The Combined Effect of Static Stretching and Foam Rolling With or Without Vibration on the Range of Motion, Muscle Performance, and Tissue Hardness of the Knee Extensor

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Abstract

Nakamura, M, Konrad, A, Kasahara, K, Yoshida, R, Murakami, Y, Sato, S, Aizawa, K, Koizumi, R, and Wilke, J. The combined effect of static stretching and foam rolling with or without vibration on the range of motion, muscle performance, and tissue hardness of the knee extensor. *J Strength Cond Res* XX(X): 000–000, 2022—Although the combination of static stretching (SS) and foam rolling (FR) is frequently used for warm-up in sports, the effect of the intervention order is unclear. This study compared mechanical tissue properties, pain sensitivity, and motor function after SS and FR (with and without vibration) performed in different orders. Our randomized, controlled, crossover experiment included 15 healthy male subjects (22.5 ± 3.3 years) who visited the laboratory 5 times (inactive control condition, FR + SS, $FR_{vibration}$ + SS, SS + FR, and SS + $FR_{vibration}$) with an interval of ≥48 hours. In each session, subjects completed three 60-second bouts of FR and SS, targeting the anterior thigh. Pressure pain threshold, tissue hardness, knee flexion range of motion (ROM), maximal voluntary isometric (MVC-ISO), and concentric (MVC-CON) torque, as well as countermovement jump height, were determined before and after the intervention. All interventions significantly ($p < 0.01$) increased knee flexion ROM ($d = 0.78$, $d = 0.87$, $d = 1.39$, and $d = 0.87$, respectively) while decreasing tissue hardness ($d = -1.25$, $d = -1.09$, $d = -1.18$, and $d = -1.24$, respectively). However, MVC-ISO torque was significantly reduced only after FR + SS ($p = 0.05$, $d = -0.59$). Our results suggest that SS should be followed by FR when aiming to increase ROM and reduce tissue hardness without concomitant stretch-induced force deficits (MVC-ISO, MVC-CON, and countermovement jump height). Additionally, adding vibration to FR does not seem to affect the magnitude of changes observed in the examined outcomes.

Key Words: isometric contraction, concentric contraction, warm-up routine, stretch-induced force deficits

Introduction

Flexibility is an essential quality in some sports, such as rhythmic gymnastics and ballet, and, as a consequence, many coaches and athletes advocate the use of stretching during warm-up (34). Indeed, it has repeatedly been demonstrated that a single exercise bout can induce acute increases in range of motion (ROM), (14,21,30). However, static stretching (SS) durations of more than 45–60 seconds are also known to cause a decrease in muscle strength and explosive performance, which is referred to as stretch-induced force deficit (3,4,32). Recently, foam rolling (FR) interventions have attracted attention from researchers and clinicians. A systematic review with the meta-analysis by Wilke et al. (39) concluded that FR significantly enhances ROM to a similar degree as stretching does. Importantly, there seems to be no detrimental effect on motor performance (20,27). Another review by Wiewelhove et al. (38) even reported a tendency of improvement in sprint performance following FR. Foam rolling, therefore, seems to represent a valuable new component of athletic warm-ups (13).

In addition to the isolated effects of FR and SS, the combined impact of both interventions merits particular consideration. Anderson et al. (1) demonstrated that FR plus dynamic stretching significantly improves flexibility compared with dynamic stretching alone. Yet, a more recent meta-analysis by Konrad et al. (13) examined all stretching techniques (i.e., static, dynamic, proprioceptive neuromuscular facilitation) but did not find superior ROM effects of combined interventions. The same applied to effects of SS + FR vs. SS or FR only on performance parameters. Interestingly, when FR was performed before stretching, the combined application improved performance slightly more than stretching alone ($p = 0.04$), although the effect size of this observation was trivial (ES = 0.17). Against this background, the order of FR and stretching interventions could be an underestimated factor that needs to be considered. To the best of our knowledge, there have been no detailed studies on the effect of the FR and stretching intervention on ROM, muscle strength, and performance.

Recently, another approach that gained popularity is FR with vibration ($FR_{vibration}$). Vibration foam rollers are commonly used

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in sports and rehabilitation and could induce greater changes than FR because of the stimulation of mechanoreceptors (e.g., Pacinian corpuscles) (6). The meta-analysis by Wilke et al. (39) suggested that $\text{FR}_{\text{vibration}}$ could induce a larger increase in ROM than FR, and Nakamura et al. (23) showed that $\text{FR}_{\text{vibration}}$ could reduce muscle stiffness, whereas this was not the case after a single FR bout without vibration. Thus, although $\text{FR}_{\text{vibration}}$ may be more beneficial than FR, no data are available on the combined effect of $\text{FR}_{\text{vibration}}$ with stretching, including the order of $\text{FR}_{\text{vibration}}$ and stretching as well as the comparison with FR.

The purposes of this study were twofold: (a) to determine the order effects of combined SS and FR on mechanical tissue properties, pain sensitivity, and motor function and (b) to elucidate the added value of $\text{FR}_{\text{vibration}}$ in this context. Previous studies investigating the combined effect of SS and aerobic warm-up demonstrated that SS intervention followed by aerobic warm-up could recover from stretch-induced force deficits while maintaining ROM and passive stiffness changes (33,35). Therefore, we hypothesized that SS followed by FR or $\text{FR}_{\text{vibration}}$ could recover from stretch-induced force deficits while maintaining other parameter changes.

Methods

Experimental Approach to the Problem

A randomized, repeated-measure, experimental design was used to compare the order effects of combined anterior thigh SS and FR (with or without vibration) on mechanical tissue properties, pain sensitivity, and ROM. The subjects were instructed to visit the laboratory 5 times with a ≥48-hour interval. They were exposed to the following 5 conditions (Figure 1): FR + SS, SS + FR, $\text{FR}_{\text{vibration}}$ + SS, SS + $\text{FR}_{\text{vibration}}$, and inactive control. For each SS, FR, and $\text{FR}_{\text{vibration}}$, three 60-second bouts were performed on the dominant leg. The control condition consisted of 600-second seated rest to match the time of the SS-FR intervention and transportation to the measurement site. Outcomes were measured before (PRE) and immediately after the intervention (POST) in each condition. We assessed (a) knee flexion ROM, (b) tissue hardness, (c) pain pressure threshold (PPT), (d) knee extensor muscle strength (maximal voluntary isometric [MVC-ISO] and maximal voluntary concentric [MVC-CON] torque), and (e) countermovement Jump (CMJ) height in this order, at both PRE and POST.

Subjects

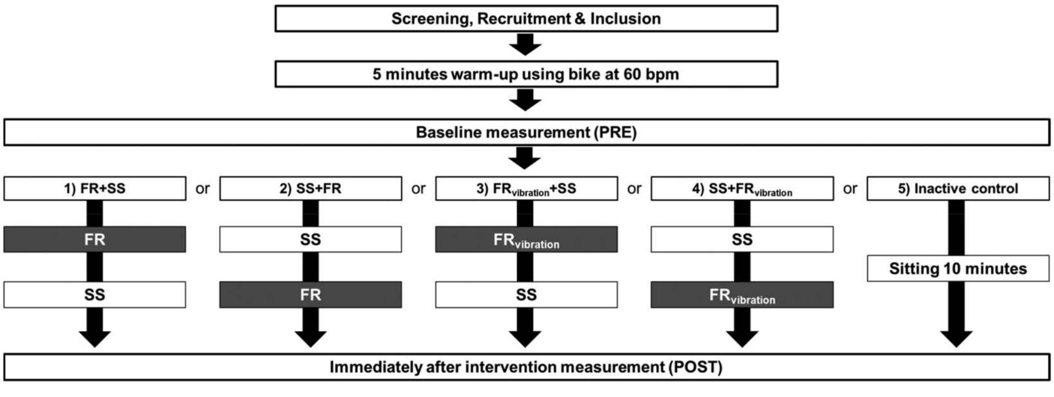
A total of 15 healthy men were enrolled (mean ± *SD*: age, 22.5 ± 3.3 years; height, 170.1 ± 5.4-cm; body mass, 69.5 ± 11.1-kg). The subjects completed the 5 conditions described above in random order. Individuals with a history of neuromuscular disease and musculoskeletal injury involving the lower extremities were excluded. The required sample size for a repeated-measure 2-way analysis of variance (ANOVA) (effect size = 0.40 [large], α error = 0.05, and power = 0.95) using G* power 3.1 software (Heinrich Heine University, Düsseldorf, Germany) was 15 subjects.

For the study, subjects were fully informed about the procedures and aims, after which they provided written informed consent. The study complied with the requirements of the Declaration of Helsinki and was approved by the Ethics Committee of the Niigata University of Health and Welfare, Niigata, Japan (Procedure #18615).

Procedures

Foam Rolling Intervention With and Without Vibration. A foam roller (Stretch Roll SR-002, Dream Factory, Umeda, Japan) was used for the FR intervention. The subjects were instructed on how to use the foam roller by a physical therapist. For familiarization, they were allowed to practice using the foam roller 3 to 5 times on the nondominant leg (nonintervention leg) immediately before the FR intervention to verify that the subjects were able to perform the FR intervention at the specified velocity and location. The subjects performed three 60-second bouts of FR (with or without vibration), with a 30-second rest between sets. The subjects were instructed to be in the plank position with the foam roller at the most proximal portion of the quadriceps of the dominant leg only. We defined 1 cycle of FR as 1 distal rolling plus 1 subsequent proximal rolling movement; FR velocity was set at 30 cycles per 60 seconds (90 cycles in 3 sets) and controlled using a metronome (Smart Metronome; Tomohiro Ihara, Japan). This was in accordance with the recommendations of Behm et al. (2) to maximize the increase in ROM. The subjects were asked to place as much body mass on the roller as tolerable. For $\text{FR}_{\text{vibration}}$, the vibrations had a frequency of 35 Hz.

Static Stretching Intervention. Static stretching was conducted similarly to the knee flexion ROM assessment (side-lying position). A well-trained investigator conducted three 60-second bouts with a 30-



※ All five conditions were performed in random order with more than 48 hours intervals

Figure 1. The experimental setup. SS = static stretching; FR = foam rolling; $\text{FR}_{\text{vibration}}$ = foam rolling with vibration.

second rest interval (20,27). The subjects were instructed to be relaxed and keep their torso upright during stretching.

Knee Flexion Range of Motion. Each subject was placed in a side-lying position on a massage bed with the hips and the knee of the nondominant leg flexed at 90° to prevent pelvic movement (25). The investigator, a licensed physical therapist, brought the dominant leg to full knee flexion with the hip joint in a neutral position. A goniometer (MMI universal goniometer Todai 300 mm, Muranaka Medical Instruments, Co., Ltd., Osaka, Japan) was used to measure the knee flexion ROM 3 times at both, PRE and POST, in each condition, and the average value was used for further analysis. The coefficients of variance (CV) and intraclass correlation coefficients (ICC [1, 1]) for knee flexion ROM measurements were calculated from PRE value in the control condition. Coefficients of variance and ICC (1, 1) were 0.2 ± 0.2% and 0.993 ($p < 0.001$), respectively.

Pain Pressure Threshold. Pain pressure threshold measurements were conducted in the supine position, using an algometer (NEUTONE TAM-22 (BT10); TRY-ALL, Chiba, Japan). The measurement location was set at the midway of the distance between the anterior superior iliac spine and the dominant side's upper end of the patella. With continuously increasing pressure, the soft tissue in the measurement area was compressed with the metal rod of the algometer. The subjects were instructed to immediately press a trigger when pain, rather than just pressure, was experienced. The value read from the device at this time point (kilograms per square centimeter) corresponded to the PPT. Based on previous studies (12,16), the mean value (kilograms per square centimeter) of 3 repeated measurements with a 30-second interval was taken for data analysis at both, PRE and POST, in each condition. Coefficients of variance and ICC (1, 1) were 6.6 ± 3.9% and 0.971 ($p < 0.001$), respectively.

Tissue Hardness. Tissue hardness was measured using a portable tissue hardness meter (NEUTONE TDM-N1; TRY-ALL Corp., Chiba, Japan). The subject's measurement position and posture were similar to PPT measurements. There is a spring in the part that should be grasped above the display, and the hemispherical indenter at the bottom end was pushed back into the body when the indenter comes in contact with an object. Thus, the object's reaction force that the indenter receives when a pushing force reaches approximately 14.71 N (1.5 kgf) could be assessed (31). The subjects were instructed to relax while tissue hardness measurements were assessed 3 times at both, PRE and POST, in each condition, and the average value was used for further analysis. Coefficients of variance and ICC (1, 1) were 2.8 ± 1.1% and 0.963 ($p < 0.001$), respectively.

Maximal Voluntary Isometric and Maximal Voluntary Concentric Contraction. Maximal voluntary isometric of the dominant leg's knee extensors was measured at 2 different angles (20° and 70° knee flexion), using an isokinetic dynamometer (Biodex System 3.0, Biodex Medical Systems Inc., Shirley, NY). The subjects sat on the dynamometer chair adopting an 80° hip flexion angle, with adjusted Velcro straps fixed over the exercised limb's trunk, pelvis, and thigh. The subjects were instructed to maximally contract the knee extensors for 3 seconds at each angle. Two repetitions with a 60-second rest between trials were performed at both, PRE and POST, in each condition (25). The mean of both repetitions was used for further analysis. Maximal voluntary concentric was measured at an angular velocity of $60°\cdot^{-1}$ between 20° and 90° knee flexion. From the 3 trials performed at both, PRE and POST, in each condition, the highest value was analyzed (25). During all tests, strong verbal encouragement was provided to elicit maximal effort.

Countermovement Jump Height. Countermovement Jump height was calculated from flight time using a contact mat (Jump mat system; 4Assist, Tokyo, Japan). The subjects started with the foot of the dominant leg on the mat with their arms crossed in front of their chest. The subjects were instructed to dip quickly (eccentric phase) from this position, reaching a self-selected depth to jump as high as possible in the next concentric phase. Landings were performed on both feet. The knee of the noninvolved leg was held at approximately 90° flexion (9). After 3 familiarization trials, 3 maximal CMJ were conducted at both, PRE and POST, in each condition, and the largest vertical jump height was used for further analysis (23).

Statistical Analysis

SPSS (version 25.0; IBM Corp., Armonk, NY) was used for statistical analyses. To verify comparability of baseline values, PRE values were tested among all conditions using a 1-way ANOVA. A repeated-measure 2-way ANOVA (time [PRE vs. POST] × conditions [Control vs. FR + SS vs. VFR + SS vs. SS + FR vs. SS + FR]) was identified interactions and main effects during the experiment. If the interaction term was significant, a post hoc analysis was conducted using paired *t*-tests with Bonferroni's correction on each condition to determine the difference between PRE and POST values. Effect sizes (ES) were calculated as the mean difference between PRE and POST divided by the pooled PRE and POST *SD*. An ES of 0.00–0.19 was considered trivial, 0.20–0.49 was little, 0.50–0.79 was moderate, and ≥0.80 was large (8). The significance level was set at 5%. All results are shown as mean ± *SD*.

Results

Comparison Between PRE Values Among the 5 Conditions

The 1-way repeated-measure ANOVA showed no significant differences in all PRE variables among the 5 conditions and thus did not yield indications of a baseline difference.

Changes in Knee Flexion Range of Motion, Pain Pressure Threshold, and Tissue Hardness

Table 1 shows knee flexion ROM, PPT, and tissue hardness before and after the 5 conditions. The 2-way repeated-measure ANOVA showed a significant interaction for knee flexion ROM ($F = 14.4$, $p < 0.01$, $\eta_p^2 = 0.50$). According to post hoc testing, ROM increased ($p < 0.01$) significantly after the 4 exercise conditions but not after the inactive control condition ($p > 0.05$). Likewise, 2-way repeated-measure ANOVAs showed significant interaction effects for PPT ($F = 3.2$, $p = 0.02$, $\eta_p^2 = 0.186$) and tissue hardness ($F = 9.02$, $p < 0.01$, $\eta_p^2 = 0.392$). Post hoc test demonstrated that PPT increased ($p < 0.01$) after both FR + SS and VFR + SS, but there were no significant changes following control ($p = 1.00$, $d = 0.05$), SS→FR ($p = 0.31$, $d = 0.34$), and SS + VFR ($p = 0.08$, $d = 0.36$). Moreover, a post hoc test showed that tissue hardness decreased ($p < 0.01$) significantly after 4 intervention conditions, but no significant change was observed in the control condition ($p = 0.052$, $d = -0.09$).

Changes in Maximal Voluntary Isometric, Maximal Voluntary Concentric, and Countermovement Jump Height

Table 2 shows knee flexion MVC-ISO, MVC-CON, and CMJ height changes before and after the 5 conditions. The 2-way repeated-measure ANOVA revealed a significant interaction for MVC-ISO ($F = 2.65$, $p = 0.043$, $\eta_p^2 = 0.159$) but not for MVC-CON ($F = 1.65$, $p = 0.227$, $\eta_p^2 = 0.102$) and CMJ height ($F = 0.518$, $p = 0.72$, $\eta_p^2 = 0.036$). The post hoc tests showed that MVC-ISO was significantly reduced after FR + SS only ($p = 0.028$, $d = -0.59$), whereas there were no significant changes in the other 4 conditions.

Discussion

Previous studies examined the impact of FR or $\text{FR}_{\text{vibration}}$ on knee ROM, muscle strength, CMJ height, and PPT (25,28,29). However, to the best of our knowledge, this trial is the first (a) to investigate the order effect of FR and SS with regard to motor function, pain sensitivity, and mechanical tissue properties and (b) to elucidate the added value of vibration in this context. Our results demonstrate that all combinations of SS and FR are capable of increasing knee flexion while decreasing tissue hardness. The addition of vibration to FR ($\text{FR}_{\text{vibration}}$) does not provide an advantage over conventional FR. Interestingly, only the combination of FR followed by SS induced a loss in MVC-ISO, suggesting that this order should be avoided by athletes and coaches aiming to preserve strength during warm-up.

As indicated, all interventions increased knee flexion and reduced anterior thigh hardness. Previous studies showed that an increase in ROM could be because of a reduction in passive stiffness and changes in stretch tolerance (15,37). Hotfiel et al. (11) found an increase in tissue perfusion following FR, which, in turn, could reduce mechanical stiffness. This is in line with evidence demonstrating lower tissue stiffness post FR (40). Also, recent reviews suggested that a single FR bout could induce thixotropic changes of intrafascial hyaluronic acid, which, in turn, could reduce viscoelastic stiffness (6,39). In addition, previous studies showed that $\text{FR}_{\text{vibration}}$ or SS could decrease tissue stiffness or muscle stiffness (17,22–24). However, a single FR bout has also been shown to modify stretch sensation, which could contribute to an increase in ROM after FR (18–20). Interestingly, tissue hardness was lower after all interventions, and PPT increased in both FR + SS and $\text{FR}_{\text{vibration}}$ + SS. Although the mechanism of changes in knee flexion ROM is unclear with regard to this study, changes in passive stiffness and stretch tolerance could both have contributed to the increases in knee flexion ROM. Contrary to our expectations, the effect of $\text{FR}_{\text{vibration}}$ was comparable to that of conventional FR. Although a meta-analysis suggested that $\text{FR}_{\text{vibration}}$ induces a greater ROM increase than FR only (39), a recent study reported no difference (23). Therefore, there seems to be evidence that the order of FR and SS interventions but also adding vibration to FR does not affect the increase in ROM.

Our results showed that MVC-ISO torque was reduced after FR + SS only but not $\text{FR}_{\text{vibration}}$ + SS, which supports the hypothesis of this study. Proposed mechanisms underlying the stretch-induced force deficit include neural and morphological factors (5). As described above, because there were similar changes in tissue hardness in the 4 intervention conditions, the reduction in MVC-ISO could rather be related to changes in neural but not morphological factors. Specifically, stretching can induce modifications in persistent inward currents (PICs)

Table 1

The changes (mean ± *SD*) in knee flexion range of motion (ROM), pain pressure threshold (PPT), and tissue hardness before and after intervention.*†

	Control condition		FR + SS		$\text{FR}_{\text{vibration}}$ + SS		SS + FR		SS + $\text{FR}_{\text{vibration}}$		ANOVA results
	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	p, F value, η_p^2
Knee flexion ROM (deg)	132.9 ± 4.5	133.3 ± 4.9	131.8 ± 7.9	138.1 ± 8.3‡	133.8 ± 7.7	140.4 ± 7.3‡	131.9 ± 5.0	138.4 ± 4.4‡	133.6 ± 5.5	138.6 ± 5.8‡	$F = 14.4$, $p < 0.01$
	$d = 0.08$		$d = 0.78$		$d = 0.87$		$d = 1.39$		$d = 0.87$		$\eta_p^2 = 0.50$
PPT (kg)	2.6 ± 1.2	2.6 ± 1.3	2.8 ± 1.3	3.2 ± 1.2‡	2.9 ± 1.3	3.8 ± 1.6‡	3.0 ± 1.6	3.6 ± 1.9	3.1 ± 1.9	3.6 ± 1.8	$F = 3.2$, $p = 0.02$
	$d = 0.05$		$d = 0.35$		$d = 0.64$		$d = 0.34$		$d = 0.36$		$\eta_p^2 = 0.186$
Tissue hardness (N)	18.6 ± 3.3	18.3 ± 3.2	18.6 ± 3.1	15.1 ± 2.5‡	20.1 ± 3.5	16.6 ± 3.0‡	18.3 ± 2.2	14.6 ± 4.0‡	19.6 ± 3.3	15.7 ± 3.1‡	$F = 9.02$, $p < 0.01$
	$d = -0.09$		$d = -1.25$		$d = -1.09$		$d = -1.18$		$d = -1.24$		$\eta_p^2 = 0.392$

*SS = static stretching; FR = foam rolling; $\text{FR}_{\text{vibration}}$ = foam rolling with vibration; ANOVA = analysis of variance.

†The 2-way ANOVA results (condition × time interaction effect; p- and F-values) and partial η^2 (η_p^2) are shown in right column.

‡A significantly ($p < 0.05$) different from the PRE-value.

Table 2

The changes (mean ± *SD*) in maximal voluntary isometric contraction (MVC-ISO), maximal voluntary concentric contraction (MVC-CON) torques, and countermovement jump (CMJ) height before and after intervention.*†

	Control condition		FR + SS		$FR_{vibration}$ + SS		SS + FR		SS + $FR_{vibration}$		ANOVA results
	PRE	POST	PRE	POST	PRE	POST	PRE	POST	PRE	POST	*p*, *F* value, η_p^2
MVC-ISO (Nm)	243.8 ± 32.4	240.5 ± 31.8	240.2 ± 33.7	220.7 ± 32.2‡	234.6 ± 35.3	221.9 ± 23.3	237.3 ± 32.6	235.2 ± 43.8	236.2 ± 32.6	225.5 ± 30.0	$F = 2.65$, $p = 0.043$
	$d = -0.10$		$d = -0.59$		$d = -0.43$		$d = -0.05$		$d = -0.34$		$\eta_p^2 = 0.159$
MVC-CON (Nm)	190.2 ± 26.5	193.8 ± 30.4	186.1 ± 22.8	178.3 ± 27.1	186.1 ± 26.3	184.4 ± 25.0	189.5 ± 30.4	186.8 ± 32.9	186.4 ± 25.3	185.4 ± 24.6	$F = 1.65$, $p = 0.227$
	$d = 0.13$		$d = -0.31$		$d = -0.07$		$d = -0.08$		$d = -0.04$		$\eta_p^2 = 0.102$
CMJ height (cm)	22.2 ± 3.2	22.2 ± 3.4	21.8 ± 2.9	21.3 ± 3.7	22.3 ± 3.8	21.7 ± 3.5	22.1 ± 3.5	21.8 ± 3.9	22.4 ± 3.1	21.8 ± 3.3	$F = 0.518$, $p = 0.72$
	$d = -0.01$		$d = -0.16$		$d = -0.17$		$d = -0.09$		$d = -0.21$		$\eta_p^2 = 0.036$

*SS = static stretching; FR = foam rolling; $FR_{vibration}$ = foam rolling with vibration; ANOVA = analysis of variance.
†The 2-way ANOVA results (condition x time interaction effect; *p*- and *F*-values) and partial η^2 (η_p^2) are shown in right column.
‡A significantly ($p < 0.05$) different from the PRE-value.

(5) and alterations of muscle spindle sensitivity (7), which both adversely affect muscle activation. A previous study suggested that $FR_{vibration}$ more strongly stimulates mechanoreceptors (e.g., Pacinian corpuscles) when compared with FR (6). Thus, the application of VFR before SS could have a protective effect against stretch-induced force deficits (e.g., by means of increasing PICs or spindle sensitivity). With regard to the other intervention combinations not inducing a force loss, it could be assumed that a potential force deficit after SS was recovered through FR and $FR_{vibration}$ after SS because motoneuron excitability could be restored by them. Normally, PIC partially recovers at 5 minutes after SS and fully recover at 10 minutes after SS (36). In this study, in SS + FR and SS + $FR_{vibration}$, SS was followed by three 60-second bouts of rolling with 30-second rests. Therefore, the time elapsed between the SS intervention and the MVC-ISO measurement may have caused the recovery of muscle spindle sensitivity. An alternative explanation for the recovery in SS + FR and SS + $FR_{vibration}$ could be a potential warm-up effect. The FR intervention of this study used plank-like posture. Planking involves isometrically holding the body prone with the maintenance of an extended leg position and can be expected to have a warm-up effect inducing increased skin and muscle temperature (10). Also, previous studies showed that a single FR bout could increase blood flow (11) and improve vascular function (26). Such warm-up effect could have counteracted potential stretch-induced force deficits.

Surprisingly, the results showed no significant changes in MVC-CON and CMJ height after all intervention conditions. Budini et al. (7) showed that isometric contraction could promote the recovery of muscle spindle sensitivity. In this study, the MVC-CON and CMJ measurements were assessed after the MVC-ISO measurements, which might have promoted the recovery of muscle spindle sensitivity. Additionally, the MVC-CON and CMJ measurements were assessed after the SS intervention, which may have led to the recovery of muscle strength, jumping, and performance in the FR + SS condition. This potential drawback should be considered when designing future trials. There was a limitation in this study. The subjects practiced on the nonintervention leg as a familiarization trial. Previous studies showed the same degree of FR intervention effect on ROM in intervention and nonintervention sides (cross-education effect) (18). Thus, it is possible that the familiarization trial might have influenced the change in ROM. However, because we used the same protocol for all conditions, the cross-education effect of FR on ROM could not affect the results of this study.

Practical Applications

This study aimed to compare the order effects of combined SS and FR, drawing conclusions for warm-up in sports. We found that the order of both flexibility interventions had no effect when the goal was to increase ROM or reduce tissue hardness. However, in sports requiring maximal strength and explosive movements, it is recommended that SS be followed by FR-$FR_{vibration}$ intervention or preceded by $FR_{vibration}$.

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