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Research article

Comparison of Isolated or Combined Static Stretching and Foam Rolling on Knee Extensors' Function

Kazuki Kasahara [1], Andreas Konrad [2], Riku Yoshida [1], Yuta Murakami [1], Shigeru Sato [1], Ryoma Koizumi [3], David G Behm [4] and Masatoshi Nakamura [5]✉

[1] Institute for Human Movement and Medical Sciences, Niigata University of Health and Welfare, Niigata, Japan; [2] Institute of Human Movement Science, Sport and Health, University of Graz, Graz, Austria; [3] Department of Physical Therapy, Niigata University of Health and Welfare, Niigata, Japan; [4] School of Human Kinetics and Recreation, Memorial University of Newfoundland, St. John's, Newfoundland and Labrador, Canada; [5] Faculty of Rehabilitation Sciences, Nishi Kyushu University, 4490-9 Ozaki, Kanzaki, Saga, 842-8585, Japan

Abstract

Static stretching (SS), foam rolling (FR), and a combination of both are used as warm-ups for sports and training. However, no reports have compared or examined the warm-up effects of short-term interventions (i.e., 30-s). Therefore, this study was designed to compare and examine the effects of short-term SS, FR, and SS+FR on knee extensors. The dominant knee extensors of 14 male university students (22.0 ± 1.3 years old) were tested. Five conditions were randomized: 60-s SS, 60-s FR, 30-s SS+ 30-s FR, 30-s SS, and 30-s FR to examine differences in intervention method, duration, and combined. The measures were knee flexion range of motion (ROM), pain pressure threshold (PPT), tissue hardness, maximum voluntary contraction-isometric (MVC-ISO), and MVC-concentric (MVC-CON) torques, measured before and after the intervention. Knee flexion ROM ($d = 0.40$, $d = 0.59$, $d = 0.54$, $d = 0.59$, $d = 0.52$ respectively) and PPT ($d = 0.77$, $d = 0.60$, $d = 0.90$, $d = 0.74$, $d = 0.52$, respectively) were significantly increased ($p < 0.01$), and tissue hardness ($d = -0.79$, $d = -0.63$, $d = -0.53$, $d = -0.59$, $d = -0.72$, respectively) was significantly decreased ($p < 0.01$) in all conditions. However, MVC-ISO decreased significantly ($p < 0.01$) in the 60-s SS and 30-s SS conditions but did not affect MVC-CON in all conditions. The results of this study revealed that SS, FR, and SS+FR interventions for a short-term as a warm-up before exercise were effective in increasing ROM, PPT, and decreasing tissue hardness. However, SS intervention with more than 30-s on the knee extensors decreased muscle strength, so short-term FR intervention is recommended when the goal is to increase ROM while maintaining both MVC-ISO and MVC-CON torques. Similarly, a short-term FR intervention after a short-term SS can eliminate the effect of strength impairments.

Key words: Warm-up, flexibility, range of motion, muscle strength.

Introduction

Static stretching (SS) is used as a warm-up before exercise, and many previous studies showed that SS increases the range of motion (ROM) (Behm et al., 2020; Thomas et al., 2018) and decreases tissue stiffness or hardness (Konrad et al., 2017; Nakamura et al., 2011). However, previous studies pointed out that longer than 60-s of SS could decrease muscle strength and performance (Behm et al., 2016; Behm et al., 2021; Kay and Blazevich, 2012). Thus, it is recommended that a longer duration (especially more than 60-s) SS intervention should not be performed during warm-up. In contrast, foam rolling (FR) has recently attracted attention as an alternative warm-up tool to SS. A recent review of the acute effects of stretching and FR on performance showed a trend toward increased performance with FR compared to stretching, although no significant differences were found (Konrad et al., 2021). In addition, it has been reported that the effect of FR on increasing ROM is comparable to that of SS (Konrad et al., 2022; Wilke et al., 2020). Moreover, many studies have been conducted on the warm-up effect of combined stretching and FR (Anderson et al., 2020; Hsu et al., 2020; Nakamura et al., 2023). Nakamura et al. (2023) examined the combined and sequential effects of SS and FR. The results showed that ROM increased in all conditions, but maximal voluntary isometric contraction (MVC-ISO) torque of the knee extensor was significantly decreased in the condition in which SS was performed after FR. On the other hand, no significant difference was observed in the condition of FR after SS. The combination of SS and FR to increase ROM while maintaining muscle strength as a warm-up is recommended to be performed FR after SS.

However, the previous study by Nakamura et al. (2023) used a total intervention time of 180-s SS, which might be challenging to apply in sports settings because practice time is limited. In the actual sports field, a previous study showed that the percentage of SS performed for less than 20-s for a single muscle group is greater than that of SS performed for more than 20-s (Duehring et al., 2009). As described above, previous review articles (Behm et al., 2016; Behm and Chaouachi, 2011; Kay and Blazevich, 2012) showed that short-term SS intervention does not adversely affect muscle strength and performance. In fact, former studies investigating the 20-s SS intervention showed a significant increase in ROM without decreasing muscle strength of the hamstrings (Takeuchi and Nakamura, 2020) and plantar flexor muscles (Sato et al., 2020). Thus, short-term SS intervention could increase ROM without decreasing muscle strength.

Moreover, another study investigating the effects of short-term, i.e., 5-s, 10-s, and 20-s FR interventions on hamstrings showed an increase in ROM without a decrease in muscle strength (Sullivan et al., 2013). A previous study that performed a 30-s FR intervention on the ankle plantar

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flexors showed no changes in both muscle strength and ROM (Nakamura et al., 2021b). The effects of short-term FR interventions have not been consistent, and further investigation is needed. In addition, no studies compare the acute effect of short-term SS and FR, and no studies have investigated the combined effects of short-term SS and FR. Therefore, it is unclear whether the combination of short-term SS and FR is more effective than SS or FR alone as a warm-up routine. With the return to the sports field in mind, it is essential to investigate the acute effects of short-term SS or FR alone or combined SS and FR interventions to establish effective warm-up routines for athletes with limited practice time. Therefore, this study aimed to investigate the effects of short-term SS or FR alone or combined SS and FR interventions on knee extensor muscle groups to establish an effective warm-up routine. The hypothesis of this study, based on previous studies (Behm and Chaouachi, 2011; Kay and Blazevich, 2012; Nakamura et al., 2021b; Sato et al., 2020; Sullivan et al., 2013; Takeuchi and Nakamura, 2020), was that short-term SS and FR intervention could increase ROM without decreasing muscle strength. We also hypothesized that ROM could be increased in the combined SS and FR intervention without reducing muscle strength.

Methods

Experimental set-up

A randomized, repeated-measures experimental design was used to compare the acute effects of combined anterior thigh SS and/or FR within the 60-s. The participants were instructed to visit the laboratory five times with a ≥48 h break. They were exposed to the following five conditions (Figure 1): 60-s SS, 60-s FR, 30-s SS + 30-s FR, 30-s SS, and 30-s FR. The 60-s SS condition consisted of two 30-s SS sessions, 60-s FR condition consisted of two 30-s FR sessions, 30-s SS+30-s FR condition consisted of 30-s each of SS and FR, and 30-s SS and 30-s FR conditions consisted of one 30-s intervention on the dominant leg. In the 60-s SS and 60-s FR conditions, the rest period between sets was 30-s. In the 30-s SS+30-s FR condition, FR was performed 30-s after SS was performed. For the 30-s SS and 30-s FR conditions, POST measurements were taken immediately after the intervention. Outcome variables were measured before (PRE) and immediately after each condition's intervention (POST). We assessed knee flexion ROM, tissue hardness, pain pressure threshold (PPT), MVC-ISO, and maximal voluntary concentric contraction (MVC-CON) torques of knee extensors, in this order, at both PRE and POST. The participants performed a warm-up on the ergometer for 5 minutes before the PRE measurements in this study. The measurement methods for knee flexion ROM, PPT, and tissue hardness were the same as in our previous study (Nakamura et al., 2023), and the reproducibility was confirmed.

Participants

Fifteen healthy, recreationally active males were enrolled (mean ± SD: age, 22.0 ± 1.3 years; height, 170.0 ± 4.9 cm; body mass, 67.8 ± 7.9 kg). The Participants with a history of disease involving the lower extremities and musculoskeletal injuries were excluded. The required sample size for a repeated-measures two-way analysis of variance (ANOVA) (effect size = 0.25 [medium when considering interaction effects for 2-way ANOVAs], αerror = 0.05, and power = 0.80) based on our previous study's ROM results (Nakamura et al., 2023) using G* power 3.1 software (Heinrich Heine University, Dusseldorf, Germany) was more than 13 participants.

For the study, participants were fully informed about the procedure 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).

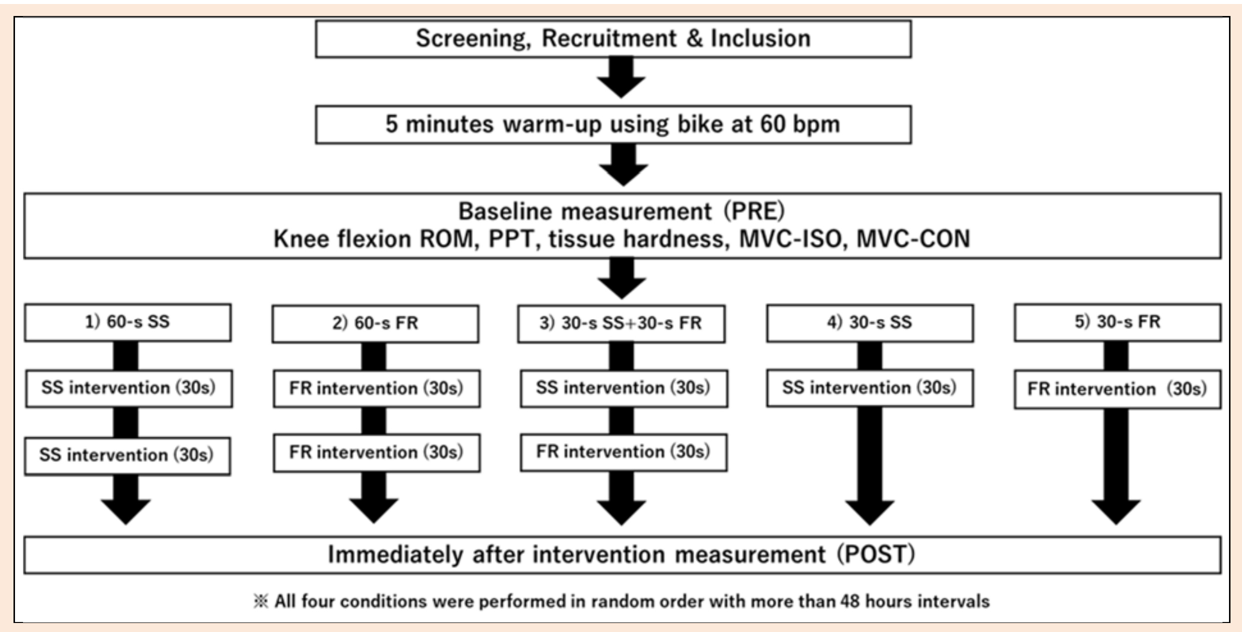

Figure 1. The Experimental set-up. SS: static stretching, FR: foam rolling, ROM: range of motion, PPT: pain pressure threshold, MVC-ISO: maximal voluntary isometric contraction, MVC-CON: maximal voluntary concentric contraction.

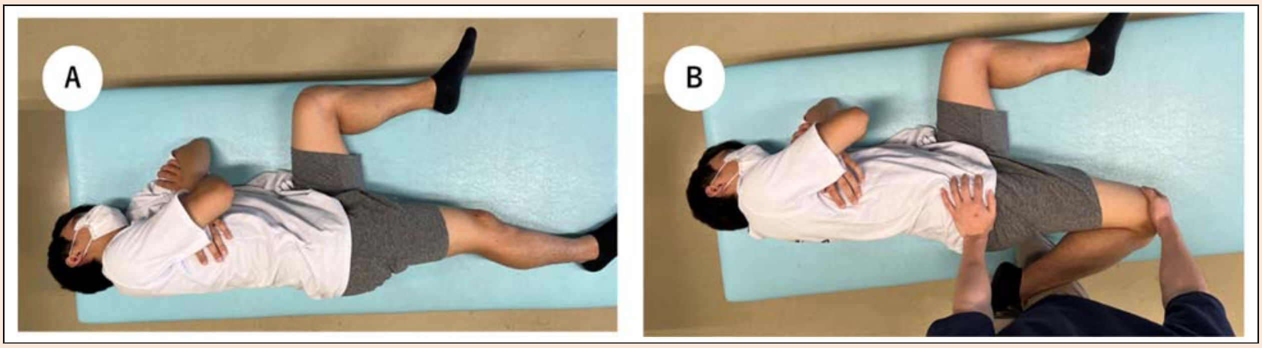

Figure 2. **The set-up for knee flexion range of motion (ROM) measurement. The participants lie in a side-lying position with the contralateral hip and knee joints flexed 90° (A). The investigator brought the dominant leg to full knee flexion with the hip joint in a neutral position (B).**

Outcome assessment

Knee flexion ROM

Each participant was placed in a side-lying position on a massage bed with the hips as well as the knee of the non-dominant leg flexed at 90° to prevent pelvic movements (Nakamura et al., 2020) (Figure 2-A). A licensed physical therapist, the investigator, brought the dominant leg to full knee flexion with the hip joint in a neutral position (Figure 2-B). A goniometer (MMI universal goniometer Todai 300 mm, Muranaka Medical Instruments, Co., Ltd., Osaka, Japan) was used to measure the knee flexion ROM three times at both PRE and POST in each condition, and the average value was used for further analysis.

Pain Pressure Threshold (PPT)

PPT measurements were conducted in the supine position using an algometer (NUTONE 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 superior border of the patella for the rectus femoris muscle. With continuously increasing pressure, the soft tissue in the measurement area was compressed with the metal rod of the algometer. The participants 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 the mean value (kilograms per square centimeter) of three repeated measurements with a 30-s interval was taken for data analysis at both PRE and POST in each condition.

Tissue hardness

Tissue hardness was measured using a portable tissue hardness meter (NEUTONE TDM-N1; TRY-ALL Corp., Chiba, Japan). The participant's measurement position and posture were similar to PPT measurements. This tissue hardness meter measured the penetration distance until a 14.71 N (1.5 kgf) pressure was reached (Sawada et al., 2020). The participants were instructed to relax while tissue hardness measurements were assessed three times at PRE and POST in each condition. The average value was used for further analysis.

Maximal Voluntary Isometric Contraction (MVC-ISO)

MVC-ISO of the dominant leg's knee extensors was measured at 90° knee flexion using an isokinetic dynamometer (BIODEX System 3.0, Biodex Medical System Inc. Shirley, NY, USA). The participants 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 participants were instructed to contract the knee extensors for 3-s maximally. Two repetitions with a 60-s rest between trials were performed at both PRE and POST (Nakamura et al., 2020). The mean of both repetitions was used for further analysis.

Maximal Voluntary Concentric Contractions (MVC-CON)

MVC-CON was measured at an angular velocity of 80° between 20° and 110° knee flexion. From the three trials performed at both PRE and POST in each condition, the highest value was analyzed. During all tests, strong verbal encouragement was provided to elicit maximal effort.

Foam Rolling (FR)

The participants were instructed on how to use the foam roller (Stretch Roll SR-002, Dream Factory, Umeda, Japan) by a physical therapist. For familiarization, they were allowed to practice using the foam roller three to five times on the non-dominant leg (non-intervention leg) immediately before the FR intervention to verify that the participants were able to perform the FR intervention at the specified velocity and location. FR was performed for one set of 30-s. The 60-s condition consisted of two sets with a 30-s rest in between. The 30-s condition was performed for one set. The participants 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 one cycle of FR as one distal rolling plus one subsequent proximal rolling movement. FR velocity was set at 15 cycles per 30s (30 cycles in second sets) and controlled using a metronome (Smart Metronome; Tomohiro Ihara, Japan). This procedure followed the recommendations of Behm (Behm et al., 2020) to maximize the increase in ROM. The participants were asked to place as much body mass on the roller as tolerable.

Static Stretching (SS)

SS was conducted similarly to the knee flexion ROM assessment (side-lying position) by a well-trained investigator for 30-s. The 60-s condition was done twice with a 30-s rest in between, and the 30-s condition was done once. During the stretch, participants were told to relax and keep their torso upright.

Statistical analysis

SPSS (version 28.0; IBM Corp., Armonk, NY, USA) was used for statistical analyses. The normality of the data was checked by a Shapiro-Wilk test, and the almost data was normally distributed. We calculated the coefficient of variation (CV) and intraclass correlation coefficient (ICC) from these data from PRE data in five conditions to check the test-retest reliability. To verify the consistency of PRE values, PRE values were tested among all conditions using a one-way ANOVA. A repeated-measures two-way ANOVA (time [PRE vs. POST] × conditions [60-s SS vs. 60-s FR vs. 30-s SS+30-s FR vs. 30-s SS vs. 30-s FR] was used to identify interactions and main effects. If the interaction effect was significant, a post-hoc analysis was conducted using paired t-tests with Bonferroni correction on each condition to determine the difference between PRE and POST values. Also, POST values were tested among all conditions using paired t-tests with Bonferroni correction. Effect sizes (ES) were calculated as the mean difference between PRE and POST divided by the pooled PRE and POST standard deviation (SD). An ES of 0.00 - 0.19 was considered trivial, 0.20 - 0.49 was small, 0.50 - 0.79 was moderate, and ≥0.80 was large (Cohen, 1988). The significance level was set at 5%. All results are shown as mean ± SD.

Results

Comparison between PRE values among the five conditions

There were no significant differences in all PRE variables among the five conditions. The CVs of measurements for MVC-ISO, MVC-CON, knee flexion ROM, PPT, and tissue hardness were 5.2 ± 2.1%, 4.5 ± 2.0%, 1.8 ± 0.7%, 14.9 ± 6.1%, and 10.6±4.8% respectively, and the ICC (1,1) and 95% confidence interval for measurements were 0.879 (95%CI: 0.766 - 0.953), 0.894 (95%CI: 0.794 - 0.959), 0.779 (95%CI: 0.606 - 0.909), 0.613 (95%CI: 0.387 - 0.823), and 0.616 (95%CI: 0.39 - 0.826), respectively.

Changes in knee flexion ROM, PPT, tissue hardness MVC-ISO, and MVC-CON

Table 1 shows the changes including the statistics and effect sizes in knee flexion ROM, PPT, tissue hardness, MVC-ISO, and MVC-CON before and after the interventions. Significant interaction effects in MVC-ISO (F [4, 56] = 3.9, $p < 0.01$, $\eta_p^2 = 0.19$) were revealed, but not in the other variables. In addition, there were main effects of time on knee flexion ROM (F [1, 56] = 175.9, $p < 0.01$, $\eta_p^2 = 0.73$), PPT (F [1, 56] = 102.8, $p < 0.01$, $\eta_p^2 = 0.61$), tissue hardness (F [1, 56] = 216.4, $p < 0.01$, $\eta_p^2 = 0.77$), and MVC-ISO (F [1, 56] = 17.0, $p < 0.01$, $\eta_p^2 = 0.21$). Post-test results showed that knee flexion ROM (small to moderate magnitudes) and PPT (moderate to large magnitudes) were significantly

Table 1. The changes (mean±SD) in knee flection range of motion (ROM), pain pressure threshold (PPT), tissue hardness, maximal voluntary isometric contraction (MVC-ISO), and maximal voluntary concentric contraction (MVC-CON) torques before (PRE) and after (POST) the intervention. The two-way ANOVA results (T: time effects, C x T: condition x time interaction effects; P- and F- value) and partial η^2 (η_p^2) are shown in the right column.

	60-s SS		60-s FR		30-s SS+30-s FR		30-s SS		30-s FR		ANOVA results
	PRE	POST	PRE	POST	PRE	POST		PRE	POST	PRE	POST
Knee flexion ROM (deg)	134.1 ± 7.0	136.9 ± 7.0*	134.9 ± 5.2	138.2 ± 5.9*	134.3 ± 6.0	137.3 ± 5.3*	133.5 ± 6.0	136.5 ± 5.8*	135.1 ± 5.9	137.4 ± 5.7*	T: F = 175.9, $p < 0.01$, $\eta_p^2 = 0.73$ C x T: F = 0.6, p = 0.66, $\eta_p^2 = 0.04$
PPT (kg)	4.2 ± 1.1	5.2 ± 1.5*	4.3 ± 1.1	5.1 ± 1.4*	4.2 ± 1.3	5.6 ± 1.8*	4.6 ± 1.0	5.5 ± 1.5*	4.3 ± 1.4	5.1 ± 1.8*	T: F = 102.8, $p < 0.01$, $\eta_p^2 = 0.61$ C x T: F = 1.4, p = 0.23, $\eta_p^2 = 0.08$
Tissue Hardness (N)	16.6 ± 3.2	14.3 ± 2.6*	17.9 ± 3.4	15.7 ± 3.5*	16.9 ± 3.9	14.9 ± 3.6*	16.9 ± 2.8	15.3 ± 2.6*	18.4 ± 3.5	16.2 ± 2.7*	T: F = 216.4, $p < 0.01$, $\eta_p^2 = 0.77$ C x T: F = 0.8, p = 0.53, $\eta_p^2 = 0.05$
MVC-ISO (Nm)	196.2 ± 37.3	185.2 ± 37.5*	198.7 ± 30.6	199.8 ± 38.4	200.6 ± 37.4	194.79 ± 34.9	200.0 ± 27.1	188.8 ± 22.8*	200.1 ± 31.2	199.8 ± 29.8	T: F = 17.0, $p < 0.01$, $\eta_p^2 = 0.21$ C x T: F = 3.9, $p < 0.01$, $\eta_p^2 = 0.19$
MVC-CON (Nm)	180.7 ± 32.0	179.7 ± 29.1	182.3 ± 28.1	184.6 ± 24.4	176.3 ± 26.7	180.3 ± 29.6	181.4 ± 24.9	181.1 ± 25.0	180.4 ± 28.3	181.6 ± 24.9	T: F = 0.9, p = 0.32, $\eta_p^2 = 0.02$ C x T: F = 0.5, p = 0.70, $\eta_p^2 = 0.03$

*: A significantly ($p < 0.05$) different from the PRE-value, SS: static stretching, FR: foam rolling

increased ($p < 0.01$) in all conditions, and tissue hardness showed a moderate magnitude significant decrease ($p < 0.01$) in all conditions. MVC-ISO responded with a small magnitude significant decrease ($p < 0.01$) in the 60-s SS and 30-s SS conditions, while no change was observed in the 30-s SS+30-s FR ($p = 0.33$), 60-s FR ($p = 1.00$), and 30-s FR ($p = 1.00$) conditions. No significant interaction or main effect was observed in MVC-CON.

Discussion

Although several previous studies have investigated the acute effects of SS and FR interventions, most studies have adopted longer durations of SS and FR than those used in most common sports settings. Therefore, to enhance ecological validity in this study, we examined the effects of short-term SS and FR interventions and the combined effects of SS and FR in terms of typical sports and training applications. To the best of our knowledge, this is the first crossover design study to examine the effects of short-term SS, FR, and the combination of SS and FR. The results showed small to moderate magnitude ROM, moderate to large magnitude PPT significant increases, and moderate magnitude tissue hardness significant decreases in all conditions. The MVC-ISO torque demonstrated a significant small-magnitude impairment in the 60-s SS and 30-s SS conditions. As we hypothesized, the short-term FR and 30-s SS+30-s FR conditions increased ROM without decreasing muscle strength. The SS-only condition decreased MVC-ISO while ROM increased. This result supports the previous study by Behm et al (Behm et al., 2016; Behm et al., 2021). For these reasons, athletes and coaches should avoid SS-only warm-up.

As shown in Table 1, knee flexion ROM significantly increased in all conditions in this study, which is consistent with the previous studies examining the effects of short-term SS (Sato et al., 2020; Takeuchi and Nakamura, 2020) and FR interventions (Nakamura et al., 2021a; Sullivan et al., 2013). Previous studies have implicated that changes in stretch tolerance could contribute to the increase in ROM immediately after SS (Chaouachi et al., 2017; Weppler and Magnusson, 2010) and FR intervention (Nakamura et al., 2021a; Nakamura et al., 2021b). Although the detailed mechanism of the increase in ROM is unknown in this study, changes in stretch tolerance could be involved. Interestingly, prior studies have reported that 30-s FR on the ankle plantar flexors did not increase ROM (Nakamura et al., 2021b), but less than 20-s FR on the hamstrings did increase ROM (Sullivan et al., 2013). We investigated the effect of FR on the knee extensors, and 30-s FR intervention significantly increased ROM. Such short-duration interventions of SS or FR are unlikely to provide sufficient stress to promote muscle or myofascial morphological modifications (Behm et al., 2016; Behm and Chaouachi, 2011; Behm et al., 2021; Behm and Wilke, 2019; Konrad and Tilp, 2020). Similarly, SS and FR-induced neurophysiological responses such as muscle spindle disaffiliation need more prolonged interventions, while cutaneous afferent and Hoffman (H) reflex inhibition and another stretch, pressure, or force-sensitive reflex effects can diminish within seconds of their application (Behm et al., 2021). Also, a previous study showed that there was no significant change in the shear elastic modulus of the knee extensor after 60-s SS intervention (Takeuchi et al., 2021). Hence, these results suggest that short-term SS and FR intervention increases ROM primarily through changes in stretch tolerance, but the effects of short-term SS and FR intervention might vary by muscle. Interestingly, increasing SS or FR duration from 30-s to 60-s or combining short-term SS and FR interventions did not induce a further increase in ROM. Therefore, considering time efficiency, a 30-s SS or FR intervention was recommended as a warm-up routine to increase ROM.

In addition, PPT was significantly increased in all conditions in this study. As described above, SS and FR could alter stretch tolerance (Chaouachi et al., 2017; Nakamura et al., 2021b; Weppler and Magnusson, 2010). The detailed mechanism of the significant increase in PPT in this study is unknown, but it may involve changes in pain perception due to SS and FR interventions. Behm and colleagues (Behm et al., 2016; Behm and Chaouachi, 2011) have suggested that hypoalgesic responses could arise from the Gate Control (Melzack and Wall, 1965) and the diffuse noxious inhibitory control (Mense, 2000) theories of pain inhibition. Therefore, it is possible that SS and FR interventions could increase PPT as well as change in stretch tolerance. Also, the results suggest that even short-term SS and FR interventions can alter pain perception. In addition, tissue hardness significantly reduced in all conditions in this study. Previous studies showed the muscle stiffness of medial gastrocnemius muscle significantly decreased immediately after 120-s SS (Nakamura et al., 2014; Nakamura et al., 2015; Nakamura et al., 2021c). Also, the previous study showed no significant change in shear modulus of knee extensor after 60-s SS intervention (Takeuchi et al., 2021). Hotfiel et al. (2017) also showed increased tissue perfusion and decreased tissue stiffness immediately after FR intervention (Hotfiel et al., 2017). Tissue hardness could reflect changes in subcutaneous tissues, aponeurosis, and muscles, and could be a different index from shear modulus and muscle stiffness. In the present study, tissue hardness decreased in all conditions, suggesting that similar effects can be obtained in short-term SS and FR interventions.

The results of this study showed that MVC-ISO torque was significantly decreased (small magnitude effect size) in both 60-s SS and 30-s SS conditions, while no significant change was observed in the 30-s SS+30-s FR, 60-s FR, and 30-s FR conditions. Previous studies showed that FR interventions have at least no adverse effects on performance (Cheatham et al., 2015; Wiewelhove et al., 2019). The results of this study extended these findings and showed that short-term FR interventions of 30-s or 60-s have no negative effects on muscle strength. Conversely, previous studies concluded that longer than 60-s SS interventions could induce impairments in muscle strength and performance, such as stretching-induced force deficits (Behm et al., 2016; Behm and Chaouachi, 2011; Kay and Blazevich, 2012). Possible mechanisms of stretching-induced force deficits might include changes in sustained or persistent inward currents to motoneurons (Behm et al., 2021) and decreased efficiency of force transmission to skeletal muscles due to decreased stiffness of muscle-tendon units (Huijing, 1999). Behm and Chaouachi (2011) also concluded that short stretching times during the warm-up might not negatively affect subsequent performance, especially in highly trained populations, if the total stretching time per muscle is 30-s or less (Behm and Chaouachi, 2011). However, the results of this study showed that the MVC-ISO torque significantly decreased after 30-s SS intervention. Subjects in this study were active male university students but not consistently highly trained. Whereas MVC-ISO was significantly decreased in the 60-s SS and 30-s SS conditions, no significant change in MVC-ISO torque was observed in the 30-s SS+30-s FR condition, in which 30-s SS intervention was followed by 30-s FR intervention. The previous study suggested that FR intervention after SS intervention restores the excitability of motoneurons produced by SS intervention, resulting in recovery from decrease in muscle strength (Nakamura et al., 2023). Therefore, it is possible that no change in MVC-ISO was observed in 30-s SS+30-s FR condition in this study.

Interestingly, MVC-CON torque did not significantly change under all conditions. As described above, FR has no adverse effect on performance (Cheatham et al., 2015; Wiewelhove et al., 2019), in accordance with the lack of impairments MVC-CON and MVC-ISO in the present study. Additionally, Sato et al. (2020) showed no significant change in MVC-CON torque after 20-s of SS for the ankle plantar flexors. Also, the previous study showed that MVC-CON is less likely to cause a decrease in strength after SS intervention than MVC-ISO (Behm et al., 2016). Thus, our results suggested that short-term SS has no adverse effect on the isokinetic contraction torque.

In practical implications, as a pre-exercise warm-up, short-term, i.e., 30-s FR intervention is recommended when the goal is to increase ROM while maintaining muscle strength. Similarly, a short-term FR intervention after a short-term SS can eliminate the effect of strength impairments. Also, we recommended that athletes and coaches should avoid warm-ups employing only SS, since decrements may accompany increases in ROM in muscle strength.

There were some limitations of this study. In this study, we investigated only the acute effect of SS and FR intervention, and the sustained effect is unknown. The subjects of this study were not athletes; therefore, future studies are needed to investigate the short-term FR and SS effects on athletes, including the sustained effects, to establish an effective warm-up routine. Knee flexion ROM was performed by a physical therapist, and measurements were taken while the hip joint was in the neutral position. However, no equipment or measurement method was used to objectively prove that the hip joint was in the neutral position. The tissue hardness measurements in this study were evaluated from above the skin, so it is unclear whether the obtained tissue hardness data reflect changes in subcutaneous tissues, tendon membranes, or muscles. There were no significant differences in all PRE variables among the five conditions, but PPT and tissue hardness measurements were not so highly reliable. Therefore, it is necessary to clarify the data by shear wave elastography in future studies.

Conclusion

This study revealed that short-term SS, FR, and SS+FR interventions significantly increased ROM, PPT, and decreased tissue hardness. In addition, the results revealed that SS for more than 30-s decreased isometric muscle strength. FR intervention is recommended when the goal is to increase ROM without decreasing MVC-ISO torque. strength. Additionally, it was suggested that a short-term FR after a short-term SS may help the participant recover from a decrease in muscle strength.

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References

Anderson, B.L., Harter, R.A. and Farnsworth, J.L. (2020) The Acute Effects of Foam Rolling and Dynamic Stretching on Athletic Performance: A Critically Appraised Topic. *Journal of Sport Rehabilitation* **30,** 501-506. https://doi.org/10.1123/jsr.2020-0059

Behm, D.G., Alizadeh, S., Hadjizadeh Anvar, S., Mahmoud, M.M.I., Ramsay, E., Hanlon, C. and Cheatham, S. (2020) Foam Rolling Prescription: A Clinical Commentary. *The Journal of Strength & Conditioning Research* **34,** 3301-3308. https://doi.org/10.1519/JSC.0000000000003765

Behm, D.G., Blazevich, A.J., Kay, A.D. and McHugh, M. (2016) Acute effects of muscle stretching on physical performance, range of motion, and injury incidence in healthy active individuals: a systematic review. *Applied Physiology, Nutrition, and Metabolism* **41,** 1-11. https://doi.org/10.1139/apnm-2015-0235

Behm, D.G. and Chaouachi, A. (2011) A review of the acute effects of static and dynamic stretching on performance. *European Journal of Applied Physiology* **111,** 2633-2651. https://doi.org/10.1007/s00421-011-1879-2

Behm, D.G., Kay, A.D., Trajano, G.S. and Blazevich, A.J. (2021) Mechanisms underlying performance impairments following prolonged static stretching without a comprehensive warm-up. *European Journal of Applied Physiology* **121,** 67-94. https://doi.org/10.1007/s00421-020-04538-8

Behm, D.G. and Wilke, J. (2019) Do Self-Myofascial Release Devices Release Myofascia? Rolling Mechanisms: A Narrative Review. *Sports Medicine* **49,** 1173-1181. https://doi.org/10.1007/s40279-019-01149-y

Chaouachi, A., Padulo, J., Kasmi, S., Othmen, A.B., Chatra, M. and Behm, D.G. (2017) Unilateral static and dynamic hamstrings stretching increases contralateral hip flexion range of motion. *Clinical Physiology and Functional Imaging* **37,** 23-29. https://doi.org/10.1111/cpf.12263

Cheatham, S.W., Kolber, M.J., Cain, M. and Lee, M. (2015) The effects of self-myofascial release using a foam roll or roller massager on joint range of motion, muscle recovery, and performance: a systematic review. *International Journal of Sports Physical Therapy* **10,** 827-838.

Cohen, J. (1988). Statistical power analysis for the behavioral sciences., Hillsdale, Routledge.

Duehring, M.D., Feldmann, C.R. and Ebben, W.P. (2009) Strength and conditioning practices of United States high school strength and conditioning coaches. *The Journal of Strength & Conditioning*

Research **23,** 2188-2203. https://doi.org/10.1519/JSC.0b013e3181bac62d

Hotfiel, T., Swoboda, B., Krinner, S., Grim, C., Engelhardt, M., Uder, M. and Heiss, R.U. (2017) Acute Effects of Lateral Thigh Foam Rolling on Arterial Tissue Perfusion Determined by Spectral Doppler and Power Doppler Ultrasound. *The Journal of Strength & Conditioning Research* **31,** 893-900. https://doi.org/10.1519/JSC.0000000000001641

Hsu, F.Y., Tsai, K.L., Lee, C.L., Chang, W.D. and Chang, N.J. (2020) Effects of Dynamic Stretching Combined With Static Stretching, Foam Rolling, or Vibration Rolling as a Warm-Up Exercise on Athletic Performance in Elite Table Tennis Players. *Journal of Sport Rehabilitation* **30,** 198-205. https://doi.org/10.1123/jsr.2019-0442

Huijing, P.A. (1999) Muscle as a collagen fiber reinforced composite: a review of force transmission in muscle and whole limb. *Journal of Biomechanics* **32,** 329-345. https://doi.org/10.1016/S0021-9290(98)00186-9

Kay, A.D. and Blazevich, A.J. (2012) Effect of acute static stretch on maximal muscle performance: a systematic review. *Medicine & Science in Sports & Exercise* **44,** 154-164. https://doi.org/10.1249/MSS.0b013e318225cb27

Konrad, A., Nakamura, M., Paternoster, F.K., Tilp, M. and Behm, D.G. (2022) A comparison of a single bout of stretching or foam rolling on range of motion in healthy adults. *European Journal of Applied Physiology* **122**, 1545-1557. https://doi.org/10.1007/s00421-022-04927-1

Konrad, A., Stafilidis, S. and Tilp, M. (2017) Effects of acute static, ballistic, and PNF stretching exercise on the muscle and tendon tissue properties. *Scandinavian Journal of Medicine & Science in Sports* **27,** 1070-1080. https://doi.org/10.1111/sms.12725

Konrad, A. and Tilp, M. (2020) The acute time course of muscle and tendon tissue changes following one minute of static stretching. *Current Issues in Sport Science (CISS)* **5,** 003. https://doi.org/10.15203/CISS_2020.003

Konrad, A., Tilp, M. and Nakamura, M. (2021) A Comparison of the Effects of Foam Rolling and Stretching on Physical Performance. A Systematic Review and Meta-Analysis. *Frontiers in Physiology* **12,** 720531. https://doi.org/10.3389/fphys.2021.720531

Melzack, R. and Wall, P.D. (1965) Pain mechanisms: a new theory. *Science* **150,** 971-979. https://doi.org/10.1126/science.150.3699.971

Mense, S. (2000) Neurobiological concepts of fibromyalgia--the possible role of descending spinal tracts. *Scandinavian Journal of Rheumatology* **113,** 24-29. https://doi.org/10.1080/030097400446599

Nakamura, M., Ikezoe, T., Kobayashi, T., Umegaki, H., Takeno, Y., Nishishita, S. and Ichihashi, N. (2014) Acute effects of static stretching on muscle hardness of the medial gastrocnemius muscle belly in humans: an ultrasonic shear-wave elastography study. *Ultrasound in Medicine and Biology* **40,** 1991-1997. https://doi.org/10.1016/j.ultrasmedbio.2014.03.024

Nakamura, M., Ikezoe, T., Takeno, Y. and Ichihashi, N. (2011) Acute and prolonged effect of static stretching on the passive stiffness of the human gastrocnemius muscle tendon unit in vivo. *Journal of Orthopaedic Research* **29,** 1759-1763. https://doi.org/10.1002/jor.21445

Nakamura, M., Ikezoe, T., Tokugawa, T. and Ichihashi, N. (2015) Acute Effects of Stretching on Passive Properties of Human Gastrocnemius Muscle-Tendon Unit: Analysis of Differences Between Hold-Relax and Static Stretching. *Journal of Sport Rehabilitation* **24,** 286-292. https://doi.org/10.1123/jsr.2014-0164

Nakamura, M., Konrad, A., Kasahara, K., Yoshida, R., Murakami, Y., Sato, S., Aizawa, K., Koizumi, R. and Wilke, J. (2023) 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. *The Journal of Strength & Conditioning Research* **37,** 322-327. https://doi.org/10.1519/JSC.0000000000004263

Nakamura, M., Konrad, A., Kiyono, R., Sato, S., Yahata, K., Yoshida, R., Yasaka, K., Murakami, Y., Sanuki, F. and Wilke, J. (2021a) Local and Non-local Effects of Foam Rolling on Passive Soft Tissue Properties and Spinal Excitability. *Frontiers in Physiology* **12,** 702042. https://doi.org/10.3389/fphys.2021.702042

Nakamura, M., Onuma, R., Kiyono, R., Yasaka, K., Sato, S., Yahata, K., Fukaya, T. and Konrad, A. (2021b) The Acute and Prolonged Effects of Different Durations of Foam Rolling on Range of Motion, Muscle Stiffness, and Muscle Strength. *Journal of Sports Science and Medicine* **20,** 62-68. https://doi.org/10.52082/jssm.2021.62

Nakamura, M., Sato, S., Kiyono, R., Yahata, K., Yoshida, R., Fukaya, T. and Konrad, A. (2021c) Comparison of the Acute Effects of Hold-Relax and Static Stretching among Older Adults. *Biology (Basel)* **10**. https://doi.org/10.3390/biology10020126

Nakamura, M., Yasaka, K., Kiyono, R., Onuma, R., Yahata, K., Sato, S. and Konrad, A. (2020) The Acute Effect of Foam Rolling on Eccentrically-Induced Muscle Damage. *International Journal of Environmental Research and Public Health* **18**, 75. https://doi.org/10.3390/ijerph18010075

Sato, S., Kiyono, R., Takahashi, N., Yoshida, T., Takeuchi, K. and Nakamura, M. (2020) The acute and prolonged effects of 20-s static stretching on muscle strength and shear elastic modulus. *Plos One* **15,** e0228583. https://doi.org/10.1371/journal.pone.0228583

Sawada, T., Okawara, H., Nakashima, D., Iwabuchi, S., Matsumoto, M., Nakamura, M. and Nagura, T. (2020) Reliability of Trapezius Muscle Hardness Measurement: A Comparison between Portable Muscle Hardness Meter and Ultrasound Strain Elastography. *Sensors (Basel)* **20**. https://doi.org/10.3390/s20247200

Sullivan, K.M., Silvey, D.B., Button, D.C. and Behm, D.G. (2013) Roller-massager application to the hamstrings increases sit-and-reach range of motion within five to ten seconds without performance impairments. *International Journal of Sports Physical Therapy* **8,** 228-236.

Takeuchi, K. and Nakamura, M. (2020) Influence of High Intensity 20-Second Static Stretching on the Flexibility and Strength of Hamstrings. *Journal of Sports Science and Medicine* **19,** 429-435. https://pubmed.ncbi.nlm.nih.gov/32390737/

Takeuchi, K., Sato, S., Kiyono, R., Yahata, K., Murakami, Y., Sanuki, F., Yoshida, R. and Nakamura, M. (2021) High-Intensity Static Stretching in Quadriceps Is Affected More by Its Intensity Than Its Duration. *Frontiers in Physiology* **12,** 709655. https://doi.org/10.3389/fphys.2021.709655

Thomas, E., Bianco, A., Paoli, A. and Palma, A. (2018) The Relation Between Stretching Typology and Stretching Duration: The Effects on Range of Motion. *International Journal of Sports Physical Therapy* **39,** 243-254. https://doi.org/10.1055/s-0044-101146

Weppler, C.H. and Magnusson, S.P. (2010) Increasing muscle extensibility: a matter of increasing length or modifying sensation? *Physical Therapy* **90,** 438-449.
, https://doi.org/10.2522/ptj.20090012

Wiewelhove, T., Döweling, A., Schneider, C., Hottenrott, L., Meyer, T., Kellmann, M., Pfeiffer, M. and Ferrauti, A. (2019) A Meta-Analysis of the Effects of Foam Rolling on Performance and Recovery. *Frontiers in Physiology* **10,** 376. https://doi.org/10.3389/fphys.2019.00376

Wilke, J., Müller, A.L., Giesche, F., Power, G., Ahmedi, H. and Behm, D.G. (2020) Acute Effects of Foam Rolling on Range of Motion in Healthy Adults: A Systematic Review with Multilevel Meta-analysis. *Sports Medicine* **50,** 387-402. https://doi.org/10.1007/s40279-019-01205-7

Key points

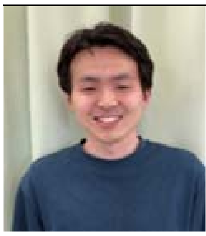
- We investigated the compare and examine the effects of short-term static stretching (SS), foam rolling (FR), and SS+FR on knee extensors.
- Five conditions were randomized: 60-s SS, 60-s FR, 30-s SS+ 30-s FR, 30-s SS, and 30-s FR to examine differences in intervention method, duration, and combined.
- The measures were knee flexion range of motion (ROM), pain pressure threshold (PPT), tissue hardness, maximum voluntary contraction-isometric (MVC-ISO), and MVC-concentric (MVC-CON) torques, measured before and after the intervention.
- Short-term FR intervention is recommended when the goal is to increase ROM while maintaining MVC-ISO and MVC-CON torques.
- Similarly, a short-term FR intervention after a short-term SS can eliminate the effect of MVC-ISO torque impairments.

AUTHOR BIOGRAPHY

Kazuki KASAHARA
Employment
Institute for Human Movement and Medical Sciences, Niigata University of Health and Welfare, Niigata, Niigata, Japan
Degree
BSc, MSc student
Research interests
Physical therapy, foam rolling, stretching, performance, muscle strength
E-mail: hpm22005@nuhw.ac.jp

Andreas KONRAD
Employment
Institute of Human Movement Science, Sport and Health, Graz University
Degree
PhD, MSc
Research interests
Biomechanics, muscle performance, training science, muscle-tendon-unit, soccer science
E-mail: andreas.konrad@uni-graz.at

Riku YOSHIDA
Employment
Institute for Human Movement and Medical Sciences, Niigata University of Health and Welfare, Niigata, Niigata, Japan
Degree
BSc, MSc
Research interests
Physical therapy, resistance training, eccentric contraction
E-mail: hpm21017@nuhw.ac.jp



Yuta MURAKAMI
Employment
Institute for Human Movement and Medical Sciences, Niigata University of Health and Welfare, Niigata, Niigata, Japan
Degree
BSc, MSc student
Research interests
Physical therapy, stretching, muscle stiffness, stretch tolerance
E-mail: hpm22003@nuhw.ac.jp

Ryoma KOIZUMI
Employment
Department of Physical Therapy, Faculty of Rehabilitation, Niigata University of Health and Welfare, Niigata, Niigata, Japan
Degree
BSc
Research interests
Physical therapy, muscle strength, resistance training
E-mail: rpa19033@nuhw.ac.jp

Shigeru SATO
Employment
Institute for Human Movement and Medical Sciences, Niigata University of Health and Welfare, Niigata, Niigata, Japan
Degree
PhD
Research interests
Physical therapy, stretching, resistance training, cross-education effect
E-mail: hpm19006@nuhw.ac.jp

David G. BEHM
Employment
University Research Professor
Degree
PhD
Research interests
Neuromuscular responses to activity
E-mail: dbehm@mun.ca

Masatoshi NAKAMURA
Employment
Associate professor, Faculty of Rehabilitation Sciences, Nishi Kyushu University, Saga, Japan
Degree
PhD
Research interests
Physical therapy, stretching, exercise physiology, flexibility
E-mail: nakamuramas@nisikyu-u.ac.jp

✉ **Masatoshi Nakamura**
Faculty of Rehabilitation Sciences, Nishi Kyushu University, 4490-9 Ozaki, Kanzaki, Saga, 842-8585, Japan