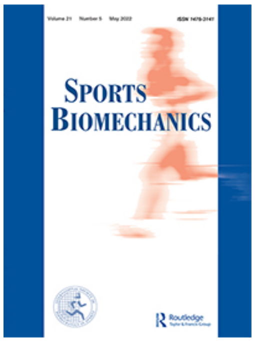

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What to stretch? - Isolated proprioceptive neuromuscular facilitation stretching of either quadriceps or triceps surae followed by post-stretching activities alters tissue stiffness and jump performance

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ABSTRACT

To overcome a possible drop in performance following longer stretch durations (>60 s), post-stretching dynamic activities (PSA) can be applied. However, it is not clear if this is true for isolated proprioceptive neuromuscular facilitation (PNF) stretching of different muscle groups (e.g., triceps surae and quadriceps). Thus, 16 participants performed both interventions (triceps surae PNF + PSA; quadriceps PNF + PSA) in random order, separated by 48 h. Jump performance was assessed with a force plate, and tissue stiffness was assessed with a MyotonPro device. While no changes were detected in the countermovement jump performance, the PNF + PSA interventions resulted in a decrease in drop jump performance which led to a large magnitude of change following the triceps surae PNF + PSA and a small-to-medium magnitude of change following the quadriceps PNF + PSA. Moreover, in the triceps surae PNF + PSA intervention, a decrease in Achilles tendon stiffness was seen, while in the quadriceps PNF + PSA intervention, a decrease in the overall quadriceps muscle stiffness was seen. According to our results, we recommend that especially triceps surae stretching is avoided during warm-up (also when PSA is included) when the goal is to optimise explosive or reactive muscle contractions.

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KEYWORDS
Stretching; proprioceptive neuromuscular facilitation; contract-relax; intermuscular responses

Introduction

Stretching is commonly used as a warm-up routine, with the goal to increase the range of motion of a joint (McHugh & Cosgrave, 2010) and to decrease pain (Behm et al., 2021). Besides static stretching, a frequently used stretching method is proprioceptive neuromuscular facilitation (PNF), where, depending on the variation, the target muscle and/or the antagonist muscle are contracted during the procedure (Sharman et al., 2006). There is evidence that a single bout of PNF stretching applied on the triceps surae muscles can cause an increase in ankle range of motion, a decrease in muscle stiffness (Kay et al., 2015;

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Konrad et al., 2017a) with unchanged active and passive tendon stiffness (Konrad et al., 2017a) or with even a decrease in active tendon stiffness (Kay et al., 2015). As increased muscle and tendon stiffnesses were reported as potential risk factors for sports injuries (Pickering Rodriguez et al., 2017; Watsford et al., 2010), PNF stretching might be a potential intervention to counteract such risks.

However, similar to static stretching (Behm et al., 2016), the potential detrimental effects of PNF stretching on subsequent performance are likely dependent on the stretch duration. Young and Elliott (2001) and Kay et al. (2015) reported no detrimental effect on performance (i.e., concentric or stretch-shortening cycle force production) after a 60-s-long PNF stretching exercise compared to a control condition. However, other studies have reported that longer stretch durations (e.g., 120 s) are accompanied by detrimental effects on performance parameters such as maximum voluntary contraction torque (Konrad et al., 2017b; Reiner et al., 2021). Thus, if PNF stretching is applied during a warm-up regime, a shorter stretch duration (i.e., ≤60 s) is recommended.

To counteract and overcome any possible detrimental effect on performance, Behm et al. (2016) suggested post-stretching dynamic activities (PSA). Various studies have reported a post-stretching potentiation effect (Reid et al., 2018; Samson et al., 2012), or at least no negative effect (Blazevich et al., 2018), when static or dynamic stretching exercises were followed by dynamic activities. Recently, no negative effect was also reported following a 120-s PNF stretching exercise (Reiner et al., 2021). While PNF stretching alone resulted in a decrease in the voluntary peak torque level, no such changes were reported when PSA was performed following the PNF stretching exercise (Reiner et al., 2021).

However, the respective responses of each individual muscle to stretching including PSA were not considered in the aforementioned studies. In these studies either all the main muscles were stretched (e.g., Blazevich et al., 2018), or one muscle group only (e.g., triceps surae; Reiner et al., 2021). The lack of change in jump performance following stretching with PSA, as reported by Blazevich et al. (2018), might be explained by the interaction of detrimental effects on some muscles and beneficial effects on other muscles. To test this hypothesis, it would be necessary to investigate the respective responses of the individual muscles (i.e., triceps surae and quadriceps) to stretching with PSA on performance parameters (such as jump height). Especially the jumping ability of an individual is a predictor of performance in various types of sports (Köklü et al., 2015; Kons et al., 2018; Pupo et al., 2020), including sprint performance (Barr et al., 2011). Therefore, it is of great interest if PNF stretching of the individual muscle-tendon units (i.e., triceps surae and quadriceps) with a short duration (i.e., 60 s) including PSA can influence the jump performance of, e.g., a drop jump (DJ) or counter movement jump (CMJ).

Furthermore, a test of the change in structural properties (e.g., muscle and tendon stiffness) which likely will result from PNF stretching and PSA would help to gain an insight into possible explanatory mechanisms (Monte & Zignoli, 2021). However, these acute changes in muscle or tendon structural properties (i.e., stiffness) will likely return back to baseline after a few minutes (i.e., 5 min), as seen in studies on the static stretching technique (Andreas Konrad & Tilp, 2020; Konrad et al., 2019). In contrast, a stretch training for several weeks can induce chronical changes in muscle (Nakamura et al., 2021) or tendon stiffness (Konrad et al., 2015), likely due to changes in cross-sectional area and/or structure of the respective tissue (Maganaris & Narici, 2005). Individual responses to muscle stiffness in the quadriceps, as opposed to the triceps surae muscles, have been reported following foam rolling and cycling (Baumgart et al., 2019); however, to date, it remains unclear if this is the case for stretching with PSA.

The purpose of this study was to investigate the acute muscle-specific effects of PNF stretching with PSA on jump performance. This was accomplished using a pre-post crossover design, with either stretching of the triceps surae or the quadriceps muscle-tendon units with PSA, and measuring the impact on DJ and CMJ performance. Moreover, a further goal was to investigate the effects on the soft tissue compliance (i.e., muscle stiffness, tendon stiffness) and to examine a possible mechanism affecting jump performance. We hypothesised that PNF stretching + PSA in both muscle groups (triceps surae, quadriceps) will induce a decrease in tissue stiffness, however will not induce changes in jump performance.

Materials and methods

Experimental design

Participants were asked to visit the laboratory on three separate days. The aim of the first visit was to familiarise the participants with the laboratory setup (i.e., jump tasks, stretching exercises, PSA). The actual tests took place on the second and third visits. Participants completed both interventions (triceps surae PNF + PSA and quadriceps PNF + PSA) in randomised order (i.e., by choosing hidden cards), with a 48-h break in between. Both test days started with a 10-min warm-up routine on a stationary bike (Lode Corival, NL) at 60 rev.min^{-1} (Konrad, Bernsteiner et al., 2020; Konrad, Glashüttner et al., 2020) and 90 W. Following the warm-up, the baseline stiffness measurements, the DJs, and the CMJs took place (pre) and were repeated after the intervention (post; Figure 1). Tests were performed in the order shown in Figure 1, while the order for the stiffness assessment for the triceps surae was gastrocnemius medialis, gastrocnemius lateralis, and Achilles tendon, and for the quadriceps, it was vastus medialis, vastus lateralis, rectus femoris, and patellar tendon.

Participants

An *a priori* sample size calculation (primary outcome variable: muscle stiffness following PNF + PSA from Reiner et al. (2021)) for a pairwise comparison suggested a necessary group size of 14 subjects (alpha = 0.05, beta = 0.8, Cohen's d = 0.71). Therefore, to be safe, we selected 16 healthy, physically active male participants (age: 30.5 ± 4.5 years; weight: 82.3 ± 11.4 kg; height: 180.5 ± 6.3 cm) as volunteers in this study. All participants meet the World Health Organization minimum activity guidelines (Bull et al., 2020) and, hence, can be classified as recreational active (McKay et al., 2022). All the study volunteers were free of any injuries to the lower extremities. Participants were asked not to perform any exhausting exercise 72 h prior to the tests. The participants were also informed about the test procedures and provided written content. The study was approved by the Ethics Commission of the Technical University of Munich (762/20 S-KH) and was performed in accordance with the Declaration of Helsinki.

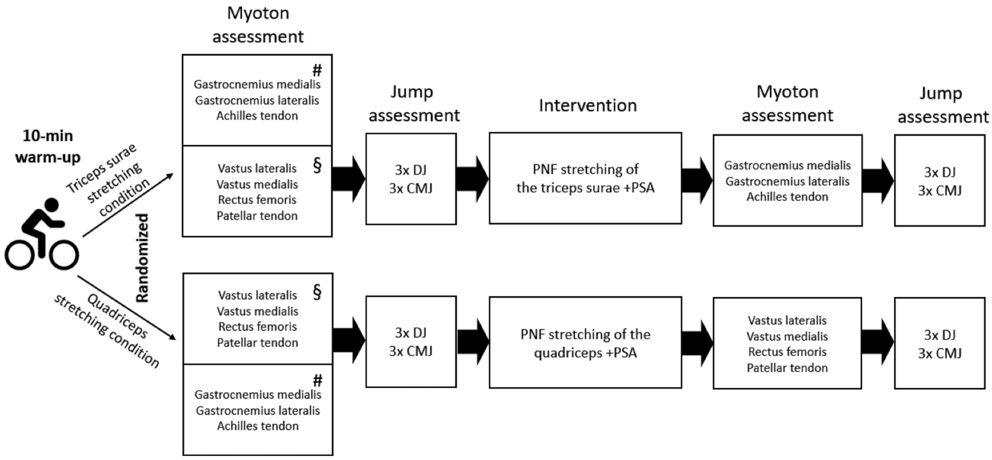

Figure 1. Schematic schedule of the study; CMJ = countermovement jump; DJ = drop jump; PNF = proprioceptive neuromuscular facilitation; PSA = post-stretching dynamic activities; # = indicates the reliability check of the stiffness assessment of the triceps surae; § = indicates the reliability check of the stiffness assessment of the quadriceps.

Procedures

Myoton measurements

A MyotonPro device (Myoton Ltd., Estonia) was used to assess the passive muscle and tendon stiffness of the triceps surae and quadriceps muscle-tendon units. For the assessment of the triceps surae muscle-tendon unit (i.e., Achilles tendon, gastrocnemius medialis, and gastrocnemius lateralis), the participant was asked to remain in a resting position, lying prone, with their foot hanging freely off the therapy couch (Chang et al., 2020). For the assessment of the quadriceps muscles (vastus lateralis, vastus medialis, and rectus femoris), the participant was asked to change into a supine position, with their hips and knees fully extended (Klich et al., 2020). For the assessment of the patellar tendon, the participant was asked to remain in a sitting position, with their hip and knee joints at 90° (Klich et al., 2020).

The mean muscle stiffness of the quadriceps was defined as the mean stiffness of the vastus lateralis, vastus medialis, and rectus femoris. The mean muscle stiffness of the triceps surae was defined as the mean stiffness of the gastrocnemius medialis and gastrocnemius lateralis (Morales-Artacho et al., 2017; Reiner et al., 2021).

For the stiffness assessment, the probe of the MyotonPro device was applied perpendicular to the tissue, as suggested by the manufacturer. The measurement sites for the different muscles were defined in accordance with Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) guidelines (Hermens et al., 1999) for electrode placement during surface electromyography measurements. For the AT, the assessment was conducted at the level of the medial malleolus (Schneebeli et al., 2020), and for the patellar tendon, the assessment was conducted at the midway point between the distal patellar rim and the tuberosity of the tibia (Klich et al., 2020). A permanent marker pen was used to highlight the positions on the skin. This allowed us to identify the same measurement positions, both within a session (pre and post intervention), but also between sessions (triceps surae stretching vs. quadriceps stretching).

Three consecutive mechanical impacts of 15 ms and a force of 0.3–0.4 N were applied from the MyotonPro device. This was then repeated three times, which resulted in nine impacts per muscle and tendon. The muscle stiffness and tendon stiffness for every single mechanical impact was then calculated as the force applied relative to the deformation of the tissue. The average value for the 3 × 3 mechanical impacts was taken for the statistical analysis (Ditroilo et al., 2012).

Jump performance assessment

DJs. Each participant was asked to perform three DJs (arms spread wide) pre- and post-intervention from a 40-cm box onto a force plate (BP600900-2000, AMTI, USA), with maximum effort, i.e., keeping the ground contact time as short as possible (Abdelsattar et al., 2018). The rest periods between jumps was set to 30 s to avoid any possible fatigue. The 40-cm box was then placed on a second force plate (BP600900-2000, AMTI, USA), which allowed us to monitor for possible vertical push-off from the box, which would have increased the jump height. Drop jumps that did not appear to be maximal (i.e., compared to the familiarisation session) and jumps with an identified push-off were repeated. The DJ with the shortest ground contact time was used for the further analysis.

CMJs. Each participant was asked to perform three CMJs, both pre and post intervention, with a 30s rest in between each jump. The CMJs were performed with the participant standing on a force plate (BP600900-2000, AMTI, USA). Start and end positions were upright in a hip-wide standing position, with arms spread wide (Konrad et al., 2021; Pedersen et al., 2019). The participant was not allowed to move their hands during the measurement (Konrad et al., 2021; Tayech et al., 2020). On instruction, the participant lowered their centre of mass by bending their knees to a self-selected position, and immediately after reaching this position, jumped vertically, as high as possible. The CMJ with the highest jump height was used for the further analysis.

Jump data analysis. For the analysis of the DJs and CMJs, only the vertical ground reaction force was used. Data were captured (1000 Hz) using Nexus motion capture software (Oxford Metrics, UK). The final analysis was performed using a self-written MATLAB script (MATLAB R2021a, The MathWorks Inc., USA). The raw force data were smoothed by the use of a 10-ms moving average window.

For the DJs, the ground contact time (= DJ_contact time) represents the time the participant was in contact with the force plate, using a threshold of 10 N. The jump height (DJ_jump height) was calculated using the flight time method (landing threshold 10 N). The ratio between DJ_jump height and DJ_contact time represents the reactive strength index (DJ_RSI; Flanagan & Comyns, 2008; Schuster et al., 2020).

For the CMJs, the jump height (CMJ_jump height) was calculated using the impulse–momentum relation. The modified reactive strength index was then calculated (CMJ_RSI mod) by calculating the ratio between CMJ_jump height and the time the participant needed for the CMJ until take-off (Ebben & Petushek, 2010). The start of the CMJ and the start of the flight phase (take-off) were defined using a threshold of 10 N deviation from the baseline. The centre of mass displacement until the deepest squat position was defined as the difference between upright standing (0-cm displacement) and the local minimum between the beginning of the CMJ and the take-off (CMJ_squat depth). The centre of mass displacement–time curve was calculated by double integration (MATLAB cumtrapz function) of the acceleration–time curve.

Interventions

Each participant performed either a single 60-s PNF stretching exercise of the triceps surae with PSA or a single 60-s PNF stretching exercise of the quadriceps with PSA. When the participant stretched their triceps surae, they were asked to perform this in a standing wall push position (A. Konrad & Tilp, 2014). For the quadriceps stretch, the participant stood upright on one leg and pulled the ankle of the contralateral leg up to the maximum knee flexion position (Stafilidis & Tilp, 2015). The participant was asked to stretch the target muscle (triceps surae or quadriceps) until the point of discomfort for 10 s, followed by a 5-s maximal contraction of the target muscle in the stretching position. This procedure was repeated three times, which resulted in a stretch duration of 60 s for each leg (Kay et al., 2015).

For the PSA, the protocol of Samson et al. (2012) was chosen. Three different running-specific tasks were performed in a constant order, immediately after the stretching exercises in both interventions. The first task was high knees (hip flexion of ~90°), followed by skippings and butt kicks. All of the tasks were repeated twice over a 20-m distance (Samson et al., 2012) and were performed at the highest possible speed. A break between the tasks of 30 s was scheduled. With ~30 s for each task, plus a 30-s break between tasks, the PSA lasted for ~5.5 min.

All interventions were supervised by an investigator. Participants were verbally encouraged to perform the intervention with maximum effort for the full duration.

Statistical analysis

SPSS (version 27.0, SPSS Inc., Chicago, Illinois) was used for all the statistical analyses. To determine the inter-day reliability of the Myoton measurements and the jump performance measurements, intraclass correlation coefficients (ICCs, two-way mixed-effect model, absolute agreement definition) of the pre-values of both conditions were used. Moreover, the standard error of measurement was determined.

Mean values and standard deviations are reported for each measurement session. Changes from pre to post sessions were calculated including confidence intervals. Cohen’s d was calculated following the suggestions of Cohen (1988). Thus, the effect size d was defined as small, medium, and large for effect sizes greater than 0.2, 0.5, and 0.8, respectively.

A Shapiro–Wilk test was used to test for the normal distribution of all the variables. If jump parameters were normally distributed, a two-way repeated-measures ANOVA (factors: time [pre vs. post]) and intervention (triceps surae PNF + PSA vs. quadriceps PNF + PSA) were performed. Otherwise, a Friedman test was performed to test the effects of the two conditions. In case of a significant interaction effect of the ANOVA with repeated measures or a significant Friedman test, a paired sample t-test or a Wilcoxon test (with Bonferroni correction) was performed between the pre and post values of the jump parameters of each condition. Since all the stiffness values were normally distributed, the pre-to-post changes of the stiffness were assessed with paired sample t-tests. The alpha level was set to 0.05.

Results

Jump and myoton parameter reliability

The jump parameters ICC values (and the standard error of measurement) between the pre-measurements of both test days (triceps surae PNF + PSA vs. quadriceps PNF + PSA) for CMJ_jump height, CMJ_squat depth, CMJ_RSI mod, DJ_contact time, DJ_jump height, and DJ_RSI were 0.96 (1 cm), 0.90 (1.9 cm), 0.95 (0.02), 0.94 (6.1 ms), 0.86 (2.2 cm), and 0.87 (0.12), respectively. Table 1 lists the stiffness baseline values for all the assessed muscles and tendons, including the ICC values, standard error of measurement, and 95% confidence intervals.

Countermovement jumps

The Friedman test showed no significant effect for CMJ_jump height ($P = 0.34$; $X^2 = 3.38$). Moreover, for CMJ_squat depth, the ANOVA test revealed no significant interaction effect ($P = 0.39$; $F_{1,15} = 0.77$; $r = 0.05$), time effect ($P = 0.40$; $F_{1,15} = 0.74$; $r = 0.05$), or intervention effect ($P = 0.92$; $F_{1,15} = 0.01$; $r = 0.001$). Furthermore, CMJ_RSI did not show a significant interaction effect ($P = 0.43$; $F_{1,15} = 0.67$; $r = 0.04$), time effect ($P = 0.61$; $F_{1,15} = 0.28$; $r = 0.02$), or intervention effect ($P = 0.62$; $F_{1,15} = 0.26$; $r = 0.02$). Table 2 lists the pre and post values of both conditions and all parameters.

Drop jumps

For DJ_jump height no significant interaction effect ($P = 0.21$; $F_{1,15} = 1.74$; $r = 0.10$) or intervention effect ($P = 0.71$; $F_{1,15} = 0.14$; $r = 0.009$) was found. However, ANOVA revealed a significant time effect ($P < 0.001$; $F_{1,15} = 28.22$; $r = 0.65$). The pairwise comparison in the separate groups showed a large decrease ($d = 1.10$; −1.9 cm; CI 95%

Table 1. Mean (mean ± standard deviation) of the baseline stiffness measurements for both conditions. ICC = intraclass correlation coefficient, SEM = standard error of measurement, CI = confidence interval (of the difference between baseline triceps surae to baseline quadriceps).

	Baseline triceps surae condition			Baseline quadriceps condition			ICC	SEM	CI 95%
Achilles tendon (N/m)	814.8	±	54.2	808.2	±	67.4	0.87	21.7	(−29.4 to 16.2)
Gastrocnemius medialis (N/m)	321.9	±	53.8	312.7	±	43.2	0.93	12.8	(−21.9 to 3.4)
Gastrocnemius lateralis (N/m)	344.0	±	53.8	334.9	±	44.5	0.91	14.6	(−23.5 to 5.4)
Patellar tendon (N/m)	856.5	±	122.0	838.7	±	109.9	0.96	22.9	(−41.9 to 6.5)
Vastus lateralis (N/m)	290.1	±	21.2	296.4	±	25.2	0.90	8.2	(−0.9 to 13.5)
Vastus medialis (N/m)	249.9	±	25.4	251.4	±	27.1	0.98	3.3	(−2.1 to 5.2)
Rectus femoris (N/m)	248.5	±	32.2	250.3	±	33.4	0.98	4.6	(−3.2 to 6.7)

Table 2. Pre and post values (mean ± standard deviation) and delta values, including the 95% confidence intervals (=CI) of the assessed parameters in the quadriceps stretching protocol (left side) and triceps surae stretching protocol. CMJ = countermovement jump; DJ = drop jump; PNF = proprioceptive neuromuscular facilitation; PSA = post-stretching dynamic activities. * = significant effect in the multivariate comparisons.

		Quadriceps PNF + PSA			Triceps surae PNF + PSA			Interaction effect	Time effect	Intervention effect
		PRE	POST	POST—PRE (CI 95%)	PRE	POST	POST—PRE (CI 95%)			
CMJ	Jump height (cm)	36.0 ± 5.7	35.6 ± 5.5	− 0.4 (−1.1 to 0.3)	35.7 ± 4.6	36.1 ± 5.2	+ 0.4 (−0.3 to 1.1)	0.34	-	-
	Squat depth (cm)	34.7 ± 6.1	34.8 ± 6.6	+0.1 (−2.1 to 2.4)	34.1 ± 6.0	35.3 ± 5.3	+1.2 (−0.5 to 2.8)	0.39	0.40	0.92
	RSI mod	0.46 ± 0.11	0.46 ± 0.10	0.00 (−0.02 to 0.02)	0.46 ± 0.08	0.45 ± 0.08	− 0.01 (−0.02 to 0.01)	0.43	0.61	0.62
DJ	Contact time (ms)	195.0 ± 26.0	193.4 ± 25.9	− 1.6 (−9.5 to 5.7)	196.4 ± 26.5	196.1 ± 26.8	− 0.3 (−5.7 to 6.9)	0.70	0.70	0.46
	Jump height (cm)	20.9 ± 6.1	19.9 ± 6.5	− 1.0 (−1.9 to 0.2)	21.7 ± 6.3	19.8 ± 6.0	− 1.9 (−2.8 to −0.9)	0.21	<0.001*	0.71
	RSI	1.09 ± 0.36	1.04 ± 0.37	− 0.05 (−0.10 to 0.01)	1.11 ± 0.33	1.02 ± 0.31	− 0.09 (−0.13 to −0.05)	0.14	0.001*	0.98

(−2.8 cm to −0.9 cm)) in DJ_jump height following the triceps surae PNF + PSA and a medium decrease (d = 0.59; −1.0 cm; CI 95% (−1.9 cm to 0.2 cm)) following the quadriceps PNF + PSA.

In addition, for DJ_RSI no significant interaction effect ($P = 0.14$; $F_{1,15} = 2.48$; $r = 0.14$) or intervention effect ($P = 0.98$; $F_{1,15} = 0.001$; $r < 0.001$) was observed. However, a significant time effect was found ($P = 0.001$; $F_{1,15} = 18.53$; $r = 0.55$). The pairwise comparison in the separate groups showed a large decrease (d = 1.26; −0.09; CI 95% (−0.13 to −0.05)) in DJ_RSI following the triceps surae PNF + PSA and a small-to-medium decrease (d = 0.25; −0.05; CI 95% (−0.10 to 0.01)) following the quadriceps PNF + PSA.

For DJ_contact time, the ANOVA test revealed no significant interaction effect ($P = 0.70$; $F_{1,15} = 0.15$; $r = 0.01$), time effect ($P = 0.70$; $F_{1,15} = 0.16$; $r = 0.01$), or intervention effect ($P = 0.46$; $F_{1,15} = 0.57$; $r = 0.04$). Table 2 lists the pre and post values for both conditions and all parameters.

Stiffness of the quadriceps muscles and tendon following quadriceps PNF + PSA

The paired t-tests revealed a significant decrease in vastus medialis stiffness ($P < 0.001$; d = 1.21), but no change in vastus lateralis stiffness (P = 0.22; d = 0.32), rectus femoris stiffness (P = 0.20; d = 0.34), or patellar tendon stiffness (P = 0.054; d = 0.52) following the quadriceps PNF + PSA. The mean muscle stiffness of all the measured quadriceps muscles (vastus medialis, vastus lateralis, rectus femoris) showed a decreased muscle stiffness (P = 0.01; d = 0.70). Table 3 lists the stiffness values before and after the quadriceps PNF + PSA.

Stiffness of the triceps surae muscles and tendon following triceps surae PNF + PSA

The paired t-tests revealed a significant decrease in Achilles tendon stiffness (P = 0.005; d = 0.83), but no change in gastrocnemius medialis stiffness (P = 0.59; d = 0.14) or gastrocnemius lateralis stiffness (P = 0.64; d = 0.12) following the triceps surae PNF + PSA. The mean muscle stiffness of all the triceps surae muscles (gastrocnemius medialis, gastrocnemius lateralis) showed no change (P = 0.59; d = 0.14). Table 4 lists the stiffness values for the Achilles tendon, gastrocnemius medialis, and gastrocnemius lateralis, before and after the triceps surae PNF + PSA.

Table 3. Pre and post values (mean ± standard deviation) and delta values, including the 95% confidence intervals (=CI) of the assessed quadriceps stiffness in the quadriceps PNF + PSA intervention. * = significant change between pre and post values.

	Quadriceps PNF + PSA							
		PRE			POST		POST—PRE (CI 95%)	*P*
Patellar tendon (N/m)	838.7	±	109.9	818.0	±	84.2	− 20.0 (−41.9 to 0.4)	0.054
Vastus lateralis (N/m)	296.4	±	25.2	293.4	±	27.6	− 3.0 (−7.9 to 1.9)	0.22
Vastus medialis (N/m)	251.4	±	27.1	244.0	±	24.6	− 7.4* (−10.7 to −4.2)	<0.001
Rectus femoris (N/m)	250.3	±	33.4	246.7	±	31.0	− 3.6 (−9.4 to 2.1)	0.20
Mean muscle (N/m)	266.0	±	22.2	261.3	±	21.7	− 4.7* (−8.3 to −1.1)	0.01

Table 4. Pre and post values (mean ± standard deviation) and delta values, including the 95% confidence intervals (=CI) of the assessed triceps surae stiffness in the triceps surae PNF + PSA intervention. * = significant change between pre and post values.

	Triceps surae PNF + PSA							
	PRE			POST			POST—PRE (CI 95%)	*P*
Achilles tendon (N/m)	814.8	±	54.2	793.9	±	59.1	−20.9* (−34.2 to −7.5)	0.005
Gastrocnemius medialis (N/m)	321.9	±	53.8	319.6	±	50.6	−2.3 (−11.1 to 6.6)	0.59
Gastrocnemius lateralis (N/m)	344.0	±	53.8	341.7	±	56.8	−2.3 (−12.3 to 7.8)	0.64
Mean muscle (N/m)	332.9	±	49.5	330.7	±	49.5	−2.2 (−11.1 to 6.6)	0.59

Discussion and Implication

The purpose of this study was to investigate the effects of a single PNF stretching exercise of either the triceps surae or the quadriceps muscles followed by PSA on jump performance. Moreover, we also tested possible changes in muscle and tendon stiffness. While there were no changes in the CMJ parameters following either intervention (triceps surae PNF + PSA and quadriceps PNF + PSA), a decrease in two out of the three DJ parameters (DJ height, DJ RSI) was observed following the interventions. The changes in DJ performance following the triceps surae PNF + PSA were accompanied by a decrease in Achilles tendon stiffness and decreases in muscle stiffness in the vastus medialis and the mean quadriceps muscle stiffness following the quadriceps PNF + PSA.

Countermovement jumps

CMJ performance did not change following either intervention (triceps surae PNF + PSA and quadriceps PNF + PSA) in all the CMJ parameters (CMJ height, CMJ squat depth, CMJ RSI mod). According to other studies (Kay et al., 2015) which used similar PNF stretching protocols (i.e., a duration of 60 s), it can be assumed that the flexibility of the ankle and knee was increased following the triceps surae PNF + PSA and quadriceps PNF + PSA, respectively. Therefore, an increase in CMJ height could have been expected when considering previous reports about significant and moderate relationships between dorsiflexion ($r = 0.47$) and hip flexor flexibility ($r = 0.39$) with CMJ height (Konrad et al., 2021). Moreover, a previous study reported a decrease in CMJ height following stretching exercises (Behm & Kibele, 2007). It is possible that the PSA in our study counteracted the decrease in CMJ height. In addition, the time pressure during the execution of a CMJ is less than that for a DJ. Therefore, possible negative effects based on the decreased AT stiffness after triceps surae PNF + PSA might play a less dominant role than in a DJ. This is supported by a study by Pentidis et al. (2020), who reported that, for non-athletes, the significant predictor for CMJ height is muscle strength and not tendon stiffness. Please note that these results were based on children (~9 yrs. Non-athletes: ~3 h of sport per week. Artistic gymnastic athletes: ~20 h systematic training per week), so a direct transfer of the results onto our subjects might not be possible. However, because our subjects were only moderately trained, a change in the Achilles tendon stiffness might have only marginally influenced the CMJ performance.

Drop jumps

In contrast to the CMJ parameters, DJ height (time effect $P < 0.001$) and DJ RSI (time effect $P = 0.001$) decreased following the interventions, while DJ contact time was unchanged (time effect $P = 0.70$). Decreases in DJ height showed a large effect size following triceps surae PNF + PSA and medium effect size following quadriceps PNF + PSA. When compared to a CMJ, there is a strong time restriction for the execution of the movement for a DJ. Therefore, acute changes in the well-coordinated interaction of the involved muscles and the series elastic component might result in a performance decrease. This coordination might be influenced by a reduction in the speed of force transmission of the tendon (Maffiuletti et al., 2016) because of the increased compliance after the triceps surae stretch intervention. In addition, reduced force transmission might also reduce the elastic recoil of the tendon, and consequently lead to a performance reduction for the stretch-shortening cycle. It has been suggested that there are four mechanisms that can influence the performance of a stretch-shortening cycle, namely, the stretch reflex, the activation dynamics, the recoil of elastic energy in the concentric phase by the tendon, and the stretch-induced sarcomeric force enhancement (Bosco et al., 1982; Fukunaga et al., 2001; Kubo et al., 1999; Seiberl et al., 2015). A more compliant tendon could result in an increased tendon length change during DJ stretch-shortening cycles when comparing pre- and post-intervention muscle-tendon dynamics. Typically, a less stiff tendon would be able to increase the storage of elastic energy. However, due to the short contact times during DJs, which did not differ between interventions, this potential increase in the storage of elastic energy may not be returned fast enough as tendon recoil before take-off during DJs. Furthermore, as this represents an acute change in the compliance, the subject's neuro-muscular system may not have had time to adapt to these changes and, consequently, might not have been able to profit from the increased storage capabilities.

With regard to stretch-induced sarcomeric force enhancement as a performance-enhancing mechanism in stretch-shortening cycles, it is known that force enhancement is related to the amount of fascicle length change (Abbott & Aubert, 1952). For a given muscle-tendon unit force, a more compliant tendon likely reduces the amount of fascicle stretch during the stretch phase, and thus the force enhancement. In addition, reduced muscle stretch would also reduce stretch reflex activity, triggered by the stretch of the muscle spindles (Matthews, 1933). Taking all these findings together, as an acute intervention, an increase in tendon compliance negatively affects fast stretch-shortening cycle force capacities during the stretch phase, resulting in reduced start forces prior to the shortening phase.

Muscle/tendon stiffness

The different acute effects of the interventions on the triceps surae muscle-tendon unit (i.e., a decrease in tendon stiffness) compared to the quadriceps muscle-tendon unit (i.e., decrease in muscle stiffness) following the PNF + PSA interventions were not expected by the authors. Tendon stiffness decreased only in the Achilles tendon, but not in the patellar tendon, following the respective PNF stretching + PSA. However, it has to be mentioned that the patellar tendon stiffness did show a tendency to decrease (P = 0.054). Such a decrease in Achilles tendon stiffness was also reported by Kay et al. (2015), who applied a comparable PNF stretching protocol (but without PSA). Kay et al. (2015) suggested that the changes in tendon stiffness are related to the isometric contraction during the PNF stretching, which produces much higher forces than passive stretching. These forces might have been greater in the Achilles tendon than the patellar tendon during the isometric contractions, due to the unfavourably long length of the quadriceps muscles with the flexed knee joint. A further explanation for the different effects on the different tendons might be the different architectures and functions of the two muscle-tendon units. The triceps surae muscle-tendon unit has a longer free tendon (49.3 to 70 mm; Kongsgaard et al., 2005) and is, in general, acting on the ankle joint with a relatively small range of motion (~60 degrees; Driller et al., 2017). The quadriceps muscle-tendon unit has a shorter tendon (~31 mm; Stäubli et al., 1999), with the knee joint working, in general, over a relatively wide range of motion (~130 degrees; Cheatham & Stull, 2018). Strains in the tendons during almost maximal isometric contractions have been reported to be about 8% in the Achilles tendon (Magnusson et al., 2003) and 5% in the patellar tendon (Arampatzis et al., 2007), with correspondingly greater length changes in the Achilles tendon. This might explain why the Achilles tendon is more prone to acute changes in stiffness than the patellar tendon during PNF stretching + PSA.

On the other hand, changes in muscle stiffness were only observed in the quadriceps muscles, and not in the triceps surae muscles. This might also be related to the different muscle-tendon unit architectures. The greater length of the Achilles tendon compared to the patellar tendon results in smaller fascicle length changes in a stretching position during a dorsiflexion movement (e.g., 18% for the gastrocnemius medialis; Konrad et al., 2017a) than during a knee flexion movement (e.g., 34% for the vastus lateralis; César et al., 2017). This is especially true for the medial head of the quadriceps, which has a shorter aponeurosis than the other heads of the quadriceps muscles. However, the lack of muscle stiffness changes in the gastrocnemii contradicts various other studies that have investigated the acute effects of PNF stretching without PSA on the ankle joint (Kay et al., 2015; Konrad et al., 2017a). Including PSA after the PNF stretching in the current study might have counteracted the stiffness-reducing effects of isolated PNF stretching. Furthermore, the duration of the PNF stretching might explain the differences. Reiner et al. (2021) performed PNF stretching of the triceps surae muscles, including PSA, for 2 min, and reported a decrease in muscle stiffness (Reiner et al., 2021). A longer duration of stretching in the current study (e.g., 1 m) might have induced similar changes in muscle stiffness. However, in the current study, we deliberately chose a shorter stretching protocol, compared to Reiner et al. (2021), to overcome any possible detrimental effects on performance (Behm et al., 2016). A major difference with the study by Reiner et al. (2021) is the method used to determine tissue stiffness (i.e., Myoton device vs. shear wave elastography). However, we assume that the outcomes should be comparable, as Lee et al. (2021) reported a correlation coefficient of 0.42 to 0.67 (depending on the tested muscles) between the two methods. Moreover, we found an excellent inter-day reliability (i.e., ICC >0.75; Portney & Watkins, 2009) in the stiffness of both analysed muscles when using the Myoton device, with ICCs between 0.87 and 0.98, indicating that stiffness changes should be detectable with this method. The high reliability of the Myoton device has also been confirmed in previous studies (quadriceps: Chen et al., 2019; Lee et al., 2021; triceps surae:, 2021; Schneebeli et al., 2020). Moreover, the construct validity of the Myoton device was also confirmed in a previous study (Schneebeli et al., 2020).

Stretching and PSA

The current study is the first study to have reported a decrease in performance following a stretching exercise with PSA (at least in the triceps surae PNF + PSA condition). Other studies have reported either no changes or an increase in performance (Blazevich et al., 2018; Reid et al., 2018; Reiner et al., 2021; Samson et al., 2012). Samson et al. (2012) found an increase in sprint time after the combination of stretching (static or dynamic) and PSA (same protocol as in the current study), but no change if the stretching was combined with a general warm-up (5 min of running). Moreover, another study showed a favourable effect in strength and jump performance following several static stretching conditions (30 s, 60 s, 120 s) with PSA, compared to the same stretching conditions without PSA (Reid et al., 2018). Furthermore, Reiner et al. (2021) reported no change in maximum voluntary isometric contraction torque when PSA was performed after a PNF stretching exercise. However, a decrease in maximum voluntary isometric contraction torque was reported when PNF stretching was performed without PSA. Hence, it was recommended that PSA be performed following stretching (Behm et al., 2016) so that the stretching-induced impairments in functional performance parameters could be reversed to baseline or even improved after performing PSA. However, we could not confirm these results.

This study has some limitations. First, the stiffness assessment was conducted following a general warm-up (10 min on the stationary bike). Hence, it is likely that this already altered stiffness at the baseline assessment (Baumgart et al., 2019). However, we have chosen this protocol since we wanted to exclusively assess the stiffness changes following the PNF stretching + PSA interventions and to avoid any risk of injury for the participants due to unprepared maximum effort jumps at baseline. Second, a further potential limitation was that we assessed the tissue stiffness in a rested and not in an isometric active state or during fast contractions similar to the jump tasks. Due to the viscoelastic characteristics of the tissue, it is likely that acute stretching has different effects on muscle–tendon interaction when loaded at different rates (i.e., at rest vs. isometric vs. fast dynamic loading in DJ vs. rather slow dynamic loading during CMJ). This is not accounted for in our study and needs further investigation. Third, in this study, only one muscle group was stretched with the PNF technique (either triceps surae or quadriceps) + PSA to investigate potential individual responses to jump performance. Although complex movements such as jumping are dependent on more than one muscle group, our results might be helpful to understand the effects of different adaptations of the various muscles to stretching on jump performance. Fourth, DJs were performed before CMJs and, hence, a potential potentiation effect could have occurred after the DJs, which might have influenced the outcome in the CMJs. However, since the order of the jumps was performed in the same manner before, and after stretching, we believe that a potentiation effect has not influenced our results. Nevertheless, as our intervention, if at all, only induced acute changes in tissue compliance that may vanish within several minutes (Andreas Konrad & Tilp, 2020; Konrad et al., 2019), it cannot be ruled out that the order of jumps influenced the results. CMJ performance might have been more affected if they were performed directly after the stretching intervention. Fifth, only male participants were included in this study. Future studies should consider both sexes and the individual responses to PNF stretching +PSA.

Conclusions

This is the first study to have compared the acute effects of isolated stretching of two major lower leg muscles (i.e., triceps surae and quadriceps) with PSA to have detected possible respective responses to stretching exercises. The results showed that PNF stretching + PSA has the potential of deteriorating performance of movements involving explosive or reactive muscle contractions (i.e., a DJ), due to the possible influence on muscle–tendon interaction. The negative effects in DJ height and DJ RSI showed a large effect size following PNF stretching + PSA of the triceps and a medium effect size following PNF stretching + PSA of the quadriceps. However, these negative effects observed in DJ do not seem to play a comparable role in movements with slower stretch-shortening cycles (i.e., a CMJ).

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Data availability statement

All data will be made available on request to the corresponding author.

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