Leg Muscle Activity during Whole-Body Vibration in Individuals with Chronic Stroke

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ABSTRACT


Purpose: It has been previously shown that whole-body vibration (WBV) can augment muscle activity in young healthy adults. However, the EMG response of leg muscles during WBV in individuals with stroke is unknown. The objective of this study was to determine the influence of WBV on the activity of the vastus lateralis (VL) and gastrocnemius (GS) muscles during the performance of different exercises in chronic stroke patients.

Methods: Forty-five chronic stroke patients were studied. Each subject was exposed to three WBV conditions of 1) no WBV, 2) low-intensity WBV protocol (peak acceleration: 0.96 unit of gravitational constant [g]), and 3) high-intensity WBV protocol (peak acceleration: 1.61 g) while performing eight different static exercises involving upright standing, semisquat, deep squat, weight shifted forward, weight shifted backward, weight shifted to the side, forward lunge, and single-leg standing. Bilateral VL and GS muscle activity was recorded with surface EMG and expressed as a percentage of the EMG amplitude recorded during a maximal voluntary contraction of the respective muscles.

Results: Two-way repeated-measures ANOVA revealed that exposure to WBV (low- and high-intensity protocols) significantly increased VL and GS EMG amplitude (large effect size, partial $\eta^2 = 0.135–0.643$, $P < 0.001$) on both the paretic and nonparetic sides in different exercise conditions compared with no WBV. No significant difference in EMG magnitude was found between the high- and the low-intensity WBV protocols ($P < 0.05$). With a few exceptions, WBV enhanced EMG activity in the paretic and nonparetic leg muscles to a similar extent in different exercise conditions.

Conclusions: Leg muscle activity was increased significantly with the addition of WBV. Further clinical trials are needed to determine the effectiveness of different WBV protocols for strengthening leg muscles in chronic stroke patients.

Key Words: CEREBROVASCULAR ACCIDENT, REHABILITATION, EXERCISE, HEMIPARESIS

Stroke is one of the most common disabling conditions and presents a major public health problem worldwide (9). Following a stroke, central excitatory drive to motor units is disrupted due to lesion in the descending motor pathways (13), causing impaired ability to voluntarily generate muscle force. In addition, other factors such as muscle atrophy and lack of physical activity may also contribute to muscle weakness (33). Muscle weakness has been identified as a major contributing factor to disability among people with stroke (33). For example, decreased leg muscle strength has been associated with reduction in gait speed and quality, walking endurance, transfer capacity, stair climbing ability, and balance function (10,20).

Recent observations have shown the possibility of using whole-body vibration (WBV) as a training tool in rehabilitation to improve muscle strength in a variety of populations, including young athletes, seniors, and people with chronic conditions (2,16,23,26,38). Several studies have shown that muscle activity can be enhanced during the application of WBV (4,14,34,36). Roelants et al. (36) examined the EMG response of rectus femoris, vastus lateralis (VL), vastus medialis, and gastrocnemius (GS) during the performance of three isometric exercises (high squat, low squat, and one-legged squat) with WBV (36). Compared with the no-WBV condition, adding WBV significantly increased the EMG amplitude for all four muscles measured during the performance of all three squatting exercises, by 49%–361% (36). Because of its ability to enhance muscle activity, increasing research has explored whether WBV training for a longer period can lead to an increase in muscle strength in older adults, who often suffer...
from muscle weakness (23). A recent meta-analysis showed that WBV has significant treatment effect on enhancing certain aspects of leg muscle strength in older adults after 6–10 wk of training (23).

Because most WBV treatment programs involve relatively brief treatment sessions and simple body movements (23), it is deemed suitable for those with neurological conditions, who often sustain considerable motor and cognitive deficits. Indeed, WBV therapy has been reported to have positive effects on muscle strength and motor performance in adults with cerebral palsy (2). Apart from resistance exercise training (11), WBV may thus offer a viable intervention approach for persons with stroke to improve muscle strength. Several randomized controlled studies have investigated the effects of 4–8 wk of WBV therapy on leg muscle strength in stroke patients. The results are mixed, with significant effects reported in some studies (37,39), but not others (4,24). Perhaps the difference in subject characteristics and WBV exercise protocols such as vibration settings, program duration, and exercise posture used in these studies may account for the difference in outcomes. In particular, the vibration intensity used across the different studies varied greatly (peak acceleration ranging from (9.5 to 92.5 m/s²) (4,24,37,39), and the rationales for the protocols used with physiologically based justifications were often not provided (4,37). Before effective WBV exercise protocols can be identified for this subject group, it is essential to address a more fundamental yet important question: What occurs to the leg muscle activity level during exposure to WBV of different intensities? Understanding the relationship between leg muscle activation and WBV intensity and exercise is essential as it would inform the design of WBV protocols for further efficacy studies (e.g., randomized controlled trials). In addition, it would also provide a physiological basis for the therapeutic effects (or lack thereof) induced by different WBV exercise protocols.

Although it is well known that exercise training is an important adjunct therapy in patients with chronic stroke that can lead to improvements in function (27,31), research evidence is scarce on examining the relationship between outcomes and different modes of exercise, including the effects of WBV exercise. To date, no study has systematically examined the effects of WBV on leg muscle activity in individuals with chronic stroke. The purpose of this study was to determine the influence of different WBV protocols on the amplitude of EMG activity in the VL and GS muscles during the performance of various exercises among people with chronic stroke.

METHODS

Study design. This was an experimental study, with subjects undergoing three different WBV conditions of no WBV, low-WBV-intensity protocol, and high-WBV-intensity protocol. In each condition, the subjects were asked to perform eight different exercises while leg muscle activity on both sides was measured using surface EMG. The sequence of WBV intensities used and exercises performed was randomized by drawing ballots using an opaque envelope to avoid order effect. For each subject, all measurement procedures were performed on the same day.

Subjects and sample size estimation. As no study has examined the EMG response during WBV in people with stroke, previous research investigating the EMG response during WBV in healthy adults was used to estimate the sample size needed for this study. In a study involving 15 healthy men, Roelants et al. (36) obtained a large effect size (Cohen’s $d = 5–8$) for various muscle groups when WBV (35 Hz) was applied. On the basis of ANOVA (three WBV conditions), assuming an effect size $f = 0.6$ (large), with an alpha of 0.05 and power of 0.8, a minimum of 30 subjects would be required.

Subjects were recruited from stroke self-help groups in the community via convenience sampling. The inclusion criteria were as follows: a diagnosis of a hemispheric stroke with onset $\geq$ 6 months (i.e., chronic stroke), community dwelling (i.e., noninstitutionalized), abbreviated Mental Test score $\geq$ 60, and having hemiparesis in the lower extremity, as indicated by a composite leg and foot motor score of 13 or lower according to the Chedoke-McMaster Stroke Assessment (12). The exclusion criteria were as follows: neurological conditions in addition to stroke, brainstem or cerebellar stroke, significant musculoskeletal conditions (e.g., recent fractures and amputations), substantial vestibular dysfunctions (e.g., vertigo), peripheral vascular disease, unable to maintain standing for 1 min with steady standing assistance of one person, severe cardiovascular conditions (e.g., unstable angina, uncontrolled hypertension, and uncontrolled cardiac dysrhythmia), and pain conditions that affected performance in standing, walking, or other daily functional activities.

The study was approved by the Research Ethics Committee of the administrating institute before commencement. The experimental procedures were first fully explained to each subject before written informed consent was obtained. The study was conducted in accordance with the Declaration of Helsinki.

Basic demographics and spasticity. The basic demographic information (e.g., age, medical history, medications, etc.) was obtained from interviewing the subjects. To test spasticity on the paretic side, subjects were placed in a supine position and asked to relax. The researcher then moved the knee on the paretic side into flexion and extension alternately, and the resistance to passive motion was noted. The same test was done on the ankle joint on the paretic side. The Modified Ashworth Scale was used to indicate the severity of spasticity in each joint tested. A higher score is indicative of more severe spasticity ($0 =$ normal muscle tone, $4 =$ tested part rigid) (3).

WBV protocol. The Jet-Vibe System (Danil SMC Co. Ltd., Seoul, Korea) was used to deliver the WBV stimulation. This device generates vertical vibrations and has an adjustable frequency range between 20 and 55 Hz with corresponding preset amplitudes.

The intensity of WBV, represented by the peak acceleration ($a_{peak}$), was calculated by the following formula:
$a_{\text{peak}} = (2\pi f)^2 A$, where $A$ is the amplitude and $f$ is the frequency (19). The $a_{\text{peak}}$ is usually represented as a unit of the gravitational constant ($g = 9.81 \text{ m/s}^2$). The peak acceleration values generated by the device were validated by a triaxial accelerometer (Model 7523A5; Dytran Instruments Inc., Chatsworth, CA).

Each participant was subject to three different WBV conditions: (a) no WBV, (b) low-intensity WBV protocol (peak acceleration = 0.96g, frequency = 20 Hz, amplitude = 0.60 mm), and (c) high-intensity WBV protocol (peak acceleration = 1.61g, frequency = 30 Hz, amplitude = 0.44 mm) while performing different exercises. We chose these frequencies because WBV frequencies lower than 20 Hz may cause destructive resonance effects to the body (35). On the other hand, our pilot experiments showed that frequencies higher than 30 Hz caused discomfort and fatigue in some individuals. The higher peak acceleration values associated with higher frequencies may also be a potential hazard for people with compromised bone mass, such as chronic stroke survivors (30).

Exercise protocol. The subjects were required to perform eight different exercises while being exposed to the three WBV conditions as described in Table 1. These exercises were commonly used in previous WBV trials in different populations (5,22,23,34,36,38). Practice trials were given to ensure that the subjects were able to perform the exercises properly before actual data collection. The knee angle was measured by a manual goniometer (Baseline® HiRes™ plastic 360° ISOM Goniometer, Fabrication Enterprises, White Plains, NY) to indicate the desired knee flexion angle in standing (10°), semisquat (30°), and deep-squat (90°) exercises. All experimental procedures were monitored closely by the researcher throughout to ensure that the subjects were performing the exercises properly and consistently. For standardization, all subjects were encouraged to gently hold on to the handrail of the WBV device for balance only. To ensure safety, the researcher provided standing guard assistance while the patient was standing on the vibration platform. The researcher was standing by the patient in a guarding position, using his hands to be ready to guard or guide the patient.

Measurement of leg muscle activity responses. Surface EMG was used to measure activity of the VL and GS muscles in all test conditions. After proper skin preparation, the bipolar bar electrodes (Bagnoli EMG system; Delsys, Inc., Boston, MA) were placed on the muscle belly of GS and distal one third of VL muscles, according to the specifications of the Surface EMG for a Non-invasive Assessment of Muscles (SENIAM) project (15). A reference electrode was placed at the head of fibula. Insulated EMG cables were fastened to avoid movement artifacts.

For each WBV condition, subjects were asked to assume each of the eight postures (Table 1) for 10 s while VL and GS EMG activity was being recorded. A total of three trials were performed for each of the eight exercises in a given WBV condition, with a 1-min rest period in between trials. After all eight exercises were completed in the first WBV condition, the subjects were then asked to do the same eight exercises in the second and third WBV conditions. A 10-min rest period was given between each WBV condition. Only the EMG data obtained during the middle 6 s of each trial was extracted to obtain the EMG root mean squares (EMG rms), and the mean value of the three trials was used for subsequent analysis.

All EMG data collected were preamplified ($\times 1000$) and sampled at 1 kHz (Bagnoli-8; DelSys, Inc.) using a personal computer with LabView version 7 software (National Instruments Corp., Austin, TX). Data processing was performed using MyoResearch XP, Master Package version 1.06 (Noraxon USA, Inc., Scottsdale, AZ). The EMG data were filtered with 20- to 500-Hz band-pass Butterworth filter, and the Infinite Impulse Response (IIR) retranslator was implemented to eliminate the associated harmonics at the frequencies of 20, 30, and 60 Hz. After filtering, bias was calculated and removed from each EMG signal, and then the data were rectified and the EMG rms calculated in 100-ms windows around every data point (1).

At the beginning of the session, the EMG activity of VL and GS during maximal voluntary isometric contraction (MVC) was first recorded. For measuring the EMG amplitude of VL during MVC of knee extension, each subject was comfortably seated, and the tested leg was fixed horizontally on a dynamometer (Cybex Norm Testing & Rehabilitation System, Stoughton, MA) with hip and knee stabilized at 90°. Subjects were then asked to perform isometric knee extension for 10 s. The same device was used to stabilize the hip and knee when measuring the EMG amplitude of GS during MVC of ankle plantarflexion. The foot was placed at 90° on a wedged platform, and the subjects were instructed to isometrically plantarflex the ankle against the wedge with maximal effort and sustain for 10 s. Subjects were provided with verbal encouragement to ensure a maximal effort during testing.

EMG root mean square values (EMG rms) were calculated during intervals of 0.5 s (8). For each muscle, the maximum EMG rms values from the three MVC trials were averaged to

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**Table 1. Static exercises performed while standing on the vibration platform.**

<table>
<thead>
<tr>
<th>Static Exercise*</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Standing</td>
<td>Feet placed apart at shoulder width, trunk upright, knees at 10° flexion</td>
</tr>
<tr>
<td>2. Semisquat</td>
<td>Feet placed apart at shoulder width, trunk upright, bilateral knees at 30° flexion</td>
</tr>
<tr>
<td>3. Deep squat</td>
<td>Feet placed apart at shoulder width, trunk upright, bilateral knees at 90° flexion</td>
</tr>
<tr>
<td>4. Weight shifted forward</td>
<td>Feet placed apart at shoulder width, trunk upright, body leaned forward with heels off the platform</td>
</tr>
<tr>
<td>5. Weight shifted backward</td>
<td>Feet placed at shoulder width, trunk upright, body leaned backward with forefoot off the platform</td>
</tr>
<tr>
<td>6. Weight shifted to the side</td>
<td>Feet placed at shoulder width, trunk upright, body weight shifted to the parietal leg as much as possible. The same exercise was performed with the weight shifted to the nonparietal leg as much as possible&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>7. Forward lunge</td>
<td>Paretic leg placed in front, body leaned forward and weight shifted onto the parietal leg as much as possible. The same exercise was performed after the positions of the two legs were switched&lt;sup&gt;e&lt;/sup&gt;</td>
</tr>
<tr>
<td>8. Single-leg standing</td>
<td>Standing on the parietal leg, with knee at 10° flexion</td>
</tr>
</tbody>
</table>

<sup>*Subjects were required to hold the posture as described above for 10 s. <sup>a</sup><sup>b</sup></sup>

<sup>a</sup>Analysis was based on the EMG data recorded from the front leg.

<sup>b</sup>Analysis was based on the EMG data recorded from the weight-bearing leg.

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*whole-body vibration in stroke*
obtain the mean value, which was then used for normalization of the EMGrms value obtained in each WBV condition. Therefore, the EMG amplitude of each muscle obtained in all WBV conditions was expressed as a percentage of the EMG amplitude obtained during the MVC (%MVC). The reliability of the EMGrms data obtained from the three MVC trials was excellent, as demonstrated by the intraclass correlation coefficients (ICC3,1) (paretic VL = 0.99, paretic GS = 0.94, nonparetic VL = 0.99, nonparetic GS = 0.99).

Statistical analysis. Analysis was performed with IBM SPSS Statistics software (version 20.0; IBM, Armonk, NY). The level of significance was set at $P \leq 0.05$. Two-way repeated-measures ANOVA (within-subject factors: intensity [no WBV vs low-intensity WBV vs high-intensity WBV] and exercises) was used to compare the normalized EMGrms data across the different conditions. When sphericity assumption was violated, the Greenhouse–Geisser epsilon adjustment was performed if any overall significant results were obtained for the EMG data. To compare the influence of WBV on the paretic side versus the nonparetic side, the ratio of normalized EMGrms (%MVC) of the VL and GS on the paretic side to the corresponding muscles on the nonparetic side was computed. A ratio greater than 1 indicated that the paretic side achieved a higher %MVC than the nonparetic side. A second two-way repeated-measures ANOVA model (within-subject factors: WBV intensity and exercises) was then constructed, using the EMGrms ratio as the dependent variable. Effect size was denoted by partial eta-squared ($\eta^2$). Large, medium, and small effect sizes were represented by partial $\eta^2$ values of 0.14, 0.06, and 0.01, respectively (29). To examine the potential effect of spasticity on the EMG data, Spearman’s rho was used to examine the relationship between (a) paretic knee spasticity score and normalized EMGrms of paretic VL and (b) paretic ankle spasticity score and normalized EMGrms of paretic GS in each testing condition.

RESULTS

Demographic characteristics of subjects. A total of 64 individuals with chronic stroke were screened, and 45 of these (34 men and 11 women) fulfilled all criteria and completed all assessments (Fig. 1). The median lower extremity composite motor score (Chedoke–McMaster Stroke Assessment) was 7 of 14, indicating moderate impairment. Most subjects had no spasticity in the paretic knee (i.e., spasticity score = 0, $n = 28$) but mild to moderate spasticity in the paretic ankle (spasticity score $= 1–2$, $n = 37$). Severe spasticity (i.e., spasticity score $= 3–4$) in the paretic knee ($n = 1$) and ankle ($n = 1$) was rare. The demographic data are summarized in Table 2.

EMG activity of paretic leg VL. There was an overall significant main effect of WBV intensity ($F_{2,88} = 27.006, P < 0.001$, partial $\eta^2 = 0.380$) and exercise ($F_{7,308} = 29.846, P < 0.001$, partial $\eta^2 = 0.404$) (Fig. 2A). The intensity–exercise interaction effect was also significant ($F_{14,616} = 2.312, P = 0.031$, partial $\eta^2 = 0.050$). In post hoc analysis of the main effect of intensity, both the low WBV intensity ($P < 0.001$) and the high WBV intensity ($P < 0.001$) protocols induced significantly higher EMG amplitude than the control condition, no matter what exercise was performed. The difference in EMG amplitude was not significant, however, between the low-intensity and the high-intensity WBV protocols ($P = 0.744$). Regarding the main effect of exercise, deep squat position induced significantly higher paretic VL EMG amplitude than other exercises, regardless of WBV intensity (all $P < 0.001$).

EMG activity of paretic leg GS. The main effect of intensity ($F_{2,88} = 36.728, P < 0.001$, partial $\eta^2 = 0.465$) and exercise ($F_{7,308} = 6.858, P < 0.001$, partial $\eta^2 = 0.135$) as well as the intensity–exercise interaction effect ($F_{14,616} = 2.701, P = 0.046$, partial $\eta^2 = 0.058$) were all significant (Fig. 2B). Post hoc analysis of the main effect of WBV intensity revealed that the EMG amplitude among the three WBV conditions were all significantly different from each other ($P < 0.01$). However, the difference in EMG amplitude between the low-intensity and the high-intensity protocols was not significant in any of the exercises after Bonferroni adjustment. Post hoc analysis of the main effect of exercise showed that the weight-shifted-forward position resulted in higher EMG than most of the other exercises ($P < 0.01$).
The main effect of intensity ($F_{2,88} = 30.887, P < 0.001, \text{ partial } \eta^2 = 0.412$) and exercise ($F_{7,308} = 79.302, P < 0.001, \text{ partial } \eta^2 = 0.643$) and the intensity–exercise interaction were all significant ($F_{14,616} = 8.380, P < 0.001, \text{ partial } \eta^2 = 0.160$) (Fig. 3A). Post hoc analysis on the effect of WBV intensity showed that adding the low-intensity or high-intensity WBV induced an overall increase in EMG amplitude when compared with the control condition ($P < 0.001$). However, there was no significant difference in EMG amplitude between low-intensity and high-intensity WBV conditions ($P = 0.071$). Post hoc analysis on the effect of exercise showed that the EMG amplitude during the deep squat position was significantly higher than other body postures ($P < 0.001$). Deep squat position was also the only exercise in which adding WBV induced no significant increase in nonparetic VL EMG amplitude ($P > 0.05$) (Fig. 3A).

**EMG activity of nonparetic leg GS.** Significant main effects of intensity ($F_{2,88} = 19.062, P < 0.001, \text{ partial } \eta^2 = 0.302$) and exercise ($F_{7,308} = 17.080, P < 0.001, \text{ partial } \eta^2 = 0.280$) were found (Fig. 3B). The intensity–exercise interaction was also significant ($F_{14,616} = 2.994, P = 0.033, \text{ partial } \eta^2 = 0.064$). Post hoc analysis showed that the nonparetic GS EMG amplitude was significantly lower when no WBV was added ($P < 0.001$). No significant difference in EMG amplitude was found between low-intensity and high-intensity WBV conditions ($P = 0.109$). Contrast analysis of the effect of exercise revealed that the weight-shifted-forward position had significantly higher EMG amplitude than other postures ($P < 0.01$). It was also the only exercise that did not show a significant increase in EMG when WBV was added ($P > 0.05$) (Fig. 3B).

**Paretic to nonparetic EMG amplitude ratio.** The EMG$_{\text{ratio}}$ ratio of paretic to nonparetic side is shown in Figure 4. The ratio was greater than 1 in all conditions, denoting that the paretic leg achieved a greater %MVC in these conditions than the nonparetic side. For the VL muscle (Fig. 4A), the main effect of WBV intensity was not significant ($P = 0.34$, partial $\eta^2 = 0.02$), whereas the main effect of exercise was significant ($P < 0.001$, partial $\eta^2 = 0.37$), with the weight-shifted-to-the-side and single-leg-standing positions yielding significantly higher paretic to nonparetic EMG ratios than other exercises ($P < 0.01$). There was an overall significant frequency–exercise interaction effect ($P < 0.001$, partial $\eta^2 = 0.20$), with the

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**TABLE 2. Characteristics of subjects ($N = 45$).**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic demographics</td>
<td></td>
</tr>
<tr>
<td>Age, yr</td>
<td>56.1 ± 10.2</td>
</tr>
<tr>
<td>Sex, men/women, n</td>
<td>34/11</td>
</tr>
<tr>
<td>Body mass index, kg m$^{-2}$</td>
<td>24.6 ± 3.3</td>
</tr>
<tr>
<td>Required walking aid for indoor mobility, none/cane/quadrupod, n</td>
<td>40/2/3</td>
</tr>
<tr>
<td>Required walking aid for outdoor mobility, none/cane/quadrupod, n</td>
<td>15/24/6</td>
</tr>
<tr>
<td>Stroke characteristics</td>
<td></td>
</tr>
<tr>
<td>Poststroke duration, yr</td>
<td>4.7 ± 3.2</td>
</tr>
<tr>
<td>Type of stroke, hemorrhagic/ischemic/unknown, n</td>
<td>21/19/5</td>
</tr>
<tr>
<td>Side of paresis, left/right, n</td>
<td>16/37</td>
</tr>
<tr>
<td>CMSA leg score (1–7), median (IQR)</td>
<td>4 (4–4)</td>
</tr>
<tr>
<td>CMSA foot score (1–7), median (IQR)</td>
<td>3 (3–4)</td>
</tr>
<tr>
<td>CMSA lower extremity composite score (out of 14), median (IQR)</td>
<td>7 (7–9)</td>
</tr>
<tr>
<td>Paretic knee Modified Ashworth Scale of spasticity score (0–4)</td>
<td>0/1/1.5/2/3/4, n 7/10/13/14/0/0</td>
</tr>
<tr>
<td>Median (IQR)</td>
<td>1.5 (1–2)</td>
</tr>
<tr>
<td>Paretic ankle Modified Ashworth Scale of spasticity score (0–4)</td>
<td>0/1/1.5/2/3/4, n 7/11/15/0/0/0</td>
</tr>
<tr>
<td>Median (IQR)</td>
<td>0 (0–1)</td>
</tr>
<tr>
<td>MVC EMG (µV)</td>
<td>151.4 ± 128.9</td>
</tr>
<tr>
<td>Paretic leg GS</td>
<td>212.0 ± 180.6</td>
</tr>
<tr>
<td>Nonparetic leg GS</td>
<td>188.2 ± 148.6</td>
</tr>
<tr>
<td>Paretic leg VL</td>
<td>245.7 ± 137.4</td>
</tr>
</tbody>
</table>

$^a$Mean ± SD presented for continuous variables.

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**FIGURE 2—Effect of WBV on EMG amplitude in the paretic leg.** The ratio of paretic to nonparetic EMG amplitude was significantly higher when no WBV was added ($P < 0.001$). It was also the only exercise that did not show a significant increase in EMG when WBV was added ($P > 0.05$) (Fig. 3B).

**FIGURE 3—Effect of WBV on EMG amplitude in the paretic leg.** The ratio of paretic to nonparetic EMG amplitude was significantly higher when no WBV was added ($P < 0.001$). It was also the only exercise that did not show a significant increase in EMG when WBV was added ($P > 0.05$) (Fig. 3B).
weight shifted to the side and single-leg standing showing significant reduction in the EMG ratio as high-intensity WBV was added ($P = 0.002$). For the GS muscle (Fig. 4B), there was an overall significant main effect of exercise ($P < 0.001$, partial $\eta^2 = 0.15$), with the weight-shifted-forward exercise showing significantly lower level of EMG ratio than all other exercises ($P < 0.05$), except upright standing. The main effect of intensity ($P = 0.53$, partial $\eta^2 = 0.01$) and intensity–exercise interaction effect ($P = 0.39$, partial $\eta^2 = 0.03$) were not significant.

**Relationship between spasticity and EMG data.** Generally, no relationship was found between normalized EMG$_{rms}$ and spasticity of the paretic knee and ankle ($P > 0.05$). The only exceptions were a negative association of the ankle spasticity score with the standing posture in the low-intensity WBV ($\rho = -0.356$, $P = 0.016$) and high-intensity WBV ($\rho = -0.316$, $P = 0.035$) conditions.

**DISCUSSION**

This is the first study to investigate the influence of different WBV intensities and exercises and their interactions on leg muscle activity in individuals with chronic stroke. The hypothesis of this study was confirmed because the results showed that adding WBV significantly enhanced muscle activity in VL and GS on both the paretic and the nonparetic sides in all eight different exercise conditions. With a few exceptions, the added WBV enhanced EMG activity in the paretic and nonparetic leg muscles to a similar extent in a variety of exercise conditions.

**Effect of WBV intensity.** The results showed that the EMG amplitude of all leg muscles measured was significantly enhanced by adding either the low-intensity or high-intensity WBV. The increase in EMG amplitude ranged from 26% to 165%, from 76% to 243%, from 4% to 253%, and from 14% to 236% for paretic VL, paretic GS, nonparetic VL, and nonparetic GS, respectively, depending on the exercises performed. Our results are generally in line with those from other studies in healthy adults, which also reported a significant increase in EMG magnitude of different leg muscle groups during WBV exposure (5,36). The magnitude of WBV-induced increase in EMG activity differed across the various studies probably due to the use of different populations, vibration devices, frequencies, amplitudes, and data processing methods.
example, Pollock et al. (34) found that adding WBV (5–30 Hz, 2.5–5.5 mm) increased EMG amplitude of various leg muscles by 5%–50% in a sample of 12 healthy adults. Other studies have shown that WBV at 30–45 Hz and amplitudes of 2–5 mm led to augmentation of leg muscle activity up to 34.5% in young adults (5,36).

It is unlikely that the increase in EMG was due to increased spasticity on the paretic side. First, spasticity should have little influence on our results as severe spasticity in either the knee or ankle in the paretic leg was observed in one subject only. Second, no strong relationship was found between the severity of spasticity and the EMG amplitude. Of the two significant correlations identified, the direction of the relationship was negative, indicating that higher EMG amplitude was associated with less severe spasticity. Finally, a previous study reported that ankle spasticity in stroke patients, as indicated by the Modified Ashworth Scale, was significantly reduced in the WBV group, but not in the control group, after a single session of WBV (6).

It is interesting that our low- and high-intensity WBV protocols are equally effective in increasing the EMG activity of all measured muscles in subjects with chronic stroke. This is in contrast with previous studies in young adults, which showed that higher WBV frequencies are associated with higher EMG amplitude (5,14,34). The discrepancies in results may be due to several reasons. First, the subject characteristics are different (chronic stroke vs young healthy adults). The presence of neurological pathology and changes in muscle properties poststroke may lead to a very different response to the same WBV stimuli. Second, the WBV protocols used also differ. The protocols used in this study have enabled us to determine the differential effects of a subgravity protocol (0.96g) and a supragravity protocol (1.61g). However, the difference in intensity between the two protocols may not be substantial enough to induce different levels of muscle activity. Perhaps the difference in muscle activation would have been significant if a higher WBV intensity had been used. We did not use a higher WBV intensity because higher peak accelerations would potentially lead to more substantial health hazards (1,19). This study examined the leg muscle activity during high- and low-intensity WBV only. Whether the two protocols are equally effective in improving muscle function after long-term WBV exercise training awaits further research. To date, only one study has compared the effects of a high-intensity WBV protocol (9.43g, 25 Hz, 3.75 mm) with a low-intensity one (0.50g, 25 Hz, 0.2 mm) in stroke patients after 12 sessions of training over a 6-wk period (4). A significant improvement in paretic knee extension strength was found only in the low-intensity WBV group, but the magnitude of improvement was within the limits of measurement errors, denoting no real clinical change. Certainly, more study is required in this area.

**Interaction between exercise and WBV intensity.** A unique aspect of this study is that we examined several different exercises during WBV exposure in an effort to identify what combination of exercise and WBV intensity may induce the highest level of muscle activity. The exercises chosen in this study are commonly used in other WBV trials and stroke rehabilitation (23,32,40). Regular training using functional leg strengthening exercises such as squatting movements and heel raises without WBV (e.g., exercise 2, 3, and 4 in Table 1) has been shown to be effective in increasing leg muscle strength in individuals with stroke (32,40). Interestingly, this study found that the muscle activation levels during these exercises are not particularly high (Figs. 2–4, black bars). It may indicate that the threshold intensity for inducing a positive strength training effect may be less than the typical training intensity (50%–80% maximal effort) used in many previous resistance training trials in stroke (33). Nevertheless, this study showed that for all eight exercises, adding WBV would significantly augment the muscle activation levels. WBV may thus be a viable option for further increasing muscle activity during leg strengthening exercises, thereby leading to better strength gains. Further randomized controlled trials are required to test this hypothesis.

The results also showed that the intensity and exercise interaction effect was significant for all four muscle groups, indicating that the WBV-induced increase in EMG activity achieved differed depending on the exercise. For the VL muscle in both the paretic and the nonparetic legs, the increase in muscle activation with the addition of WBV was significantly less in deep squat exercise when compared with other exercises. For GS, the WBV-induced increase in muscle activation in weight-shifted-forward exercise was significantly less when compared with most of the other exercises. Muscle preactivation could be a potential factor affecting the extent of muscle activation caused by WBV (16). For example, it is noted that the level of activation in VL and GS muscles are already quite high in deep squat exercise and weight-shifted-forward exercise, respectively, even without vibration. The potential for a further increase in muscle activation upon the addition of WBV is thus smaller.

Overall, the deep squat and forward-weight-shift exercises, when combined with WBV, resulted in the highest level of EMG activity in paretic VL and GS, respectively. The results thus suggested that these two exercises may be more effective in WBV training programs for enhancing strength of the respective muscles in subjects with chronic stroke. Mikael et al. (28) studied the effect of standing posture during WBV training on muscle strength outcomes. Interestingly, they found that WBV with flexed knees induced similar gain in leg press strength compared with WBV with locked knees after 29 sessions of training for a 13-wk period. However, the sample size is small (19 subjects), thus making it difficult to draw meaningful conclusions.

**Analysis of paretic to nonparetic EMG amplitude ratio.** The analysis of the paretic EMG to nonparetic EMG ratio provided us with some insight into the activation of the paretic leg relative to the nonparetic leg in different WBV conditions. The ratio was greater than 1.0 in all test conditions, indicating that the muscle activity in the paretic leg achieved a greater %MVC in these conditions relative to the nonparetic leg.

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It was most likely due to the fact that the nonparetic leg was much stronger than the paretic leg, as reflected by the greater EMG amplitude recorded during MVC (Table 1). As the EMG amplitude measured in different WBV conditions was normalized according to the EMG data recorded during MVC, it is not surprising that the paretic leg would tend to show a higher normalized EMG$_{rms}$ value compared with the nonparetic leg when performing the same activity, which explained why the ratios were greater than 1.0. The results showed that the choice of exercise did affect the EMG ratio. In general, the weight-shifted-to-the-side and single-leg standing positions resulted in the highest ratios (Fig. 4), mostly due to the relative low level of muscle activation in the nonparetic leg when these two postures were assumed (Fig. 3). In contrast, the semi-squat and deep-squat positions, which involved greater knee and ankle flexion angles, required a higher level of VL muscle activation even on the nonparetic side (Fig. 3). This may in turn account for the lower paretic/nonparetic EMG ratio in VL (Fig. 4A). Similarly, the weight-shifted-forward posture induced a high level of EMG activity in the nonparetic GS muscle, thereby accounting for the lower EMG amplitude ratios (Fig. 4B).

There was no main effect of WBV intensity for both VL and GS EMG amplitude ratios, meaning that application of WBV resulted in similar activation of the paretic and the nonparetic leg muscles in general. The only exception was the weight-shifted-to-the-side and single-leg standing exercises, which demonstrated substantial reduction in the VL EMG ratio as WBV intensity was increased (Fig. 4A), thereby contributing to the significant exercise–intensity interaction effect. This finding indicated that the increasing WBV intensity induced a greater EMG response in the nonparetic VL than the paretic VL when performing the weight-shifted-to-the-side and single-leg standing exercises. The differential response to alterations in WBV intensity was more apparent in these two exercises, probably because the body weight was borne primarily by the exercising leg whereas in the other six exercises, the weight bearing was shared by both legs.

**Limitations and future research directions.** First, because all of our subjects are ambulatory and community dwelling, the results are only generalizable to a population with similar characteristics. Second, we studied the effects of the overall intensity of WBV (indicated by peak acceleration) on leg EMG activity. However, WBV frequency and amplitude could have independent contribution to muscle activation (34). Pollock et al. (34) demonstrated that WBV amplitude is positively correlated with muscle performance while others believed that frequency is the most important variable in WBV (18). However, the vibration platform used in this study did not allow us to adjust the frequency and amplitude of WBV independently. Hence, the isolated contribution of frequency and amplitude on leg muscle activation requires further study. Third, the EMG amplitude was used as the outcome. Although no muscle torque measurements were done, it is known that EMG amplitude has a strong, positive relationship with muscle force in isometric conditions (21). It is thus reasonable to assume that the muscle force was increased during WBV exposure among our subjects. In addition, the VL and GS muscles were measured because of their key roles in gait and other functional tasks (10,20). Among the various knee extensor muscles (e.g., rectus femoris, vastus medialis, etc.), VL was selected because it has been examined in several previous studies and would facilitate the comparison of results (5,14,36). There is also no consistent evidence proving that the activation of VL relative to other knee extensors is significantly different in various knee extension or squatting exercises in healthy individuals (7,17). However, it is acknowledged that the flexor muscle groups are also important for daily function. For example, toe drag during the swing phase of walking owing to decreased activation of the ankle dorsiflexors on the paretic side is a common clinical observation in hemiparetic gait (25). The response to WBV in the flexor muscle groups after stroke will need further investigations. Finally, while this study showed that WBV could significantly augment leg muscle activity during the performance of various static exercises, whether improvement in muscle strength can be induced by these WBV protocols after a longer intervention period (e.g., 8–10 wk) is uncertain. A randomized controlled study with measurement of maximum voluntary torque as the outcome will be required to test this hypothesis.

**CONCLUSIONS**

In conclusion, the present study suggested that leg muscle activity on both the paretic and nonparetic sides was increased significantly by adding the low-intensity and high-intensity WBV. The added WBV induced a similar increase in EMG activity in the paretic and nonparetic legs, except in weight-shifted-to-the-side and single-leg standing exercises, where the nonparetic leg VL was more responsive to the added WBV than the paretic VL muscle. A randomized controlled trial will be required to determine whether these two protocols could induce any gain in muscle strength in stroke patients following long-term WBV exercise training, and whether the high-intensity protocol could lead to better muscle strength than the low-intensity one.

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The authors declare that they have no conflict of interest. The results of the present study do not constitute endorsement by the American College of Sports Medicine.

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