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Research article

Comparison of the Prolonged Effects of Foam Rolling and Vibration Foam Rolling Interventions on Passive Properties of Knee Extensors

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Abstract

Foam rolling (FR) and vibration foam rolling (VFR) interventions have received attention as pre-exercise warm-ups because they maintain performance and increase range of motion (ROM). However, the immediate and prolonged effects and the comparisons between FR and VFR interventions are unknown. Therefore, this study was designed to compare the effects of FR and VFR interventions on passive properties of knee extensors over time (up to 30 min after interventions). A crossover, random allocation design was used with 14 male college students (22.1 ± 1.0 years old) in the control, FR, and VFR conditions. The knee flexion ROM, pain pressure threshold (PPT), and tissue hardness were measured before and immediately after, 10, 20, and 30 minutes after the intervention. The results showed that knee flexion ROM increased significantly immediately after the intervention in both the FR and VFR conditions and maintained up to 30 minutes after both conditions. PPT increased significantly ($p < 0.01$) immediately after the FR intervention. In the VFR condition, there was a significant increase in PPT immediately after the intervention ($p < 0.01$) and 10 minutes after the intervention ($p < 0.05$). Tissue hardness was significantly decreased ($p < 0.01$) immediately after and 10 minutes after the FR intervention. However, tissue hardness in the VFR condition was significantly decreased ($p < 0.01$) up to 30 minutes after the intervention. The results suggest that FR and VFR interventions increase knee flexion ROM, and the effect lasts at least 30 minutes, but the effects on PPT and tissue hardness are maintained a longer time in the VFR condition compared to the FR condition. Therefore, VFR can be recommended as a warm-up before exercise to change the passive properties of knee extensors.

Key words: Range of motion, warm-up routine, pain pressure threshold, tissue hardness.

Introduction

Enhancing flexibility is crucial for both rehabilitation and athletics. Foam Rolling (FR) has recently attracted attention as an intervention method to improve flexibility. An acute bout of FR can increase a joint's range of motion (ROM) (Behm et al., 2020; Konrad et al., 2022b; Wilke et al., 2020). In addition, a single FR intervention has no negative impact on performance (Cheatham et al., 2015; Wiewelhove et al., 2019). Therefore, it has been suggested that an FR intervention can be an effective warm-up method (Wiewelhove et al., 2019). In addition, the effects of a vibration foam roller (VFR) intervention, in which a Foam Roller is equipped with a vibration function, have been investigated in recent years. A meta-analysis examining the effect of VFR intervention on ROM reported a greater improvement in ROM in the hip and knee joints with VFR intervention compared to FR intervention (Park et al., 2021). A previous study showed a significantly higher hip extension ROM increase in the VFR intervention group compared to the FR intervention group (Reiner et al., 2021). Furthermore, a meta-analysis by Alenso-Calvete et al. concluded that VFR intervention might improve jumping performance, agility, and muscle strength, although they found no significant differences aside from recovery (Alonso-Calvete et al., 2022). These findings suggest that VFR is more effective than FR intervention in increasing ROM and may improve performance, and further application of VFR in sports and rehabilitation is desirable.

However, when FR or VFR intervention is used as a warm-up method in the sports field, it is likely that sporting events are rarely performed immediately after the intervention. Therefore, investigating the prolonged effects of FR and VFR interventions is necessary. In a previous study investigating the prolonged effects of different FR intervention durations on the ankle plantar flexors (Nakamura et al., 2021b), 30 seconds of FR intervention showed no immediate change in ankle dorsiflexion ROM as well as over time (i.e., 30 min after the intervention). The group that received 3x30s (total 90 seconds) interventions and the group that received 10x30s (total 300 seconds) intervention showed a significant increase in dorsiflexion ROM at 2 min post-intervention. However, after 30 minutes, the dorsiflexion ROM was returned to the baseline value in both groups. On the other hand, in a previous study investigating the prolonged effects of two different frequencies of VFR intervention on knee extensors (Nakamura et al., 2022a), the results showed that knee flexion ROM increased significantly compared to PRE values regardless of frequency and the increase in knee flexion ROM was sustained until 20 minutes. Thus, VFR intervention might have a greater prolonged effect than FR intervention, or the effects are muscle/joint specific. To our knowledge, so far, no studies have compared the prolonged effects of FR and VFR interventions. FR and VFR inter-

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ventions have recently attracted attention in sports and rehabilitation settings (Ikutomo et al., 2022; Konrad et al., 2022a). Therefore, it is essential for athletes, coaches, and rehabilitation settings to examine the effects of FR and VFR interventions over time.

Therefore, this study was designed to compare and examine the effects of FR and VFR interventions on knee extensors over time. Our hypothesis in this study was that the effect would be sustained in the VFR group compared to the FR group, in accordance with our previous study (Nakamura et al., 2022a).

Methods

Experimental set-up

The study was conducted in a randomized, repeated-measures controlled experiment. Participants were instructed to come to the laboratory three times with an interval of at least ≥ 48 hours. Participants were exposed to three conditions: FR, VFR, and Control (Figure 1). FR and VFR were performed three times for 60 seconds each on the dominant leg. The rest between sets was 30 seconds. The control condition was 300 seconds of rest in order to match the time of FR or VFR intervention. Outcomes were measured in each condition before (PRE), immediately after (POST), 10, 20, and 30 minutes after the intervention. Knee flexion ROM, pain pressure threshold (PPT), and tissue hardness were measured in the knee extensors on the dominant side.

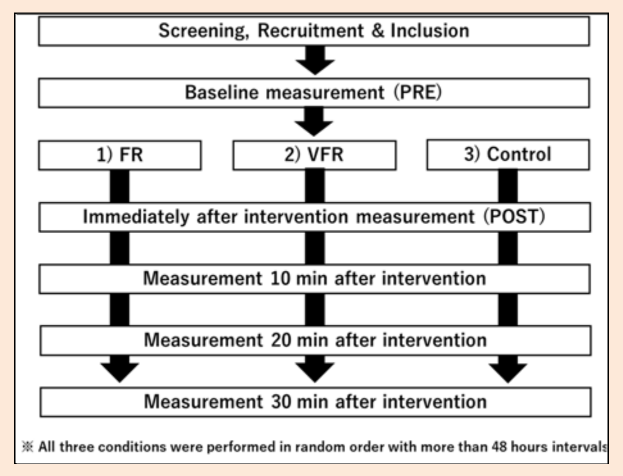

Figure 1. The Experimental set-up. FR: foam rolling, VFR: vibration foam rolling.

Participants

Fourteen healthy, recreationally active males were enrolled (mean ± SD: age, 22.1 ± 1.0 years; height, 170.4 ± 5.9 cm; weight, 68.3 ± 10.0 kg). Individuals with a history of neuromuscular disease and musculoskeletal injury involving the lower extremities were excluded. The required sample size for a repeated-measures two-way analysis of variance (ANOVA) (effect size = 0.25 [large when considering interaction effects for 2-way ANOVAs], α error = 0.05, and power = 0.95) based on our previous study's ROM results (Nakamura et al., 2022b) using G* power 3.1 software (Heinrich Heine University, Dusseldorf, Germany) was more than 10 participants.

For the study, participants 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).

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). A licensed physical therapist (i.e., the investigator) 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. Knee flexion ROM was measured three times in each measurement period, and the average value at each measurement period 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 noted from the device at this time point (kilograms per square centimeter) corresponded to the PPT. In each condition, PPT was measured three times at each measurement period, and the mean value at each measurement period was used for further analysis.

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 was measured three times at each measurement, and the mean value at each measurement period was used for further analysis.

Foam Rolling (FR), and Vibration Foam Rolling (VFR) intervention

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. The participants performed three 60-s bouts of FR or VFR with a 30-s rest between sets. 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 30 cycles per 60s (90 cycles in three sets) and controlled using a metronome (Smart Metronome; Tomohiro Ihara, Japan). This procedure followed the recommendations from a previous study to maximize the increase in ROM (Behm et al., 2020). The participants were asked to place as much body mass on the roller as tolerable.

Statistical analysis

SPSS (version 24.0, SPSS Japan Inc., Tokyo, Japan) was used for the statistical analysis. To verify the consistency of PRE values, PRE values were tested among all conditions using a one-way ANOVA. For all the variables, a two-way repeated-measures ANOVA using two factors (test time [PRE vs. POST vs. 10 min vs. 20 min vs. 30 min] and conditions [FR vs. VFR vs. control]) was used to analyze the interaction and main effects. Classification of effect size (ES) was set where $\eta_p^2 < 0.01$ was considered small, 0.02 – 0.1 was considered medium, and more than 0.1 was considered to be a large effect size (Cohen, 1988; Kasahara et al., 2022).Where appropriate, post hoc analyses were performed using multiple comparison tests with Bonferroni correction to determine differences between PRE, POST, 10, 20, and 30 minutes. Additionally, we calculated the Cohen's d ES as differences in the mean value divided by the pooled SD between pre and post-intervention in each condition, an ES of 0.00 - 0.19 was considered as trivial, 0.20 - 0.49 as small, 0.50 - 0.79 as moderate, and ≥0.80 as large (Cohen, 1988). The significance level was set to 5%, and all the results are shown as mean ± SD.

Results

Comparison between PRE values among the three conditions

There were no significant differences in all PRE variables among the three conditions and, thus, did not yield indications of a baseline difference.

Changes in knee flexion ROM, PPT, and tissue hardness

Table 1 shows the changes in knee flexion ROM, PPT, and tissue hardness before and after interventions. The two-way repeated-measures ANOVA indicated significant interactions for all the variables (ROM: $F = 13.4$, $p < 0.01$, $\eta_p^2 = 0.41$, PPT: $F = 2.7$, $p < 0.01$, $\eta_p^2 = 0.12$, tissue hardness: $F = 4.9$, $p < 0.01$, $\eta_p^2 = 0.19$). In addition, there were main effects for time for all the variables (ROM: $F = 68.0$, $p < 0.01$, $\eta_p^2 = 0.64$, PPT: $F = 8.9$, $p < 0.01$, $\eta_p^2 = 0.19$, tissue hardness: $F = 16.1$, $p < 0.01$, $\eta_p^2 = 0.29$).

The post-hoc test results showed a significant increase ($p < 0.01$) in ROM compared to PRE in both FR and VFR conditions at POST, 10 min, 20 min, and 30 min post-intervention, respectively. However, compared to POST values, ROM significantly decreases ($p < 0.01$) at 10, 20, and 30 minutes post-intervention in both FR and VFR conditions. Furthermore, the FR condition showed a significant decrease ($p < 0.01$) only at 30 minutes compared to the value at 10 minutes, while the VFR condition showed a significant decrease ($p < 0.01$) at 20 and 30 minutes. Only the FR condition showed a significant decrease ($p < 0.01$) at 30 minutes compared to the value at 20 minutes.

In the PPT, the FR condition showed a significant increase ($p < 0.01$) at POST compared to the PRE value, and the VFR condition showed a significant increase ($p < 0.01$) at POST and after 10 minutes after the intervention. In the FR condition, PPT decreased significantly ($p < 0.01$) at 20 and 30 minutes compared to the POST value. In tissue hardness, the FR condition showed a significant decrease ($p < 0.01$) at POST and after 10 min compared to the PRE value, and the VFR condition showed a significant decrease ($p < 0.01$) at POST, after 10 min, after 20 min, and after 30 min compared to the PRE value. In the FR condition only, the PRE value significantly increased at 30 minutes compared to the POST value ($p < 0.01$). In the control condition, there were no significant changes in all variables.

Discussion

The results showed that both FR and VFR interventions could increase knee flexion ROM significantly up to 30 minutes after the intervention. On the other hand, the changes in PPT and tissue hardness after VFR intervention were sustained longer than FR intervention. The results of this study suggest that both FR and VFR interventions may be recommended for increasing ROM as a pre-exercise warm-up. However, VFR intervention is recommended rather than FR intervention if the goal is to sustain the changes in PPT and tissue hardness longer. When FR intervention is performed as a warm-up in a sports field, there are likely few competitive events in which the athlete must perform immediately after the warm-up. Therefore, information about the prolonged effect of FR and VFR intervention is essential for athletes, coaches, and physical therapists. To the best of our knowledge, this is the first study to compare the prolonged effect of FR and VFR on the passive properties of knee extensors.

The results showed that FR and VFR interventions could increase knee flexion ROM, which is consistent with some previous studies (Behm et al., 2020; Kasahara et al., 2022; Konrad et al., 2022a; Nakamura et al., 2022a). These studies have suggested that the increase in ROM with FR and VFR interventions may involve changes in stretch tolerance (Behm and Wilke, 2019; Konrad et al., 2022a; Nakamura et al., 2021a; Nakamura et al., 2021b). Also, PPT was significantly increased after FR and VFR intervention in this study. Taken together, the detailed mechanism of the increase in knee flexion ROM in this study is unknown, but we believe that changes in stretch tolerance due to FR and VFR interventions could be involved in the increase in knee flexion ROM. Interestingly, our results showed that FR and VFR interventions could increase knee flexion ROM for up to 30 minutes, which is inconsistent with the previous study (Nakamura et al., 2021b), showing that dorsiflexion ROM returned to baseline 30 minutes

Table 1. The changes in knee flexion range of motion (ROM), pain pressure threshold, and tissue hardness before and after control, Foam Rolling, and Vibration Foam Rolling intervention, 10 minutes after intervention, 20 minutes after intervention, and 30 minutes after intervention, as mean ± SD. The two-way ANOVA results (T: time effect, C x T: condition x time interaction effect; F-value) and partial η2 (η_p^2) are shown in the right column.

	Control					Foam Rolling					Vibration Foam Rolling					ANOVA results
	PRE	POST	10min	20min	30min	PRE	POST	10min	20min	30min	PRE	POST	10min	20min	30min	P value, F value, η_p^2
Knee Flexion ROM (degrees)	139.5± 3.7	139.7± 3.6	139.8± 3.6	139.7± 3.7	139.7± 3.8	138.5± 3.3	141.5± 4.2*	140.8± 4.1*†	140.3± 4.1*†	139.7± 4.2 *†‡§	140.1± 3.5	143.1± 4.1*	142.5± 3.9 *†	141.9± 3.8 *†‡	141.5± 3.9 *†‡	T: F=68.0, p<0.01, η_p^2=0.64 CxT: F=13.4, p <0.01, η_p^2=0.41
	d=	0.05	0.08	0.06	0.04	d=	0.80	0.63	0.48	0.33	d=	0.77	0.64	0.47	0.37	
PPT (kg)	4.16± 1.4	4.18± 1.4	4.10 ± 1.4	4.08 ± 1.5	4.12 ± 1.7	4.04 ± 1.2	4.78 ± 1.7*	4.31 ± 1.3	4.15 ± 1.4†	4.05 ± 1.2†	4.25 ± 1.5	5.02 ± 1.7*	4.84 ± 2.1*	4.60 ± 1.9	4.65 ± 2.0	T:F=8.9, p<0.01, η_p^2=0.19 CxT: F=2.7, p<0.01, η_p^2=0.12
	d=	0.01	-0.04	-0.05	-0.03	d=	0.51	0.21	0.08	0.00	d=	0.48	0.33	0.20	0.23	
Tissue hardness (N)	18.76± 0.6	18.8± 1.9	18.5± 1.9	18.8± 1.6	18.6± 1.7	18.1± 1.9	16.7± 1.6*	16.7± 2.1*	17.2± 2.0	17.5± 2.0†	18.5± 2.4	16.9± 2.3*	16.9± 2.5*	16.8± 2.4*	17.2± 2.2*	T: F=16.1, p<0.01, η_p^2=0.29 CxT: F=4.7, p<0.01, η_p^2=0.19
	d=	0.01	-0.15	0.03	-0.11	d=	-0.78	-0.67	-0.43	-0.29	d=	-0.72	-0.66	-0.73	-0.58	

*: Significant difference from PRE value ($p<0.01$); †: Significant difference from POST value ($p<0.01$); ‡: Significant difference from 10min value ($p<0.01$); §: Significant difference from 20min value ($p<0.01$)

after more than 90 or 300 seconds FR intervention. On the other hand, the results supported and extended the previous study's findings (Nakamura et al., 2022a), showing a significant increase in knee flexion ROM after VFR intervention was sustained for up 20 minutes. Taking all this information together, the prolonged effect of FR and VFR intervention effects might differ depending on the target muscle. Therefore, investigating the effects of different target muscles in FR and VFR interventions is necessary.

The results showed a significant increase in PPT immediately after the intervention in both FR and VFR intervention., and the change in PPT was sustained after 10 minutes after VFR intervention, not FR intervention. Previous studies have shown that mechanical stimulation with FR intervention could reduce pain perception (Weerapong et al., 2005). The vibration stimulation is supposed to produce a more in-depth stimulation of the muscle and myofascial tissue due to a greater contribution of the mechanoreceptors, specifically the interstitial type I and II receptors, which respond to sustained pressure and modulate the sympathetic and parasympathetic activity (Behm and Wilke, 2019; Cheatham and Stull, 2019). Thus, the changes in PPT after VFR intervention could be sustained longer than FR intervention.

Furthermore, the results revealed that FR intervention significantly decreased tissue hardness immediately after the intervention and up to 10 minutes after the intervention. Conversely, VFR intervention significantly decreased this hardness up to 30 minutes after intervention. A previous study reported increased tissue perfusion and decreased tissue stiffness after FR intervention (Hotfiel et al., 2017). In addition, FR and VFR interventions might induce thixotropic changes in intramuscular hyaluronan and alter muscle viscoelasticity (Behm and Wilke, 2019). As described above, vibration stimulation has a greater effect on mechanoreceptors, such as interstitial type I and type II receptors, and may result in deeper stimulation of muscle and fascia (Behm and Wilke, 2019). Thus, the decrease in tissue hardness after VFR intervention could be sustained longer than FR intervention.

This study had some limitations. First, we investigated the prolonged effect of FR and VFR intervention for up to 30 minutes. It is unclear when the knee flexion ROM could return to the baseline value after FR and VFR intervention. A future study is needed to investigate the prolonged effects for a longer duration. Second, the duration of different total intervention times is unknown. This study performed a total of 180 seconds of FR and VFR interventions. However, 180 seconds of FR intervention as a pre-exercise warm-up may be too long, and the duration of the short-term FR intervention is unknown. Therefore, investigating the prolonged effect of shorter-duration FR and VFR intervention is needed in the future.

Conclusion

In this study, we investigated the effects of FR and VFR interventions on knee flexion ROM, PPT, and tissue hardness over time. The results showed that knee flexion ROM increased in FR and VFR intervention groups at least up to 30 minutes after intervention. In addition, the changes in PPT and tissue hardness could be sustained for a longer duration after VFR intervention rather than FR intervention. Therefore, VFR intervention is recommended as a pre-exercise warm-up to increase ROM with changing PPT and tissue hardness.

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References

Alonso-Calvete, A., Lorenzo-Martínez, M., Padrón-Cabo, A., Pérez-Ferreirós, A., Kalén, A., Abelairas-Gómez, C. and Rey, E. (2022) Does Vibration Foam Roller Influence Performance and Recovery? A Systematic Review and Meta-analysis. *Sports Medicine - Open.* https://doi.org/10.1186/s40798-022-00421-2

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. *Journal of Strength & Conditioning Research* **34**, 3301-3308. https://doi.org/10.1519/JSC.0000000000003765

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

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.

Cheatham, S.W. and Stull, K.R. (2019) Roller massage: Comparison of three different surface type pattern foam rollers on passive knee range of motion and pain perception. *Journal of Bodywork and Movement Therapies* **23**, 555-560. https://doi.org/10.1016/j.jbmt.2019.05.002

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

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. *Journal of Strength & Conditioning Research* **31**, 893-900. https://doi.org/10.1519/JSC.0000000000001641

Ikutomo, H., Nagai, K., Tagomori, K., Miura, N., Okamura, K., Okuno, T., Nakagawa, N. and Masuhara, K. (2022) Effects of foam rolling on hip pain in patients with hip osteoarthritis: a retrospective propensity-matched cohort study. *Physiotherapy Theory and Practice* **38**, 995-1002. https://doi.org/10.1080/09593985.2020.1812138

Kasahara, K., Konrad, A., Yoshida, R., Murakami, Y., Sato, S., Aizawa, K., Koizumi, R., Thomas, E. and Nakamura, M. (2022) Comparison between 6-week foam rolling intervention program with and without vibration on rolling and non-rolling sides. *European Journal of Applied Physiology* **122**, 2061-2070. https://doi.org/10.1007/s00421-022-04975-7

Konrad, A., Nakamura, M., Paternoster, F.K., Tilp, M. and Behm, D.G. (2022a) A comparison of a single bout of stretching or foam rolling on range of motion in healthy adults. *European Journal of Applied Physiology* **122(7)**, 1545-1557. https://doi.org/10.1007/s00421-022-04927-1

Konrad, A., Nakamura, M., Tilp, M., Donti, O. and Behm, D.G. (2022b) Foam Rolling Training Effects on Range of Motion: A Systematic Review and Meta-Analysis. *Sports Medicine* **52(10)**, 2523-2535. https://doi.org/10.1007/s40279-022-01699-8

Nakamura, M., Kasahara, K., Yoshida, R., Murakami, Y., Koizumi, R., Sato, S., Takeuchi, K., Nishishita, S., Ye, X. and Konrad, A. (2022a) Comparison of The Effect of High-and Low-Frequency Vibration Foam Rolling on The Quadriceps Muscle. *Journal of Sports Science and Medicine* **21**, 376-382. https://doi.org/10.52082/jssm.2022.376

Nakamura, M., Konrad, A., Kasahara, K., Yoshida, R., Murakami, Y., Sato, S., Aizawa, K., Koizumi, R. and Wilke, J. (2022b) 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. *Journal of Strength & Conditioning Research*. Online ahead of print. 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 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., 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(1)**, 75. https://doi.org/10.3390/ijerph18010075

Park, S.J., Lee, S.I., Jeong, H.J. and Kim, B.G. (2021) Effect of vibration foam rolling on the range of motion in healthy adults: a systematic review and meta-analysis. *Journal of Exercise Rehabilitation* **17**, 226-233. https://doi.org/10.12965/jer.2142322.161

Reiner, M.M., Glashüttner, C., Bernsteiner, D., Tilp, M., Guilhem, G., Morales-Artacho, A. and Konrad, A. (2021) A comparison of foam rolling and vibration foam rolling on the quadriceps muscle function and mechanical properties. *European Journal of Applied Physiology* **121**, 1461-1471. https://doi.org/10.1007/s00421-021-04619-2

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(24)**, 7200. https://doi.org/10.3390/s20247200

Weerapong, P., Hume, P.A. and Kolt, G.S. (2005) The mechanisms of massage and effects on performance, muscle recovery and injury prevention. *Sports Medicine* **35**, 235-256. https://doi.org/10.2165/00007256-200535030-00004

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 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 sustained effects of foam rolling (FR) and vibration foam rolling (VFR) interventions on knee flexion range of motion (ROM), pain pressure threshold, and tissue hardness.
- FR and VFR intervention for 180 seconds increased ROM for at least up to 30 minutes.
- The changes in pain pressure threshold and tissue hardness after VFR intervention were sustained for a longer duration rather than FR intervention.
- VFR intervention could be recommended in sports and rehabilitation settings to increase ROM by changing the pain pressure threshold and tissue hardness.

AUTHOR BIOGRAPHY

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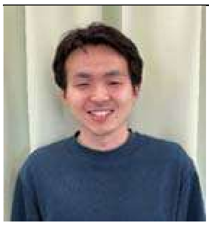

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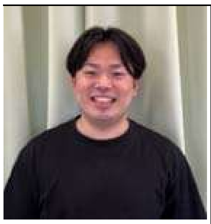

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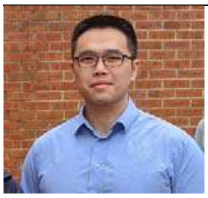

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