Vlt)—at the midpoint

between the greater trochanter and lateral femoral condyle; rectus femoris (RF)—at the midpoint of the anterior thigh; vastus medialis (Vm)—at the distal third of the thigh, 3 cm medial to the midline; semitendinosus (Sem)—at the midpoint of the posterior thigh; biceps femoris (Bic)—at the midpoint of the posterior thigh, lateral aspect; gluteus maximus (GM)—at the midpoint of the muscle belly; gastrocnemius medialis (Gcm) and lateralis (Gclt)—at the proximal third of the posterior leg. The same examiner performed all measurements to ensure consistency. The device body was gently pressed against the skin until the probe tip's green indicator illuminated. Five consecutive measurements were taken at each site (each lasting 15 or 12 milliseconds, with the built-in accelerometer measuring the damped natural oscillations caused by the probe impact at 3200 Hz). The arithmetic mean of these five muscle stiffness measurements (N/m) was used for further analysis. During field testing, this digital palpation instrument demonstrated high reliability and effectiveness in measuring stiffness characteristics [10].

2.4. Interventions

The stretching sessions were composed of four exercises (corresponding to four muscles). Subjects were required to perform three sets of muscle stretches 30 s apart, exercising each muscle once for each set of exercises (left then right): quadriceps, hamstrings, gluteus maximus, and gastrocnemius.

All stretching methods are based on the scheme proposed by previous studies such as that by Jay Blahnik [1]. For passive stretching, the stretch should be held at its maximum range for a period of 30 s. For active stretching, each repetition of the movement sequence should last three seconds. This sequence is to be repeated 10 times in a continuous, controlled and fluid manner. It is imperative that the stretch is released as the return to the initial position is commenced. For dynamic stretching, the participants performed oscillatory stretching movements at a rate of 1:1 s per cycle for one minute; the frequency is controlled by a metronome. For PNF stretching, this is analogous to that of passive stretching: firstly, a 5 s passive stretch is initiated, followed by a 5 s submaximal isometric contraction, and subsequently, a 20 s passive stretch is undertaken. The intensity of the stretching was controlled at 100% of the point of discomfort (POD), corresponding to level 100 on a 0–150 a.u. scale of effort perception developed and validated for stretching exercises [11]. POD was determined by asking each participant to indicate the point at which the stretching sensation transitioned from comfortable stretching to initial discomfort. The same examiner assessed all participants. All stretching exercises are shown in Table 1.

Table 1. Stretching exercises.

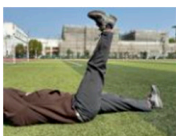
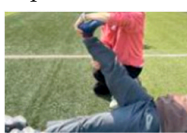
	AC	PA	DS	PNF
Quadriceps femoris	Prone Knee Bend 	Knee Flexion 	Dynamic Knee Flexion 	Holding- Relaxation Technique
Hamstrings	Supine Leg Raises 	Supine Leg Stretch 	Dynamic Forward Bend 	

Table 1. Cont.

	AC	PA	DS	PNF
Gluteus maximus	Push the Hip 	Folded Leg Stretch 	Dynamic Knee-to-Chest 	Holding-Relaxation Technique
Gastrocnemius	Seated Flexion and Extension 	Supine Foot Press 	Forward Bend with Leg Stretch 	

2.5. Statistical Analysis

Data normality was assessed using the Shapiro–Wilk test, followed by descriptive analysis (mean $\pm$ standard deviation). To examine the effects of stretching methods on muscle stiffness at each measured muscle site and ROM, separate two-way repeated-measures ANOVAs were conducted with time (pre vs. post) and condition (CO, AC, PA, PNF, DS). Mauchly’s test of sphericity was performed, and the Greenhouse–Geisser correction was applied when the assumption of sphericity was violated ($p < 0.05$). Post hoc pairwise comparisons were adjusted using the Bonferroni correction within each outcome-specific analysis (i.e., separately for each muscle site and ROM), rather than across all outcomes examined in the study. Partial eta squared (η^2) was reported as an estimate of effect size. All statistical analyses were performed using SPSS version 27.0, with the significance level set at $p < 0.05$.

3. Results

The Shapiro–Wilk test confirmed that the data in each group were normally distributed. A two-factor repeated-measures ANOVA was conducted with time (pre vs. post) as the within-subjects factor and group (AC, BA, CO, PA, PNF) as the between-subjects factor. Mauchly’s test of sphericity was applied to the time factor, which had only two levels; sphericity was automatically satisfied (Mauchly’s $W = 1.000$, $df = 0$, no p -value reported, $\epsilon = 1.000$). Therefore, the unadjusted results under the sphericity assumption were used for interpretation. The corrected results are reported below.

3.1. Range of Motion

For the ROM, the main effect of the stretching method was non-significant ($F = 0.57$, $p = 0.68$, $\eta^2 = 0.04$). Similarly, the main effect of measurement time was significant ($F = 106.76$, $p < 0.001$, $\eta^2 = 0.66$). There were significant interaction effects between measurement time and stretching method ($F = 7.44$, $p < 0.001$, $\eta^2 = 0.35$). Simple effects analysis showed that the effect of stretching method was not significant at pre-test ($F = 0.32$, $p = 0.87$, $\eta^2 = 0.02$) or at post-test ($F = 1.35$, $p = 0.26$, $\eta^2 = 0.09$). Multiple comparisons revealed significantly higher values of ROM in the post-test than in the pre-test for all stretching methods (see Table 2).

Table 2. Effects of stretching methods on range of motion.

Condition	Pre-Test (cm)	Post-Test (cm)	Δ (cm)	<i>p</i>	95% CI	ES
CO	9.93 $\pm$ 5.75	10.02 $\pm$ 5.74	0.09	0.89	[−1.35, 1.17]	0.0004
PA	11.57 $\pm$ 6.61	14.97 $\pm$ 5.82	3.40	<0.001	[2.15, 4.66]	0.35
PNF	9.33 $\pm$ 7.06	12.39 $\pm$ 6.37	3.06	<0.001	[1.80, 4.32]	0.30
AC	9.11 $\pm$ 5.84	12.29 $\pm$ 4.84	3.18	<0.001	[1.92, 4.43]	0.32
DS	9.49 $\pm$ 4.99	14.24 $\pm$ 5.93	4.76	<0.001	[3.50, 6.01]	0.51

3.2. The Left-Sided Muscle Stiffness

For the Left-Sided Muscle Stiffness, the main effect of the GM-L stretching method was non-significant ($F = 1.979$, $p = 0.11$, $\eta^2 = 0.126$). Similarly, the main effect of measurement time was also non-significant ($F = 0.36$, $p = 0.55$, $\eta^2 = 0.006$). Finally, the interaction effect between measurement time and stretching method was also non-significant ($F = 2.42$, $p = 0.06$, $\eta^2 = 0.15$). Although the Bonferroni-adjusted post hoc comparison demonstrated a significant reduction following PA ($p = 0.048$), this finding should be interpreted cautiously because the overall interaction was not statistically significant (see Table 3).

Table 3. Effects of stretching methods on the left-sided muscle stiffness. Abbreviations: quadriceps: vastus lateralis (Vlt), rectus femoris (RF), vastus medialis (Vm); hamstrings: semitendinosus (Sem), biceps femoris (Bic); gluteus maximus (GM); gastrocnemius: medial (Gcm)/lateral (Gclt).

Stretching	Muscle	Pre-Test (N/m)	Post-Test (N/m)	Δ (N/m)	<i>p</i> -Value	95% CI	ES
PA	Gcm	307.67 $\pm$ 27.70	289.31 $\pm$ 29.30	−18.37	<0.001	[−28.00, −8.74]	0.210
	Gclt	325.92 $\pm$ 17.67	316.57 $\pm$ 14.01	−9.35	0.012	[−16.52, −2.18]	0.110
	Sem	358.57 $\pm$ 27.74	340.27 $\pm$ 27.11	−18.30	<0.001	[−25.32, −11.28]	0.331
	RF	275.71 $\pm$ 17.18	289.58 $\pm$ 16.24	+13.87	<0.001	[6.16, 21.58]	0.191
PNF	Sem	337.72 $\pm$ 26.55	347.20 $\pm$ 29.00	+9.48	0.009	[2.46, 16.51]	0.117
DS	Vlt	304.66 $\pm$ 19.68	291.09 $\pm$ 18.07	−13.57	<0.001	[−21.23, −5.90]	0.186

The detailed numerical data for all muscle groups have been moved to Appendix A, and the main manuscript now presents only the primary statistical outcomes in streamlined tables.

The primary effect of stretching method on Sem-L was not significant ($F = 0.318$, $p = 0.865$, $\eta^2 = 0.023$), and the primary effect of measurement time was not significant ($F = 1.756$, $p = 0.191$, $\eta^2 = 0.031$). The interaction effect between Sem-L measurement time and stretching method was significant ($F = 9.168$, $p < 0.001$, $\eta^2 = 0.400$). The simple effect of stretching method was not significant at pre-test ($F = 1.302$, $p = 0.281$, $\eta^2 = 0.087$) or at post-test ($F = 0.178$, $p = 0.949$, $\eta^2 = 0.013$). Multiple comparisons revealed that for PA stretching, post-measurement muscle stiffness values were significantly lower than their pre-measurement counterparts ($p < 0.001$); conversely, under PNF stretching methods, post-measurement muscle stiffness values were observed to be significantly higher than their pre-measurement values ($p = 0.009$).

The primary effect of the Bic-L stretching method was non-significant ($F = 0.508$, $p = 0.730$, $\eta^2 = 0.036$). The primary effect of measurement time was also non-significant ($F = 0.643$, $p = 0.426$, $\eta^2 = 0.012$). The interaction effect between measurement time and stretching method was also non-significant ($F = 1.626$, $p = 0.181$, $\eta^2 = 0.106$).

The primary effect of stretching method on Gcm-L was not significant ($F = 2.429$, $p = 0.059$, $\eta^2 = 0.150$), while the primary effect of measurement time was significant ($F = 5.805$, $p = 0.019$, $\eta^2 = 0.095$). The interaction effect between Gcm-L measurement time and stretching method was significant ($F = 2.953$, $p = 0.028$, $\eta^2 = 0.177$). Simple effects analysis showed that the effect of stretching method was significant at pre-test ($F = 3.170$, $p = 0.020$, $\eta^2 = 0.187$) but not at post-test ($F = 1.586$, $p = 0.191$, $\eta^2 = 0.103$).

Multiple comparisons revealed that under PA stretching methods, post-measurement muscle stiffness values were significantly lower than pre-measurement values ($p < 0.001$).

The primary effect of stretching method on GcLt-L was significant ($F = 4.283$, $p = 0.004$, $\eta^2 = 0.238$), while the primary effect of measurement time was not significant ($F = 1.036$, $p = 0.313$, $\eta^2 = 0.018$). The interaction effect between GcLt-L measurement timing and stretching method was significant ($F = 2.965$, $p = 0.027$, $\eta^2 = 0.177$). Simple effects analysis showed that the effect of stretching method was significant at both pre-test ($F = 4.516$, $p = 0.003$, $\eta^2 = 0.247$) and post-test ($F = 3.711$, $p = 0.010$, $\eta^2 = 0.213$). Multiple comparisons revealed that under PA stretching methods, post-measurement muscle stiffness values were significantly lower than pre-measurement values ($p = 0.012$).

The primary effect of the Vm-L stretching method was not significant ($F = 1.078$, $p = 0.376$, $\eta^2 = 0.073$); the primary effect of measurement time was significant ($F = 4.607$, $p = 0.036$, $\eta^2 = 0.077$); the interaction effect between measurement time and stretching method was not significant ($F = 1.902$, $p = 0.123$, $\eta^2 = 0.122$). Although the Bonferroni-adjusted post hoc comparison demonstrated a significant reduction following PA ($p = 0.034$) and AC ($p = 0.019$), this finding should be interpreted cautiously because the overall interaction was not statistically significant.

The primary effect of stretching method on RF-L was not significant ($F = 0.695$, $p = 0.599$, $\eta^2 = 0.048$), and the primary effect of measurement time was not significant ($F = 0.444$, $p = 0.508$, $\eta^2 = 0.008$). The interaction effect between RF-L measurement time and stretching method was significant ($F = 3.523$, $p = 0.012$, $\eta^2 = 0.204$). Simple effects analysis showed that the effect of stretching method was not significant at pre-test ($F = 1.638$, $p = 0.178$, $\eta^2 = 0.106$) or at post-test ($F = 1.066$, $p = 0.382$, $\eta^2 = 0.072$). Multiple comparisons revealed that under PA stretching methods, post-measurement muscle stiffness values were significantly higher than pre-measurement values ($p < 0.001$).

The primary effect of stretching method on Vlt-L was not significant ($F = 0.571$, $p = 0.685$, $\eta^2 = 0.040$), and the primary effect of measurement time was not significant ($F = 0.973$, $p = 0.328$, $\eta^2 = 0.017$). The interaction effect between Vlt-L measurement time and stretching method was significant ($F = 3.651$, $p = 0.010$, $\eta^2 = 0.210$). Simple effects analysis showed that the effect of stretching method was not significant at pre-test ($F = 1.521$, $p = 0.209$, $\eta^2 = 0.100$) or at post-test ($F = 0.536$, $p = 0.710$, $\eta^2 = 0.038$). Multiple comparisons revealed that under DS stretching methods, post-measurement muscle stiffness values were significantly lower than pre-measurement values ($p < 0.001$).

3.3. The Right-Sided Muscle Stiffness

For the Right-Sided Muscle Stiffness, the primary effect of stretching method on GM-R was not significant ($F = 1.28$, $p = 0.29$, $\eta^2 = 0.09$), and the primary effect of measurement time was not significant ($F = 3.53$, $p = 0.066$, $\eta^2 = 0.60$). The interaction effect between GM-R measurement timing and stretching method was significant ($F = 4.05$, $p = 0.006$, $\eta^2 = 0.23$). Simple effects analysis showed that the effect of stretching method was not significant at pre-test ($F = 1.92$, $p = 0.12$, $\eta^2 = 0.12$) or at post-test ($F = 0.99$, $p = 0.42$, $\eta^2 = 0.07$). Multiple comparisons revealed that under AC stretching methods, post-measurement muscle stiffness values were significantly higher than pre-measurement values ($p < 0.001$) (see Table 4).

The primary effect of stretching method on Sem-R was not significant ($F = 0.657$, $p = 0.625$, $\eta^2 = 0.046$), while the primary effect of measurement time was significant ($F = 5.500$, $p = 0.023$, $\eta^2 = 0.091$). The interaction effect between Sem-R measurement time and stretching method was significant ($F = 3.163$, $p = 0.021$, $\eta^2 = 0.187$). Simple effects analysis showed that the effect of stretching method was not significant at pre-test ($F = 0.161$, $p = 0.957$, $\eta^2 = 0.012$) or at post-test ($F = 1.986$, $p = 0.109$, $\eta^2 = 0.126$). Multiple comparisons

revealed that under AC stretching methods, post-measurement muscle stiffness values were significantly lower than pre-measurement values ($p = 0.034$); under DS stretching methods, a significant decrease in muscle stiffness values was observed in comparison to the initial values ($p = 0.010$).

Table 4. Effects of stretching methods on the right-sided muscle stiffness.

Stretching	Muscle	Pre-Test (N/m)	Post-Test (N/m)	Δ (N/m)	p -Value	95% CI	ES
PA	Gclt	336.05 $\pm$ 39.09	315.63 $\pm$ 25.53	−20.42	0.002	[−32.75, −8.10]	0.167
PNF	Vm	269.54 $\pm$ 14.78	280.06 $\pm$ 11.21	+10.52	<0.001	[4.83, 16.21]	0.200
AC	GM	134.37 $\pm$ 12.87	146.18 $\pm$ 19.13	+11.82	<0.001	[6.34, 17.29]	0.254
	Sem	331.18 $\pm$ 23.48	320.47 $\pm$ 16.94	−10.71	0.034	[−20.59, −0.83]	0.079
DS	Sem	331.11 $\pm$ 22.64	317.90 $\pm$ 21.86	−13.21	0.010	[−23.09, −3.33]	0.115

The detailed numerical data for all muscle groups have been moved to Appendix A, and the main manuscript now presents only the primary statistical outcomes in streamlined tables.

The primary effect of the Bic-R stretching method was not significant ($F = 0.327$, $p = 0.859$, $\eta^2 = 0.023$); the primary effect of measurement time was not significant ($F = 0.010$, $p = 0.920$, $\eta^2 < 0.001$); and the interaction effect between measurement time and stretching method was not significant ($F = 2.500$, $p = 0.053$, $\eta^2 = 0.154$). Although the Bonferroni-adjusted post hoc comparison demonstrated a significant reduction following passive stretching ($p = 0.048$), this finding should be interpreted cautiously because the overall interaction was not statistically significant. Although the Bonferroni-adjusted post hoc comparison demonstrated a significant reduction following DS ($p = 0.010$), this finding should be interpreted cautiously because the overall interaction was not statistically significant.

The primary effect of the Gcm-R stretching method was significant ($F = 2.919$, $p = 0.029$, $\eta^2 = 0.175$). The primary effect of measurement time was significant ($F = 11.069$, $p = 0.002$, $\eta^2 = 0.168$). However, the interaction effect between measurement time and stretching method was not significant ($F = 1.891$, $p = 0.125$, $\eta^2 = 0.121$). Although the Bonferroni-adjusted post hoc comparison demonstrated a significant reduction following PA ($p < 0.001$), this finding should be interpreted cautiously because the overall interaction was not statistically significant.

The primary effect of stretching method on Gclt-R was not significant ($F = 1.782$, $p = 0.146$, $\eta^2 = 0.115$), and the primary effect of measurement time was not significant ($F = 3.215$, $p = 0.078$, $\eta^2 = 0.055$). The interaction effect between Gclt-R measurement time and stretching method was significant ($F = 3.425$, $p = 0.014$, $\eta^2 = 0.200$). Simple effects analysis showed that the effect of stretching method was not significant at pre-test ($F = 1.990$, $p = 0.109$, $\eta^2 = 0.126$) or at post-test ($F = 1.877$, $p = 0.127$, $\eta^2 = 0.120$). Multiple comparisons revealed that under PA stretching methods, post-measurement muscle stiffness values were significantly lower than pre-measurement values ($p = 0.002$).

The primary effect of stretching method on Vm-R was not significant ($F = 2.127$, $p = 0.090$, $\eta^2 = 0.134$), and the primary effect of measurement time was not significant ($F = 0.063$, $p = 0.803$, $\eta^2 = 0.001$). The interaction effect between Vm-R measurement time and stretching method was significant ($F = 5.828$, $p < 0.001$, $\eta^2 = 0.298$). Simple effects analysis showed that the effect of stretching method was not significant at pre-test ($F = 0.892$, $p = 0.475$, $\eta^2 = 0.061$) but was significant at post-test ($F = 3.897$, $p = 0.007$, $\eta^2 = 0.221$). Multiple comparisons revealed that under PNF stretching methods, post-measurement muscle stiffness values were significantly higher than pre-measurement values ($p < 0.001$).

The primary effect of the RF-R stretching method was non-significant ($F = 1.198$, $p = 0.322$, $\eta^2 = 0.080$). The primary effect of measurement time was also non-significant ($F = 0.003$, $p = 0.957$, $\eta^2 < 0.001$). The interaction effect between measurement time and stretching method was also non-significant ($F = 2.382$, $p = 0.063$, $\eta^2 = 0.148$). Although the

Bonferroni-adjusted post hoc comparison demonstrated a significant reduction following PA ($p = 0.016$), this finding should be interpreted cautiously because the overall interaction was not statistically significant.

The primary effect of the Vlt-R stretching method was non-significant ($F = 0.577$, $p = 0.681$, $\eta^2 = 0.040$). The primary effect of measurement time was non-significant ($F = 1.031$, $p = 0.314$, $\eta^2 = 0.018$). The interaction effect between measurement time and stretching method was also non-significant ($F = 2.054$, $p = 0.099$, $\eta^2 = 0.130$). Although the Bonferroni-adjusted post hoc comparison demonstrated a significant reduction following DS ($p = 0.009$), this finding should be interpreted cautiously because the overall interaction was not statistically significant.

4. Discussion

The primary aim of the present study was to compare the acute effects of four distinct stretching methods—passive stretching (PA), proprioceptive neuromuscular facilitation (PNF), active stretching (AC), and dynamic stretching (DS)—on range of motion (ROM) and lower-limb muscle stiffness in physically active male physical education students. The main findings can be summarized as follows: (1) all four stretching methods led to significant increases in ROM from pre-test to post-test, with no statistically significant differences between any of the stretching groups; (2) the effects on muscle stiffness were method- and muscle-specific, with PA producing predominantly widespread stiffness reductions, PNF and AC yielding mixed responses, and DS inducing a generally stiffness-decreasing pattern, albeit with notable exceptions.

Across all stretching methods (PA, PNF, AC, and DS), ROM significantly increased from pre-test to post-test. However, no statistically significant differences were observed between any of the stretching groups. This finding is consistent with Oliveira et al., who experimentally compared different stretching modalities on lower-limb mobility and similarly reported comparable efficacy among various protocols [9]. The question of which stretching technique maximizes flexibility gains remains debated in the literature, with conflicting evidence: some studies advocate for the superiority of PNF over AC [12], whereas others report equivalent effects between different methods [12–14]. Given the absence of significant between-group differences in our data, our findings do not support the superiority of any single method. Notably, although the DS condition exhibited the numerically largest increase in ROM, this trend lacks statistical confirmation and should be interpreted with caution.

When interpreting our ROM data in the context of the previous literature, several physiological parameters have been proposed to explain stretching-induced adaptations. A critical threshold appears to exist between stretching volume/intensity and performance impairment; protocols lasting ≥ 2 min (e.g., 4×30 s at 100% POD) may impair subsequent physical performance, whereas shorter or lower-intensity protocols (e.g., 1 min at 100% POD, or 2 min at 90% POD) induce no significant alterations [15]. Furthermore, increased ROM following stretching has been associated with enhanced stretch tolerance [16] and reduced muscle–tendon unit (MTU) stiffness [17], with PNF specifically linked to autogenous inhibition [18].

From a broader biomechanical perspective, the mechanical properties of tendons and MTU are fundamental to force transmission from skeletal muscles to bones. Based on established theoretical models, MTU with lower stiffness exhibit greater extensibility, which has been hypothesized to impede force transmission efficiency [19]. Additionally, sarcomeres exhibit an optimal force-producing length between 2.00 and 2.25 μm [20]; deviations from this range reduce actin–myosin cross-bridge formation probability, thereby diminishing force output [19]. In the context of stretching interventions, it has been speculated that

diminished MTU stiffness might position sarcomeric contractile elements in mechanically suboptimal orientations for force generation [19]. On the neural side, the previous literature has suggested that reduced motor unit recruitment capacity may occur, potentially mediated by Golgi tendon organ (GTO)-induced reciprocal inhibition as a protective proprioceptive mechanism against excessive passive or active tension [21]. Furthermore, some authors have proposed that yet-unidentified central nervous system inhibitory pathways might also contribute to performance decrements following stretching [21].

It is imperative to stress, however, that none of the above-mentioned mechanisms—including sarcomere length–tension alterations, GTO afferent activity, motor unit firing rates, or central inhibitory pathways—were directly measured or experimentally manipulated in the present study. Our experimental design was limited to functional and mechanical outcome assessments (ROM and tissue stiffness). Consequently, these physiological models are offered solely as theoretical frameworks to contextualize our observations and to generate hypotheses for future investigations. They should not be interpreted as demonstrated causal mechanisms underlying our specific results. Direct verification of these pathways would require concurrent electromyography, ultrasonography, or neurophysiological recordings in future experimental designs.

Regarding muscle stiffness, our measurements revealed that the PA method significantly reduced stiffness values in the Sem-L, GcLt-L/R, Gcm-L while paradoxically increasing stiffness in the RF-L. The widespread reductions are consistent with prior reports that passive stretching enhances flexibility and reduces tissue stiffness, albeit with potential transient force decrements [3,21–23]. The observation that 100% stretching intensity, but not 75%, reduces stiffness [24] aligns with the intensity parameters employed in our PA protocol. The unexpected increase in RF-L stiffness following PA warrants particular attention. We tentatively hypothesize that this may reflect a protective neuromuscular response to prolonged passive tension, particularly in biarticular muscles such as the rectus femoris, which are subjected to complex mechanical demands across two joints.

For the PNF condition, our statistical analyses revealed a significant increase in muscle stiffness values in the left semitendinosus and the right vastus medialis following the intervention. This finding is in contrast to Dallas et al., who reported a significant reduction in leg stiffness among female gymnasts after PNF application [25]. We speculate that this discrepancy may be partially attributable to the specific PNF technique employed in our study—the hold-relax method—in which the passive stretching component constitutes 20 s of the 30 s stretch duration. It is plausible that the isometric contraction phase inherent to this technique contributes to the observed stiffness increases, possibly via post-contraction residual tension or altered viscoelastic properties of the target muscles.

For the AC condition, our data demonstrated muscle stiffness significantly increasing in the GM-R and decreasing in the Sem-R. This dual effect is partially consistent with previous reports indicating that active stretching can both improve muscle stiffness profiles and enhance subsequent athletic performance [3]. In line with our findings, Lim et al. observed a slight (though non-significant) decrease in vastus lateralis aponeurosis stiffness following AC intervention [3]. One possible explanation for the site-specific stiffness variations observed in our study might involve differential activation patterns across biarticular and monoarticular muscles during active stretching, as well as potential left–right asymmetries in baseline muscle tone or neuromuscular control. Given the relatively small sample size, the observed region-specific effects should be interpreted with caution and confirmed in larger studies.

The DS condition yielded a predominantly stiffness-reducing effect, with significant decreases observed in the Vlt-L and Sem-R. This result is partially at odds with the existing literature; for instance, previous research has shown that DS significantly increases quadri-

ceps and gastrocnemius stiffness, although the addition of foam rolling has been reported to mitigate this effect [26]. The discrepancy between our findings and prior reports is most likely attributable to differences in stretching methods—the DS regimen in the cited study involved eight movements with progressive increases in range of motion and speed, which may have induced substantial muscular fatigue and consequent stiffness elevation. Based on our protocol parameters, we hypothesize that the absence of such fatigue-inducing progressive overload in our DS procedure may explain the net stiffness reduction observed.

More broadly, the resistance encountered during stretching is theorized to arise from both structural components (muscle fascicles, tendons, aponeuroses, joint capsules, and ligaments) and neurophysiological reflexes (muscle spindles, GTO, and central presynaptic/postsynaptic inhibition) [2]. Nevertheless, because our study did not differentiate between these structural and neural contributors, the precise mechanisms underlying our DS-induced stiffness changes remain unresolved. Importantly, while increased muscle stiffness has been positively correlated with strength, power, and countermovement jump performance via enhanced stretch–shortening cycle efficiency [27], the acute stiffness reductions observed in our DS condition should not be directly extrapolated to chronic performance outcomes without further longitudinal investigation. This apparent paradox—whereby reduced stiffness may benefit flexibility but potentially impair explosive performance—underscores the need for context-specific prescription of stretching modalities based on training objectives.

From a statistical perspective, however, these mechanistic interpretations should be considered alongside the overall pattern of inferential results. Consistent with the need for cautious interpretation, although Bonferroni-adjusted post hoc comparisons suggested significant pre–post changes in several muscles (PA: GM-L, Vm-L, Gcm-R, RF-R; AC: Vm-L; DS: Bic-R, Vlt-R), these findings were not accompanied by significant time $\times$ condition interactions. Consequently, these isolated pairwise differences should be regarded as exploratory rather than conclusive. Further studies with larger sample sizes are required to determine whether these observations reflect true intervention effects or chance findings.

This study has several limitations that should be considered when interpreting the findings. First, the *a priori* power analysis based on the within-subjects crossover design indicated a required sample of 14 participants. The actual sample fell two participants short of this estimate, which modestly increases the risk of Type II error. However, the observed effect sizes for the primary outcomes (e.g., ROM: $\eta^2 = 0.35$) substantially exceeded the assumed effect size ($f = 0.25$), indicating adequate post hoc power for these findings. Non-significant results, particularly those with small effect sizes, should be interpreted with caution.

Second, the sample consisted exclusively of male physical education students, all of whom were healthy young adults. Consequently, the present findings cannot be directly generalized to female athletes, older adult populations, elite athletes, or clinical patient cohorts. Sex-related differences, age-associated neuromuscular changes, varying states of training adaptation, and the presence of pathological conditions may all substantially influence ROM and muscle stiffness responses to stretching interventions. Future research should include female participants, individuals across different age groups, athletes at various performance levels, and specific clinical populations to examine the applicability of our findings to broader populations.

Third, the homogeneous stretching method (uniform duration, intensity, and sequencing across all conditions) precluded analysis of dose–response relationships, meaning that optimal parameters for each method could not be determined.

Fourth, only acute effects were assessed, with no longitudinal follow-up; therefore, the chronic adaptations to repeated stretching sessions remain unknown.

Fifth, most critically in the context of our physiological interpretations, all discussions concerning neuromuscular inhibitory mechanisms, sarcomere length–tension relationships, motor unit recruitment patterns, and GTO-mediated reflexes—as presented in the preceding sections—are derived from prior theoretical models and were not experimentally verified in our study. These speculative explanations are offered as hypothesis-generating frameworks rather than evidence-based conclusions. Future research incorporating direct neurophysiological and biomechanical measurements (e.g., surface electromyography, real-time ultrasonography, tendon force probes, or transcranial magnetic stimulation) is warranted to validate or refute these proposed pathways.

Sixth, intra-rater reliability for MyotonPRO measurements was not formally assessed in this protocol, which should be considered when interpreting stiffness estimates.

Seventh, although Bonferroni correction was applied within each outcome-specific analysis, the large number of measured variables may still introduce the possibility of study-wide Type I error inflation. Therefore, the results, particularly those involving individual muscle sites, should be interpreted with caution.

5. Conclusions

In conclusion, all four stretching methods—PA, PNF, AC, and DS—are effective for acutely increasing ROM, with no single technique demonstrating statistically superior efficacy. However, their effects on muscle stiffness are method- and muscle-specific, suggesting that stretching prescription should be tailored to the specific goals of the training or rehabilitation program.

Based on these findings, the selection of stretching modalities should be guided by sport-specific demands and training objectives. Specifically, our data indicate that PNF stretching was associated with increased stiffness in the semitendinosus and vastus medialis. Given that elevated muscle stiffness has been theoretically linked to enhanced stretch–shortening cycle efficiency, but may also reflect increased passive tension, we suggest that PNF be applied cautiously prior to explosive or high-intensity activities until its acute effects on subsequent performance are directly evaluated. In contrast, AC and DS produced predominantly stiffness-reducing or neutral effects in the majority of measured muscles, which, based on our findings, makes them more suitable candidates for pre-exercise preparation, particularly when minimizing residual mechanical stress is a priority.

For specific applications: DS significantly improved lower-limb flexibility and reduced stiffness in multiple posterior and anterior thigh muscles, supporting its use as a dynamic warm-up component. AC was associated with reduced stiffness in the adductor longus and semitendinosus, although its heterogeneous response (increased gluteus maximus stiffness) warrants attention. PA effectively reduced stiffness across the posterior chain musculature (gluteus maximus, hamstrings, and gastrocnemius), making it a viable option for post-exercise recovery. Nevertheless, we recommend that all pre-exercise stretching methods be integrated with task-specific warm-up activities rather than implemented in isolation, as the functional relevance of stretching is likely context-dependent.

From a monitoring perspective, the MyotonPRO device may serve as a practical tool for detecting acute changes in muscle stiffness. However, its clinical utility in real-time training decision-making has not been established by this study and requires further validation through longitudinal interventions that link stiffness measurements to performance and injury outcomes.

It should be noted that the practical recommendations offered above—particularly those concerning performance outcomes such as explosive activity or injury risk—are derived partly from our stiffness data in conjunction with prior theoretical frameworks, and were not directly tested in the present experimental design. Therefore, these suggestions should be interpreted as hypothesis-generating guidance for practitioners, rather than evidence-based prescriptions.

Looking forward, future research should implement adequately powered, stratified protocols with larger and more diverse samples (including female participants), assess intra- and inter-rater reliability for stiffness measurements, incorporate direct neurophysiological monitoring to test the proposed mechanisms, and examine both transient and chronic adaptations to various stretching regimens. Such investigations will help bridge the gap between empirical observations and the underlying physiological mechanisms, ultimately informing evidence-based practice in sports medicine and rehabilitation.

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Abbreviations

The following abbreviations are used in this manuscript:

AC	Active Stretching
a.u.	Arbitrary Units
Bic	Biceps Femoris
CMJ	Countermovement Jump
CO	Control
DS	Dynamic Stretching
Gclt	Gastrocnemius Lateralis
Gcm	Gastrocnemius Medialis
GM	Gluteus Maximus
GTO	Golgi Tendon Organ
L	Left
MTU	Muscle–Tendon Unit
PA	Passive Stretching
PNF	Proprioceptive Neuromuscular Facilitation
POD	Point of Discomfort
R	Right
RF	Rectus Femoris
ROM	Range of Motion
SD	Standard Deviation

Sem Semitendinosus
 SSC Stretch–Shortening Cycle
 Vlt Vastus Lateralis
 Vm Vastus Medialis

Appendix A

Table A1. The left-sided muscle stiffness.

Muscle	CO	PA	PNF	AC	DS
Bic (N/m)					
Mean ± SD (pre)	335.61 ± 18.34	345.57 ± 25.07	341.33 ± 16.62	334.97 ± 23.99	333.26 ± 20.82
Mean ± SD (post)	335.53 ± 18.14	347.65 ± 28.87	336.37 ± 25.64	329.69 ± 29.48	336.87 ± 22.25
Δ	−0.08	2.08	−4.96	4.73	3.61
ES	-	-	-	-	-
Gclt (N/m)					
Mean ± SD (pre)	315.23 ± 20.18	325.92 ± 17.67	309.75 ± 23.78	294.74 ± 29.22	290.88 ± 25.71
Mean ± SD (post)	309.77 ± 20.99	316.57 ± 14.01 *	312.81 ± 21.10	300.54 ± 23.77	288.69 ± 19.44
Δ	−5.47	−9.35	3.06	5.8	−2.18
ES	0.041	0.110	0.013	0.046	0.007
Gcm (N/m)					
Mean ± SD (pre)	293.53 ± 28.79	307.67 ± 27.70	297.12 ± 35.83	286.18 ± 32.19	266.95 ± 21.04
Mean ± SD (post)	286.05 ± 31.30	289.31 ± 29.30 *	294.22 ± 24.85	286.85 ± 23.21	269.13 ± 20.22
Δ	−7.48	−18.37	−2.9	0.67	2.18
ES	0.042	0.210	0.210	0.001	0.004
GM (N/m)					
Mean ± SD (pre)	145.06 ± 21.70	159.22 ± 21.24	151.76 ± 22.65	135.04 ± 16.77	141.00 ± 18.80
Mean ± SD (post)	145.92 ± 25.27	154.43 ± 22.22	150.81 ± 19.91	139.77 ± 15.34	137.98 ± 17.26
Δ	0.86	−4.78	−0.95	4.73	−3.02
ES	-	-	-	-	-
RF (N/m)					
Mean ± SD (pre)	283.55 ± 15.34	275.71 ± 17.18	289.81 ± 13.18	285.63 ± 11.23	283.79 ± 11.42
Mean ± SD (post)	282.72 ± 10.88	289.58 ± 16.24 *	288.34 ± 15.00	283.94 ± 14.05	279.64 ± 11.76
Δ	−0.83	13.87	−1.47	−1.68	−4.15
ES	0.001	0.191	0.003	0.003	0.021
Sem (N/m)					
Mean ± SD (pre)	343.33 ± 26.40	358.57 ± 27.74	337.72 ± 26.55	335.01 ± 24.24	343.63 ± 32.71
Mean ± SD (post)	341.67 ± 27.23	340.27 ± 27.11 *	347.20 ± 29.00 *	339.77 ± 27.96	338.98 ± 23.61
Δ	−1.67	−18.30	9.48	4.76	−4.66
ES	0.004	0.331	0.117	0.032	0.031
Vlt (N/m)					
Mean ± SD (pre)	299.78 ± 8.01	291.93 ± 15.37	290.37 ± 26.20	301.10 ± 10.81	304.66 ± 19.68
Mean ± SD (post)	296.07 ± 10.90	295.57 ± 17.52	294.24 ± 18.29	302.43 ± 28.89	291.09 ± 18.07 *
Δ	−3.71	3.63	3.88	1.33	−13.57
ES	0.017	0.016	0.018	0.002	0.186
Vm (N/m)					
Mean ± SD (pre)	267.77 ± 13.59	270.61 ± 21.70	271.34 ± 19.31	268.87 ± 23.27	254.82 ± 17.19
Mean ± SD (post)	263.43 ± 14.72	262.43 ± 22.17 *	272.28 ± 19.51	259.75 ± 22.69 *	257.19 ± 24.30
Δ	−4.10	−8.18	0.94	−9.12	2.37
ES	-	-	-	-	-

* Indicates significant difference from the pre-test, $p < 0.05$.

Table A2. The right-sided muscle stiffness.

Muscle	CO	PA	PNF	AC	DS
Bic (N/m)					
Mean $\pm$ SD (pre)	343.92 $\pm$ 26.32	343.78 $\pm$ 27.06	348.85 $\pm$ 23.23	335.67 $\pm$ 31.55	346.28 $\pm$ 30.79
Mean $\pm$ SD (post)	346.77 $\pm$ 20.88	347.48 $\pm$ 25.00	347.99 $\pm$ 27.65	337.15 $\pm$ 32.64	338.46 $\pm$ 32.15 *
Δ	2.85	3.69	−0.86	1.48	−7.82
ES	-	-	-	-	-
Gclt (N/m)					
Mean $\pm$ SD (pre)	317.57 $\pm$ 33.96	336.05 $\pm$ 39.09	326.23 $\pm$ 43.57	308.68 $\pm$ 35.65	297.58 $\pm$ 29.81
Mean $\pm$ SD (post)	311.21 $\pm$ 36.40	315.63 $\pm$ 25.53 *	322.73 $\pm$ 37.23	320.32 $\pm$ 30.05	291.57 $\pm$ 25.50
Δ	−6.36	−20.42	−3.49	11.63	−6.02
ES	0.019	0.167	0.006	0.061	0.017
Gcm (N/m)					
Mean $\pm$ SD (pre)	292.383 $\pm$ 27.39	303.66 $\pm$ 25.98	306.01 $\pm$ 26.87	284.51 $\pm$ 35.42	274.45 $\pm$ 28.07
Mean $\pm$ SD (post)	287.94 $\pm$ 20.66	286.33 $\pm$ 15.94 *	300.42 $\pm$ 29.03	284.83 $\pm$ 27.84	266.16 $\pm$ 20.64
Δ	−4.44	−17.33	−5.58	0.32	−8.30
ES	-	-	-	-	-
GM (N/m)					
Mean $\pm$ SD (pre)	148.26 $\pm$ 22.00	151.77 $\pm$ 21.48	150.63 $\pm$ 22.09	134.37 $\pm$ 12.87	138.43 $\pm$ 17.61
Mean $\pm$ SD (post)	147.89 $\pm$ 21.59	150.34 $\pm$ 20.16	152.83 $\pm$ 21.99	146.18 $\pm$ 19.13 *	137.68 $\pm$ 17.32
Δ	−0.37	−1.43	2.20	11.82	−0.75
ES	0.001	0.005	0.012	0.254	0.001
RF (N/m)					
Mean $\pm$ SD (pre)	287.30 $\pm$ 13.77	288.48 $\pm$ 22.69	287.88 $\pm$ 16.08	287.98 $\pm$ 10.61	281.54 $\pm$ 14.68
Mean $\pm$ SD (post)	283.58 $\pm$ 14.31	295.23 $\pm$ 14.58 *	288.33 $\pm$ 12.01	287.36 $\pm$ 11.04	278.36 $\pm$ 12.81
Δ	−3.72	6.75	0.45	−0.62	−3.18
ES	-	-	-	-	-
Sem (N/m)					
Mean $\pm$ SD (pre)	337.24 $\pm$ 27.53	332.72 $\pm$ 17.06	331.48 $\pm$ 19.79	331.18 $\pm$ 23.48	331.11 $\pm$ 22.64
Mean $\pm$ SD (post)	327.68 $\pm$ 21.29	332.58 $\pm$ 18.39	339.26 $\pm$ 27.41	320.47 $\pm$ 16.94 *	317.90 $\pm$ 21.86 *
Δ	−9.57	−0.14	7.77	−10.71	−13.21
ES	0.064	0.001	0.043	0.079	0.115
Vlt (N/m)					
Mean $\pm$ SD (pre)	311.94 $\pm$ 20.82	297.65 $\pm$ 38.49	305.49 $\pm$ 27.89	313.45 $\pm$ 18.93	312.40 $\pm$ 24.99
Mean $\pm$ SD (post)	307.89 $\pm$ 22.85	301.20 $\pm$ 26.55	306.74 $\pm$ 25.77	314.53 $\pm$ 21.63	301.22 $\pm$ 21.65 *
Δ	−4.05	3.55	1.25	1.08	−11.17
ES	-	-	-	-	-
Vm (N/m)					
Mean $\pm$ SD (pre)	273.52 $\pm$ 14.08	274.31 $\pm$ 14.38	269.54 $\pm$ 14.78	265.40 $\pm$ 22.93	246.03 $\pm$ 17.21
Mean $\pm$ SD (post)	277.35 $\pm$ 16.20	272.51 $\pm$ 17.05	280.06 $\pm$ 11.21 *	259.78 $\pm$ 22.46	258.68 $\pm$ 18.18
Δ	3.83	−1.80	10.52	−5.62	−5.34
ES	0.032	0.007	0.200	0.066	0.060

* Indicates significant difference from the pre-test, $p < 0.05$.

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