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Research article

Comparison of The Effect of High- and Low-Frequency Vibration Foam Rolling on The Quadriceps Muscle

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Abstract

Vibration foam rolling (VFR) intervention has recently gained attention in sports and rehabilitation settings since the superimposed vibration with foam rolling can affect several physiological systems. However, the sustained effect and a comparison of the effects of different VFR vibration frequencies on flexibility and muscle strength have not been examined. Therefore, in this study, we aimed to investigate the acute and sustained effects of three 60-s sets of VFR with different frequencies on knee flexion range of motion (ROM) and muscle strength of the knee extensors. Using a crossover, random allocation design, 16 male university students (21.2 ± 0.6 years) performed under two conditions: VFR with low (35 Hz) and high (67 Hz) frequencies. The acute and sustained effects (20 min after intervention) of VFR on knee flexion ROM, maximum voluntary isometric contraction (MVC-ISO) torque, maximum voluntary concentric contraction (MVC-CON) torque, rate of force development (RFD), and single-leg countermovement jump (CMJ) height were examined. Our results showed that knee flexion ROM increased significantly ($p < 0.01$) immediately after the VFR intervention and remained elevated up to 20 min, regardless of the vibration frequency. MVC-ISO and MVC-CON torque both decreased significantly ($p < 0.01$) immediately after the VFR intervention and remained significantly lowered up to 20 min, regardless of the vibration frequency. However, there were no significant changes in RFD or CMJ height. Our results suggest that VFR can increase knee flexion ROM but induces a decrease in muscle strength up to 20 min after VFR at both high and low frequencies.

Key words: Foam roller, flexibility, maximal voluntary muscle contraction, rate of force development, countermovement jump, prolonged effect.

Introduction

Foam rolling (FR) intervention is now being widely used in sports and rehabilitation settings (Konrad et al., 2022b; Wiewelhove et al., 2019; Wilke et al., 2020). Moreover, it is believed that adding vibration serves as a facilitator for the FR intervention effect. Specifically, it is thought that that the superimposed vibration can affect several physiological systems, such as skin receptors, muscle spindles, ligament proprioceptors, and joint mechanoreceptors (e.g., the Golgi tendon organ) (Moezy et al., 2008). In fact, previous studies have shown that FR with vibration (VFR) can increase joint range of motion (ROM) and decrease muscle stiffness without decreasing muscle strength or jump performance (Nakamura et al., 2021d; 2021e). A recent meta-analysis also suggested that VFR can induce a larger increase in ROM than FR alone; however, there are few previous studies available (Wilke et al., 2020). With regard to the effect of VFR on muscle strength and athletic performance, a meta-analysis concluded that VFR has great potential to improve jump performance, agility, and muscle strength, but there were no significant results among the data currently available (Alonso-Calvete et al., 2022). Although there is still room for further study, it is believed that VFR can be applied safely and effectively in sports and rehabilitation settings.

Rate of force development (RFD) has been widely used for the evaluation of explosive strength (Maffiuletti et al., 2016; Rodríguez-Rosell et al., 2018). Since VFR can affect several physiological systems, VFR may also affect RFD in addition to muscle strength. Furthermore, Andersen and Aagaard (2006) pointed out that RFD is influenced by different physiological factors in the early (less than 100 ms) and late (more than 100 ms) phases of isometric contraction (Andersen and Aagaard, 2006). Through a detailed investigation of the effect of VFR on RFD, it would be possible to investigate the effects of VFR on neuromuscular function in more detail. However, to the best of our knowledge, the effect of VFR on RFD, including both the early and late phases of RFD, is not clear. In addition, Germann et al. (2018) noted that the physiological and neuromuscular responses might differ when different frequencies are applied. To date, previous studies have investigated the effects of VFR on ROM, muscle strength, and jump performance at only one frequency, and it is unclear whether the effects of VFR vary with frequency. Furthermore, examining the sustained effects and comparing the effects of different frequencies of VFR could be useful for athletes and coaches in the fields of sports and rehabilitation. Therefore, in this study, we aimed to investigate the acute and sustained effects of VFR with different frequencies on knee flexion ROM, knee extensor muscle strength, RFD, pain pressure threshold (PPT), and single-leg countermovement jump (CMJ) height. Our previous study

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showed no significant differences between low and high VFR frequencies on the damaged muscle (Kasahara et al., 2022b). Therefore, we hypothesized that there will be no significant difference in acute and sustained effects of VFR with different frequencies.

Methods

Experimental design

A randomized, controlled, crossover experimental design was used to compare the time-course of changes after low-frequency VFR (LF-VFR) and high-frequency VFR (HF-VFR) on knee flexion ROM, PPT, maximum voluntary isometric contraction (MVC-ISO) torque, maximum voluntary concentric contraction (MVC-CON) torque, and CMJ height, for the dominant knee extensor. We measured the outcome variables in this order in all the time periods. The dominant leg was defined as the preferred leg for kicking a ball. All participants visited the laboratory on two occasions (LF-VFR and HF-VFR), with a break interval of >48 h between sessions. All variables were measured before (PRE), immediately after (POST), and 20 min after (20 min), for both the LF-VFR and HF-VFR interventions.

Participants

The sample size required for a two-way repeated-measures analysis of variance (ANOVA) (effect size = 0.25 [medium], α error = 0.05, and power = 0.95) was calculated using G* power 3.1 software (Heinrich Heine University, Düsseldorf, Germany). The required number of participants was found to be more than 15 for this study. The participants enrolled in this study were 16 sedentary healthy young male volunteers (age 21.2 ± 0.6 years; height 1.71 ± 0.4 m; body mass 71.1 ± 11.7 kg) who had not performed habitual exercise activities for at least the past six months before the assessment. Participants who had a history of neuromuscular disease or musculoskeletal injury in the lower extremity were excluded. All subjects were fully informed of the study's procedures and purpose and provided written informed consent. The study was approved by the Ethics Committee of the Niigata University of Health and Welfare, Niigata, Japan (#18561).

Knee flexion range of motion (ROM)

Each participant was placed in a side-lying position with the non-dominant side on a massage bed, and the hip and knee of the non-dominant leg were flexed at 90° to prevent movement of the pelvis during the ROM measurements (Kasahara et al., 2022b; Konrad et al., 2022a; Nakamura et al., 2020b). The investigator brought the dominant leg to full knee flexion, with the hip joint in a neutral position. A goniometer was used to measure the knee flexion ROM twice, and the average value was used for the further analysis.

Maximal voluntary isometric contraction (MVC-ISO) torque and rate of force development (RFD) measurements

MVC-ISO torque was measured at a 90° knee angle using the Biodex System 3.0 (Biodex Medical Systems, Shirley, NY, USA). Each participant was seated in the dynamometer chair at an 80° hip flexion angle, with adjusted Velcro straps fixed over the trunk, pelvis, and thigh of the measured limb. After several warm-up submaximal knee extension contractions, the participant was instructed to perform knee extension as fast and hard as possible and to maintain the maximum effort for about 3 s (Ema et al., 2016). The trials were conducted two times, with a 60-s rest between each trial, and the average value of two MVIC torque measurements was adopted for further analysis. If there was more than a 5% difference between the first two MVC-ISO measurements, a third MVC-ISO measurement was performed. Verbal encouragement was provided during all the tests.

Torque signals were recorded on a computer through an A/D converter operating at 1 kHz (PowerLab16/35, AD Instruments, Australia). Torque signals were low-pass filtered at 15 Hz using a fourth-order zero-phase lag Butterworth filter (Aagaard et al., 2002; Ema et al., 2016; Nakamura et al., 2021c). The onset of knee extension was defined as the torque increasing by two standard deviations (SD) above baseline, and it was ensured that the torque did not fall below baseline throughout the contraction. The RFD was defined as the slope of the filtered time-torque curve over time intervals of 0–50, 0–100, and 0–200 ms from the onset of plantar flexion (Aagaard et al., 2002; Ema et al., 2016; Nakamura et al., 2021c).

Maximal voluntary concentric contraction (MVC-CON) torque measurement

MVC-CON torque was measured at an angular velocity of 60°/s for a ROM of 70° (20–90° knee angles) for three continuous MVC-CONs of knee extension (Kasahara et al., 2022b; Nakamura et al., 2020b). For further analysis, the highest value among the three trials was adopted. Verbal encouragement was provided during all the tests.

Countermovement jump (CMJ) height

CMJ height was calculated from the flight time using a jump mat system (4Assist, Tokyo, Japan). Each participant started with the foot of the dominant leg on the mat, with their hands in front of their chest. From this position, the participant was instructed to dip quickly (eccentric phase), reaching a self-selected depth, and then jump as high as possible in the next concentric phase. The landing phase was performed on two feet. The knee of the uninvolved leg was held at approximately 90° of flexion (Fort-Vanmeerhaeghe et al., 2016). After three familiarization repetitions, three sets of CMJs were performed and measured, and the maximum vertical jump height was used for further analysis.

Pain pressure threshold (PPT)

PPT measurements were carried out using an algometer (NEUTONE TAM-22 (BT10), TRY_ALL, Chiba, Japan), with the participant in a supine position. The measurement position was set at the midpoint of the distance between the anterior superior iliac spine and the upper end of the patella of the dominant side (Kasahara et al., 2022b; Konrad et al., 2022a). With continuously increasing pressure, the metal rod of the algometer was used to compress the soft tissue in the measurement area. The participant was 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 (Kim and Lee, 2018; Naderi et al., 2020), the mean value (kilograms per square centimeter) of three repeated measurements (with a 30-s interval between each measurement) was taken for further analysis.

High- and low-frequency vibration foam rolling interventions

A foam roller (Stretch Roll SR-002, Dream Factory, Umeda, Japan) was used for the VFR intervention. Before the VFR intervention, a physical therapist instructed each participant on how to use the foam roller. For the familiarization, each participant was allowed to practice using the foam roller three to five times on the non-dominant leg (non-intervention leg). The participant performed three sets of 60-s VFR in both conditions, with a 30-s rest between each set. This was conducted in accordance with the recommendations of Behm et al. (2020), to maximize the increase in ROM (Behm et al., 2020). The participant was instructed to get into the plank position, with the foam roller at the most proximal portion of the quadriceps of the dominant leg only. In this study, one cycle of VFR intervention was defined as one distal rolling plus one subsequent proximal rolling movement, whereas the frequency was defined as 30 cycles for every 60-s set (hence a total of 90 cycles in three sets), measured using a metronome (Smart Metronome, Tomohiro Ihara, Japan). One cycle of VFR intervention was defined as between the top of the patella and the anterior superior iliac spine, and was conducted under the direct supervision of the investigator (Kasahara et al., 2022b). The participant was asked to place as much body mass on the roller as was tolerable. The VFR intervention was performed at 35 Hz in the LF-VFR condition and at 67 Hz in the HF-VFR condition (Kasahara et al., 2022b).

Statistical analysis

SPSS (version 24.0, SPSS Japan Inc., Tokyo, Japan) was used for the statistical analysis. The distribution of the data was assessed using a Shapiro-Wilk test, and it was confirmed that the data followed a normal distribution. For all the variables, a two-way repeated-measures ANOVA using two factors (test time [PRE vs. POST vs. 20 min] and conditions [LF-VFR vs. HF-VFR]) 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 (Akiyama et al., 2016; Cohen, 1988; Kasahara et al., 2022b).When appropriate, a post-hoc analysis was conducted using paired t-tests with Bonferroni correction to determine the difference between PRE, POST, and 20 min. Additionally we calculated the ES as differences in the mean value divided by the pooled SD between pre- and post-intervention in each group, 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; Nakamura et al., 2020a). The significance level was set to 5%, and all the results are shown as mean ± SD.

Results

Table 1 lists the knee flexion ROM, MVC-ISO torque, RFD, MVC-CON torque, CMJ height, and PPT changes. The two-way repeated-measures ANOVA indicated no significant interactions for all the variables. However, there were main effects for time for knee flexion ROM (F = 59.3, $p < 0.01$, $\eta_p^2 = 0.809$), MVC-ISO torque (F = 16.5, $p < 0.01$, $\eta_p^2 = 0.541$), MVC-CON torque (F = 8.61, $p < 0.01$, $\eta_p^2 = 0.381$), and PPT (F = 10.8, $p < 0.01$, $\eta_p^2 = 0.437$), but not for RFD (0 - 50 ms: F = 0.16, p = 0.85, $\eta_p^2 = 0.006$; 0 - 100 ms: F = 0.861, p = 0.15, $\eta_p^2 = 0.005$; 0 - 200 ms: F = 0.37, p = 0.37, $\eta_p^2 = 0.012$, respectively).

The post-hoc test revealed that knee flexion ROM increased significantly ($p < 0.01$) and remained significantly elevated up to 20 min. However, knee flexion ROM at 20 min was significantly lower than the POST ROM at 20 min was significantly lower than the POST value.

Table 1. Changes (mean ± SD) in knee flexion range of motion (ROM), maximal voluntary isometric contraction torque of knee extensor (MVC-ISO), rate of force development (RFD) at 0 - 50, 0 - 100, and 0 - 200 ms, maximal voluntary concentric contraction torque (MVC-CON) at 60°/s, counter movement jump (CMJ) height before maximal eccentric contraction task (baseline), pre- and post-vibration foam rolling (VFR) intervention at both low-frequency (LF)- and high-frequency (HF) intervention. The two-way ANOVA results (T: time effect, C x T: condition x time interaction effect; F-value) and partial η^2 (η_p^2) are shown in right column.

	LF-VFR condition			HF-VFR condition			ANOVA results
	PRE	POST	20 min	PRE	POST	20 min	P value, F value, η_p^2
Knee flexion ROM (deg)	131.5 ± 4.5	135.8 ± 5.0	133.7 ± 5.1	130.9 ± 6.6	135.6 ± 5.6	133.6 ± 6.3	T: $p < 0.01$, F = 59.3, $\eta_p^2 = 0.809$ C x T: p = 0.748, F = 0.293, $\eta_p^2 = 0.021$
MVC-ISO (Nm)	198.2 ± 31.2	189.4 ± 32.8	188.8 ± 29.5	199.7 ± 29.5	188.4 ± 33.5	185.8 ± 31.2	T: $p < 0.01$, F = 16.5, $\eta_p^2 = 0.541$ C x T: p = 0.81, F = 0.21, $\eta_p^2 = 0.015$
RFD at 0-50 ms (Nm/ms)	0.44 ± 0.35	0.51 ± 0.31	0.51 ± 0.22	0.39 ± 0.28	0.54 ± 0.34	0.47 ± 0.26	T: p = 0.27, F = 1.33, $\eta_p^2 = 0.044$ C x T: p = 0.85, F = 0.16, $\eta_p^2 = 0.006$
RFD at 0-100 ms (Nm/ms)	0.67 ± 0.30	0.71 ± 0.23	0.79 ± 0.22	0.67 ± 0.27	0.70 ± 0.32	0.71 ± 0.25	T: p = 0.47, F = 0.77, $\eta_p^2 = 0.026$ C x T: p = 0.15, F = 0.861, $\eta_p^2 = 0.005$
RFD at 0-200 ms (Nm/ms)	0.59 ± 0.19	0.63 ± 0.13	0.69 ± 0.12	0.60 ± 0.17	0.60 ± 0.19	0.64 ± 0.11	T: p = 0.19, F = 1.69, $\eta_p^2 = 0.06$ C x T: p = 0.37, F = 0.37, $\eta_p^2 = 0.012$
MVC-CON (Nm)	193.1 ± 31.2	178.6 ± 23.7	175.2 ± 24.4	195.4 ± 32.4	175.3 ± 22.3	172.2 ± 26.1	T: $p < 0.01$, F = 8.61, $\eta_p^2 = 0.381$ C x T: p = 0.38, F = 1.00, $\eta_p^2 = 0.067$
CMJ height (cm)	22.2 ± 3.7	22.4 ± 3.6	22.4 ± 3.1	21.8 ± 3.5	21.9 ± 3.9	21.7 ± 3.4	T: p = 0.298, F = 1.26, $\eta_p^2 = 0.083$ C x T: p = 0.88, F = 0.126, $\eta_p^2 = 0.009$
PPT (kg)	3.5 ± 1.4	4.7 ± 1.9	3.9 ± 1.5	3.3 ± 1.6	4.3 ± 1.7	4.2 ± 2.2	T: $p < 0.01$, F = 10.8, $\eta_p^2 = 0.437$ C x T: p = 0.25, F = 1.45, $\eta_p^2 = 0.094$

ROM at 20 min was significantly lower than the POST value. For MVC-ISO torque and MVC-CON torque, both the POST and 20 min values were significantly ($p < 0.01$) lower than the PRE values, and there were no significant differences between the POST and 20 min values of MVC-ISO torque ($p = 1.00$) and MVC-CON torque ($p = 0.50$). For PPT, the POST values were significantly ($p < 0.01$) higher than the PRE values, but not at 20 min ($p = 0.26$). In addition, there were no significant differences between the PRE and 20-min values ($p = 0.10$).

Discussion

In this study, we aimed to investigate the acute and sustained effects of high-and low-frequency VFR on knee flexion ROM, muscle strength, and jump performance. The results showed that VFR can increase knee flexion ROM but induces a decrease in knee extensor muscle strength up to 20 min after both high- and low-frequency VFR. However, there were no significant changes in RFD or CMJ height after the VFR interventions at high or low frequencies. These results suggest that VFR intervention increases ROM without impairing dynamic performance (such as jump height or explosive muscle strength), regardless of the frequency used, and its effect remains for up to 20 min.

The results showed that high-and low-frequency VFR intervention can increase knee flexion ROM, which is consistent with previous studies (Nakamura et al., 2022; Nakamura et al., 2021d; Nakamura et al., 2021e; Reiner et al., 2021). In addition, the results showed that the increase in ROM continued until 20 min after the VFR intervention at both frequencies. This information expands on previous research findings on the acute effects of VFR, and will be useful information for athletes and coaches. Interestingly, Nakamura et al. (2021b) showed that a 90-s (30 s × 3 sets) or 300-s (30 s × 10 sets) FR intervention can increase ankle dorsiflexion ROM, but the ankle dorsiflexion ROM returned to the baseline after 30 min.

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). Taking all this information together, since VFR intervention can have a lasting effect in increasing ROM, it will be necessary to investigate the potential difference in the sustained effects between FR and VFR. In addition, previous studies have shown that the increase in ROM following a single or chronic FR or VFR intervention can be associated with a change in the participant's experience, i.e., stretch tolerance (Kasahara et al., 2022a; Kiyono et al., 2020; Nakamura et al., 2021a; Nakamura et al., 2021b), even though the precise mechanism of the increase in ROM is unknown. In this study, PPT was found to be significantly increased immediately after the VFR intervention, regardless of the frequency, and the changes in stretch tolerance could contribute to the increase in knee flexion ROM. Another possible mechanism for this change in knee flexion ROM could be that the VFR on the muscle tissues induced thixotropic effects by reducing visco-elasticity (Behm and Wilke, 2019; Konrad et al., 2022b). Thus, it is possible that changes in stretch tolerance and thixotropy could contribute to an increase in knee flexion immediately after VFR and up to 20 min after the intervention.

Surprisingly, high- and low-frequency VFR induced significant decreases in MVC-ISO and MVC-CON torque of the knee extensors, and the decreases lasted up to 20 min. Previous studies have either shown that VFR increases muscle strength (Lee et al., 2018; Lyu et al., 2020; Reiner et al., 2021) or that there are no significant changes in muscle strength (Nakamura et al., 2021d; Nakamura et al., 2021e). Furthermore, the systematic review and meta-analysis suggested that VFR could have great potential for increasing jump performance and muscle strength, although no significant results were found (Alonso-Calvete et al., 2022). The discrepancy between the results of this study and the previous studies could be related to vibration-induced muscle fatigue. Previous studies have suggested that vibration stimulation can cause post-activation performance enhancement by neural potentiation but can induce muscle fatigue (Lamont et al., 2010; Tsai and Chen, 2021). Furthermore, Reiner et al. (2021) investigated the effect of a 180-s VFR intervention on recreational athletes and reported a significant increase in MVC-ISO torque. However, in this study, we investigated the effect of a 180-s VFR intervention on sedentary healthy young males. It is possible that a 180-s VFR intervention was too long for sedentary healthy young males and may have caused muscle fatigue. In addition, VFR can decrease muscle stiffness (Nakamura et al., 2021d; Nakamura et al., 2021e; Reiner et al., 2021). Thus, these changes, caused by the VFR intervention, could have decreased the MVC-ISO and MVC-CON torque, which persisted up to 20 min.

Interestingly, our results showed no significant changes in RFD, the index of explosive muscle strength, or jump performance after the VFR intervention. Andersen and Aagaard (2006) pointed out that RFD is influenced by different physiological factors in the early (less than 100 ms) and late (more than 100 ms) phases of isometric contraction (Andersen and Aagaard, 2006). Our results showed that the early and late phase RFD did not change with the VFR, regardless of the frequency. MVC-ISO and MVC-CON torque significantly decreased after the VFR intervention, but due to the fact that RFD is a sports performance related variable, the adverse effects of a VFR intervention can be considered to be small.

In this study, we compared the effect of high- and low-frequency VFR on knee flexion ROM, muscle strength, PPT, and jump performance. Our results showed no significant differences between the high and low frequencies. According to Germann et al. (2018), the 30–50 Hz frequency has been found to be suitable for fostering therapeutic adaptations since it is similar to the motor unit's discharge rate during maximal exertion (Germann et al., 2018). The frequencies used in this study were 35 Hz (low-frequency VFR) and 67 Hz (high-frequency VFR). Because of the proximity to the 30 - 50 Hz frequency band, there could be no significant difference between the high- and low-frequency VFR interventions. Therefore, future studies should investigate the acute effect of VFR at higher frequencies. From a clinical perspective, because high-frequency VFR is difficult to control, it is recommended that low-frequency VFR be incorporated into warm-up routines.

Conclusion

In this study, we compared the effect of high- and low-frequency VFR on knee flexion ROM, knee extensor muscle strength, PPT, and jump performance. The results suggested that VFR can increase knee flexion ROM but induces a decrease in muscle strength up to 20 min after both high- and low-frequency VFR. However, there were no significant changes in RFD or CMJ height after the VFR intervention. Therefore, if the goal is to increase ROM without decreasing explosive muscle strength or jump performance, it is recommended that VFR could serve as an effective warm-up tool in sports and rehabilitation settings, regardless of the frequency.

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References

Aagaard, P., Simonsen, E.B., Andersen, J.L., Magnusson, P. and Dyhre-Poulsen, P. (2002) Increased rate of force development and neural drive of human skeletal muscle following resistance training. *Journal of Applied Physiology*. **93,** 1318-1326. https://doi.org/10.1152/japplphysiol.00283.2002

Akiyama, K., Akagi, R., Hirayama, K., Hirose, N., Takahashi, H. and Fukubayshi, T. (2016) Shear Modulus of the Lower Leg Muscles in Patients with Medial Tibial Stress Syndrome. *Ultrasound in Medicine & Biology*. **42,** 1779-1783. https://doi.org/10.1016/j.ultrasmedbio.2016.03.010

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*. **8,** 32. https://doi.org/10.1186/s40798-022-00421-2

Andersen, L.L. and Aagaard, P. (2006) Influence of maximal muscle strength and intrinsic muscle contractile properties on contractile rate of force development. *European Journal of Applied Physiology*. **96,** 46-52. https://doi.org/10.1007/s00421-005-0070-z

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. 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. 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.

Ema, R., Saito, M., Ohki, S., Takayama, H., Yamada, Y. and Akagi, R. (2016) Association between rapid force production by the plantar flexors and balance performance in elderly men and women. *Age* **38,** 475-483. https://doi.org/10.1007/s11357-016-9949-3

Fort-Vanmeerhaeghe, A., Gual, G., Romero-Rodriguez, D. and Unnitha, V. (2016) Lower Limb Neuromuscular Asymmetry in Volleyball and Basketball Players. *Journal of Human Kinetics* **50,** 135-143. https://doi.org/10.1515/hukin-2015-0150

Germann, D., El Bouse, A., Shnier, J., Abdelkader, N. and Kazemi, M. (2018) Effects of local vibration therapy on various performance parameters: a narrative literature review. *The Journal of the Canadian Chiropractic Association* **62,** 170-181.

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

Kasahara, K., Yoshida, R., Yahata, K., Sato, S., Murakami, Y., Aizawa, K., Konrad, A. and Nakamura, M. (2022b) Comparison of the Acute Effects of Foam Rolling with High and Low Vibration Frequencies on Eccentrically Damaged Muscle. *Journal of Sports Science and Medicine*. **21,** 112-119. https://doi.org/10.52082/jssm.2022.112

Kim, S.J. and Lee, J.H. (2018) Effects of sternocleidomastoid muscle and suboccipital muscle soft tissue release on muscle hardness and pressure pain of the sternocleidomastoid muscle and upper trapezius muscle in smartphone users with latent trigger points. *Medicine (Baltimore)* **97,** e12133. https://doi.org/10.1097/MD.0000000000012133

Kiyono, R., Onuma, R., Yasaka, K., Sato, S., Yahata, K. and Nakamura, M. (2020) Effects of 5-Week Foam Rolling Intervention on Range of Motion and Muscle Stiffness. *The Journal of Strength & Conditioning Research*. **36**, 1890-1895. https://doi.org/10.1519/JSC.0000000000003757

Konrad, A., Kasahara, K., Yoshida, R., Yahata, K., Sato, S., Murakami, Y., Aizawa, K. and Nakamura, M. (2022a) Relationship between Eccentric-Exercise-Induced Loss in Muscle Function to Muscle Soreness and Tissue Hardness. *Healthcare* **10,** 96. https://doi.org/10.3390/healthcare10010096

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

Lamont, H.S., Cramer, J.T., Bemben, D.A., Shehab, R.L., Anderson, M.A. and Bemben, M.G. (2010) The acute effect of whole-body low-frequency vibration on countermovement vertical jump performance in college-aged men. *The Journal of Strength & Conditioning Research*. **24,** 3433-3442. https://doi.org/10.1519/JSC.0b013e3181c1ff7e

Lee, C.L., Chu, I.H., Lyu, B.J., Chang, W.D. and Chang, N.J. (2018) Comparison of vibration rolling, nonvibration rolling, and static stretching as a warm-up exercise on flexibility, joint proprioception, muscle strength, and balance in young adults. *Journal of Sports Sciences*. **36,** 2575-2582. https://doi.org/10.1080/02640414.2018.1469848

Lyu, B.J., Lee, C.L., Chang, W.D. and Chang, N.J. (2020) Effects of Vibration Rolling with and without Dynamic Muscle Contraction on Ankle Range of Motion, Proprioception, Muscle Strength and Agility in Young Adults: A Crossover Study. *International Journal of Environmental Research and Public Health*. **17**, 354. https://doi.org/10.3390/ijerph17010354

Maffiuletti, N.A., Aagaard, P., Blazevich, A.J., Folland, J., Tillin, N. and Duchateau, J. (2016) Rate of force development: physiological and methodological considerations. *European Journal of Applied Physiology*. **116,** 1091-1116. https://doi.org/10.1007/s00421-016-3346-6

Moezy, A., Olyaei, G., Hadian, M., Razi, M. and Faghihzadeh, S. (2008) A comparative study of whole body vibration training and conventional training on knee proprioception and postural stability after anterior cruciate ligament reconstruction. *British Journal of Sports Medicine* **42,** 373-378. https://doi.org/10.1136/bjsm.2007.038554

Naderi, A., Rezvani, M.H. and Degens, H. (2020) Foam Rolling and Muscle and Joint Proprioception After Exercise-Induced Muscle Damage. *Journal of Athletic Training*. **55,** 58-64. https://doi.org/10.4085/1062-6050-459-18

Nakamura, M., Konrad, A., Kasahara, K., Yoshida, R., Murakami, Y., Sato, S., Aizawa, K., Koizumi, R. and Wilke, J. (2022) 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.* 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., Nishishita, S. and Knorad, A. (2021c) Relationship between changes in passive properties and muscle strength after static stretching. *Journal of Bodywork and Movement Therapies.* **28,** 535-539. https://doi.org/10.1016/j.jbmt.2021.09.012

Nakamura, M., Sato, S., Kiyono, R., Yoshida, R., Murakami, Y., Yasaka, K., Yahata, K. and Konrad, A. (2021d) Acute Effect of Vibration Roller With and Without Rolling on Various Parts of the Plantar Flexor Muscle. *Frontiers in Physiology.* **12,** 716668. https://doi.org/10.3389/fphys.2021.716668

Nakamura, M., Sato, S., Kiyono, R., Yoshida, R., Yasaka, K., Yahata, K. and Konrad, A. (2021e) Comparison Between Foam Rolling With and Without Vibration on Passive and Active Plantar Flexor Muscle Properties. *The Journal of Strength & Conditioning Research.* https://doi.org/10.1519/JSC.0000000000004123

Nakamura, M., Sato, S., Hiraizumi, K., Kiyono, R., Fukaya, T. and Nishishita, S. (2020a) Effects of static stretching programs performed at different volume-equated weekly frequencies on passive properties of muscle-tendon unit. *Journal of Biomechanics.* **16:103**, 109670. https://doi.org/10.1016/j.jbiomech.2020.109670

Nakamura, M., Yasaka, K., Kiyono, R., Onuma, R., Yahata, K., Sato, S. and Konrad, A. (2020b) 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

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

Rodríguez-Rosell, D., Pareja-Blanco, F., Aagaard, P. and González-Badillo, J.J. (2018) Physiological and methodological aspects of rate of force development assessment in human skeletal muscle. *Clinical Physiology and Functional Imaging.* **38,** 743-762. https://doi.org/10.1111/cpf.12495

Tsai, W.C. and Chen, Z.R. (2021) The Acute Effect of Foam Rolling and Vibration Foam Rolling on Drop Jump Performance. *International Journal of Environmental Research and Public Health.* **18**, 3489. https://doi.org/10.3390/ijerph18073489

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 acute and sustained effects of VFR with different frequencies on knee flexion range of motion and muscle strength of knee extensors.
- A 180-s vibration foam rolling intervention with low and high frequencies can increase knee flexion range of motion but impairs maximal voluntary isometric and concentric contraction torque of knee extensors up to 20 min after the intervention.
- However, there we no significant changes in rate of force development, i.e., index of explosive muscle strength and countermovement jump height.

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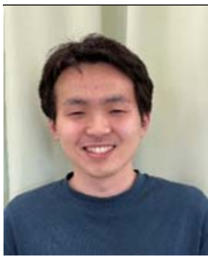

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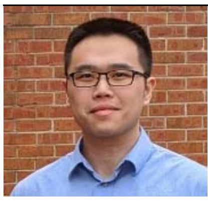

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