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TITLE: The effect of vertical whole-body vibration on lower limb muscle activation in older adults: influence of vibration frequency, amplitude and exercise.

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ABSTRACT

Objective: Whole-body vibration (WBV) therapy has gained popularity in training muscle strength and balance in the older population. How different WBV parameters affect neuromuscular activation in older adults remains uncertain. This study aimed to investigate how WBV frequency, amplitude, exercise and their interactions influenced leg muscle activity in in the older population.

Study Design: A cross-sectional experimental study that involved ambulatory, community-dwelling older people (n=30; 23 women; mean age=61.4±5.3 years).

Main outcome measures: Muscle activity of the vastus lateralis (VL), biceps femoris (BF), tibialis anterior (TA), and gastrocnemius (GS) were measured by surface electromyography (EMG), during seven different exercises in four WBV conditions (frequency: 30Hz or 40Hz, peak-to-peak amplitude: 1.2mm or 1.8mm) and a no-vibration condition.

Results: Significant increase in muscle activity in VL (3% to 148%), GS (19% to 164%), and BF (16% to 202%), but not TA upon adding WBV ($p \leq 0.015$). The vibration intensity and exercise interaction effect was significant in VL ($p=0.002$), and marginally significant in GS ($p=0.052$). The frequency and amplitude interaction effect was significant in GS only ($p=0.048$). The degree of WBV-induced leg muscle activity was higher during those exercises where the baseline level of muscle activation was low.

Conclusions: WBV significantly increased the EMG amplitude of majority of leg muscles tested, and the effect tended to be more pronounced than that previously reported in healthy young adults. WBV may hence be particularly suitable for muscle strengthening purpose in the frail elderly population, who may not tolerate other forms of vigorous exercise.

Keywords: Older adults; whole body vibration; muscle activity

1. INTRODUCTION

Muscle strength deteriorates during the process of aging [1]. Poor muscle strength has been identified as one of the key components in the diagnosis of frailty, which can lead to physical inactivity, and increase in the risk of acquiring other diseases (e.g., cerebrovascular diseases, depression) [2,3]. Muscle weakness was also found to be associated with balance problems and falls in elderly, resulting in deleterious health consequences (e.g. fractures) and reduced quality of life [4]. An effective intervention is needed to tackle this eminent problem in the aging population.

One of the intervention methods that has been gaining popularity in geriatric rehabilitation is whole-body vibration (WBV). Recent meta-analyses supported the use of WBV training on improving balance and mobility in the elderly population, especially for individuals with poorer balance ability [5,6]. The majority of the studies attributed the improvement in balance and mobility to the increase in muscle strength [7,8]. However, the optimal protocol and the dose-response relationship have not been established due to the wide range of vibration parameters adopted across the different studies.

A number of experimental studies have demonstrated the effect of WBV on muscle activation [9–23], and virtually all reported an increase in EMG amplitude upon adding vibration to various exercises [10–19,21–23]. However, all existing WBV studies on EMG responses were conducted in either the healthy young population [9–11,13–20] or in people with stroke [12,24]. Aging is associated with muscle weakness and related diseases such as sarcopenia [25]. Muscle structure and composition also changes during the aging process [25]. People with stroke, on the other hand, suffer other impairments in muscle function such as spasticity. Evidence on the effect of WBV on neuromuscular activation in the older population is currently not available despite its rising popularity.

In the younger population, several studies reported that the EMG amplitude, increased with source vibration frequency up to 30Hz [11,13]. However, whether a further increase in vibration frequency would lead to a further increase in muscle activation remains controversial [10,11,15–17,21]. While it is likely that the muscle activity induced is influenced by the interaction among vibration frequency, amplitude, and exercise assumed on the platform, most of the studies on WBV adopted either a single vibration frequency [9,14,19], amplitude [9–11,14,16,19], or exercise in the testing protocol [10,18,21–23]. Very few studies varied all three parameters [13,15,17]. And even in these studies, only a few static squatting positions were tested [15,17]. Key factors leading to the difference in results obtained in previous studies hence could not be deduced.

To address the knowledge gaps identified above, a study was undertaken to examine how neuromuscular activation was influenced by different WBV frequencies, amplitudes and exercises in the elderly. We hypothesized that 1) Adding WBV would lead to significantly higher EMG amplitude in all the leg muscles tested compared with the control condition without WBV; 2) The increase in neuromuscular activation induced by WBV of higher frequencies would be significantly higher than that induced by lower WBV frequencies, 3) WBV with higher amplitude would lead to a higher degree of leg muscle activation than WBV with lower amplitude, and 4) There would be significant interaction among exercise, vibration frequency and vibration amplitude on leg muscle activation.

2. METHODS

2.1. Participants and sample size estimation

A cross-sectional experimental study was conducted. Older adults were recruited from the community using convenience sampling though an existing database and snowballing. The inclusion criteria were: (1) aged ≥50 years, (2) medically stable, (3) able to stand for at least 1 minute with hand support, and (4) able to understand simple verbal commands. Exclusion criteria were: (1) neurological conditions, (2) musculoskeletal conditions affecting leg muscle performance, (3) metal implants in the lower extremity, (4) recent fracture in the lower extremity (within 1 year post-onset), (5) diagnosis of osteoporosis, (6) vestibular disorders, (7) peripheral vascular disease, and (8) other serious illnesses or contraindications to exercise. Written informed consent was obtained from each participant prior to data collection. The study was approved by the Human Research Ethics Subcommittee of the University.

Previous studies examining the effect of WBV on lower limb muscle activities in young adults (Cohen's d=3-5) [14] and stroke populations (partial eta-squared=0.064-0.643) [12] yielded large effect sizes. Assuming an effect size of f=0.4 for our ANOVA analysis, alpha of 0.05, and power of 0.8, a minimum of 26 participants would be required.

2.2. Experimental protocol

All the experimental procedures were conducted in the same university laboratory. Data collection for each participant was completed in one single experiment session. During the testing session, the demographic information (e.g. age, medical history) was first obtained via interviewing the participants.

A WBV machine that generates vertical vibration was used (Fitvibe medical, GymnaUniphy NV, Bilzen, Belgium). The WBV protocols involved the use of two frequencies (30Hz and 40Hz) and two amplitudes (approximate peak-to-peak amplitude = 1.2mm and 1.8mm), resulting in 4 unique combinations with different peak acceleration values (i.e. intensity, expressed as units of Earth's gravity g) at 2.25g, 3.40g, 3.65g, and 5.50g respectively [26]. The peak accelerations were verified by triaxial accelerometers (Dytran 7523A5; Dytran Instrumetns, Inc., California, US). A control condition with no WBV was also imposed.

Under each WBV condition, participants were asked to perform seven different exercises: (1) static erect standing (knees flexed at 10°), (2) static semi-squat (knees flexed at 45°), (3) static deep squat (knees flexed at 90°), (4) static tip-toeing, (5) static single-leg-standing (right leg), (6) dynamic semi-squat (moving the knee between 10° and 45° of flexion), and (7) dynamic deep squat (moving the knee between 10° and 90° of flexion). Practice trials were given prior to actual data collection to ensure proper performance of the exercises. An electronic goniometer was used to monitor the knee angle of the particpants throughout the experiment (Twin Axis Goniometer SG150; Biometrics Ltd, Newport, UK).Surface EMG activity of the vastus lateralis (VL), biceps femoris (BF), gastrocnemius (GS), and tibialis anterior (TA) of the right leg were recorded using bipolar bar electrodes (Bagnoli EMG system; Delsys, Inc., Boston, MA) [27], for each of the five static exercises for 10 seconds. Two trials were performed. For the two dynamic exercises, the participants were instructed to perform seven movement cycles as EMG was recorded. A metronome was used to guide the duration of each complete up and down cycle (dynamic semi-squat: 3 seconds; dynamic deep squat: 6 seconds). Intermittent rest was provided upon the request of the participants.

The sequence of the vibration frequency, amplitude and exercise performed were randomized for each individual participant to minimize the potential bias arising from the order effect.

2.3. Data Analysis

All EMG data were collected at 1000Hz using LabView version 7 software (National Instruments Corp., Austin, TX). The collected raw data would be processed using MyoResearch XP, Master Package version version 1.06 (Noraxon USA, Inc., Scottsdale, AZ). The bias for each EMG signal was first calculated and removed. The frequency domains of the signals were then checked. Significant peaks were noted at the nominal frequencies of the data collected in respective WBV conditions. Finite Impulse Response bandpass filter was applied 20 to 250Hz and the Infinite Impulse Response rejector at 30, 40, 50Hz were implemented to eliminate motion artifacts associated with WBV and electrical current. For the five static exercises, the middle three seconds of the data was used for the calculation of EMG root mean square (EMGrms) value, and the EMGrms values of the two trials were averaged to obtain a mean value. For the two dynamic squat exercises, the middle 5 repetitions were used to calculate the EMGrms.

2.4. Statistical Analysis

Statistical analyses were conducted with IBM SPSS software (version 20.0; IBM, Armonk, NY) with the level of significance set at $p \leq 0.05$. Two-way ANOVA with repeated measures (within-subject factor: vibration intensity, exercises) was conducted to examine the EMG data across different conditions. Greenhouse-Geisser epsilon adjustment was used when sphericity assumption was violated. A partial eta-squared of 0.14, 0.6, and 0.01 represent large, medium, and small effect sizes respectively [28]. In cases the main effect of vibration intensity or exercise was significant, post-hoc contrast analysis using paired t-test with Bonferroni adjustment would be performed. Further, for each individual exercise, paired t test was used to compare muscle activation in WBV conditions with no WBV condition. To address the potential inflation of type I error associated with multiple comparisons in this analysis, the level of significance was set at $p \leq 0.01$.

Further, to examine the effect of WBV amplitude and possible interaction effect between WBV frequency and vibration and exercise, a three-way ANOVA with repeated measures was conducted for each muscle (within-subject factors: WBV frequency at 30Hz vs 40Hz; 7 exercises; WBV amplitude: 1.2mm vs 1.8mm).

3. RESULTS

3.1. Demographics

Thirty older adults participated in the study (23 women, mean age=61.4±5.3 years). All participants were able to ambulate independently outdoors (Table 1). The muscle activation during different exercises in the no-WBV condition is illustrated in table 2.

Missing data (0.48% of all dependent variables) due to errors of the data collection processes (human errors, EMG system faults) were replaced by the mean value of other participants in the same conditions prior to data analysis. The results generated from the three-way ANOVA analysis are shown in table 3.

3.2. Muscle activity of VL

Significant main effects of intensity (F=3.932, p=0.015, partial η^2=0.119), exercise (F=48.473, p<0.001, partial η^2=0.626), and exercise × intensity interaction effect (F=4.198, p=0.002, partial η^2=0.126) were found. Post-hoc analysis indicated that all vibration conditions led to significantly higher EMG amplitude than the no-vibration condition ($p \leq 0.038$), by an average of 3% to 148%, depending on the exercise (Fig. 1). However, the EMG amplitude induced by the four WBV intensities was similar but there was a tendency for the 5.50g protocol to trigger higher level of neuromuscular activation than other intensities ($p \leq 0.087$). Post-hoc comparisons indicated that the EMG amplitude was significantly different among all exercises, except for the comparisons between static erect standing and static single-leg-standing (p=0.604), and between static semi-squat and dynamic semi-squat (p=0.291).

3.3. Muscle activity of BF

A significant main effect of intensity (F=7.139, p=0.005, partial η^2=0.198) was found. The main effect of exercise (F=1.659, p=0.206, partial η^2=0.054) and exercise × intensity interaction effect were not significant (F=1.032, p=0.386, partial η^2=0.034). Post-hoc analysis indicated that adding WBV, regardless of the intensity used, yielded higher EMG amplitude (by an average of 16-202%) than the no-vibration condition

($p \leq 0.007$)(Fig. 4). However, no significant difference among the four vibration intensities was noted ($p \geq 0.066$). Dynamic semi-squat and dynamic deep squat led to significantly greater muscle activation than static erect standing, static semi-squat, and static deep squat ($p \leq 0.036$).

3.4. Muscle activity of TA

Significant main effect of exercise ($F=12.585$, $p<0.001$, partial $\eta^2=0.303$) was found. The main effect of intensity ($F=0.254$, $p=0.847$, partial $\eta^2=0.009$), and exercise × intensity interaction effect were not significant ($F=1.640$, $p=0.111$, partial $\eta^2=0.054$) (Fig. 2). Post-hoc comparison indicated that static deep squat and dynamic deep squat induced significantly higher EMG amplitude than all other exercises ($p \leq 0.006$), except static tip-toeing ($p=0.016$). In contrast, static erect standing led to significantly lower TA EMG amplitude when compared with all other exercises ($p \leq 0.003$).

3.5. Muscle activity of GS

Significant main effects of intensity ($F=19.367$, $p<0.001$, partial $\eta^2=0.400$) and exercise ($F=40.901$, $p<0.001$, partial $\eta^2=0.585$) and were found. The exercise × intensity interaction effects, however, was only marginally significant ($F=2.122$, $p=0.052$, partial $\eta^2=0.068$). All four WBV intensities induced significantly higher muscle activation than the no-WBV condition ($p<0.001$). The increase ranged from 19% to 164% on average (Fig. 3). Post-hoc analysis showed that the two highest intensities used (3.65g, and 5.50g) led to significantly higher muscle activation than the lowest intensity used (2.25g) ($p \leq 0.003$). Static tip-toeing exercise ($p<0.001$) and static single-leg-standing ($p \leq 0.005$) yielded significantly higher EMG amplitude than all remaining exercises, while static semi-squat positioned to significantly lower level of GS activation than other exercises ($p \leq 0.051$).

3.6. Three-way ANOVA

Three-way ANOVA analysis indicated a significant main effect of amplitude ($p=0.002$), and a frequency × amplitude interaction effect ($p=0.048$) for GS and frequency × exercise effect for TA only ($p=0.001$) (Table 3).

4. DISCUSSION

This is the first study that examined the EMG activity during exposure to WBV in the elderly population. Using various combinations of vibration parameters, we could provide important insight on the complex interaction among exercise, WBV frequency and amplitude on the effect of lower limb muscle activity induced.

4.1. Influence of WBV intensity

Our findings largely supported our first hypothesis that WBV can effectively induce leg muscle activity in various exercises, with the exception of TA. Our results obtained in VL, BF and GS are generally in line with those reported in the young adult population. When compared with the no-vibration condition, muscle activity was found to be increased significantly in VL (by 3% to 148%), GS (19% to 164%), and BF (16% to 202%) upon adding WBV.

Generally, the increase in muscle activation through WBV achieved in our sample appears to be higher than similar studies in the younger populations [11,15,21]. For example, using a squatting position (70°of knee flexion), Lienhard et al. [21] reported that vertical WBV (intensity: 2.17g and 3.86g) led to increase in muscle activation by 9.2% and 5.2% in VL, and 3.4% and 20.7% in GS respectively. This is comparable to our finding in the static deep squat exercise in VL (2.25g: +5.6%; 3.65g: +7.4%), but lower than our finding in GS (2.25g: 33.6%; 3.65g: 44.3%). In another study on younger adults that involved even higher WBV intensity (peak acceleration: 32.6g), the increase in EMG amplitude in VL (+12%), BF (+26%), and gastrocnemius (+110%) [16] during dynamic squat exercise were in general lower than our findings here (VL:+36%, BF:+74%, GS:+91%).

On the other hand, in the four similar exercises that were adopted in this study (i.e. static erect standing, static semi squat, static deep squat, static single-leg-standing), the increase in muscle activation of VL and GS induced by the lowest intensity (2.25g) was 3 to 34% and 34% to 91%, which is more modest than that reported in a stroke trial that involved an even lower WBV intensity (1.61g; 4% to 215% and 151% to 202%) [12].

Considering the overall evidence generated from this study and previous work in the young adult and stroke populations, it is hence reasonable to suggest that the effect of WBV on muscle activation appears to be more pronounced in those with poorer muscle strength.

4.2. Vibration frequency and amplitude

Our results revealed that higher vibration frequency (40Hz) did not lead to a significant increase in muscle activity when compared with the lower vibration frequency (30Hz), hence our second hypothesis was not supported.

Upon examining the data, it is clear that the frequency effect varied greatly depending on exercises, especially for VL, TA, and BF (Table 3) (Fig 1-2). For example, in static erect standing, both VL and TA experienced much higher increase in muscle activity in 40Hz, but such increase was less apparent in other exercises. The difference in body postures adopted in previous studies may hence explain the contrasting results related to the effects of WBV frequency in the young adult population [10,11,16,17,21]. For example, smaller knee flexion angle (i.e. lower baseline muscle activation) tends to result in further increase in muscle activation when the vibration frequency is increased from 30Hz to 40Hz. During static squat exercise, Cardinale and Lim(16) (knee flexed 100°) and Di Giminiani et al. [11] (mean activation of two squat positions: knee flexed 60° and 90°) showed that the VL activation induced by WBV at 40Hz was less than that when 30Hz was used. Hazell et al. [16,17], in contrast, showed that increasing the frequency to 40Hz led to further increase in VL EMG amplitude compared with 30Hz during static and dynamic squat exercises involving smaller knee flexion angle (knee flexed 60° and 20°-90° respectively).

Our third hypothesis of this study was partially supported in that increase in WBV amplitude increased the level of neuromuscular activation in GS. The WBV-induced EMG response was marginally significant in BF, but not significant in VL and TA. This demonstrated that influence of WBV amplitude on neuromuscular activation could be muscle-specific. Hazell et al. [17] reported that in static semi-squat position, a WBV amplitude of 4mm, compared to 2mm, led to significantly higher muscle activation in BF but not VL. Marin et al. [20] found that at 30Hz of vertical WBV, changing the amplitude from 2mm to 4mm led to further increase in muscle activity in GS but not VL.

The results generated by the 3-way ANOVA were mostly non-significant, with only GS demonstrating a significant main effect of amplitude and frequency × amplitude interaction effect. Thus, hypothesis 4 was not supported. Taken together, the results showed that the independent effect of frequency and amplitude was overall less apparent than the effect of overall intensity.

4.3. Influence of exercises

Among the various exercises adopted in this study, WBV induced the most increase in neuromuscular activation during static erect standing and static single-leg-standing. For the most part, static erect standing is the exercise with the lowest level of muscle activation in the control condition, and thus may have a larger room for further increase in muscle activation upon the addition of WBV (Table 2) [12]. This, however, cannot explain the situation for static single-leg standing exercise, especially in GS and BF, where the baseline muscle activation is already quite high. Similar observation has been found also in the younger population [14].

One potential explanation is that single-leg standing is the only exercise in which the body weight was fully borne by one leg. The increase in weight bearing on a particular lower limb could simulate the increase in load receptors as reported previously [13,21], which facilitates increase in muscle activation through WBV.

Another potential reason could be the higher level of transmissibility of WBV in these two exercises. Transmissibility of the vibration signals measured at hip and head was reported to decrease with increasing knee angle below 30° [29,30]. Other than the static tip-toeing position, in which significant signal damping occurred already at the ankle joint, static erect standing and static single-leg-standing were the only two exercises in this study that involved a knee flexion angle less than 30°. The reduced damping and hence higher transmissibility of WBV signals may lead to a greater increase in muscle activity.

Taken together, these findings may have important clinical implications for frailer individuals. Even in a simple static erect standing exercise, which involved relatively low baseline muscle activity, the amount of WBV-induced muscle activity was actually greater. WBV may thus be particularly suitable to weaker individuals who cannot assume or sustain more difficult exercises (e.g. static deep squat) on the vibration platform.

4.4. Limitations

The results of this study can only be generalized to community dwelling elderly. The WBV was found to generate significant peaks in the frequency spectrum analysis, especially at its nominal frequency. Notch filter was applied to minimize related artifacts, which unavoidably also eliminated the real muscle activity signals at that particular frequency. To allow fair comparisons, all muscle activity signals underwent the same filtering process to minimize the impact.

5. CONCLUSION

Vertical WBV increased muscle activation of VL, GS, and BF, but not TA in older adults. The effect of exercise, frequency, amplitude and their interactions differed depending on the muscle tested. This should be considered while prescribing WBV exercise training for older adults. The degree of WBV-induced leg muscle activity the older adult population was higher when the baseline level of muscle activation was low. The effect of WBV on leg muscle activation in our participants also tended to be more pronounced than that previously reported in healthy young adults. WBV should hence be particularly suitable for muscle strengthening purpose in the frail elderly population, who may not tolerate other forms of vigorous exercise.

Contributors

MYCP, FMHL and LRL contributed to the study design for the study. FMHL and LRL data collection. FMHL and MYCP provided data analysis. MYCP, TCYK and FMHL provided data interpretation. FMHL drafted the manuscript. All authors revised and approved the manuscript.

Conflict of Interest

FMHL was granted a full-time research scholarship by the Hong Kong Polytechnic University (RTSF). MYCP was provided with a research grant by the Hong Kong Polytechnic University (G-YJ41).

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The funder had no role in the study design, data collection, data analysis, interpretation of data, or preparation of the manuscript.

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Table 1. Demographics of participants

	Mean (SD)
Age	61.4 (5.3)
Gender (Women/Men, n)	23/7
Weight, kg	55.1 (7.1)
Height, cm	155.2 (8.2)
Hypertension, n	9
Diabetes, n	1
Other comorbidities, n	3

Table 2. Muscle activation measured in the no-vibration condition

	Static erect standing	Static semi squat	Static deep squat	Static tip-toeing	Static single-leg-standing	Dynamic semi squat	Dynamic deep squat
Vastus lateralis (μV)	26.53 ± 3.20	46.99 ± 4.99	62.87 ± 5.93	19.10 ± 2.44	31.26 ± 3.73	46.58 ± 4.73	55.23 ± 5.19
Biceps femoris (μV)	2.62 ± 0.25	3.30 ± 0.33	4.81 ± 0.76	5.45 ± 1.20	4.78 ± 1.38	5.22 ± 1.11	5.31 ± 0.86
Tibialis anterior (μV)	3.38 ± 0.61	14.11 ± 3.08	26.43 ± 4.67	14.35 ± 3.27	9.49 ± 1.72	14.44 ± 2.86	26.76 ± 4.33
Gastrocnemius (μV)	3.18 ± 0.53	2.88 ± 0.44	4.11 ± 0.58	27.23 ± 4.10	7.07 ± 1.33	6.82 ± 1.41	6.70 ± 1.67

Table 3. Effect of exercise, vibration frequency, vibration amplitude and their interactions on muscle activation (p-values).

	Main effect of exercise	Main effect of frequency	Main effect of amplitude	Exercise × frequency interaction	Exercises × amplitude interaction	Frequency × amplitude interaction	Exercise × frequency × amplitude interaction
Vastus lateralis	<0.001*	0.199	0.141	<0.001*	0.260	0.261	0.250
Biceps femoris	0.245	0.349	0.075	0.053	0.730	0.165	0.443
Tibialis anterior	<0.001*	0.886	0.502	0.055	0.296	0.936	0.881
Gastrocnemius	<0.001*	0.131	0.002*	0.295	0.171	0.048*	0.449

*Significant with p<0.05 in three-way analysis of variance with repeated measures

FIGURE CAPTIONS

Figure 1. Muscle activation of vastus lateralis induced by WBV

The muscle activation level of the vastus lateralis (VL) in various WBV conditions was expressed as a percentage of that in the no-vibration (control) condition for the same exercise. A value greater than 100% represents a greater EMG amplitude than the control condition for the same exercise. The error bars represent one standardized error of the mean. *Significant increase in muscle activation relative to the control condition (paired t-test; $p<0.01$). The same convention is used for all figures. The results showed that both main effect of intensity and exercise × intensity interaction were significant. Post-hoc comparison indicates that only static erect standing had a significantly higher EMG amplitude during exposure to WBV at 3.65g and 5.50g relative to the no-vibration condition.

Figure 2. Muscle activation of bicep femoris induced by WBV

The results showed an overall significant main effect of intensity. The exercise × intensity interaction was not significant. Post-hoc comparison indicated that only static erect standing and static single-leg-standing showed significant increase in muscle activation upon adding WBV.

Figure 3. Muscle activation of tibialis anterior induced by WBV

Both the main effect of intensity and exercise × intensity interaction were not significant. Post-hoc comparison showed that only static erect standing showed a significant increase in muscle activity when WBV at 3.65g and 5.50g was applied, when compared with the no-vibration condition.

Figure 4. Muscle activation of gastrocnemius induced by WBV

The results showed an overall significant main effect of intensity. The exercise × intensity interaction was marginally significant. All exercises, except static tip-toeing and dynamic deep squat, showed significant increase in muscle activation upon adding WBV.