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Research article

Comparison of the Acute Effects of Foam Rolling with High and Low Vibration Frequencies on Eccentrically Damaged Muscle

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Abstract

Previous research has shown that vibration foam rolling (VFR) on damaged muscle shows greater improvement in muscle soreness and range of motion (ROM) compared with foam rolling (FR) without vibration. However, the effect of frequency in VFR on muscle soreness and loss of function caused by damaged muscles is unknown. The purpose of this study was to compare the acute effects of 90-s low-frequency (LF)- and high-frequency (HF)-VFR intervention on ROM, muscle soreness, muscle strength, and performance of eccentrically damaged muscle. Study participants were sedentary healthy adult volunteers (n = 28) who performed a bout of eccentric exercise of the knee extensors with the dominant leg and received 90-s LF-VFR or HF-VFR intervention of the quadriceps 48 h after the eccentric exercise. The dependent variables were measured before the eccentric exercise (baseline) and before (pre-intervention) and after VFR intervention (post-intervention) 48 h after the eccentric exercise. The results showed that both LF-VFR and HF-VFR similarly ($p < 0.05$) improved the knee flexion ROM (11.3 ± 7.2%), muscle soreness at palpation (-37.9 ± 17.2%), and countermovement jump height (12.4 ± 12.9%). It was concluded that it was not necessary to perform VFR with a high frequency to improve muscle soreness and function.

Key words: Muscle strength, range of motion, knee extensor, pain pressure threshold, maximal voluntary muscle contraction.

Introduction

Many factors affect muscle strength and hypertrophy in resistance training. Although further discussion is needed regarding the effect of muscle contraction mode, it is well known that resistance training emphasizing eccentric contraction (ECC) has a superior effect on muscle strength and hypertrophy than resistance training emphasizing concentric contraction (Katsura et al., 2019; Sato et al., 2021; Tseng et al., 2020). Although ECC resistance training can be applied in sports and medical fields, delayed onset muscle soreness (DOMS) often occurs as an adverse effect. DOMS includes increased muscle stiffness, decreased pain threshold, decreased muscle strength, and decreased range of motion (ROM) (Heiss et al., 2019; Nosaka et al., 2011). As the adverse effects of DOMS can impair motivation to continue exercising, it is necessary to establish a means of reducing the adverse effects of DOMS. Treatment for DOMS includes stretching and massage in the sports field. Herbert et al. (2011) concluded that muscle stretching, whether conducted before, after, or before and after exercise, does not produce clinically important reductions in DOMS in healthy adults (Herbert et al., 2011). However, Matsuo et al. (2015) found that static stretching can improve muscle soreness, ROM, and passive stiffness of the muscle-tendon unit in damaged muscle. In addition, FR interventions using foam rollers and balls have been identified as self-care tools. Regarding the recovery effects of an FR intervention, previous studies have shown that an FR intervention was beneficial in attenuating muscle soreness and counteracting decreases in ROM and athletic performance (Macdonald et al., 2014; Pearcey et al., 2015). A previous study found that FR interventions on damaged muscle could improve ROM, muscle soreness, and muscle strength (Nakamura et al., 2020b). FR is a self-care tool that is expected to be increasingly used in sports and rehabilitation fields in the future.

In recent years, vibration FR (VFR) - a foam roller with additional vibration function - has been used to increase the FR effect. The potentially superior effect of VFR over FR alone could be attributed to the greater changes in mechanoreceptors as a result of the vibration (Behm and Wilke, 2019). Previous studies have demonstrated that VFR produced a superior increase in ROM compared with FR intervention (Cheatham et al., 2018; Reiner et al., 2021), and a systematic review and meta-analysis concluded that VFR was more effective in improving the ROM compared with FR for the hip and knee joints (Park et al., 2021). Previous literature has also shown that VFR could reduce muscle stiffness more than could FR intervention (Nakamura et al., 2021d; Reiner et al., 2021).

Romero-Moraleda et al. (2019) investigated the superior effect of VFR and demonstrated that the effect of VFR on damaged muscle was greater than that of FR in improving muscle soreness and ROM. However, one of the limitations of their study (Romero-Moraleda et al., 2019) is that the effect of VFR was examined at only one frequency (18 Hz) and that the effects of other frequencies on damaged muscle were not compared. Germann et al. (2018) noted that the physiological and neuromuscular responses might be different when different frequencies are applied. Therefore, a comparison of the effects of different frequencies of VFR on damaged muscle could provide useful information in the field of sports and rehabilitation.

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The purpose of this study was to investigate the acute effects of different frequencies of VFR intervention on ROM, muscle soreness, muscle strength, and performance of eccentrically damaged muscle. In addition, previous research that investigated the effects of different frequencies of whole-body vibration on knee extension muscle strength found that maximal voluntary isometric contraction (MVC-ISO) torque in the knee extensor significantly improved in the frequency of 30 Hz compared with 50 Hz (Esmaeilzadeh et al., 2015). Therefore, it was hypothesized that the acute effect on damaged muscle would be greater in the low-frequency (LF)-VFR group than in the high-frequency (HF)-VFR group.

Methods

Experimental design

A randomized repeated measures experimental design was used to compare the acute effect of different frequencies (HF- vs. LF-VFR) on eccentrically damaged muscle. The participants (n = 28) performed 60 repetitions of eccentric exercise (10 repetitions × 6 set) of the knee extensors with the dominant leg (preferred leg for kicking a ball) as described below (see also Figure 1). Participants also received 90-s VFR intervention (30 s × 3 sets) of the quadriceps 48 h after the eccentric exercise (Nakamura et al., 2020b). The dependent variables consisted of knee flexion ROM, MVC-ISO, maximal voluntary concentric contraction (MVC-CON) torque of the knee extensor, countermovement jump (CMJ) height, pain pressure threshold (PPT), and muscle soreness at MVC-ISO, MVC-CON, and stretching. These variables were measured before the maximal ECC task (baseline) and before (pre-intervention) and after (post-intervention) both LF- and HF-VFR interventions. Our previous study already confirmed the high reliabilities of these outcome variables (Konrad et al., 2022).

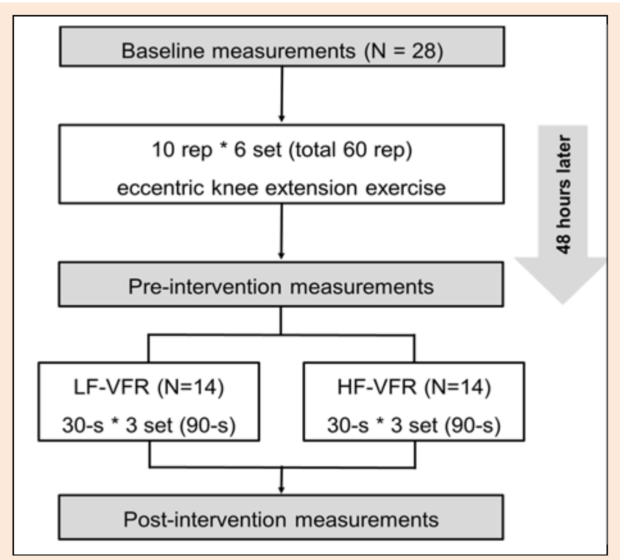

Figure 1. **Flow Chart**

Post-intervention measurements were performed immediately after the VFR intervention. All measurements were taken at the same time of the day for each participant between days. Furthermore, the participants practiced the FR intervention on the opposite side (non-dominant leg) before baseline and pre-intervention measurements. The participants familiarized all measurements and ECC exercises before baseline measurement in the measurement leg (dominant leg).

Participants

Participants enrolled in this study included 28 sedentary healthy young male volunteers (age 21.2 ± 1.0 years; height 173.0 ± 5.4 cm; body mass 66.1 ± 9.0 kg) who had not performed habitual exercise activities for at least the past 6 months before the assessment. Participants who had a history of neuromuscular disease or musculoskeletal injury in the lower extremity were excluded. No participants had been involved in any regular resistance training or flexibility training. They were allocated to one of two groups randomly as follows: LF-VFR group (n = 14, age 21.3 ± 1.2 years; height 1.73 ± 0.06 m; body mass 63.7 ± 6.3 kg) and HF-VFR group (n = 14, age 21.1 ± 0.6 years; height 1.73 ± 0.04 m; body mass 65.7 ± 7.7 kg). There were no significant differences in age, height, and body mass among groups using an un-paired t-test. The sample size required for a split-plot analysis of variance (ANOVA) (effect size = 0.40 [large], α error = 0.05, and power = 0.80) using G* power 3.1 software (Heinrich Heine University, Düsseldorf, Germany) was more than 10 participants in each group. Therefore, to be safe, we included a large sample size based on the previous study (Nakamura et al., 2020b).
All subjects were fully informed of the procedures and purpose of the study and written informed consent was obtained. The study was approved by the ethics committee (#18220) at the Niigata University of Health and Welfare, Niigata, Japan.

Eccentric exercise

All participants performed six sets out of 10 maximal ECC exercises of the unilateral knee extensors (dominant leg) on an isokinetic dynamometer (Biodex System 3.0, Biodex Medical Systems Inc., Shirley, NY, USA), (Nakamura et al., 2020b). Participants were seated in the dynamometer chair at an 80° hip flexion angle, with adjusted Velcro straps fixed over the trunk, pelvis, and thigh of the exercised limb. The participants were instructed to perform the maximal ECC from a slightly flexed position (20°) to a flexed position (110°) at an angular velocity of 60°/s (Nakamura et al., 2020b). After each ECC, the lever arm passively returned the knee joint to the starting position at 10°/s, which gave a 9-s rest between contractions. Each set was repeated 10 times, and the participants had a 100-s rest between sets and completed six sets. To generate maximum force, strong verbal encouragement was given to the participants during each ECC.

Vibration foam rolling intervention

A foam roller (Stretch Roll SR-002, Dream Factory, Umeda, Japan) was used for VFR intervention. Before VFR intervention, a physical therapist instructed the participants on how to use the foam roller. For familiarization, they were allowed to practice using the foam roller three to five times on the non-dominant leg (non-intervention leg).

The participants performed 30-s bouts of VFR intervention in both groups for three sets, with a 30-s rest between each set. This was in accordance with the recommendations of Behm et al. (2020) to maximize the increase in ROM (Behm et al., 2020). 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. Here, this study defined one cycle of VFR intervention as one distal rolling plus one subsequent proximal rolling movement, whereas the frequency was defined as 15 cycles per 30 s (for a total of 45 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 under the direct supervision of investigators. The participants were asked to place as much body mass on the roller as tolerable. VFR intervention was performed at 35 Hz in the LF-VFR group and at 67 Hz in the HF-VFR group.

Maximal voluntary isometric contraction and maximal voluntary concentric contraction

MVC-ISO was measured at 70° knee angles. The participants were instructed to perform maximal contraction for 3 s at each angle two times with 60-s rest between trials, and the average value was adopted for further analysis. MVC-CON was measured at an angular velocity of 60°/s for a ROM of 70° (20 - 90° knee angles) for three continuous MVC-CONs for both directions. For further analysis, the highest value among the three trials was adopted. During all tests, verbal encouragement was provided consistently.

Countermovement jump

CMJ height was calculated from flight time using the jump mat systems (Jump mat system; 4Assist, Tokyo, Japan). The participants started with the foot of the dominant leg on the mat with their hands in front of their chest. From this position, the participants were instructed to dip quickly (eccentric phase), reaching a self-selected depth to 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 CMJ were performed and measured, and the maximal vertical jump height was used for further analysis.

Knee flexion range of motion

Each participant was placed in a side-lying position on a massage bed, and the hip and knee of the non-dominant leg were flexed at 90° to prevent the movement of the pelvis during ROM measurements (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 further analysis (Figure 2).

Muscle soreness

Using a visual analog scale that had a 100-mm continuous line with ‘‘not sore at all’’ on one side (0 mm) and ‘‘very, very sore’’ on the other side (100 mm), the magnitude of knee extensor muscle soreness was assessed by muscle contraction, stretching, and palpation (Chen et al., 2010; Nakamura et al., 2020b). Muscle soreness at contraction was assessed during both MVC-ISO and MVC-CON. For muscle soreness during palpation, the participants laid supine on a massage bed, and the investigator palpated the proximal, middle, and distal points of the vastus medialis, vastus lateralis, and rectus femoris (Mavropalias et al., 2020; Nakamura et al., 2020b). The average value of the knee extensor palpation points was used for further analysis. Muscle soreness during ROM measurement was measured twice to determine soreness during stretching, and the average value was used for further analysis.

Figure 2. Knee flexion rand of motion measurement

Pain pressure threshold

PPT measurements were carried out using an algometer (NEUTONE TAM-22 (BT10); TRY ALL, Chiba, Japan) in the supine position. The measurement position was set at the midway of the distance between the anterior superior iliac spine and the upper end of the patella of the dominant side. With continuously increasing pressure, the metal rod of the algometer was used to compress the soft tissue in the measurement area. The participants were instructed to immediately press a trigger when the 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 were taken with a 30-s interval for data analysis.

Statistical analysis

SPSS (version 24.0; SPSS Japan Inc., Tokyo, Japan) was used for statistical analysis. The distribution of the data was assessed using the Shapiro-Wilk test, and it was confirmed that the data followed a normal distribution. Among groups, differences in characteristics were assessed using an unpaired t-test. For all variables, a split-plot ANOVA using two factors (time [baseline vs. pre-intervention vs. post-intervention] and group [LF-VFR vs. HF-VFR groups]) was used to determine 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 over 0.1 was considered to be a large effect size based on previous studies (Akiyama et al., 2016; Cohen, 1988). The Bonferroni post hoc test was used to determine the differences between measurements taken at baseline, pre-intervention, and post-intervention. Also, we calculated the effect size (ES) as differences in the mean value divided by the pooled standard deviation (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). Differences were considered statistically significant at an alpha of $P < 0.05$. Descriptive data are shown as mean ± SD.

Results

No significant differences were found in all variables between the LF- and HF-VFR groups.

Changes in knee flexion range of motion, maximal voluntary isometric contraction, maximal voluntary concentric contraction, and countermovement jump height

Table 1 shows the changes in knee flexion ROM, MVC-ISO, MVC-CON, and CMJ height. The split-plot ANOVA indicated a significant interaction for the knee flexion ROM ($P < 0.01$, F = 32.0, $\eta_p^2 = 0.552$). The post hoc test showed that the pre-intervention knee flexion ROM values had decreased significantly compared with the baseline value. In contrast, the post-intervention knee flexion ROM value had increased significantly compared with pre-intervention values in both groups (LF-VFR: %change = 6.1 ± 4.4%, d = 0.68, HF-VFR: %change = 16.6 ± 5.5%, d = 1.88). Also, although there was no significant difference in baseline value between LF- and HF-VFR (P = 0.41), the knee flexion ROM values in the LF-VFR group at pre-and post-intervention were significantly ($P < 0.01$) lower than in the HF-VFR group.

In addition, there were no significant interaction effects for MVC-ISO, MVC-CON, and CMJ height, but there were significant main effects for the time factor. In both groups, MVC-ISO and MVC-CON values in pre-and post-intervention were significantly lower than were baseline values, but CMJ height had significantly improved in post-intervention rather than in pre-intervention (LF-VFR: %change = 10.9 ± 14.4%, d = 0.35, HF-VFR: %change = 13.8 ± 11.0%, d = 0.31). However, the CMJ height in LF-VFR was significantly lower in post-intervention than at baseline.

Changes in pain pressure threshold and muscle soreness at maximal voluntary isometric contraction, maximal voluntary concentric contraction, stretching, and palpation

Table 2 shows the changes in PPT and muscle soreness at MVC-ISO, MVC-CON, stretching, and palpation. There were no significant interaction effects, but there were significant main effects for all variables. In both groups, PPT values in pre-intervention decreased significantly compared with baseline values. But the values significantly improved after VFR intervention to the same extent as the baseline values (LF-VFR: change = 1.1 ± 0.9kg, d = 0.93, HF-VFR: change = 1.1 ± 0.9kg, d = 1.34).

For muscle soreness at MVC-ISO, MVC-CON, stretching, and palpation, the pre-and post-intervention values were significantly higher than baseline values except for muscle soreness at stretching in the HF-VFR group. All variables improved significantly after both LF- and HF-VFR interventions (muscle soreness at MVC-ISO: LF-VFR: change = -18.1 ± 12.6mm, d = -0.95, HF-VFR: change = -15.0 ± 11.1mm, d = -0.66, muscle soreness at MVC-CON: LF-VFR: change = -16.4 ± 11.9mm, d =-0.86, HF-VFR: change = -10.0 ± 9.6mm, d = -0.56, muscle soreness at stretching: LF-VFR: change = -13.6 ± 8.0mm, d =-0.60, HF-VFR: change = -12.9 ± 9.2mm, d = -0.59, muscle soreness at palpation: LF-VFR: change =-15.2 ± 10.4mm, d = -1.27, HF-VFR: change = -21.0 ± 12.8mm, d = -1.41).

Discussion

In this study, the acute effect of different VFR frequencies, i.e., LF- vs. HF-VFR, on eccentrically damaged muscle was investigated. The results found that both 90-s LF- and HF-VFR improved the knee flexion ROM, CMJ height, and muscle soreness, but there were no significant improvements in MVC-ISO and MVC-CON. Moreover, the improvement effect of VFR intervention on the damaged muscles was comparable with those of LF- and HF-VFR. Although Romero-Moraleda et al. (2019) investigated the acute effect of VFR on the damaged muscle, to our knowledge, this is the first study comparing the acute effects of VFR using different frequencies (35 vs. 67 Hz).

Table 1. Changes (mean ± SD) in knee flexion range of motion (ROM), maximal voluntary isometric contraction torque of knee extensor at 70° (MVC-ISO), 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, G x T: group x time interaction effect; F-value) and partial η^2 (η_p^2) are shown in right column.

	LF-VFR Group (N = 14)			HF-VFR Group (N = 14)			ANOVA results
	Baseline	Pre-intervention	Post-intervention	Baseline	Pre-intervention	Post-intervention	P value, F value, η_p^2
Knee flexion ROM (°)	139.6 ± 6.0	126.5 ± 12.7*†	133.7 ± 8.6#†	135.9 ± 6.1	94.6 ± 9.9*	109.8 ± 6.3*#	T: p < 0.01, F = 113.3, η_p^2 = 0.813 G x T: p < 0.01, F = 32.0, η_p^2 = 0.552
MVC-ISO (Nm)	209.4 ± 33.7	121.2± 34.6*	135.5 ± 41.2*	217.3 ± 26.1	147.2 ± 56.0*	153.0 ± 54.5*	T: p < 0.01, F = 42.8, η_p^2 = 0.622 G x T: p =0.45, F = 0.62, η_p^2 = 0.018
MVC-CON (Nm)	164.6 ± 23.8	103.6 ± 38.4*	107.9 ± 38.1*	171.9 ± 17.2	111.1 ± 42.8*	121.8 ± 40.5*	T: p < 0.01, F = 36.3, η_p^2 = 0.583 G x T: p = 0.89, F = 0.12, η_p^2 = 0.004
CMJ height (cm)	19.7 ± 3.3	14.3 ± 3.8*	15.7 ± 3.9* #	21.4 ± 4.5	15.8 ± 6.3*	17.9 ± 6.8#	T: p < 0.01, F = 34.3, η_p^2 = 0.569 G x T: p = 0.88, F = 0.13, η_p^2 = 0.005

*: A significantly (p < 0.05) different from the baseline value; #: A significantly (p < 0.05) different from the pre-intervention value; †: A significantly (p < 0.05) different from HF-VFR group.

Table 2. **Changes (mean ± SD) in pain pressure threshold (PPT), muscle soreness at maximal voluntary isometric contraction (MVC-ISO), maximal voluntary concentric contraction (MVC-CON), stretching, and palpation 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, G x T: group x time interaction effect; F-value) and partial η^2 (η_p^2) are shown in right column.**

	LF-VFR Group (N=14)			HF-VFR Group (N=14)			ANOVA results
	Baseline	Pre-intervention	Post-intervention	Baseline	Pre-intervention	Post-intervention	P value, F value, η_p^2
PPT (kg)	2.7 ± 1.0	2.1 ± 1.0*	3.2 ± 1.2#	2.7 ± 1.6	1.4 ± 0.7*	2.4 ± 0.9#	T: $p < 0.01$, F = 17.5, $\eta_p^2 = 0.403$ G x T: $p = 0.10$, F = 2.38, $\eta_p^2 = 0.084$
Muscle Soreness							
at MVC-ISO (mm)	2.3 ± 4.8	37.0 ± 22.3*	18.9 ± 15.6* #	4.0 ± 6.0	35.9 ± 25.1*	20.9 ± 20.5* #	T: $p < 0.01$, F = 47.2, $\eta_p^2 = 0.645$ G x T: $p = 0.89$, F = 0.12, $\eta_p^2 = 0.005$
at MVC-CON (mm)	6.0 ± 9.4	39.5 ± 22.5*	23.1 ± 15.7* #	3.2 ± 5.7	28.3 ± 18.8*	18.3 ± 16.9* #	T: $p < 0.01$, F = 37.5, $\eta_p^2 = 0.59$ G x T: $p = 0.44$, F = 0.84, $\eta_p^2 = 0.031$
at stretching (mm)	12.4 ± 22.9	47.1 ± 23.4*	33.6 ± 21.9* #	5.3 ± 7.4	32.1 ± 23.0*	19.2 ± 20.6#	T: $p < 0.01$, F = 45.1, $\eta_p^2 = 0.634$ G x T: $p = 0.41$, F = 0.90, $\eta_p^2 = 0.033$
at palpation (mm)	10.9 ± 11.3	40.4 ± 16.2*	25.2 ± 7.7* #	9.8 ± 9.2	45.4 ± 18.7*	24.4 ± 11.1* #	T: $p < 0.01$, F = 70.1, $\eta_p^2 = 0.73$ G x T: $p = 0.46$, F = 0.78, $\eta_p^2 = 0.029$

*: A significantly ($p < 0.05$) different from the baseline value; #: A significantly ($p < 0.05$) different from the pre-intervention value.

Study results showed that both LF- and HF-VFR interventions could decrease muscle soreness at MVC-ISO, MVC-CON, stretching, and palpation, as well as increase the PPT similarly. These results expand on Romero-Moraleda et al. 2019 study, which investigated the acute effect of VFR at 18 Hz on the damaged muscle. Interestingly, there could be a dose–response relationship between FR duration and FR intervention effect (Hughes and Ramer, 2019; Nakamura et al., 2021b). A systematic review (Hughes and Ramer, 2019) concluded that a minimum of 90-s FR intervention duration could decrease pain sensation, prevent DOMS-induced myalgia, and increase PPT. Also, a study by Aminian-Far et al. (2011) revealed that a vibration intervention could improve DOMS-induced pain (Aminian-Far et al., 2011). Although the mechanism for the effect of VFR on analgesia remains unclear in this study, previous studies (Aboodarda et al., 2015; Behm and Wilke, 2019; Cavanaugh et al., 2017) suggest that the proposed global pain modulatory response might be related to the gate control theory of pain, diffuse noxious inhibitory control, or parasympathetic nervous system alterations. In addition, VFR could induce selectively activating through pressure and vibration and the large rapid contraction for muscle, improving the pain sensation (Romero-Moraleda et al., 2019). This study shows that VFR intervention could improve pain sensation significantly; however, no significant differences were found between LF- and HF-VFR on muscle soreness.

Study results indicate that both LF- and HF-VFR interventions increase knee flexion, and the changes in knee flexion ROM after HF-VFR could be larger than those after LF-VFR ($\Delta = 15.0 \pm 4.0$ vs. 7.0 ± 4.7, respectively, $p < 0.01$). In addition, muscle soreness when stretching post-intervention was significantly higher than the baseline value in the LF-VFR group. Equally, no significant differences were found between baseline and post-intervention values in the HF-VFR group. This might suggest that LF-VFR has a positive impact on muscle soreness. Behm and Wilke (2019) suggest that VFR is more effective than FR in increasing ROM because mechanoreceptors, such as Pacinian and Ruffini corpuscles, are more responsive at high frequencies (Behm and Wilke, 2019). The stimulation for mechanoreceptors via HF-VFR could contribute to the larger increase in knee flexion ROM compared with those via LF-VFR. However, these results show that pre-intervention values are smaller in the HF-VFR group than those in the LF-VFR group. Thus, further study is needed to determine whether HF-VFR effectively reduces ROM caused by DOMS in comparison with LF-VFR.

Research by Graven-Nielsen et al. (2002), suggests that the voluntary contractile capacity of the muscle is reduced by muscle pain (Graven-Nielsen et al., 2002). Since muscle soreness at both MVC-ISO and MVC-CON decreased after both LF- and HF-VFR interventions, it is possible that VFR intervention might improve MVC-ISO and MVC-CON torques of the damaged muscle. However, surprisingly, no significant changes were found in MVC-ISO or MVC-CON after both LF- and HF-VFR interventions. However, previous research that investigated the acute effect of FR without vibration on the eccentrically damaged muscle showed that FR without vibration could improve MVC-ISO and MVC-CON torques (Nakamura et al., 2020b). The discrepancy between the results of this study and the previous study could be related to vibration-induced muscle fatigue. Previous studies have suggested that vibration stimulation could cause postactivation performance enhancement by neural potentiation and induce muscle fatigue (Lamont et al., 2010; Tsai and Chen, 2021). Therefore, although both LF- and HF-VFR may have improved MVC-ISO and MVC-CON torques, they may have been offset by muscle fatigue, resulting in no significant changes in muscle strength. However, both LF- and HF-VFR interventions increased CMJ height significantly. This discrepancy might be because knee extension MVC-ISO and MVC-CON torques were measured using single-joint motion, whereas CMJ height was measured using multi-joint motion. However, the details of the effects of VFR intervention on muscle strength and CMJ height are unclear and need further investigation.

Germann et al. (2018) suggest that a frequency of 30 - 50 Hz is the same frequency as the discharge rate of the motor unit during maximal effort, and this frequency has been identified as appropriate for promoting therapeutic adaptations (Germann et al., 2018). However, in contrast to the hypothesis, no significant difference was found in the change of almost all variables between LF- and HF-VFR in this study. The frequencies used in this study were 35 Hz (LF-VFR) and 67 Hz (HF-VFR), and because of their proximity to this frequency band (30-50Hz), there were no significant differences in the effect of intervention in VFR using both frequencies. Therefore, future studies should investigate the acute effect of VFR at higher frequencies.

Previous research investigated the effects of static stretching and FR without vibration (Matsuo et al., 2015; Nakamura et al., 2020b), while this study investigated the effect of VFR intervention on eccentrically damaged muscles. These intervention methods showed improvement in ROM and muscle soreness. Interestingly, static stretching and VFR intervention did not improve muscle strength, while FR intervention improved muscle strength. In addition, VFR intervention improved CMJ height, which is a more dynamic index of performance than muscle strength measurement. These results suggest that both FR and VFR interventions for damaged muscles may be useful intervention methods in sports and rehabilitation because they not only improve ROM and muscle soreness but also lead to improved performance. In addition, previous studies have found that muscle stiffness increased after repeated ECCs (Ema et al., 2021; Lacourpaille et al., 2017). Research has also shown that FR intervention did not change in muscle stiffness but VFR did decrease muscle stiffness (Nakamura et al., 2021a; 2021b; 2021c; 2021d). Therefore, if the goal is to decrease the muscle stiffness of damaged muscle, research suggests that VFR may be a practical approach.

There were some limitations in this study. First, we investigated exclusively the effect of LF- and HF-VFR on damaged muscle with rolling. A previous study showed that static compression using VFR has the same effect as VFR with rolling (Nakamura et al., 2021c). Thus, future studies are needed to investigate the effects of static compression using VFR on the damaged muscle. Second, the participants in this study did not perform any regular resistance training. Thus, future studies should investigate the effects of VFR on damaged muscle in resistance-trained participants.

Conclusion

The effect of 90-s LF- and HF-VFR intervention on eccentrically damaged muscle was investigated. Results showed that both LF- and HF-VFR interventions could improve knee flexion ROM, muscle soreness, and CMJ height similarly. Therefore, it is concluded that VFR is an effective recovery tool for eccentrically damaged muscles in sports and rehabilitation settings regardless of the frequency difference.

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Key points

- We compared the acute effects of low-frequency- and high-frequency-vibration foam rolling intervention on eccentrically damaged muscle.
- Vibration foam rolling intervention with both low- and high-frequencies could improve range of motion, muscle soreness, and countermovement jump performance.
- Vibration foam rolling is an effective recovery tool for eccentrically damaged muscles in sports and rehabilitation settings, regardless of the frequency difference.

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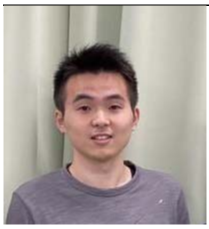

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