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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

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ABSTRACT

Warm-up is an essential component for optimizing performance before an exercise session. This study investigated that the immediate effects of vibration rolling (VR), nonvibration rolling (NVR), and static stretching as a part of a warm-up regimen on the flexibility, knee joint proprioception, muscle strength, and dynamic balance of the lower extremity in young adults. Compared with the preintervention, VR induced the range of motion of knee flexion and extension significantly increased by 2.5% and 6%, respectively, and isokinetic peak torque and dynamic balance for muscle strength and dynamic balance increased by 33%–35% and 1.5%, respectively. In the three conditions, most outcomes between VR and NVR were comparable; however, the participants had a significantly higher knee joint reposition error after NVR than after VR, indicating that NVR would have a hampering knee joint proprioception effect. In particular, compared with static stretching, VR significantly increased the quadriceps muscle strength by 2-fold and dynamic balance by 1.8-fold. These findings suggest that athletic professionals may take VR into account for designing more efficient and effective preperformance routine to improve exercise performances. VR has high potential to translate into an on-field practical application.

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KEYWORDS
Vibration; self-myofascial release; foam rolling; exercise; performance

Introduction

Warm-up is an essential component for optimizing performance before an exercise session. Myofascial release is one type of warm-up regimen (Cheatham, Kolber, Cain, & Lee, 2015). Foam rolling exercise is used as a new tool for “self” myofascial release (SMR) (Cheatham, Kolber, & Cain, 2017; Cheatham & Stull, 2018). In this exercise, individuals use their own body mass to apply pressure on target soft tissues over a dense foam roller. The motions place both direct and sweeping pressure on the target soft tissue, stretching it and generating friction between it and the foam roller. Previous research proposed that the friction generated may result in restoration of the fascia to take on a more thixotropic property, splitting of fibrous adhesions between the layers of the fascia, and promotion of soft-tissue extensibility (Sefton, 2004). Foam rolling, as a recovery strategy, increases joint range of motion (ROM), particularly after experiencing delayed-onset muscular soreness (Jay et al., 2014; Macdonald, Button, Drinkwater, & Behm, 2014; MacDonald et al., 2013). However, foam rolling appears to have no beneficial effects on the maximum voluntary contraction force (MacDonald et al., 2013), isometric force (Healey, Hatfield, Blanpied, Dorfman, & Riebe, 2014), and muscle strength (Su, Chang, Wu, Guo, & Chu, 2016).

Vibration therapy may be an alternative method; it has been adopted to enhance flexibility (Houston, Hodson, Adams, & Hoch, 2015), improve balance, (Tseng et al., 2016) and reduce postexercise delayed-onset muscle soreness (Bakhtiary, Safavi-Farokhi, & Aminian-Far, 2007; Imtiyaz, Veqar, & Shareef, 2014). Vibration results in mechanical oscillatory motion, which enhances reflex activity by stimulating the muscle spindle Ia to initiate a tonic vibratory reflex (Cardinale & Lim, 2003; Rehn, Lidstrom, Skoglund, & Lindstrom, 2007) and increases blood flow corresponding to intramuscular temperature (Kerschan-Schindl et al., 2001). Vibration can be applied to the whole body or locally. An acute whole-body vibration (WBV) more rapidly increased muscle temperature compared with the traditional methods of cycling and passive warm-up, corresponding to increased countermovement jump peak power and height; this finding indicates that vibration may be adopted as a warm-up strategy (Cochrane, Stannard, Sargeant, & Rittweger, 2008). However, the application of WBV in the sideline sports is not practical. Furthermore, WBV has been associated with discomfort (Kiiski, Heinonen, Jarvinen, Kannus, & Sievanen, 2008; Rittweger, 2010). By contrast, local vibration techniques target a specific muscle group, potentially enhancing the immediate effects of an increase in muscle activity and metabolic response (Couto et al., 2013; Pamukoff, Ryan, & Blackburn, 2014).

Recently designed vibrating foam rollers have emerged from the designs of traditional therapeutic apparatus. The design of a vibrating foam roller is combined with SMR and a local vibration technique. A study showed that compared with a nonvibrating roller, a vibrating roller significantly increased pressure pain thresholds and knee joint motion of the quadriceps musculature (Cheatham, Stull, & Kolber, 2017). The other study showed that foam roller was applied locally to

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muscle group with vibration exercises induced an increment in counter movement jump and sit-and-reach flexibility performance before and after both training sessions (Sağiroğlu, 2017). However, a few literatures on the use of vibration foam rolling are currently being investigated, particularly in warm-up exercises. Furthermore, no study has compared the effect of vibration rolling (VR) to nonvibration rolling (NVR) and static stretching on flexibility, joint proprioception and performance. Accordingly, this study investigated the immediate effects of VR, NVR, and static stretching during warm-up on the exercise performance of young adults. We hypothesized that VR would exert an SMR effect on targeted muscles of lower limbs and thus increase flexibility; concurrently, VR would exert positive effects on knee joint proprioception, maximal muscle strength, and balance as measured by the Y balance test (YBT) through facilitating vibration-induced neuromuscular activation (Cochrane, 2011).

Methods

Participants

Thirty male college students (age: 20.4 ± 1.2 y, body mass: 68.8 ± 8.9 kg, height: 1.7 ± 0.6 m) were received three trials: (1) vibrating foam roller, (2) nonvibrating foam roller, and (3) static stretching (Figure 1). Exclusion criteria included the presence of cardiovascular or respiratory diseases; contra-indications to exercise (e.g., neuromusculoskeletal injury or low back pain); ligament sprains and muscle strains; joint instability in the lower extremity; head or spinal injury; and visual, vestibular, or balance disorders during the preceding 6 months. The study protocol was approved by the Institutional Review Board. All participants were informed regarding the benefits and risks of the investigation, and written informed consent was obtained from all participants.

Experimental procedures

This study used a within-subject design to investigate the acute effects of VR, NVR, and static stretching exercises of the quadriceps and hamstrings muscles as a warm-up regimen on flexibility, proprioception, isokinetic muscle strength, and dynamic balance. Before the test session, participants underwent a familiarization session, in which they were instructed how to perform VR, NVR, and static stretching exercises. During this orientation, they were also familiarized with the procedures and practiced using the equipment for the investigation. Twenty-four hours after the familiarization session, each participant performed three warm-up exercises on three separate occasions in a randomized order, with 48 hours of rest between each test. Participants were requested to avoid strenuous activities 24 hours before each test session. During each test session, 5 minutes of light aerobic cycling (Aerobike 75XLII; 70 rpm and 80 W) was initiated before all participants performed the pretest. Participants underwent flexibility tests (i.e. ROM of knee flexion and extension), isokinetic strength and knee joint proprioception tests, and Y balance test (YBT). After completing pretest measurements, participants performed 6 minutes of VR, NVR, or static stretching randomized for that session. The protocols for exercises are described in detail below. Posttest measures were performed in the same order as the pretest measures immediately after the intervention. The flowchart of the study design is presented in Figure 1.

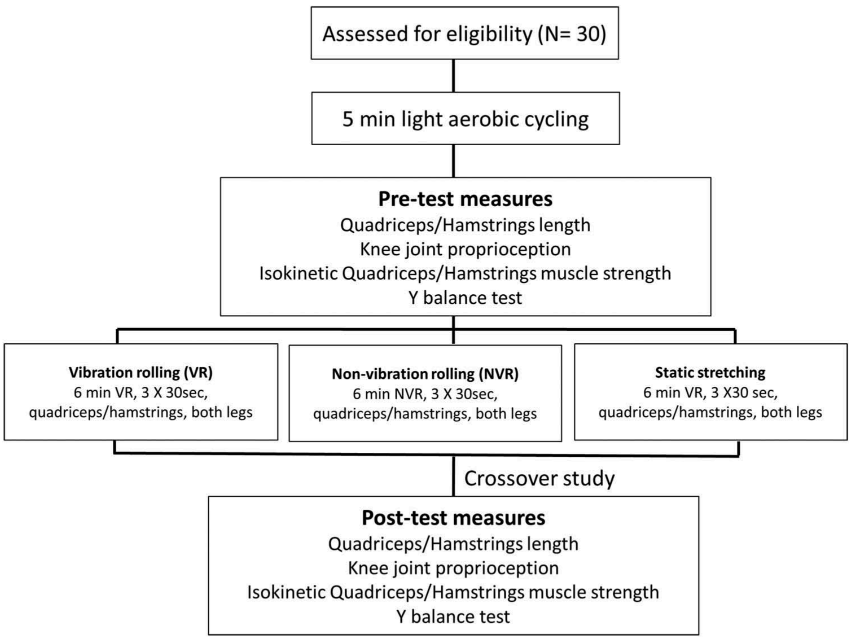


Figure 1. Flowchart of the study design.

Measures

Knee flexion range of motion

Quadriceps femoris muscle length during passive knee flexion was measured with the participant in the prone position (also known as Ely's test). Ely's test has a high intraclass correlation coefficient (ICC) of 0.94 (Piva et al., 2006). The angle of right knee flexion in the prone position was measured using a plastic goniometer that is commonly used by clinical practitioners. As hip flexes while knee is flexed, pelvis cannot be remained on floor or compensation with hip abduction and/or hyper-lordosis of the lumbar spine, the result indicated rectus femoris tightness for determining the end of ROM. The average measurement of two trials was recorded. In this study, the ICC was 0.908, indicating excellent test-retest reliability. In addition, minimum detectable change (MDC) value was calculated as 2.769° in corresponding to stand standard error of measurement (SEM) of 0.999.

Knee extension range of motion

The popliteal angle hamstring test was performed using a universal goniometer. This test has a high ICC of 0.94 (Youdas, Krause, Hollman, Harmsen, & Laskowski, 2005). The participant was in the supine position, and the hip of the right leg was flexed to 90°. Subsequently, the knee of participant actively brought upward until participant somewhat felt discomfort but without pain, and the angle between the thigh and calf was measured. The average measurement of two trials was recorded.

In this study, the ICC was 0.954, indicating excellent test-retest reliability. In addition, MDC value was calculated as 1.353° in corresponding to SEM of 0.488.

Knee joint proprioception and muscle strength tests

A Biodex isokinetic dynamometer (Biodex System 3 Pro, New York, USA) was used to assess knee joint proprioception and knee muscle strength. For the knee joint proprioception test, participants sat in an upright position on the Biodex dynamometer chair with their torso and right thigh stabilized by straps to minimize compensatory body movements. The right leg was positioned on the dynamometer. Each participant wore an eye mask to eliminate the visual feedback input. Next, the participants actively moved the limb to the target angle of 45° of flexion for 10 seconds to memorize the position and then returned to 90° of knee flexion (Callaghan, Selfe, Bagley, & Oldham, 2002). The participants were asked to perform that angle again through active contraction without being able to see their leg while the participants reached the target angle and then stopped. The 90 degree angle was tested three times and averaged. The difference (absolute error) between the setting and reproduced angle (perceived angle) was recorded as an index of proprioception.

The isokinetic knee muscle strength measurements of the participants were conducted in the same position, but the eye mask was removed. The participants were asked to actively perform knee extension and instant knee flexion as fast as they could three times at a set of the angular velocity of 60°/second. The peak torque in N•m was recorded using the Biodex software, and its highest torque value of the data was used in the statistical analysis. Peak torque was normalized to body weight. The isokinetic quadriceps and hamstrings muscle strengths measured at 60°/second using the Biodex System had high ICC values, ranging from r = 0.88 to r = 0.97 (Pincivero, Lephart, & Karunakara, 1997).

Y balance test

Dynamic balance in one-leg stance was assessed using the YBT, which is a high reliable test (ICC: 0.99–1.00) (Butler, Southers, Gorman, Kiesel, & Plisky, 2012). In the YBT, Participants must maintain balance on their dominant leg, barefoot, on a centralized stance platform while simultaneously reaching as far as possible with the other leg in three directions, namely anterior, posterolateral, and posteromedial. Six trial attempts of YBT were performed for their dominant leg (Linek, Sikora, Wolny, & Saulicz, 2017). The YBT composite score is calculated by averaging the three distances reached and normalizing the results based on the lower limb length and multiplied by 100. The measurement for each direction was obtained three times and averaged for data analysis. In this study, the ICC was 0.933, indicating excellent test-retest reliability. In addition, MDC value was calculated as 4.617% in corresponding to SEM of 1.665.

Exercise protocols

In this study, VR, NVR, and static stretching exercises were executed on quadriceps and hamstrings. The protocols for all exercises are detailed in Figure 2.

VR exercise

The participants performed VR using a vibrating foam roller (dimensions: 36 × 20 × 15 cm; weight: 1.8 kg) that comprised a vibration generating motor surrounded by an expanded polypropylene foam outer shell (Vyper By Hyperice). First, the participants positioned their right lower limb into the assigned position and subsequently put as much of their body weight as possible onto the vibrating foam roller (frequency of 28 Hz), which is the lowest frequency of the vibrating featured foam roller equipment Then, to perform 30 seconds of VR they moved back and forth at 40 beats per minute by using a metronome. Subsequently, the same exercise was performed on the left lower limb. The vibrating foam roller exercise was performed on quadriceps and hamstrings three times in a rotational order.

NVR exercise

The exercise protocols were the same as those used for the VR exercise, except for the vibration generator was turned off. In this study, we used the same roller for both exercises to eliminate the bias resulting from the use of foam outer shells of different stiffnesses (Curran, Fiore, & Crisco, 2008)

Static stretching exercise

The participants first positioned their right lower limb into each of the stretch positions, slowly stretched the target muscle to the point of discomfort, and held this position for 30 seconds. Next, the same stretching exercise was performed on

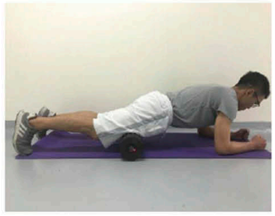
Vibration rolling (VR)		
Quadriceps	Position in the prone on elbow position. Place quadriceps of the right thigh on the vibrating foam roller. Roll from the proximal side of quadriceps scroll to the above patellar and back and forth 20 times in 30 seconds, after change to the left thigh. The total regimen included three sets for each muscle group.	
Hamstrings	Place hamstrings of the right thigh on the vibrating foam roller. Roll from approximately near to gluteal portion of hamstrings scroll to the knee and back and forth 20 times in 30 seconds, then change to the left thigh. The total regimen included three sets for each muscle group.	
Non-vibration rolling (NVR)		
Quadriceps	The same exercise protocols as VR, but the vibrating generator power was turn off.	
Hamstrings	The same exercise protocols as VR, but the vibrating generator power was turn off.	
Static stretching		
Quadriceps	In high kneeling squat position, flex the right knee and lean body backward. Stretch in the position for 30 seconds, then change to the left side.	
Hamstrings	Position in the supine position. Extend the stretched leg and slowly elevate from the floor toward to the chest. Stretch in the position for 30 seconds, then change to the left side.	

Figure 2. Protocols for vibration rolling, nonvibration rolling, and static stretching.

the left lower limb. Each stretching exercise was performed three times for the quadriceps and hamstrings in a rotational order.

Statistical analyses

All data analyses were performed using SPSS, version 19 (Chicago, IL, USA). Data are presented as mean ± standard deviation (SD). Data were inspected visually and statistically for normality (Shapiro–Wilk's test, $P > 0.05$), and all variables were normally distributed. Descriptive statistics were performed for the characteristics of the participants. If the sphericity assumption was violated in Mauchly's sphericity test, the Greenhouse–Geisser adjustment was used to correct the degrees of freedom. A 2 (time: pretest vs. posttest) × 3 (condition: VR vs. NVR vs. static stretching) analysis of variance (ANOVA) was performed to examine the effects of different conditions on dependent variables. Any significant condition by time interaction was followed by a full analysis of simple main effects. If a significant ($P < 0.05$) effect was found, the analysis was continued with a one-way ANOVA and post-hoc testing involving pairwise comparisons with Bonferroni correction method, as suggested by Munro (Munro, 2005). The effect size (Cohen's d) – the difference between pretest and posttest means divided by their common SD – was calculated and interpreted as small (d = 0.2), medium (d = 0.5) or large (d = 0.8) to present the magnitude of the effect. (Lakens, 2013) Statistical power was measured using G*Power 3.1 (Faul, Erdfelder, Buchner, & Lang, 2009). The significance level (α) was set at 0.05.

To certify that measures on ROM and YBT were greater than measurement error, MDC value was calculated. To calculate MDC, SEM was calculated first by the formula SEM = SD_{test} x √ (1-ICC), where SD_{test} is the standard deviation of scores from the first test and ICC is the test-retest intraclass correlation coefficient (Monteiro, Vigotsky, Novaes, & Skarabot, 2018). Subsequently, MDC was calculated as 1.96 × √2 × SEM.

Results

The results for all outcomes are shown in Table 1.

Knee range of motion outcomes

For the knee flexion ROM, the condition × time interaction ($F_{2,58}$ = 0.33, P = 0.56) and main effect of condition ($F_{1,29}$ = 0.33, P = 0.56) were not significant. However, the main effect of time was significant ($F_{1,29}$ = 18.83, $P < 0.01$), indicating a difference between pre and postintervention knee flexion ROM. Compared with preintervention, participants showed significant improvement in Ely's test after VR ($P < 0.01$) and static stretching (P = 0.01) but not after NVR (P = 0.41).

For the knee extension ROM test, the condition × time interaction ($F_{2,58}$ = 0.57, P = 0.56) and main effect of condition ($F_{1,29}$ = 0.09, P = 0.89) were not significant. However, a significant main effect of time ($F_{1,29}$ = 76.16, $P < 0.01$) was observed, indicating a difference between pre and postintervention knee extension ROM. Compared with preintervention, participants showed significant improvements in the popliteal angle test for all the three conditions (All $P < 0.01$).

Joint proprioception outcomes

For the knee joint proprioception test, the condition × time interaction ($F_{2,58}$ = 2.77, P = 0.07), main effect of condition ($F_{1,29}$ = 0.41, P = 0.66), and main effect of time ($F_{1,29}$ = 0.18, P = 0.67) were not significant. Compared with the preintervention, participants had significant changes in the knee joint proprioception after NVR (P = 0.04) but not after VR (P = 0.10) and static stretching (P = 0.95). In particular, participants had a significantly higher knee reposition angle error after NVR than after VR (P = 0.02).

Muscle strength outcomes

For the knee extension peak torque, the condition × time interaction ($F_{2,58}$ = 8.27, $P < 0.01$) was significant, indicating a difference in groups and time interventions. We further analyzed the simple main effect. The participants showed significant improvements in knee extension peak torque after VR ($P < 0.01$) and NVR (P = 0.01), but not after static stretching (P = 0.58). Compared with preintervention, participants improved significantly more in knee extension peak torque after NVR ($P < 0.01$) compared with that after static stretching. For the knee flexion peak torque, the condition × time interaction ($F_{2,58}$ = 2.16, P = 0.12) and main effect of condition ($F_{1,29}$ = 2.82, P = 0.06) were not significant. However, the main effect of time was significant ($F_{1,29}$ = 4.75, P = 0.03), indicating a difference between pre and postintervention knee flexion peak torque. Compared with preintervention, participants exhibited significant improvement in knee flexion peak torque after VR ($P < 0.01$) but not after NVR (P = 0.25) and static stretching (P = 0.86).

Balance outcomes

For the YBT, the condition × time interaction ($F_{2,58}$ = 3.16, P = 0.05) and main effect of condition ($F_{1,29}$ = 3.11, P = 0.05) were not significant. However, the main effect of time was significant ($F_{1,29}$ = 52.23, $P < 0.01$), indicating a difference between pre and postintervention YBT. Compared with preintervention, participants improved more significantly by 1.8-fold in dynamic balance after VR compared with that after static stretching (P = 0.01).

Table 1. Outcomes for vibration rolling, nonvibration rolling, and static stretching conditions.

	Knee Range of motion		Joint proprioception	Muscle strength		Balance
	Flexion (degrees)	Extension (degrees)	Proprioception (degrees)	Quadriceps ($N·m·Kg^{-1}$)	Hamstrings ($N·m·Kg^{-1}$)	Y balance test (%)
Vibration rolling						
Pre	123.00 ± 8.00	134.42 ± 9.86	4.14 ± 1.98	2.36 ± 0.56	1.61 ± 0.32	98.42 ± 6.32
Post	126.08 ± 7.65*	142.08 ± 11.35*	3.48 ± 1.85	2.56 ± 0.63*	1.67 ± 0.33*	102.07 ± 5.53*
Change	3.08 ± 3.06	7.67 ± 6.98	−0.66 ± 2.15	0.20 ± 0.26	0.06 ± 0.11	3.64 ± 2.45
Effect size	1.01	1.10	0.3	0.78	0.57	1.49
Nonvibration rolling						
Pre	123.67 ± 8.83	135.5 ± 10.57	3.13 ± 1.85	2.39 ± 0.54	1.62 ± 0.31	97.19 ± 6.17
Post	124.42 ± 7.18	141.75 ± 11.84*	4.08 ± 2.56*	2.49 ± 0.50*	1.65 ± 0.31	99.94 ± 6.39*
Change	0.75 ± 4.91	6.25 ± 8.35	0.95 ± 2.43[a]	0.09 ± 0.19	0.03 ± 0.16	2.76 ± 3.51
Effect size	0.15	0.75	0.4	0.47	0.21	0.79
Static stretching						
Pre	123.42 ± 8.13	135.58 ± 11.57	3.95 ± 2.11	2.45 ± 0.50	1.56 ± 0.37	97.34 ± 6.48
Post	126 ± 7.18*	141.58 ± 10.49*	3.98 ± 2.34	2.42 ± 0.56	1.56 ± 0.39	99.36 ± 6.25*
Change	2.58 ± 3.69	6.00 ± 4.23	0.03 ± 3.05	−0.02 ± 0.22[a]	−0.003 ± 0.11	2.02 ± 2.78[a]
Effect size	0.7	1.14	0.01	0.09	0.03	0.73

Values are mean ± standard deviation. *Significant difference ($P < 0.05$) compared with pre-test. [a] Significant difference ($P < 0.05$) compared with vibration rolling.

Discussion

To the best of our knowledge, this was the first study to investigate whether the practical use of VR as a warm-up protocol improves the flexibility, joint proprioception, muscle strength, and dynamic balance of the lower extremity. Our results indicated that VR considerably improved muscle performance. Overall, the main findings of this study were as follows. (1) Time effect (preintervention vs. postintervention): after VR, there were significant increases in both Knee flexion and extension ROM and muscle strengths as well as dynamic balance. However, there were no significant changes in the knee joint proprioception after VR, indicating that VR does not exert detrimental effects on knee joint proprioception. (2) Condition effect: among the three conditions (VR, NVR, and static stretching), VR was significantly more effective than static stretching because VR increased quadriceps muscle strength by 2-fold and dynamic balance ability by 1.8-fold.

The efficacy of VR in ROM, muscle strength, proprioception, and balance

Regarding the effects of knee ROM, we found that VR increased the ROM on knee flexion and extension with a large effect size (d = 1.01 and 1.1). Regarding the effect of knee proprioception, we found that the participants had a significantly lower knee joint reposition error after VR than after NVR. That is, this study provided the first data verifying that VR may not disturb proprioception changes (i.e., joint reposition angle error). Because proprioception is the conscious perception of the body position in space and provides immediate feedback to joint stability once joint proprioception is disturbed, it is a critical factor that can increase the susceptible to joint sprain injury. Similar to a previous study, vibration stimulation of the muscles is believed to affect afferent nerve pathways (Pollock, Provan, Martin, & Newham, 2011), and vibration stimuli have a sound effect on the proprioceptive sense (Wall & Kentala, 2010).

Next, we considered the effects of muscle strength after rolling. However, previous studies (Macdonald et al., 2014; MacDonald et al., 2013; Su et al., 2016) have found that an acute bout of foam rolling caused no change in muscle strength. Especially, a previous study compared with the acute effects of a single-bout of lower extremity self-myofascial release using foam rolling, and dynamic stretching exercise. The results yielded no significant changes in both foam rolling and dynamic stretching groups for knee extensor and flexor muscle strengths before and after the application (Behara and Jacobson, 2017). By contrast, the results of current study showed significantly increased knee muscle strength after VR with a medium-to-large effect size, indicating VR may be directly to affect target muscle from activation of vibrational afferent feedback. Finally, we found that the participants had significantly improved dynamic balance (P = 0.014) and peak torque of quadriceps after VR (P < 0.001) compared with that after static stretching. Regarding the relationship between dynamic balance and peak torque after VR, the changes in balance and peak torque of quadriceps were significantly correlated (Pearson's r = 0.5, P = 0.001). The eccentric contraction of quadriceps is crucial for the participants because they should maintain balance on standing leg and reach as far as possible on another leg simultaneously. Therefore, the quadriceps muscle acts as a dynamic stabilizer of the knee joint and has some association with balance. VR may be helpful to improve dynamic balance (reaching distance) through the effective improvement of muscle strength of the quadriceps muscle in young adults.

Possible mechanisms for VR as a warm-up

The mechanism underlying the positive effects after VR is postulated as follows. SMR may mechanically breakdown these abnormal crosslinks, remobilizing the fascia back to its normal aligned state, and in response, comfortably increasing soft-tissue compliance to enable longer muscle length (Stone, 2000). Concurrently, the additional transmission of mechanical oscillations to the limb through VR affects several physiological systems, such as skin receptors, muscle spindles, ligament proprioceptors, and joint mechanoreceptors (e.g., the Golgi tendon organ) (Moezy, Olyaei, Hadian, Razi, & Faghihzadeh, 2008). Therefore, vibrations induce high activities at the muscle belly, potentially increasing the number of motor units being recruited (Cochrane, 2011; Lau & Nosaka, 2011) and thus maintaining the sense of the knee joint. Meanwhile, vibration increases blood flow (Games, Sefton, & Wilson, 2015), which may boost muscle contraction activity.

Strengths and limitations

Current data suggested that VR on quadriceps and hamstring muscles as a warm-up exercise yields significant benefits in increasing knee ROM, muscle strengths, and balance, without disturbing knee joint proprioception. Because the optimized warm-up strategy in athletes is still unconcluded, athletic professionals may take this information into account when planning how to exploit the time in preperformance routines effectively. Some limitations warrant investigation in the future. First, this investigation was performed only in healthy participants; thus, the results may not be directly translated to the injured population. Second, there is no specific or skill-based portion to the warm-up. Third, the vibrating roller was investigated at only one frequency (28 Hz) within the optimal frequency range to affect the musculoskeletal system (Luo, Zhang, Zhang, He, & Wang, 2016; Slatkovska, Alibhai, Beyene, & Cheung, 2010). Other frequencies may have generated different outcomes.

Conclusions

VR, as a warm-up exercise, significantly increased ROM, isokinetic peak torque, and balance, without hampering knee joint proprioception. Furthermore, compared with NVR or static stretching, VR was significantly more effective than static stretching in increasing quadriceps muscle strength and balance. Hence, we recommend including VR as a part of the warm-up regimen in young adults. This investigation provides new insights into future research on this technology. Athletic professionals may take this information into account for designing more efficient and effective preperformance routines.

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Disclosure statement

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