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Original Article

The effects of two different frequencies of whole-body vibration on knee extensors strength in healthy young volunteers: a randomized trial

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Abstract

The aim of this study was to investigate the effects of two different frequencies of whole-body vibration (WBV) training on knee extensors muscle strength in healthy young volunteers. Twenty-two eligible healthy untrained young women aged 22-31 years were allocated randomly to the 30-Hz (n=11) and 50-Hz (n=11) groups. They participated in a supervised WBV training program that consisted of 24 sessions on a synchronous vertical vibration platform (peak-to-peak displacement: 2-4 mm; type of exercises: semi-squat, one-legged squat, and lunge positions on right leg; set numbers: 2-24) three times per week for 8 weeks. Isometric and dynamic strength of the knee extensors were measured prior to and at the end of the 8-week training. In the 30-Hz group, there was a significant increase in the maximal voluntary isometric contraction (p=0.039) and the concentric peak torque (p=0.018) of knee extensors and these changes were significant (p<0.05) compared with the 50-Hz group. In addition, the eccentric peak torque of knee extensors was increased significantly in both groups (p<0.05); however, there was no significant difference between the two groups (p=0.873). We concluded that 8 weeks WBV training in 30 Hz was more effective than 50 Hz to increase the isometric contraction and dynamic strength of knee extensors as measured using peak concentric torque and equally effective with 50 Hz in improving eccentric torque of knee extensors in healthy young untrained women.

Keywords: Exercise, Muscle, Isometric, Concentric, Eccentric

Introduction

Recently, whole-body vibration (WBV) training has been widely used in gyms, sports medicine, and rehabilitation clinics with potential beneficial effects for improving muscle strength and power, balance, bone health, or pain[1]. Indeed, two meta-anaylses evaluating the effects of WBV on muscular strength and power provided evidence that WBV was more effective in improving muscle strength and power in terms of knee extensor muscle strength and jumping performance when compared with controls without WBV[2] and similarly effective in enhancing chronic muscle power adaptations when compared with traditional plyometric exercises[3]. However, these meta-analyses[2,3] included/pooled studies with diverse populations (men and/or women, trained and/or untrained participants and/or athletes with differing ages) as well as with discrepant treatment protocols in relation to the type of vibration platform, either vertical or side-to-side alternating, exercise performed on the vibration platform (static and/or dynamic), the frequency and amplitude of WBV, the amount or duration of treatment, and the measurement methods. Along with this, while overall results were encouraging with regard to muscle strength and power, subgroup analyses yielded varying results in terms of participant profiles (young or middle-aged) and lower (≤30 Hz, <2-4 mm) or higher (>30 Hz-up to >4-6 mm) WBV frequencies and amplitudes[2]. The results of more recent studies (not included in the aforementioned meta-analyses[2,3]) on muscle performance in healthy adults also varied. Some studies indicated no significant effect of WBV on knee extensor muscle strength despite an increase in knee flexor muscle strength with vibration stimuli of 25 Hz and 6 mm on a side-to-side alternating vibration device[4] and with 40 Hz and 2-4 mm[5], or when added to resistance training with 20-40 Hz and 2.5-5 mm on a vertical vibrating platform[6]. Some others demonstrated significant improvements in jump performance with 30-45 Hz of frequency and 4 mm of peak-to-peak displacement on a vertical vibration platform[7] and with 18-

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32 Hz frequency and 1-3 mm amplitude[8]. Another study found an increase in knee extensor peak torque performance with a 40 Hz frequency and 0.76 peak-to-peak displacement on a vertically vibrating platform[9]. It is apparent that the results of studies on the effects of WBV on muscle strength and power are inconsistent thus far, not allowing inferences on the optimal WBV frequency for achieving significant muscle strength gain.

Since differing vibration frequencies are known to be significant predictors of neuromuscular responses[1], it is important to determine which vibration frequency is better than the other for improving muscle strength. However, studies comparing different vibration frequencies for this purpose are not as many as those utilizing specific frequencies and focus on acute effects of WBV in the majority. In acute WBV effect studies (one bout of application) utilizing vibration frequencies and amplitudes ranging from 20 to 50 Hz and 2 to 5 mm (constant in most studies), while some studies favored 30 Hz frequency[10-12], some others favored frequencies within the range of 30-35 Hz[13], 40 Hz[14], or 50 Hz[15,16] for eliciting peak muscle activity, jump performance, or muscle strength and power when compared with other frequencies regardless of vibration amplitude in healthy young, middle-aged or older men and women. Adams et al.[17], comparing WBV stimuli of 30, 35, 40, and 50 Hz with amplitudes of 2-4 mm vs. 4-6 mm pointed to the effectiveness of higher vibration frequencies combined with higher amplitudes and lower frequencies combined with lower amplitudes for eliciting peak muscle performance in young males and females. Among the few long-term WBV training studies comparing different frequencies, while Petit et al.[18] reached the same conclusion with Adams et al.[17], the results of the study by Chen et al.[8] were in contradiction with those of Adams et al.[17] indicating higher frequencies with lower amplitudes (32 Hz, 1 mm) and lower frequencies with higher amplitudes (18 Hz, 3 mm) and with similar acceleration both led to improvement in jumping performance after 8 weeks of training. Thus, the impact of different frequencies of vibration on lower extremity muscle strength and power is still unclear and the debate seems to revolve around WBV frequencies between 30 Hz and 50 Hz.

Based on all the aforementioned issues, there is a need for more research using different vibration frequencies over longer WBV training periods to be conducted on healthy people to identify which vibration frequency is better than the other to improve knee extensors muscle strength.

The aim of the current study was to examine the effects of an 8-week WBV training program with two different frequencies of synchronous vertical vibration platform (30 and 50 Hz) with the same peak-to-peak displacement on isometric contraction and concentric/eccentric peak torques of knee extensor muscles in young healthy untrained women, and to compare the difference between 30 Hz and 50 Hz to provide more evidence for optimizing a WBV training protocol.

Materials and methods

Study design

This study was a prospective randomized 8-week interventional trial, which was conducted between December 2011, and December 2012, at the Department of Physical Medicine and Rehabilitation in the Faculty Hospital. The study protocol was approved by the Faculty's Local Ethics Committee in conformity with the Declaration of Helsinki. All participants provided written informed consent before participating in the study after they were informed of the purpose of the study.

Participants

Twenty-two eligible healthy untrained young women aged between 22-31 years volunteered to participate in the study. The exclusion criteria were as follows: (i) prior experience of WBV training, (ii) participation in any systematic training programs that encompass strengthening and/or aerobic exercises at least 2 days per week, (iii) history of operation, severe trauma, and/or fracture, (iv) presence of musculoskeletal diseases such as acute herniated disc or spondylolisthesis, (v) presence of any condition that would complicate participation in exercise training programs (e.g. osteoarthritis in hip or knee joints), (vi) presence of malignancies, cardiovascular, pulmonary, gastrointestinal, urogenital, neuromuscular and/or any chronic diseases that might affect neuromuscular performance (e.g. diabetes mellitus, epilepsy), (vii) use of any medication that affects neuromuscular performance, (viii) presence of gall or kidney stones, prosthesis, and intraocular lens, (ix) smoking and alcohol consumption, and (x) pregnancy. Demographic characteristics of the participants were obtained at baseline assessment.

Randomization

By the order of application to the department, 22 eligible participants were randomly allocated equally to the two groups using the computer-generated random numbers: 30-Hz Group (n=11) and 50-Hz Group (n=11).

Dynamometric muscle strength assessment

In this study, strength of knee extensors was measured using Biodex Multi-joint System 3 Pro (Biodex Medical Systems, Inc., Shirley, New York, USA). To obtain more accurate results, all tests were performed at the same time of day (±1 h) by an experienced physiotherapist. During the test sessions, the temperature and humidity of the examination room was 21°C and 40%, respectively.

All measurements were made unilaterally on the knee extensor muscles of the right lower extremity which was practically regarded as the dominant leg based on the right-handedness of all the participants shown to be in agreement with right-footedness in nearly 90% of women[19]. For all isokinetic tests, the participants were placed in a seated position with a trunk-thigh angle of 105° and strapped securely around the chest and waist to minimize movement of the trunk. During the testing procedure, each participant kept their arms crossed on their chest to minimize upper body influence on torque output. The rotation axis of the dynamometer was aligned with the knee flexion-extension axis on lateral condyle of the femur and the leg was strapped to the dynamometer lever arm 2 cm proximal to the lateral malleolus. For familiarization, all participants performed three habituation tests.

Parameters	1-2 weeks LFG	1-2 weeks HFG	3-4 weeks LFG	3-4 weeks HFG	5-6 weeks LFG	5-6 weeks HFG	7-8 weeks LFG	7-8 weeks HFG
Vibration frequency (Hz)	30	50	30	50	30	50	30	50
Peak-to-peak displacement (mm)	2	2	2	2	4	4	4	4
Peak acceleration (g)	3.6	10.0	3.6	10.0	7.6	20.1	7.6	20.1
Exposure to vibration without rest (s)	30	30	30	30	45	45	45	45
Repetition of each exercise (n)	2	2	4	4	6	6	8	8
Rest period between repetitions (s)	30	30	30	30	45	45	45	45
Total exposure to WBV in each session (min)	2	2	4	4	13.5	13.5	18	18
Different exercises which performed on the WBV platform								
- Semi-squat	+	+	+	+	+	+	+	+
- One-legged squat	+	+	+	+	+	+	+	+
- Lunge	-	-	-	-	+	+	+	+

WBV, whole-body vibration; LFG, low frequency group; HFG, high frequency group.

Table 1. The volume and intensity of the WBV training program.

The participants were also motivated with verbal encouragement throughout all tests to ensure that each test was performed with maximal effort. The participants were tested within 2 weeks of the beginning and the end of the study. To avoid any acute effect of training sessions on test results, post training measures were conducted at least 72 h after the last WBV training session. The testing procedure was performed under two conditions: isometric and dynamic contractions of the knee extensors.

Isometric strength: The participants were examined for maximal voluntary isometric contraction of the knee extensors at 60° knee joint flexion (where 0° corresponded to full knee extension). Two trials (3-second duration) separated by a 60-second rest interval between attempts were completed and the highest value was recorded as maximal voluntary isometric contraction (Nm).

Dynamic strength: Concentric and eccentric peak torques of knee extensors were evaluated at an angular velocity of 60°/s during isokinetic knee extension and flexion between 10° and 90° of knee angles. The participants performed a series of four consecutive isokinetic knee flexion and extension movements against the lever arm of the dynamometer. The greatest peak torque (Nm) for each of the concentric and eccentric contractions was used for analysis.

Vibration training

All participants were advised to continue normal daily living and maintain their current physical activity levels and asked not to participate in any systematic exercise training programs throughout the study.

Training sessions: The WBV training program for both groups consisted of 20-60-minute sessions on three non-consecutive days per week (Monday, Wednesday, and Friday) for eight weeks. Each exercise session was strictly supervised by the investigators at the Department of Physical Medicine and Rehabilitation. Attendance of the participant was recorded by the investigators and was analyzed at the end of the study. All volunteers who participated in at least 80% of the WBV training sessions were defined as being adherent to the WBV training program and were included in the final analysis.

In each WBV training session, the participants firstly performed a standardized 5-minute warm-up program consisting of lower extremity stretching exercises (primarily for quadriceps) and cycling on a stationary bike (50 watts) and then they were subjected to a WBV training program (see details below). Finally, they were trained to cool down with lower extremity stretching exercises (primarily for quadriceps) for about 10 minutes.

The WBV training program consisted of unloaded static exercises. The WBV training volume was increased systematically over the 8 weeks by increasing the amplitude of vibration, the exposure time to vibration, the number of repetition for each exercise, and/or the number of different exercises. The duration of WBV training session, including warm up and cool down, was between 20-60 minutes, depending on the stage of the study. Details of the WBV training program are described in Table 1.

Vibration conditions: A tri-planar (mostly vertical, Z axis) oscillating vibration platform (Power Plate® pro5™; Power Plate North America, Inc., Northbrook, IL, USA) was used in all training sessions for generating mechanical vibration. The frequency of vibration platform was fixed at 30 Hz for the 30-Hz Group and 50 Hz for the 50-Hz Group throughout of the study. We used the predetermined setting of "low amplitude" (peak-to-peak displacement of the vibration platform: 2 mm) in the first four weeks, and "high amplitude" (peak-to-peak displacement of the vibration platform: 4 mm) during the second four weeks of the study similarly for both groups (Table 1). All participants were familiarized with the vibration platform and the correct positioning for use. During all training sessions, the participants stood on the vibration platform with sport socks (without shoes) and the foot position was standardized for all participants.

Exercise positions: The participants in the two groups performed the following 3 unloaded static exercises that targeted knee extensor muscles:

	30-HZ Group (n=10)	**50-HZ Group** (n=9)	
	Mean ± SD (min-max)	*Mean ± SD (min-max)*	*p**
Age (years)	23.8 ± 2.7 (22-31)	24.7 ± 2.7 (22-31)	*0.451*
Height (cm)	165.1 ± 5.4 (153-172)	166.2 ± 5.1 (160-172)	*0.650*
Weight (kg)	64.2 ± 6.7 (49-74)	57.8 ± 5.1 (51-66)	*0.036*
BMI (kg/m^2)	23.5 ± 2.1 (20.7-27.5)	21.1 ± 2.3 (17.5-24.3)	*0.031*

SD, Standard Deviation; BMI, Body Mass Index.
* *Independent-samples t test*.

Table 2. The homogeneity of demographic characteristics of the participants at baseline between the two groups.

	Dropped-out	**Included in the study**					
Number of Completed Sessions, Maximum n. 24; n (%)	**< 20 (83.3)**	**20 (83.3)**	**21 (87.5)**	**22 (91.6)**	**23 (95.8)**	**24 (100)**	*p**
Number of participants							
30-Hz Group (Total n. 11)	1	2	1	3	1	3	*0.286*
50-Hz Group (Total n. 11)	2	3	2	2	1	1	

* *Independent-samples t test (n.19).*

Table 3. The attendance rate of the participants in vibration training programs and the comparison between the two groups.

- Semi-squat position: The participants stood on the vibration platform while the hands were placed on their waist and the trunk-thigh angle was 130°. Knee angles were 110° and 90° in the first and second halves of the study, respectively.
- One-legged squat position: The participants stood on the vibration platform using their right lower limb with their arms positioned such that their hands were holding the handlebars and the right knee angle was 90°. During vibrating periods, the left lower limb was not placed on the ground.
- Lunge position: The right foot was placed on the vibration platform with the right knee angled at 90°. The left foot was placed on the ground and the handlebars were permitted to be held to support their balance.

Reporting of the study was made according to the recommendations of the International Society of Musculoskeletal and Neuronal Interactions[20].

Data analysis

The normality of distribution was determined by the Shapiro-Wilk test. Since all measures were normally distributed, the parametric tests were used for all statistical analyses. The homogeneity between the two groups was assessed using the independent-samples t test. To compare the posttest – pretest changes within each group, we used the paired-samples t test for two related samples. Improvement percent [(posttest group mean – pretest group mean) / (pretest group mean) x 100] was calculated for each group and compared by the independent-samples t test. To estimate effect size, the Cohen's d value was determined on the basis of the calculated t values. A p-value of <0.05 was considered as the significance level. All analyses were conducted using the SPSS software, version 17.0 for Windows (Statistical Package for the Social Sciences, Chicago, IL, USA).

Results

Participant characteristics and program adherence

Demographic characteristics of the participants at beginning of the study are shown in Table 2. No significant difference existed between the two groups in age (p=0.451) and height (p=0.650) at the baseline. However, there was a significant difference between the two groups in terms of weight (p=0.036) and body mass index (p=0.031).

Of the 22 participants who participated in the training sessions, 19 individuals (10 in the 30-Hz and 9 in the 50-Hz groups) attended at least in 20 of the 24 training sessions (83.3%). The three participants (1 in the 30-Hz and 2 in the 50-Hz groups) who had an attendance rate below 80% were excluded from the final analysis (see Table 3). No significant difference existed between the two groups in the attendance rates (p=0.286).

Outcome measures

There was no significant difference between the two groups at the baseline assessment in terms of all outcome measures (p>0.05). The maximal voluntary isometric contraction significantly increased in the 30-Hz Group (+20.3%; p=0.014); whereas, the slight increase in the 50-Hz Group (+2.6%; p=0.445) was

Outcome measures	Group	Mean ± SD Baseline	Mean ± SD 8-week	Change (%)	Within-group $p^{\dagger}$	Between-groups $p^{\dagger\dagger}$	Between-groups Cohen's d †††
Isometric strength, MVIC (nm)	30-Hz	113.7 ± 26.1	136.6 ± 17.0	+20.3	0.014	0.039	1.08
	50-Hz	119.3 ± 14.7	122.5 ± 22.8	+2.68	0.445		
Dynamic strength, concentric PT (nm)	30-Hz	107.2 ± 15.1	121.8 ± 17.7	+13.6	<0.001	0.018	1.27
	50-Hz	108.4 ± 16.7	110.7 ± 9.8	+2.1	0.605		
Dynamic strength, eccentric PT (nm)	30-Hz	104.2 ± 17.4	119.9 ± 22.6	+16.0	0.001	0.873	0.07
	50-Hz	93.3 ± 16.2	108.3 ± 13.6	+16.0	0.003		

SD, standard deviation; MVIC, maximal voluntary isometric contraction; PT, peak torques.
† *Paired-samples t test*
†† *Independent-samples t test*
††† *Based on the t values*

Table 4. Changes in knee extensors strength from the baseline to the 8-week by the training groups.

not found statistically significant (see Table 4) with a significant between-group difference (p=0.039). The Cohen's d effect size was 1.08 for maximal voluntary isometric contraction.

Similarly, over 8 weeks, a statistically significant increase has occurred in the concentric peak torque of knee extensors in the 30-Hz (+13.6%; p<0.001) group, while not in the 50-Hz (+2.1%; p=0.605) group. When the groups were compared, there was a significant (p=0.018) difference between the two groups in terms of improvements in the concentric peak torque. The Cohen's d effect size was 1.27 for concentric peak torque.

As seen in Table 3, there was a significant increase in the eccentric peak torque of knee extensors in both the 30-Hz (+16.0%; p=0.001) and the 50-Hz (+16.0; p=0.003) groups after the 8-week WBV training program without any significant difference between the two groups (p=0.873). The effect size (Cohen's d) was 0.07 for eccentric peak torque.

Discussion

In the current research, we examined the impact of two different vibration frequencies on knee extensors muscle strength in untrained healthy young volunteers. Taken together, we concluded that the supervised 8-week WBV training program in 30 Hz of vibration frequency was more effective than 50 Hz in increasing knee extensors strength in terms of maximal isometric contraction and peak concentric torque and equally effective with 50 Hz in terms of peak eccentric torque.

Our finding demonstrating better effectiveness of a WBV frequency of 30 Hz on increasing muscle strength is not surprising and is highly supported by other WBV studies. Acute WBV studies (using a similar WBV device) suggested greater effectiveness of WBV frequency of 30 Hz than those of 20 or 40 Hz (with an amplitude of 4 mm)[10] and 35, 40 or 50 Hz (with amplitudes of 2 and 5 mm)[11] and with a low amplitude (2-4 mm) (specifically when measured at 10 minutes post exposure)[17] in improving jumping performance, a muscle power variable shown to be significantly associated with maximal strength[21] in young untrained or moderately trained men and women. Cardinale and Lim[22] found the frequency of 30 Hz as generating the highest muscular electromyographic activity in a half-squat position on a sinusoidal vertical vibration platform allowing up to 10 mm peak-to-peak displacement in female volleyball players when compared with WBV frequencies of 40 Hz, 50 Hz, and sham WBV. The same situation applied to physically active middle-aged men and women in whom 30 Hz of vibration frequency on a side alternating platform produced the highest muscle electromyographic activity with a significantly greater increase than that produced by 6 Hz or 12 Hz; however, without any significant difference between other tested frequencies of 18 and 24 Hz[12]. Furthermore, Da Silva-Grigoletto et al.[23] pointed to the effectiveness of 30 Hz WBV frequency with an amplitude of 4 mm in improving jumping performance in young men. Contrarily, Ronnestad[15] and Marin et al.[16], again using vertically vibrating platforms, proposed a vibration frequency of 50 Hz with amplitudes of 3 mm and 2.51 mm, respectively, as more beneficial than 20 and 35 Hz in improving 1 RM squatting performance[15] and as more effective than 30 Hz with an amplitude of 1.15 mm in increasing muscle activity as measured using electromyography[16].

It is important to note that acute effect studies favoring 50 Hz included heavily loaded dynamic exercises such as squatting either on the vibration platform[15] or before exposure to vibration[16]; whereas, none of the other acute effect studies favoring 30 Hz involved dynamic heavily loaded exercises other than cycle-ergometer, range of motion or stretching exercises for warm-up before vibration exposure[10,11,17,22,23] as was the case also in our study. A very recent study that demonstrated improvement in quadriceps strength after dynamic squats and a decrease in strength after static squats with WBV (synchronous vibrating platform, set at 30 Hz and 4 mm amplitude) in untrained young males and females[24] may well provide an explanation on why 30 Hz of vibration frequency in studies by Ronnestad[15] and Marin et al.[16] was inferior to 50 Hz of frequency which was in an advantageous position for increasing squat performance in trained and/or untrained males and females due to the greater thigh muscle stimulating capability of higher frequencies than that of lower frequencies during squatting[15].

Proceeding to long-term studies, Petit et al.[18], comparing the effects of 6-week WBV training programs with different frequency and peak-to-peak displacement (30 Hz/2 mm versus 50 Hz/4 mm) also demonstrated that high-frequency/high peak-to-peak displacement WBV training was more effective than low frequency/low peak-to-peak displacement WBV or sham training to increase the eccentric knee extensor muscle strength, thus indicating superiority of 50 Hz of vibration frequency to 30 Hz, however, with only statistically significant difference from baseline when compared to 30 Hz in eccentric knee eccentric peak torque (increasing by 16.3%) and not in either isometric strength or concentric peak torque with regard to isokinetic testing. It was interesting to note that we also found 16.0% increase from baseline in the peak knee extensor eccentric torque, however, in both groups. The discrepancy between our results and those of the study by Petit et al.[18] regarding other isokinetic testing parameters might be explained by several factors: differing number of repetition of exercise on the vibration platform (starting from 2 and increasing to 8 in our study vs 10 repetitions in their study) and duration of vibration exposure (between 2 and 18 minutes in each session vs 10 min in each session), demonstrated to have been important in strength gain[23]. Additionally, the difference between the amplitude of vibration, knee angle (with a significant influence on strength gains[12,25,26]) and the profile of the participants [physically active but nonresistance-trained young males (physical education students) in the study by Petit et al.[18] and young untrained females in our study] may play a role in this difference. On the other hand, another long-term study by Martinez-Pardo et al.[27] did find that WBV training with stimuli of 50 Hz and 4 mm significantly increased concentric torque of knee extensors after 6 weeks of WBV training with a working time of 60s and 60s rests and with incremental training of 8 to 13 sets of exercises with a synchronous vibrating platform in recreationally active young men and women, contrary to the findings of Petit et al.[18] who observed no significant changes in concentric torque.

Yet in another long-term study, Chen et al.[8] demonstrated that an 8-week WBV training with high vibration frequency and low amplitude (32 Hz and 1 mm) and with low vibration frequency and high amplitude (18 Hz and 3 mm) with the same acceleration both led to significant increases in jumping performance in moderately trained young adults, attributable to different neuromuscular adaptations[8], including 'tonic vibration reflex[28], proprioception, and body control[29] and balance[8]. Therefore, the study by Chen et al.[8] partly supported our finding of strength gain with a vibration frequency of 30 Hz in a long-term study. On the contrary, de Ruiter et al.[30] reported that WBV training of the same frequency but with a different amplitude (30 Hz, 8 mm) had no effect either on maximal voluntary isometric contraction of knee extensors or on countermovement jump height in healthy students after 11 weeks.

The design of our study does not allow valid comments on the mechanism of why 30 Hz did a better job than did 50 Hz because we did not assess WBV induced changes on muscular activity or other contractile properties of the muscles. Proposed mechanisms include reflex contraction of muscles, the so-called 'tonic vibration reflex' associated with Ia afferents of the muscle spindle, increased responsiveness of Golgi tendon related Ib afferents influencing muscle length, neuromuscular facilitation including increased motor unit recruitment, synchronization, proprioception, coordination, better co-contraction of synergist muscles, increased ability of the muscles to generate force due to hypergravity, enhancement of muscle perfusion, and muscle hypertrophy[1,28,31]. We may speculate that mechanisms other than 'tonic vibration reflex' might be at play in our study due to the notion that the effect of this mechanism is mostly seen in combined dynamic strength training and WBV protocols and at higher frequencies particularly in athlete populations[31]. Whatever the mechanisms may be, the capability of 30 Hz of vibration to increase electromyographic activity of knee extensors has been shown in immediate effect studies[12,28] and its effect on knee extensor strength is also supported by other long-term studies demonstrating effectiveness of frequencies as little as 24-28 Hz with 2-4 mm of amplitude in increasing concentric torque of knee extensors when added to resistance training better than resistance training alone even in competitive skiers[32]. Indeed, effect sizes as calculated using Cohen's d in our study could be considered large for isometric contractions and concentric peak torque with d values of 1.08 and 1.27, respectively, (Table 4) indicating a nonoverlap of estimably more than 50% in the 30 and 50 Hz groups based on the descriptions relevant to Cohen's d as d=0.8 indicating a nonoverlap of 47.4. However, Cohen's d effect size of 0.07 for eccentric peak torque showed that 30 Hz and 50 Hz groups did not differ as also reflected by independent samples t-test (p=0.873)[33]. The reason why isometric contraction and concentric peak torque showed significantly greater increase with 30 Hz vibration frequency and eccentric peak torque did not remains to be elucidated in larger sample sized studies including control groups.

It is apparent that the effect of WBV training program on muscle strength is a matter of vast debate in many aspects, particularly with regard to frequency. In our study, we demonstrated a significant increase in the maximal voluntary isometric contraction of knee extensors, concentric and eccentric peak torque of knee extensors over 8 weeks with a vibration frequency of 30 Hz. While there was a trend to improve in isometric contraction and concentric torque of knee extensors with 50 Hz, the strength gain did not reach a statistical significance; however, 50 Hz of vibration frequency with amplitude incrementally increasing from 2 mm to 6 mm did significantly increase the eccentric peak torque of knee extensors. We believe that our study contributes to evidence in WBV research by providing an efficient protocol that had a progressive nature because the intensity of all variables including vibration conditions, set numbers, and types of static exercises on the platform increased systematically throughout the study. Although it has recently been shown in an acute effect study that dynamic squats on a vibration platform with a frequency of 35-40 Hz was associated with increased quadriceps force production contrary to static squats leading to decreased strength in young men and women indicated not having performed resistance exercises within the past year[24], we observed the opposite, that is, muscle strength increasing effects of WBV training with static squats with either 30 Hz or 50 Hz. However, we cannot tell if static squats had an additive effect to WBV training or vice versa due to the methodology of the study. Siu et al.[34] also found immediate knee extensor concentric peak torque changes with 26 and 40 Hz vibration frequency with peak-to-peak displacements 8 mm and

3.38 mm which were significantly greater than that in the controls exercising static half-squats on a side alternating vibration platform. Advantageous aspects of the combination of static squats with WBV training could be the rapid increase in muscle temperature (for recommending as a warm-up exercises) and less oxygen demand (oxygen uptake) when compared to the combination of dynamic squats with WBV (difference being not statistically significant) as found in a study in young active men and women having exercised on a side alternating platform with a frequency of 26 Hz[35]. Another study found the lowest heart rate response and peak oxygen uptake in sedentary young males after WBV training with static squats than in those after WBV training with dynamic or loaded squats with a vibration frequency of 32 Hz on an oscillatory vibration platform[36], which may have implications for better tolerability, however, with less beneficial effects on aerobic capacity. The demonstration of the effectiveness of 30 Hz of vibration frequency with incrementally increasing amplitudes from low (2 mm) to high (4 mm) on increasing all isokinetic test variables is important based on the findings that this frequency was shown to cause significantly lower rate of perceived exertion as well as lower heart rate compared to 50 Hz[37], allowing its prescription to untrained individuals who may have difficulty in continuing a WBV training program or other exercise programs because of their high demand. Moreover, high frequencies have been found associated with greater muscle fatigue[38] as well as impaired balance as reflected by center of pressure velocity and length, having been found higher in vibration frequencies of 40 and 44 Hz than those of 31 and 35 Hz with approximately 1 mm amplitude on a vertical synchronous vibration device[39].

Strength and limitation of the study

Our study had a number of strengths. A major strength of this study was the relatively long period of WBV training (8 weeks). While quite a number of studies have investigated the acute effects of different vibration frequencies as discussed previously[10-17,34,37], the number of studies that compared the effects of different vibration frequencies for a long period of time is limited[8,18,27]. Secondly, in the current study we included healthy untrained volunteers who have not been exercising more than two times a week. This is important considering that most previous investigations on the effectiveness of WBV training have included moderately active/recreationally trained females and/or males[4,8,11,14,16,27], even physical education students[18], or men and/or women participating regularly in sports[10], except a few including both trained and untrained individuals[15] or only untrained participants[17]. In terms of maintaining good attendance, it is difficult to conduct a training program on healthy and untrained individuals multiple times per week for several weeks who, possibly, are not that interested to improve their musculoskeletal condition. Another strength of the study was the progressive property of WBV training program within 8 weeks in terms of vibration conditions (see Table 1). Furthermore, we prescribed exercises in different knee angles such as one-legged squat and lunge positions to increase the impacts of vibration on the knee extensor muscles, specifically (see Table 1). Additionally, in the current study, all WBV training sessions were supervised by investigators. Finally, the relatively high rate of attendance at WBV training sessions also gave strength to the study. Despite these strengths, our study had a number of limitations that should be considered when interpreting the results. First and most notable, the sample size of the study was too small. Second, the lack of control group was another major limitation of the study. It should be considered that application of really sham vibration on participants is very hard and partly inapplicable.

In conclusion, the findings of this study indicated that 30 Hz of vibration frequency was more effective than 50 Hz in increasing of isometric and concentric peak torque of knee extensor muscles after 8 weeks of WBV training and equally effective with 50 Hz in increasing eccentric torque of knee extensors in young healthy volunteers. Additionally, the contents of the present training protocol can be used to produce optimal recommendations for effective WBV training programs in clinical practice and training centers for improving the strength of knee extensors particularly in untrained individuals who might prefer easier and less strenuous training. However, there is still a need to undertake more randomized controlled studies with different vibration conditions and a larger number of participants to confirm these results.

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