Title: 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 electromyography 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 people with chronic stroke. **Methods:** Forty-five subjects with chronic stroke 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: 1.61G) while performing 8 different static exercises involving upright standing, semi squat, deep squat, weight-shifted-forward, weight-shifted-backward, weight-shifted-to-the-side, forward lunge and single-leg-standing. The level of the VL and GS muscle activity on both sides was recorded with surface electromyography (EMG), and expressed as percentage maximal voluntary contraction (%MVC). **Results:** Two-way analysis of variance with repeated measures revealed that exposure to WBV (low- and high-intensity protocols) significantly increased VL and GS EMG amplitude (large effect size, partial η^2= 0.135-0.643, $p<0.001$) on both the paretic and non-paretic sides, compared with no WBV, regardless of the exercise performed. No significant difference in EMG magnitude was found between the high- and low-intensity WBV protocols ($p>0.05$), except in paretic GS ($p=0.004$). **Conclusions**: This study suggested that leg muscle activity was increased significantly with addition of WBV. Using the high-intensity protocol may further enhance the activation of the paretic GS muscle. Further clinical trials are needed to determine the effectiveness of different WBV protocols for strengthening lower limb muscles in individuals with chronic stroke.

Key words: cerebrovascular accident; rehabilitation; exercise; hemiparesis

INTRODUCTION

Paragraph Number 1 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 (10,20,21). Conventional graded resistance exercise training may be effective in increasing muscle strength in people with stroke (11,25,29), but may not be feasible for those with more sensorimotor deficits or spasticity.

Paragraph Number 2 Recent observations have shown the possibility of utilizing 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 diseases (7,23,27,28). A number of studies have shown that muscle activity can be enhanced during the application of WBV (5,6,16,35). Roelants et al. (36) examined the electromyography (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. Compared with the no-WBV condition, adding WBV had significantly increased the EMG amplitude for all four muscles measured during the performance of all three squatting exercises, by 49%-361%. Because of its ability to enhance muscle activity, increasing research has explored whether WBV training for a longer time period can lead to increase in muscle strength in older adults, who often suffer from muscle weakness (2,23,39). A recent meta-analysis (23) showed that WBV has significant treatment effect on enhancing certain aspects of leg muscle strength in older adults after 6-10 weeks of training.

Paragraph Number 3 Since most WBV treatment programs involve relatively brief exposure to WBV and simple body movements, it is deemed suitable for those with cognitive deficits and more severe motor impairment, for whom conventional muscle strengthening may not be feasible. WBV may thus offer a viable exercise alternative for persons with stroke. In a study involving 20 subjects with subacute stroke, Tihanyi et al (37) showed that the maximum torque and EMG amplitude of the VL muscle was significantly enhanced in the paretic leg following 4 weeks (12 sessions) of WBV treatment. However, two recent randomized controlled studies (4,24) have examined the effects of 6-8 weeks of WBV training on knee muscle strength in subjects with chronic stroke and found no significant results. Perhaps the WBV exercise protocols such as vibration settings, program duration, and exercise posture used in these studies are not optimal for enhancing leg muscle strength for the subjects. Before effective WBV exercise protocols can be identified for this subject group, it is essential to study how leg muscle activity is affected by different WBV protocols and exercises used.

Paragraph Number 4 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

Paragraph Number 5 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 electromyography (EMG). The sequence of WBV intensities used and exercises performed was randomized by drawing ballots using an opaque envelope to avoid order effect.

Subjects and sample size estimation

Paragraph Number 6 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. Based on ANOVA analysis (3 WBV conditions), assuming an effect size f=0.6 (large), with an alpha of 0.05, power of 0.8, a minimum of 30 subjects would be required.

Paragraph Number 7 Subjects were recruited from stroke self-help groups in the community via convenience sampling. The inclusion criteria were: a diagnosis of a hemispheric stroke with onset ≥ 6 months (i.e. chronic stroke), community-dwelling (i.e., non-institutionalized), abbreviated Mental Test score ≥6, 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: neurological conditions in addition to stroke, brainstem or cerebellar stroke, significant musculoskeletal conditions (e.g. recent fractures, amputations), substantial vestibular dysfunctions (e.g., vertigo), peripheral vascular disease, unable to maintain standing for 1 minute with the assistance of one person, severe cardiovascular conditions (e.g., unstable angina, uncontrolled hypertension), and other contraindications to exercise.

Paragraph Number 8 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.

WBV Protocol

Paragraph Number 9 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 20-55Hz with corresponding preset amplitudes.

Paragraph Number 10 The intensity of WBV, represented by the peak acceleration (a_{peak}), was calculated by the formula: $a_{peak} = (2\pi f)^2 A$**,** where A is the amplitude, and f is the frequency (19). The a_{peak} is usually represented as a unit of the gravitational constant (1G = $9.81 m/s^2$). The peak acceleration values generated by the device were validated by a triaxial accelerometer (Model 7523A5, Dytran Instruments Inc., CA, USA).

Paragraph Number 11 Each participant was subject to three different WBV conditions: (a) no WBV, (b) low- intensity WBV protocol (peak acceleration: 0.96 G, frequency: 20 Hz, amplitude: 0.60mm), and (c) high-intensity WBV protocol (peak acceleration: 1.61 G, frequency: 30 Hz, amplitude: 0.44mm) 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 (31).

Exercise protocol

Paragraph Number 12 The subjects were required to perform eight different exercises while being exposed to the three WBV conditions as described in Table 1. These exercises are commonly used in previous WBV trials in different populations (5,22,23,34,36,38). Three repetitions were performed for each of the above activities. For safety and standardization, all subjects were encouraged to gently hold on to the handrail of the WBV device for balance only.

Measurement of leg muscle activity responses

Paragraph Number 13 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, USA) 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.

Paragraph Number 14 For each WBV condition, subjects were asked to assume each of the 8 postures (Table 1) for 10 seconds while VL and GS EMG activity was being recorded. A total of three repetitions were performed, with a 1-minute rest interval in between trials. Only the EMG data obtained during the middle six seconds of each trial was extracted to obtain the EMG root mean squares (EMGrms), and the mean value of the three trials was used for subsequent analysis.

Paragraph Number 15 All EMG data collected were pre-amplified (×1000) and sampled at 1 kHz (Bagnoli-8, DelSys, Inc., Boston, MA, USA), using a personal computer with LabView version 7 software (National Instruments Corp., Austin, TX, USA). Data processing was performed using MyoResearch XP, Master Package version 1.06 (Noraxon USA, Inc., Scottsdale, AZ). The EMG data were filtered with 20-500 Hz band-pass Butterworth filter, and the Infinite Impulse Response (IIR) rejector was implemented to eliminate the associated harmonics at the frequencies of 20 Hz, 30 Hz and 60 Hz. After filtering, bias was calculated and removed from each EMG signal, and then the data were rectified and the EMGrms calculated in 100-ms windows around every data point (1).

Paragraph Number 16 At the beginning of the session, the EMG activity of VL and GS during maximal voluntary isometric contraction (MVC) was first recorded. For testing MVC of VL (i.e., knee extension), each subject was comfortably seated and the tested leg was fixed horizontally on a dynamometer (Cybex Norm Testing & Rehabilitation System, USA) with hip and knee stabilized at 90 degrees. Subjects were then asked to perform isometric knee extension for 10 seconds. The same device was used to stabilize the hip and knee when evaluating the MVC of GS (i.e., ankle plantarflexion). The foot was placed at 90 degrees on a wedged platform and the subjects were instructed to isometrically plantarflex the ankle against the wedge with maximal effort and sustain for 10 seconds. Subjects were provided with verbal encouragement to ensure a maximal effort during testing.

Paragraph Number 17 EMG root mean square values (EMGrms) were calculated during intervals of 0.5 seconds (8). For each muscle, the maximum EMGrms values from the three

MVC trials were averaged to obtain the mean value, which was then used for normalization of the EMGrms value obtained in each WBV condition. The reliability coefficients [intraclass correlation coefficients ($ICC_{3,1}$)] from our three MVC trials in the present study are 0.99, 0.94, 0.99, 0.99 for paretic VL, paretic GS, non-paretic VL, and non-paretic GS, respectively.

Statistical analysis

Paragraph Number 18 Analysis was performed with IBM SPSS Statistics software (version 20.0, IBM, Armonk, NY, USA). Two-way analysis of variance (ANOVA) with repeated measures [within-subject factors: 1. intensity (no WBV Vs low-intensity WBV Vs high-intensity WBV); and 2. exercises] was used to compare the EMG data across the different conditions. When sphericity assumption was violated, the Greenhouse-Geisser epsilon adjustment was used. Contrast analysis using paired t-test with Bonferroni adjustment was performed if any overall significant results were obtained for the EMG data. A p value of less than 0.05 was considered statistically significant. Effect size was denoted by partial eta-squared (partial η^2). Large, medium and small effect sizes were represented by partial η^2 values of 0.14, 0.06, and 0.01, respectively (30).

RESULTS

Demographic characteristics of subjects

Paragraph Number 19 A total of 45 individuals (34 men and 11 women) with chronic stroke participated in the study. The median lower extremity composite motor score (Chedoke-McMaster Stroke Assessment) was 7 out of 14, indicating moderate impairment. The demographic data are summarized in Table 2.

EMG activity of Paretic leg VL

Paragraph Number 20 There was an overall significant main effect of WBV intensity ($F_{2,88}$=27.006, p<0.001, partial η^2=0.380) and exercise ($F_{7,308}$=29.846, p<0.001, partial η^2=0.404) (Figure 1). The intensity × exercise interaction effect was also significant ($F_{14, 616}$=2.312, p=0.031, partial η^2=0.050). In post-hoc analysis of the main effect of intensity, both the low WBV intensity (p<0.001) and 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 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

Paragraph Number 21 The main effect of intensity ($F_{2,88}$=36.728, p<0.001, partial η^2=0.465) and exercise ($F_{7,308}$=6.858, p<0.001, partial η^2=0.135), as well as the intensity × exercise interaction effect ($F_{14,616}$=2.701, p=0.046, partial η^2=0.058) were all significant (Figure 2). 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). Post-hoc analysis of the main effect of exercise showed that the forward-weight-shift position resulted in higher EMG than most of the other exercises (all p<0.01).

EMG activity of Non-Paretic leg VL

Paragraph Number 22 The main effect of intensity ($F_{2,88}$=30.887, p<0.001, partial η^2=0.412) and exercise ($F_{7,308}$=79.302, p<0.001, partial η^2=0.643) and the intensity × exercise interaction were all significant ($F_{14,616}$=8.380, p<0.001, partial η^2=0.160) (Figure 3). Post-hoc analysis on the effect of WBV intensity showed that adding the low-intensity or high-intensity WBV resulted in significantly higher EMG amplitude than the control condition (p<0.001), regardless of the exercise performed. There was no significant difference in EMG amplitude between low-intensity and high-intensity WBV conditions, however (p=0.071). Post-hoc analysis on the effect of exercise showed that the EMG amplitude during upright standing position was significantly lower than other body postures (p=0.013). Deep squat position, on the other hand, induced significantly higher EMG amplitude than other exercises (all p<0.001).

EMG activity of Non-Paretic leg GS

Paragraph Number 23 Significant main effects of intensity ($F_{2,88}$=19.062, p<0.001, partial η^2=0.302) and exercise ($F_{7,308}$=17.080, p<0.001, partial η^2=0.280) were found (Figure 4). The intensity × exercise interaction was also significant ($F_{14,616}$=2.994, p=0.033, partial η^2=0.064). Post-hoc analysis showed that the non-paretic 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 forward-weight-shift position had significantly higher EMG amplitude than others (p<0.001).

DISCUSSION

Paragraph Number 24 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 non-paretic sides in all eight different exercise conditions. Using the higher intensity protocol could further enhance the activity in the GS on the paretic side.

Effect of WBV intensity

Paragraph Number 25 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%, 76% to 243%, 4% to 253%, and 14% to 236% for paretic VL, paretic GS, non-paretic VL, and non-paretic 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. For example, Pollock et al. (34) found that adding WBV (5Hz-30Hz, 2.5-5.5mm) increased EMG amplitude of various leg muscles by 5-50% in a sample of 12 healthy adults. Other studies have shown that WBV at 30-45Hz and amplitudes of 2-5mm led to augmentation of leg muscle activity up to 34.5% in young adults (5,36).

Paragraph Number 26 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, except in the GS of paretic leg. This is in contrast with previous studies in other populations, which showed that higher WBV frequencies are associated with higher EMG amplitude (1,5). For example, using a sample of 13 young men, Hazell et al. (14) has demonstrated that increase in muscle activity in VL, biceps femoris (BF), tibialis anterior (TA), and GS muscles was significantly more with WBV at 45Hz, when compared with 35Hz and 25Hz. The discrepancies in results may be due to several reasons. First, the subject characteristics are different (chronic stroke vs. young health adults). The presence of neurological pathology and changes in muscle properties post-stroke may lead to 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 sub-gravity protocol (0.96G) and a supra-gravity 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 (19). This is particularly true for people with chronic stroke, whose skeleton may be fragile (31). If both the low- and high-WBV intensity protocols can induce similar increase in muscle activity, and considering that the latter may be more related to safety concerns, the low-intensity protocol may be preferred for muscle training in the present subject group. 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, 25Hz, 3.75mm) with a low-intensity one (0.50G, 25Hz, 0.2mm) in subjects with stroke after 12 sessions of training over a 6-week period (4). While no significant between-group difference in knee muscle strength was found after training, a significant but small improvement in paretic knee muscle strength was found only in the low-intensity WBV group. Perhaps the duration of the training program was too short before any the effects of the two different WBV protocols can be delineated. Certainly, more study is required in this area.

Paragraph Number 27 The high-intensity WBV protocol further increased the activity of the paretic GS muscle only, compared with the low-intensity protocol. One possible explanation is that the GS muscle is located closer to the platform, where the vibration signals are generated. A substantial damping of the WBV energy may occur by the time the signals reach the knee joints (19). Using a sample of 15 healthy adults, Pollock et al. (34) showed that in upright standing, the EMG amplitude of the soleus muscle reached 30%-50% MVC when WBV at 20-30Hz (2.5-5.5mm) was applied, which was considerably higher than that of the more proximal muscle groups, such as biceps femoris and rectus femoris (10-20%MVC). Secondly, the paretic side has more muscle strength deficits than the non-paretic side, and the addition of higher WBV intensity to the former may induce a greater response. There is some evidence from previous studies that those with more compromised neuromotor performance at baseline may benefit more from WBV (22,23), it is hence not surprising for weaker muscles to be more responsive to the increase in WBV intensity.

Interaction between exercise and WBV intensity

Paragraph Number 28 A unique aspect of the present study is that we examined a number of 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 (Figure 1-4, 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 conventional resistance training trials in stroke (33). Nevertheless, this study showed that for all 8 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. It may be particularly relevant for frail individuals with stroke, who may respond better to WBV due to poorer baseline performance, and have difficulty with the conventional resistance training due to severely impaired voluntary drive to muscles, lack of selective joint movements, and presence of spasticity. Further randomized controlled trials are required to test these hypotheses.

Paragraph Number 29 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 activation in both paretic and non-paretic leg, 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 forward-weight-shift exercise was significantly less when compared with most of the other exercises. Muscle pre-activation could be a potential factor affecting the extent of muscle activation caused by WBV (17). For example, it is noted that the level of activation in VL and GS muscles are already quite high in deep squat exercise and forward weight shift exercise, respectively, even without vibration. The potential for a further increase in muscle activation upon the addition of WBV is thus smaller.

Paragraph Number 30 Overall, the deep squat and forward-weight-shift exercises, when combined with WBV, resulted in the highest level of EMG activity in 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. Mikhael 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 following 29 session of training over a 13-week period. However, the sample size is small (19 subjects), thus making it difficult to draw conclusion. Whether adding the deep squat and forward-weight-shift exercises during WBV stimulation would lead to more gain in muscle strength than other exercises following long-term training in subjects with stroke requires further investigations.

Limitations and future research directions

Paragraph Number 31 Firstly, since all of our subjects are ambulatory and community-dwelling, the results are only generalizable to a population with similar characteristics. Further research is needed to investigate the acute effects of different WBV intensities and exercises on subjects at acute or sub-acute stages of stroke recovery with more severe limitations in mobility function. Secondly, 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). Torvinen et al (38) 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. Thirdly, only the VL and GS (anti-gravity muscles) of both paretic and non-paretic leg were studied. We chose these muscles because of their key roles in gait and other functional tasks such as transfers (20). 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 (26). The response to WBV in the flexor muscle groups after stroke will need further investigations.

Conclusion

Paragraph Number 32 In conclusion, the present study suggested that leg muscle activity on both the paretic and non-paretic sides was increased significantly by adding WBV, regardless of the exercise performed. The low- and high-intensity WBV protocols induced similar effects, although the high-intensity protocol may further augment the activation of the GS muscle on the paretic side. A randomized controlled trial will be required to determine whether these two protocols could induce any gain in muscle strength in people with stroke following long-term WBV exercise training, and whether the high-intensity protocol could lead to better muscle strength outcomes than the low-intensity one.

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FIGURE LEGENDS

Figure 1. Effect of WBV on paretic leg VL EMG amplitude. The EMG amplitude expressed as %MVC (vertical axis) in each test condition is displayed. The EMG amplitude recorded in the no-WBV, low-intensity WBV and high-intensity WBV conditions is represented by black, gray, and white vertical bars, respectively. Eight exercises were tested: upright standing (ST), semi squat (SS), deep squat (DS), weight-shifted-forward (WSF), weight-shifted-backward (WSB), weight-shifted-to-the-side (WSTS), forward lunge (FL), and single-leg-standing (SLS). The error bars represent 1 standard deviation from the mean. * indicates significant difference from the no-WBV condition. The same conventions are used in other figures.

Figure 2. Effect of WBV on paretic leg GS EMG amplitude. Adding WBV led to significant increase in paretic leg GS EMG amplitude. Moreover, high-intensity WBV induced significantly higher level of muscle activity in paretic leg GS, compared with low-intensity WBV condition. * indicates significant difference from the no-WBV condition, whereas # indicates significant difference from the low-intensity WBV condition.

Figure 3. Effect of WBV on non-paretic leg VL EMG amplitude. High- and low-intensity WBV significantly increased non-paretic leg VL muscle activity to a similar extent.

Figure 4. Effect of WBV on non-paretic leg GS EMG amplitude. Both the high- and low-intensity WBV protocols significantly increased non-paretic leg GS muscle activity.