Effects of Vibration Intensity, Exercise, and Motor Impairment on Leg Muscle Activity Induced by Whole-Body Vibration in People With Stroke

Lin-Rong Liao, Gabriel Y.F. Ng, Alice Y.M. Jones, Raymond C.K. Chung, Marco Y.C. Pang

Background. Whole-body vibration (WBV) has increasingly been used as an adjunct treatment in neurological rehabilitation. However, how muscle activation level changes during exposure to different WBV protocols in individuals after stroke remains understudied.

Objective. The purpose of this study was to examine the influence of WBV intensity on the magnitude of biceps femoris (BF) and tibialis anterior (TA) muscle activity and its interaction with exercise and with severity of motor impairment and spasticity among individuals with chronic stroke.

Methods. Each of the 36 individuals with chronic stroke (mean age=57.3 years, SD=10.7) performed 8 different static exercises under 3 WBV conditions: (1) no WBV, (2) low-intensity WBV (frequency=20 Hz, amplitude=0.60 mm, peak acceleration=0.96*g*), and (3) high-intensity WBV (30 Hz, 0.44 mm, 1.61*g*). The levels of bilateral TA and BF muscle activity were recorded using surface electromyography (EMG).

Results. The main effect of intensity was significant. Exposure to the low-intensity and high-intensity protocols led to a significantly greater increase in normalized BF and TA muscle electromyographic magnitude in both legs compared with no WBV. The intensity × exercise interaction also was significant, suggesting that the WBV-induced increase in EMG activity was exercise dependent. The EMG responses to WBV were similar between the paretic and nonparetic legs and were not associated with level of lower extremity motor impairment and spasticity.

Limitations. Leg muscle activity was measured during static exercises only.

Conclusions. Adding WBV during exercise significantly increased EMG activity in the TA and BF muscles. The EMG responses to WBV in the paretic and nonparetic legs were similar and were not related to degree of motor impairment and spasticity. The findings are useful for guiding the design of WBV training protocols for people with stroke.

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Stroke is a major public health issue that poses challenges to health care systems worldwide.[1] Muscle weakness is one of the most common physical poststroke impairments[2] and is related to poor balance, functional limitations, and a lower level of participation in community activities.[3–5] Therefore, researchers have been investigating effective rehabilitation strategies to tackle poststroke muscle weakness.

Whole-body vibration (WBV) training has attracted much attention in both clinical practice and research recently.[6,7] Recent meta-analyses have revealed that WBV has significant therapeutic effects on balance, muscle strength, and mobility in older adults, although the optimal WBV protocol is unknown.[8,9] There are 2 major types of WBV: synchronous vibrations and side-alternating vibrations.[10] In the former type, the vibration platform generates vibrations in a predominantly vertical direction, and thus the amplitude of the vibrations received would be largely the same regardless of the position of the feet on the vibration platform.[10] In contrast, in side-alternating vibrations, the platform rotates about an anteroposterior horizontal axis. Therefore, a greater distance from the axis of rotation would result in vibrations of larger amplitude. Side-alternating WBV also differs from synchronous WBV in that the force is applied alternately between the 2 sides and in that a mediolateral component of the force also is produced.[10] The use of synchronous[11–18] or side-alternating[12,19,20] WBV during exercise has been shown to increase the level of muscle activation in young adults, as measured with surface electromyography (EMG).

More recently, research has focused on the effects of WBV in people with neurological disorders.[21–25] A recent systematic review of randomized controlled trials (RCTs) showed insufficient evidence to refute or support the use of WBV in individuals with stroke to improve neuromuscular function, mainly due to the limited number of studies and methodological weaknesses of the studies reviewed.[26] The systematic review also emphasized that more fundamental research questions need to be addressed before a large-scale RCT is conducted.[26] One of the important questions pertains to the relationship between WBV intensity and the activation levels of different muscle groups and how these factors interact with the different exercises performed and the severity of stroke.

Only one study has examined leg muscle activity during WBV in people after stroke.[27] The results showed that leg muscle activity in both the vastus lateralis (VL) and gastrocnemius (GS) muscles could be significantly increased by 10% to 20% (expressed as a percentage of maximal voluntary contraction [MVC]) during WBV exposure in people with chronic stroke, depending on the exercise performed.[27] In addition, the EMG responses in the VL and GS muscles on the paretic and nonparetic sides during WBV were similar and were not associated with spasticity.[27] However, the EMG responses of the knee flexors and ankle dorsiflexors were not investigated, even though these muscles are equally, if not more highly, affected by stroke.[4] The weakness in these muscles contributes to abnormal gait patterns, including the failure to attain a heel-strike at initial contact and ineffective ankle dorsiflexion during the swing phase, causing the "drop foot" phenomenon.[28] Other studies also demonstrated that knee flexor and ankle dorsiflexor strength was strongly related to walking speed, endurance, and balance in people with stroke.[29,30] However, the way in which the EMG activity of the biceps femoris (BF) and tibialis anterior (TA) muscles changes during exposure to different WBV exercise protocols in individuals after a stroke remains unclear. Whether the EMG responses are related to severity of motor impairment also has never been investigated.

The objective of this study was to examine the influence of WBV intensity on muscle activity of the bilateral BF and TA muscles and its interaction with exercise and the severity of leg motor impairment and spasticity among people with chronic stroke. We hypothesized that: (1) the magnitude of the EMG activity of the bilateral BF and TA muscles would increase significantly with increasing WBV intensity; (2) the magnitude of the WBV-induced increase in leg muscle EMG activity would be exercise dependent (ie, WBV intensity × exercise interaction effect); (3) the WBV would exert similar effects on the EMG magnitude on the paretic side as on the nonparetic side (ie, no WBV intensity × side interaction effect); and (4) the WBV-induced EMG activity in the BF and TA muscles on the paretic side would not be significantly associated with severity of leg motor impairment and spasticity. The findings would be crucial for guiding the design of WBV training protocols for people with stroke.

Method

Study Design

A 3-way repeated-measures design was adopted to investigate the bilateral TA and BF muscle activity during exposure to 3 different WBV protocols and 8 exercise conditions.

Participants

Participants were recruited from local stroke self-help groups between September 2012 and May 2013. The inclusion criteria were: the diagnosis of a hemispheric stroke ≥6 months, being a community dweller, the ability to perform the experimental exercises in the present study, and having some degree of paresis in the affected leg (Chedoke-McMaster Stroke Assessment [CMSA] lower limb motor score of ≤13).[31] The exclusion criteria were: severe cardiovascular conditions (eg, cardiac pacemaker), neoplasms, other neurologic disorders, cerebellar stroke or brain-stem stroke, significant musculoskeletal conditions (eg, amputations), or vestibular disorders. All individuals gave written informed consent before enrollment.

WBV Protocols

All experimental procedures were conducted in a laboratory located in Hong Kong Polytechnic University, Hong Kong. A vibration platform that delivered synchronous vibrations (Jet-Vibe System, Danil SMC Co Ltd, Seoul, Korea) with a frequency range of 20 to 55 Hz and corresponding preset amplitudes was used. The peak acceleration (a_{peak}) was calculated using the formula: $a_{peak}=(2\pi f)^2 A$, where A and f represent the amplitude and frequency of vibrations, respectively.[32] The peak acceleration was usually represented in terms of gravity of Earth (1g=9.81 m/s^2) to facilitate comparisons across studies. We used synchronous WBV, as there is some evidence that it induces a higher level of muscle activity than side-alternating WBV.[12] The Jet-Vibe vibration parameters were verified with a triaxial accelerometer (model 7523A5, Dytran Instruments Inc, Chatsworth, California).

Each participant underwent 3 different WBV conditions in a single experimental session: (1) no WBV, (2) low-intensity WBV (frequency=20 Hz, amplitude=0.60 mm, peak acceleration=0.96g [ie, subgravity]), and (3) high-intensity WBV (30 Hz, 0.44 mm, 1.61g [ie, supragravity]). The sequence of WBV protocols used was decided randomly by drawing lots. A frequency higher than 30 Hz was not used because it was shown in our pilot work to be associated with increased discomfort in this population. Frequencies lower than 20 Hz were not used due to potential resonance effects.[32]

Exercise Protocols

The complete set of 8 static exercises (Fig. 1) was repeated 3 times. The order of the exercises performed for each WBV condition was randomized. Practice trials were given to familiarize the participants with the exercises before the collection of actual EMG data. During each WBV condition, we used a goniometer (Baseline HiRes Plastic 360° ISOM Goniometer, Fabrication Enterprises, White Plains, New York) to check that the desired knee angle was achieved for a specific exercise. The duration of the rest period between the different exercises was set at 1 minute. For standardization, all participants held gently on to the handrail of the WBV device for maintaining body balance only.

Measurements

At the beginning of the first session, the demographic information and clinical history of all participants was obtained through interviews. Motor impairment level of the leg and foot was evaluated using the CMSA.[31] The rating for each body part (ie, the leg and foot) was based on a 7-point ordinal scale (ie, 1=flaccidity, 3=obligatory synergistic movements, 7=normal movement patterns). The CMSA lower extremity total score was computed by summing the leg and foot scores (minimum score=2, maximum score=14), with a higher score denoting less severe motor impairment. The spasticity of the paretic knee and ankle joints was examined using the Modified Ashworth Scale (MAS), which is a 6-point ordinal scale (ie, 0=no spasticity, 4=affected part rigid).[33]

The activity of the bilateral BF and TA muscles was measured using surface EMG. After palpation of the muscle belly and appropriate skin preparation, the bipolar bar electrodes (Bagnoli EMG System, Delsys Inc, Boston, Massachusetts) were attached longitudinally over the middle of the belly of the bilateral BF and TA muscles.[34] In addition, the ground electrode was attached at the fibula head, on the paretic side. The insulated EMG cables were secured to prevent their excessive motion.

Before measuring the EMG response during WBV exercise, participants were asked to undergo a test for MVC. The participants were seated on a chair with backrest placed against a wall and with the hip and knee joint placed at 90 degrees of flexion. The participants were asked to grasp the edge of the chair on each side for further stabilization. To measure the MVC of knee flexion (ie, BF muscle), the tested lower leg was strapped using a nonelastic belt that was attached to a fixed structure. The tested thigh was stabilized by the researcher's hand, and the participants were instructed to perform a maximal isometric knee flexion by pulling against the belt and sustaining it for 10 seconds. To test the MVC of ankle dorsiflexion (ie, TA muscle), the foot was placed in a neutral dorsiflexion/plantar-flexion position. One hand of the researcher stabilized the tested lower leg. The other hand was placed on the dorsal aspect of the tested foot to provide resistance as the participants were asked to perform a maximal isometric ankle dorsiflexion by pushing against the researcher's hand and to maintain for 10 seconds. Three trials were performed for each muscle group, with a 1-minute rest interval between trials. Verbal encouragement was given by the researcher during the contractions to elicit maximal effort from the participants.

The EMG root mean square (EMG_{rms}) value was calculated at intervals of 500 milliseconds.[35] For each participant, the average of the peak EMG_{rms} values obtained in the 3 MVC trials was used to normalize the EMG_{rms} obtained during the WBV exercise trials. Therefore, the EMG magnitude measured in the 3 WBV conditions was expressed as a percentage of the peak EMG magnitude in the MVC trials (%MVC). We used the average of the 3 MVC trials, rather than the highest value achieved out of the 3 trials, to normalize the EMG data because the former value may better reflect the typical performance of the participants. In addition, the reliability of the EMG measurements was excellent, based on the data from our 3 MVC trials (ICC [2,1]=0.96–1.00). Therefore, using the average or highest MVC value for normalizing the data should not create a substantial difference in the results.

The participants were required to maintain each of the 8 exercises (ie, static exercises) (Fig. 1) for 10 seconds and repeat them 3 times, with a 5-second pause between trials. During that period, the bilateral TA and BF muscle EMG activity was recorded. A 5-minute rest period was allowed after the completion of all 8 static exercises for a given WBV condition.

The EMG signals were preamplified (×1,000) and sampled at 1.0 kHz (Bagnoli-8, Delsys Inc) using LabView version 7.0 (National Instruments Corp, Austin, Texas) and saved directly onto a hard disk for offline analysis. The EMG data were further processed using a 20- to 500-Hz band-pass Butterworth filter. Using the Infinite Impulse Response Rejector (MyoResearch XP, Master Package version 1.06, Noraxon USA Inc, Scottsdale, Arizona), the associated harmonics (20, 30, and 60 Hz) were removed from the EMG signals.[27] Bias was calculated and eliminated from the signals, followed by full-wave rectification of the data. The EMG_{rms} was then

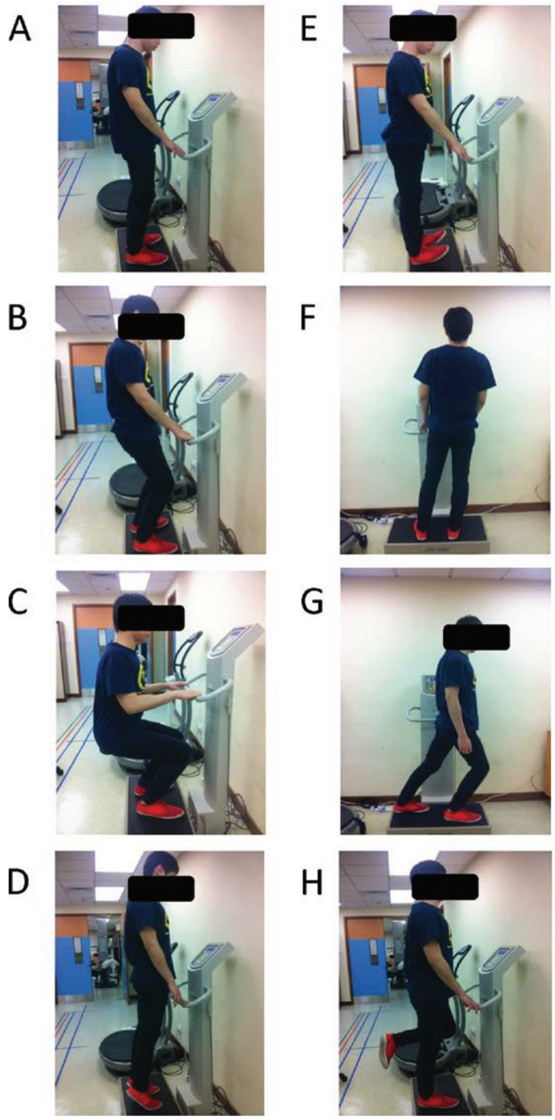

Figure 1.
Exercise protocol: (A) upright standing position—standing with feet placed apart at shoulder width and knees slightly flexed at about 10° and holding for 10 seconds; (B) semi-squat position—standing with feet placed apart at shoulder width and knee flexed at 30° and holding for 10 seconds; (C) deep-squat position—standing with feet placed apart at shoulder width and knees flexed to 90° and holding for 10 seconds; (D) weight-shifted-forward position—starting position same as in upright standing exercise (exercise A), then leaning body weight forward (right) as much as possible and raising heels up and holding for 10 seconds; (E) weight-shifted-backward position—starting position same as in upright standing exercise (exercise A), then leaning body weight backward as much as possible and raising forefoot and holding for 10 seconds; (F) weight-shifted-to-the-side position—starting position same as in upright standing exercise (exercise A), then shifting body weight onto one leg as far as possible and holding for 10 seconds and repeating on the other side; (G) forward lunge position—standing in a forward lunge position with the paretic leg placed in front of the nonparetic leg and flexed at 10°, then leaning forward and shifting body weight onto the paretic leg as much as possible with knee flexed at 30° and holding for 10 seconds, then switching the positions of the 2 legs with the nonparetic leg placed in front of the paretic leg; (H) single-leg-standing position—standing on the paretic leg with knee flexed at 10° and holding for 10 seconds, then repeating on the nonparetic side.

calculated in 100-millisecond windows around every data point.[20] The middle 6 seconds of each trial was selected to calculate the EMG_{rms}.[27] For each specific WBV and exercise combination, the average of the normalized EMG_{rms} values obtained in the 3 trials (expressed as %MVC) was used for analysis.

Data Analysis

Statistical analysis was conducted using IBM SPSS software (version 20.0, IBM Corp, Armonk, New York) to test the 4 research hypotheses, using a desired power level of 0.9. The sample size estimation was based on a previous study that examined leg extensor EMG magnitude during WBV in people after stroke,[27] using G*Power 3.1 software (Universitat Dusseldorf, Dusseldorf, Germany). It was found that WBV significantly increased EMG_{rms} in the VL and GS muscles, yielding large effect sizes for the main effect of intensity (f=0.66–0.93) and a moderate-to-large intensity × exercise interaction effect (f=0.23–0.44).[27] Therefore, for addressing the main effect of WBV intensity (hypothesis 1), intensity × exercise interaction effect (hypothesis 2), and side × intensity interaction effect (hypothesis 3), a large effect size (f=0.4) was assumed.

For hypothesis 1, based on an analysis of variance (ANOVA) (WBV intensity at 3 levels, exercise at 8 levels) and an alpha level of .017 (adjusted for comparisons of 3 WBV intensities), 24 participants would be required to detect a significant difference in normalized EMG response (%MVC) among the different WBV intensities. For hypothesis 2, based on the ANOVA (WBV intensity at 3 levels, exercise at 8 levels) and an alpha level of .05, a minimum of 32 participants would be required to detect a significant intensity × exercise interaction effect. For hypothesis 3, a minimum of 16 participants would be required to detect a significant intensity × side interaction effect (WBV intensity at 3 levels, limb involvement at 2 levels) at an alpha level of .05. For the correlation analysis between normalized EMG responses and CMSA and MAS scores (hypothesis 4), we assumed a moderate correlation (r=.5). A total of 34 participants would be required for this analysis.

First, 2 separate 3-way ANOVAs with repeated measures (limb involvement at 2 levels, WBV intensity at 3 levels, exercise at 8 levels) were used to analyze the normalized EMG_{rms} values for the TA and BF muscles. The 3-way ANOVA would simultaneously yield the results regarding the intensity × exercise × side interaction, main effect of WBV intensity (hypothesis 1), intensity × exercise interaction (hypothesis 2), and intensity × side interaction (hypothesis 3). If a significant intensity × exercise × side interaction was found in the 3-way ANOVA, separate 2-way ANOVAs with repeated measures would be done for the TA and BF muscles of the paretic and nonparetic sides. The Greenhouse-Geisser epsilon adjustment was applied when the sphericity assumption was not fulfilled. When significant results were obtained, contrast analysis using the Bonferroni adjustment was performed.

To further address how the increase in WBV intensity affected the normalized EMG responses (hypothesis 1), a trend analysis was performed. For each exercise, the mean normalized EMG_{rms} values for the 3 WBV intensities were used for trend analysis using Microsoft Excel (version 2007, Microsoft Corp, Redmond, Washington).

Next, to address hypothesis 4, the degree of association of the difference in normalized EMG_{rms} (ie, normalized EMG_{rms} during WBV minus normalized EMG_{rms} without WBV) in the paretic TA muscle with CMSA foot motor score and ankle MAS score was assessed with Spearman correlation coefficients. A similar correlational analysis was carried out for the paretic BF muscle, using the CMSA leg motor score and knee MAS score.

We did not formally test for order effects related either to exercise or to WBV protocol but relied on randomization to minimize order effects.

Role of the Funding Source

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Results

Characteristics of Participants

The study flowchart is shown in Figure 2. Thirty-six individuals with chronic stroke (26 men, 10 women; mean age=57.3 years, SD=10.7) completed all of the measures (Tab. 1). Overall, the impairment level of the affected lower limb was moderate, as revealed by the CMSA lower extremity composite motor score (median=7, first quartile=4, third quartile=12). All participants were ambulatory, and 24 (67%) required a walking aid for outdoor mobility.

Three-Way ANOVA

Our 3-way ANOVAs revealed a significant intensity × exercise × side interaction effect for the TA ($F_{6.42,224.75}$=2.82, P=.01) and BF ($F_{7.87,275.33}$=2.34, P=.019) muscles, indicating that the EMG response to WBV was influenced by the interaction of all 3 factors. The subsequent paragraphs address the main effect of intensity (hypothesis 1), intensity × exercise interaction (hypothesis 2), intensity × side interaction (hypothesis 3), and the associations of EMG responses with motor impairment and spasticity (hypothesis 4).

Main Effect of Intensity

Our 3-way ANOVA models revealed a significant main effect of intensity on normalized EMG responses in the TA ($F_{1.11,38.82}$=80.58, P<.001) and BF ($F_{1.06,37.23}$=140.08, P<.001) muscles, indicating that increasing WBV intensity resulted in an overall increase in EMG magnitude in these muscles. Further analyses using 2-way ANOVA showed that the main effect of intensity remained significant if the TA and BF muscles in the paretic leg and nonparetic leg were analyzed separately (Tab. 2). Post hoc contrast analysis with Bonferroni adjustment revealed that the normalized EMG_{rms} values for the 3 WBV conditions all differed significantly from each other in the BF muscles on both the paretic and nonparetic sides (P<.05). In the paretic and nonparetic TA muscles, the addition of low-intensity and high-intensity WBV during exercise led to significantly higher normalized EMG_{rms} values compared with the same exercises without WBV (P<.05), but the difference between the low-intensity and high-intensity protocols did not quite reach statistical significance (P=.06). The average increase in EMG activity was 10.8% to 12.1%, 19.9% to 22.7%, 10.0% to 10.7%, and 20.6% to 23.1% in the paretic TA, paretic BF, nonparetic TA, and nonparetic BF muscles, respectively, depending on the WBV intensity.

Based on the trend analysis (Fig. 3), it is clear that adding WBV to exercise considerably increased the EMG activity in the 4 muscle groups tested, but the relationship between WBV intensity and normalized EMG response was not a linear one. The data for each muscle group were fitted with a logarithmic curve.

Intensity × Exercise Interaction

The normalized EMG responses during the WBV trials are displayed in Figure 4. The 3-way ANOVA models revealed a significant WBV intensity × exercise interaction effect in the TA ($F_{6.72,235.30}$=15.49, P<.001) and BF ($F_{5.41,189.53}$=2.78, P=.02) muscles, indicating that the differences in normalized EMG_{rms} among the different WBV conditions were exercise dependent. Further analyses using a 2-way ANOVA showed that the WBV intensity × exercise interaction effect remained significant if the TA and BF muscles in the paretic and nonparetic legs were analyzed separately (Tab. 2).

Intensity × Side Interaction

The 3-way ANOVA model revealed no significant intensity × side interaction effect for the TA ($F_{1.26,43.93}$=0.61, P=.48) and BF ($F_{1.08,37.71}$=0.10, P=.91) muscles, suggesting that the normalized EMG responses to WBV did not significantly differ between the 2 sides.

Association With Leg Motor Impairment and Spasticity

Of the 24 WBV exercise conditions for the 4 muscles tested, no relationship was found between WBV-induced changes in EMG activity in the paretic TA and BF muscles and the CMSA motor score or MAS score (P>.05).

Discussion

Our results showed that paretic and nonparetic TA and BF muscle activity was increased significantly by adding WBV

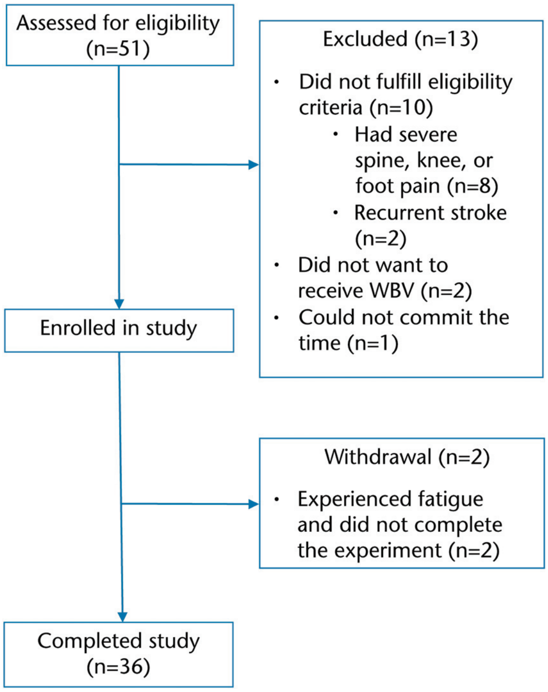

Figure 2.
Study flowchart. A total of 36 people with stroke completed all measurements. WBV=whole-body vibration.

during exercise and that the high-intensity WBV protocol (supragravity, 1.61*g*) resulted in a significantly higher EMG response than the lower-intensity WBV protocol (subgravity, 0.96*g*) in the BF muscles among individuals with chronic stroke. The degree of WBV-induced increase in muscle activity was consistent, regardless of the severity of motor impairment and spasticity.

Influence of WBV Intensity

The first hypothesis was supported because the results revealed that the higher WBV intensity led to a significantly greater increase of muscle activity in the TA and BF muscles of both legs. Our results generally concur with previous WBV research in healthy adults. Typically, a higher WBV intensity is associated with greater EMG responses.[11–20] The increase in muscle activity with WBV varied across the various studies and could be due to difference in characteristics of the participants (eg, people with disability versus people without disability), types of vibration, frequency, amplitudes, additional load, data processing methods, and exercises performed.

Liao et al[27] examined the activity in the VL and GS muscles during WBV in people with stroke. Using the same WBV intensities, the EMG activity of both the paretic VL and GS muscles was significantly increased by the application of WBV, by an average of 10.0% to 10.1% and 14.9% to 17.5%, respectively, depending on the WBV intensity used.[27] However, they did not identify any significant difference in VL and GS muscle EMG activity level induced by the low-intensity and high-intensity WBV protocols. In contrast, the effect of WBV intensity was more apparent in our study. First, the high-intensity protocol induced significantly higher EMG magnitude than the low-intensity protocol in the paretic BF muscle during weight-shifted-forward, weight-shifted-backward, and single-standing exercises and in the nonparetic BF muscle during deep-squat, weight-shifted-backward, and single-standing exercises. Second, the increase in BF muscle EMG activity reported here (by 19.9%–23.1%MVC) was somewhat greater than that in leg extensors (Tab. 2). The greater increase in EMG magnitude reported in this study was partially attributable to the very low EMG activity in the BF muscle without WBV (<5%MVC for most exercises) (Fig. 4), whereas the EMG activity was higher in the VL and GS muscles under control conditions (>10%MVC for the majority of exercises).[27]

The effects of WBV on muscle activation may not be entirely restricted to the peripheral mechanisms (eg, reflex activation of muscles)[36,37] but also may involve corticospinal and intracortical processes.[38,39] Using transcranial magnetic stimulation, Mileva et al[39] showed that, in a sample of healthy men, the application of WBV (30 Hz, 1.5 mm) during static squat exercises increased the motor-evoked potential of the TA muscle, indicating an increase in excitability of the corticospinal pathway. There was also evidence of a WBV-induced alteration of the intracortical processes (increased short-interval intracortical inhibition and decreased facilitation).[39]

Interaction Effect Between WBV Intensity and Exercise

The second hypothesis also was confirmed because a significant overall intensity × exercise interaction effect was found in all 4 muscles tested, indicating that the degree of WBV-induced increase in EMG magnitude was exercise dependent (Fig. 4).

Some other studies investigated intensity × exercise interaction effects,[18,40] but the results were conflicting. For example, Di Giminiani et al[40] showed that the EMG response recorded during different positions was not affected by different vibration frequencies. In contrast, Roelants et al[18] found a significantly greater increase in VL muscle EMG activity in the one-leg-squat position (ie, weight bearing on one leg) than in the high-squat and low-squat positions (ie, weight bearing on both legs) when WBV was applied. In the present study, the intensity × exercise interaction effect was more apparent in the TA muscles (Fig. 4). The WBV-induced TA muscle EMG activity was less during weight-shifted-backward and deep-squat exercises compared with the other exercises after WBV was applied (Figs. 4A and 4B). This difference may have occurred because the bilateral TA muscles had the greatest preactivation without WBV during these 2 exercises, and thus the further increase in EMG activity achieved by the application of WBV may have been slighter. In addition, the vibration energy transmitted to the participants could have been affected by contact of the surface area with the vibration platform.[15] In the weight-shifted-backward exercise, the contact of the surface area with the vibration platform was the smallest among all exercises. Hence, the effect of WBV may be reduced.

Hazell et al[14] also studied the EMG responses of the TA muscle during WBV in young healthy participants. Their results showed that the EMG magnitude of the TA muscle was significantly lower during loaded dynamic squats compared with the same exercise under the unloaded condition. During loaded dynamic squat, the TA muscle EMG magnitude was significantly increased with the application of WBV at 45 Hz, but not 25 Hz or 35 Hz, when compared with the no-WBV condition.[14] Overall, it appears that the activation of the TA muscle is highly dependent on specific exercise conditions and the intensity of WBV stimulation.

Table 1.
Characteristics of the Participants (N=36)[a]

Variable	Value
Basic demographics	
Age (y)	57.6±10.2
Sex, male/female (n)	26/10
Body mass index (kg/m^2)	24.9±2.8
Required walking aid for outdoor mobility, none/cane/quadruped (n)	12/20/4
Abbreviated Mental Test Score (out of 10)	9.1±0.8
Stroke characteristics	
Time since stroke onset (y)	5.0±3.2
Type of stroke, ischemic/hemorrhagic/unknown (n)	22/12/2
Side of hemiparesis, left/right, (n)	16/20
CMSA lower extremity composite score (out of 14), median (first and third quartiles)	7 (4–12)
CMSA leg score (out of 7), median (first and third quartiles)	4 (3–6)
CMSA foot score (out of 7), median (first and third quartiles)	3 (1–6)
Paretic knee MAS score (0–4)[b], median (first and third quartiles)	0 (0–1)
Paretic ankle MAS score (0–4), median (first and third quartiles)	1.5 (1–2)
Comorbid conditions	
Hypertension (n)	23
High cholesterol (n)	19
Diabetes mellitus (n)	6
Knee osteoarthritis (n)	1
Medications	
Antihypertensive agents	21
Hypolipidemic agents (n)	19
Antidiabetic agents (n)	6
MVC EMG_{rms} (μV)	
Paretic leg TA	479.3±222.8
Nonparetic leg TA	700.5±302.5
Paretic leg BF	251.2±102.9
Nonparetic leg BF	377.4±183.8

[a] Mean±SD presented for continuous variables. CMSA=Chedoke–McMaster Stroke Assessment, EMG=electromyography, MAS=Modified Ashworth Scale, MVC=maximal voluntary contraction, EMG_{rms}=electromyography root mean square, BF=biceps femoris muscle, TA=tibialis anterior muscle.
[b] Modified Ashworth Scale is a 6-point ordinal scale. The category 1+ was converted to 1.5 for statistical analysis.

Comparison of EMG Responses Between Paretic and Nonparetic Legs

Our results revealed no significant intensity × side interaction and thus supported our hypothesis that the WBV would induce similar EMG responses in the paretic and nonparetic sides. Hence, there was no evidence of preferential activation of either leg by WBV when performing the exercises described in our study. Similar results were found in a previous study that investigated the EMG responses in VL and GS muscles in people with chronic stroke.[27]

Relationship With Motor Impairment and Spasticity

Our final hypothesis was supported, as no significant relationship was found between the WBV-induced increase in EMG magnitude and the CMSA and MAS scores. The results suggested that WBV had a similar influence on leg muscle activation, regardless of the severity of motor impairment and spasticity. The lack of association of EMG responses during WBV and spasticity also has been shown by Liao et al[27] in their study of VL and GS muscle responses to WBV. Thus, it is highly improbable that the increase in EMG activity during WBV exposure was due to muscle activity triggered by spasticity.

Clinical Implications

Many of the exercises chosen here have been used in previous WBV studies and stroke exercise trials.[9,41] Significant improvements in leg muscle strength have been reported after regular training using these exercises without WBV.[9,41] Our findings showed that TA and BF muscle activity in both paretic and nonparetic legs can be increased considerably

Table 2.
Effect of WBV Intensity on Normalized EMG_{rms} Values[a]

Muscle	WBV Intensity × Exercise Interaction Effect		Main Effect of WBV Intensity		Post Hoc Contrast Analysis					
					No WBV vs Low-Intensity WBV		No WBV vs High-Intensity WBV		Low-Intensity WBV vs High-Intensity WBV	
	F_{df}[b]	P	F_{df}[b]	P	Mean Difference[c] (95% CI)	P[d]	Mean Difference (95% CI)	P[d]	Mean Difference (95% CI)	P[d]
Paretic TA	$6.13_{6.36,222.75}$	<.001*	$55.13_{1.20,42.03}$	<.001*	10.8 (7.0, 14.6)	<.001*	12.1 (8.3, 15.9)	<.001*	1.3 (−0.1, 2.7)	.06
Nonparetic TA	$15.64_{6.08,212.87}$	<.001*	$63.34_{1.07,37.45}$	<.001*	10.0 (6.9, 13.1)	<.001*	10.7 (7.4, 14.1)	<.001*	0.8 (0.0, 1.5)	.06
Paretic BF	$3.00_{5.63,196.89}$	.01*	$119.88_{1.08,37.85}$	<.001*	19.9 (15.5, 24.3)	<.001*	22.7 (17.5, 27.9)	<.001*	2.8 (1.4, 4.2)	<.001*
Nonparetic BF	$2.20_{6.56,229.47}$	.04*	$96.84_{1.05,36.89}$	<.001*	20.6 (15.4, 25.9)	<.001*	23.1 (17.2, 28.9)	<.001*	2.4 (1.2, 3.6)	<.001*

[a] WBV=whole-body vibration, EMG_{rms}=electromyography root mean square, CI=confidence interval, TA=tibialis anterior, BF=biceps femoris. *Statistically significant ($P<.05$).
[b] Greenhouse-Geisser epsilon adjustment was used to generate the *F* score, degrees of freedom (df), and *P* values due to violation of the sphericity assumption.
[c] Electromyography magnitude expressed as percent maximal voluntary contraction.
[d] The *P* values for the contrast analysis are Bonferroni corrected values.

by the application of WBV, particularly the high-intensity protocol, during exercise. Lee et al[42] investigated the level of EMG activity of the TA muscle during the squatting exercise, an exercise commonly used in stroke rehabilitation programs for muscle strengthening purposes. They found that the paretic TA muscle EMG magnitude recorded during the maintenance phase of the dynamic squat exercise was, on average, 3.4 times that during static standing in people with stroke. In our study, we also found that the paretic TA muscle EMG magnitude was greater during semi-squat exercise (2.7%±2.9%MVC) than during static standing exercise (0.9%±0.8%MVC). When high-intensity WBV was added, the paretic TA muscle EMG magnitude was further increased by an average of 12.5%MVC (SD=9.5%MVC). Only one study has examined BF muscle EMG activity after WBV training in people with stroke.[21] Tihanyi et al[21] showed that after one WBV session (20 Hz, peak-to-peak amplitude=5 mm), the EMG_{rms} of the VL muscle during maximal isometric contraction was significantly increased by 44.9%, but that of the BF muscle was not significantly changed.

Some studies have investigated the level of TA or BF muscle EMG activation in people with stroke after different forms of exercise training.[43,44] For example, Andersen et al[43] showed that, after 12 weeks of intervention comprising high-intensity resistance training and body-weight–supported treadmill training, the EMG magnitude of the paretic hamstring muscles during concentric and eccentric knee flexion was increased by approximately 20% to 30% (expressed as a percentage of EMG magnitude of the corresponding muscle on the unaffected side) in a sample of people with chronic stroke. Lee et al[44] found that, in individuals with chronic stroke, 6 weeks of closed kinetic chain exercises led to a significant increase in the EMG magnitude of the paretic TA and BF muscles (by 7%–8%), whereas open kinetic chain exercises resulted in a significant increase (by about 5%–6%) in the EMG magnitude of the paretic BF muscle only. In our study, the amount of WBV-induced increase in EMG magnitude was approximately 10.8% to 12.1% and 19.9% to 22.7% in the paretic TA and BF muscles, respectively (Tab. 2), compared with the no-WBV condition. When comparing these values with those obtained from other forms of exercise training mentioned in the above studies, it appears that the WBV protocols used here may have potential in improving muscle activation in the paretic leg, but our current study design did not allow us to determine the effects on EMG activation after sustained WBV training. Nevertheless, our results suggested that, in addition to WBV intensity, both the choice of exercise and the target muscle group should be considered when prescribing WBV because these factors also affect the muscle response to WBV.

The increase in EMG activity was similar regardless of the level of motor impairment and spasticity, suggesting that individuals with more severe impairments or spasticity may potentially benefit equally from WBV as those with less severe impairments or spasticity. This finding is important because people with severe stroke and limited active movements may find it difficult to engage in other forms of exercise for muscle strengthening purposes. In contrast, WBV training involves holding simple body exercises only and may suit those individuals who have more severe motor or even cognitive impairments.

Methodological Considerations

Surface EMG signals can be easily disturbed by vibration artifacts. Needle electrodes would probably have been a better choice, but we did not use them because of their invasive nature. As in previous studies that used surface EMG to measure muscle responses to WBV,[11–20] proper processing and filtering of the EMG signals were done to

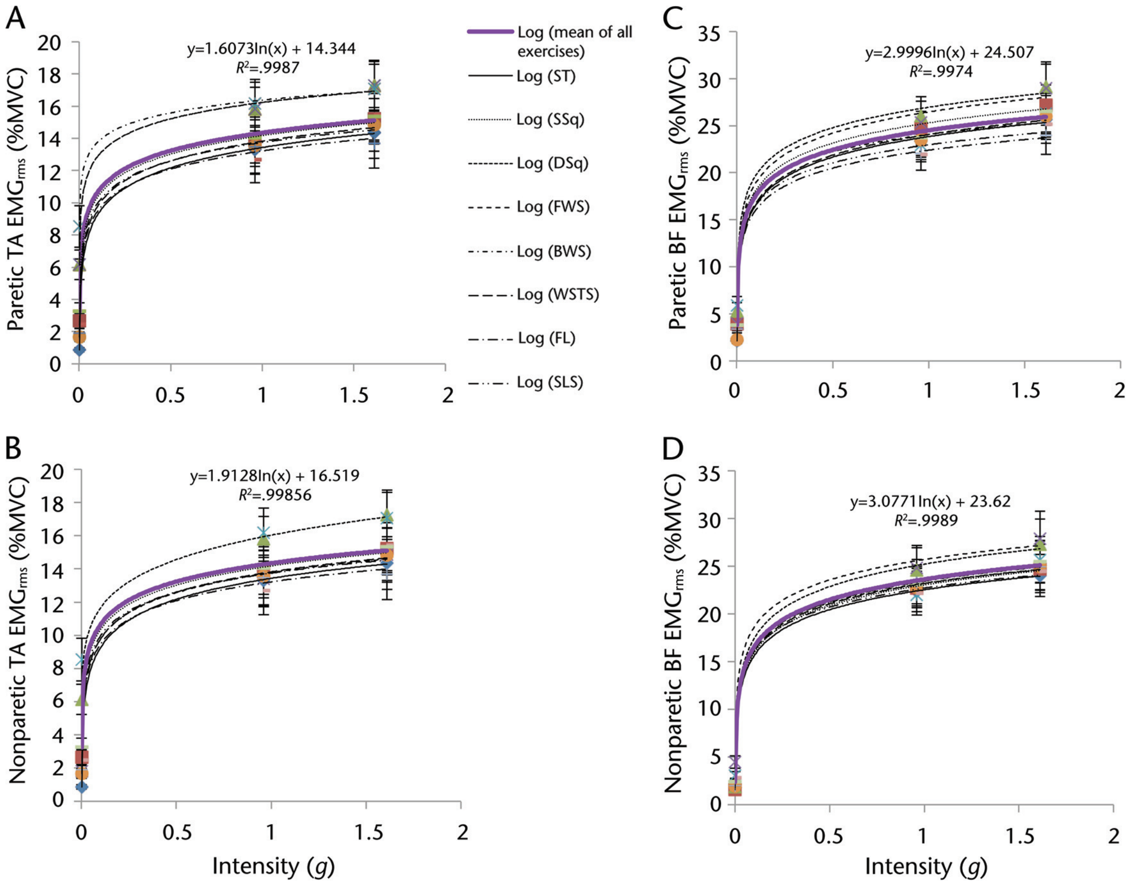

Figure 3.

Trend analysis: illustration of the effect of whole-body vibration (WBV) intensity. The relationship between normalized electromyography root mean square (EMG_{rms}) and WBV intensity is shown for (A) paretic tibialis anterior muscle (TA), (B) nonparetic TA, (C) paretic biceps femoris muscle (BF), and (D) nonparetic BF. Each data point represents the mean value of the normalized EMG_{rms} value for a given exercise at a particular WBV intensity. The error bar represents 1 standard error of the mean. For each exercise, the 3 data points were best fitted with a logarithmic curve. The thick purple line represents the trend after pooling the data of all 8 exercises. As it is impossible to fit the data with a logarithmic curve if one of the WBV intensities is 0*g*, a factor of 0.001*g* was added to yield WBV intensities of 0.001*g*, 0.961*g*, and 1.611*g*, respectively. Eight different static exercises were examined in each WBV condition: upright standing (ST), semi-squat (SSq), deep squat (DSq), weight-shifted-forward (FWS), weight-shifted-backward (BWS), weight-shifted-to-the-side (WSTS), forward lunge (FL), and single-leg-standing (SLS). %MVC=percent maximal voluntary contraction.

minimize the effects of artifacts that may be induced by WBV. The magnitude of increase in EMG activity reported in this study was quite comparable to previous research in other populations.[11–20] The origin of the EMG signals during WBV has been previously studied by Ritzmann et al.[37] In their experiments, dummy electrodes were placed close to the EMG electrodes to monitor motion artifacts. Their results showed that the dummy electrodes registered almost no activity during WBV. On rare occasions when the dummy electrodes showed peaks of activity, they did not systematically concur with the preset vibration frequency and had large standard deviations. Thus, their results showed that the contribution of motion artifacts to overall EMG activity is insignificant. Taken together, we believe our data reasonably reflect the muscle activation level during WBV.

Limitations and Future Research Directions

First, many of the participants were middle-aged adults (<65 years), and more men than women were tested. The generalizability of the findings may be compromised as a result. Second, the study only measured leg muscle activity during static exercises. The muscle response to WBV during dynamic exercises also should be addressed in the future to provide a more comprehensive picture of WBV-induced muscle response. In addition, we compared the EMG responses among only 3 WBV intensities. Incorporating more WBV intensities would enable us to more accurately estimate the trend of EMG responses with increasing WBV intensity as well as EMG responses for intensities beyond 1.61*g*. Finally, although this study showed that low- and high-intensity WBV protocols could increase leg muscle activity during different exercises, whether long-term training using these protocols can bring about actual improvement in muscle strength remains

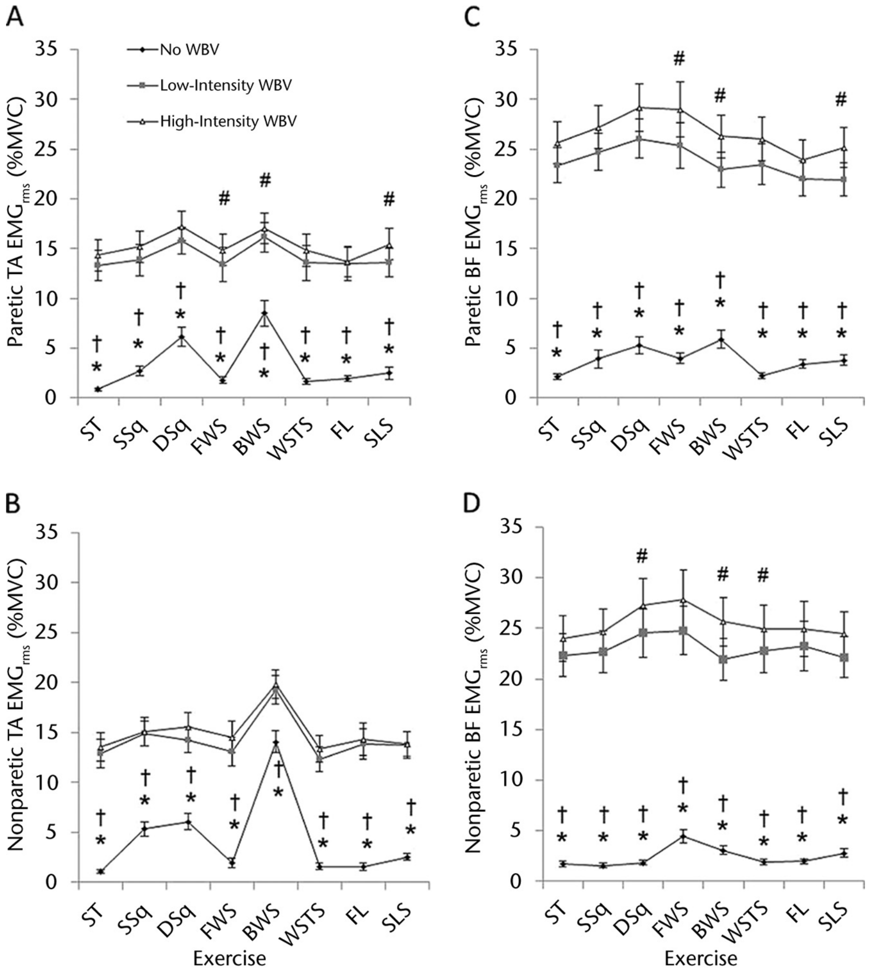

Figure 4.
Normalized electromyography (EMG) magnitude under different whole-body vibration exercise conditions. The normalized electromyography root mean square (EMG_{rms}) value of (A) paretic tibialis muscle (TA), (B) nonparetic TA, (C) paretic biceps femoris muscle (BF), and (D) nonparetic BF in each test condition is expressed as percent maximal voluntary contraction (%MVC). The white triangles (Δ), gray squares (■), and black diamonds (♦) represent the mean normalized EMG_{rms} values recorded in the high-intensity WBV, low-intensity WBV, and no-WBV conditions, respectively. The error bars represent 1 standard error of the mean. Eight different static exercises were examined in each WBV condition: upright standing (ST), semi-squat (SSq), deep squat (DSq), weight-shifted-forward (FWS), weight-shifted-backward (BWS), weight-shifted-to-the-side (WSTS), forward lunge (FL), and single-leg-standing (SLS). Application of WBV resulted in an overall significant increase in normalized EMG_{rms} of the TA and BF on both sides. *Significant difference between the control condition (no WBV) and low-intensity WBV condition. †Significant difference between the control condition and high–intensity WBV protocol. #Significant difference between the low-intensity and high-intensity WBV protocols.

unknown. Randomized controlled trials that incorporate the measurement of muscle force production and functional capacity as outcomes are needed.

We found a positive relationship between the EMG magnitude of the TA and BF muscles in both legs using a WBV intensity of up to 1.61*g*. The increase in EMG activity evoked by WBV was influenced by the specific exercise performed, but not degree of motor impairment and spasticity. Therefore, the WBV intensity and the exercise chosen are important guiding factors in designing WBV exercise protocols for the stroke population. The EMG magnitude was the greatest during exposure to the high-intensity protocol. Thus, our results have provided a basis for future RCTs to test the efficacy of this protocol in modifying neuromuscular function after stroke.

Mr Liao, Professor Ng, Professor Jones, and Professor Pang provided concept/idea/research design and writing. Mr Liao provided data collection. Mr Liao, Dr Chung, and Professor Pang provided data analysis. Professor Pang provided project management, fund procurement, study participants, and facilities/equipment. Professor Ng, Professor Jones, Dr Chung, and Professor Pang provided consultation (including review of manuscript before submission).

The study was approved by the Human Subjects Ethics Subcommittee of the Hong Kong Polytechnic University (approval number: HSEARS20130209001-01), and all experiments were conducted in accordance with the Declaration of Helsinki.

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The experiments comply with the current laws of the country in which they were performed.

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