Effect of Whole-body Vibration on Neuromuscular Activation of Leg Muscles during Dynamic Exercises in Individuals with Stroke

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Abstract

Objective: To investigate the muscle activity of biceps femoris (BF), vastus lateralis (VL), tibialis anterior (TA) and gastrocnemius (GS) in the affected and unaffected legs during exposure to different whole body vibration (WBV) intensities while performing various dynamic exercises in individuals with chronic stroke.

Design: A single-group experimental study with cross-over design.

Setting: A university laboratory.

Subjects: Thirty individuals with chronic stroke.

Interventions: Six dynamic exercises under three different WBV conditions: (1) low-intensity WBV [0.60mm, 20Hz, peak acceleration value: 0.96*g* (unit of Earth's gravitational constant)], (2) high-intensity WBV (0.44mm, 30Hz, 1.61*g*), and (3) no WBV.

Main measures: Amplitude of electromyographic (EMG) signals (root mean square) of bilateral BF, VL, TA and GS (normalized to the EMG amplitude measured in maximal voluntary contraction).

Results: The EMG amplitude of bilateral BF, VL, TA and GS was significantly increased by adding WBV during dynamic exercise (P<0.05). The EMG amplitude of BF, TA and GS during exposure to high-intensity WBV was significantly greater than low-intensity WBV (P<0.05). The increase in EMG amplitude caused by WBV were exercise-dependent in the GS and TA (P<0.05). The EMG response to WBV in the GS and BF in the affected leg was significantly greater than the corresponding muscles in the unaffected leg (P<0.05).

Conclusions: The extent of muscle activity induced by WBV was dependent upon the dynamic exercise, WBV intensity, and muscle trained among individuals with chronic stroke.

Keywords

Cerebrovascular accident; muscles; electromyography; dynamic exercise; rehabilitation; whole body vibration

Introduction

A wealth of literature has investigated how whole-body vibration (WBV) influences the neuromotor function in both young and older adult populations.[1-7] It has been demonstrated in surface electromyography (EMG) studies that adding WBV to exercise regimen can significantly augment the level of muscle activation during static and dynamic exercise in young adults,[2,8-14] suggesting that WBV may have potential impact on neuromuscular function after long-term training. A number of meta-analyses have indeed revealed some positive impact on postural control, muscle strength and mobility in elderly population associated with the use of WBV. However, the most optimal WBV parameters for improving various clinical outcomes are yet to be identified.[15-17] Individuals with stroke may be beneficiaries of WBV therapy, as they also sustain deficits in muscle weakness,[18] balance and functional mobility.[19-21]

Increasing research effort has investigated the efficacy of WBV therapy in the stroke population in the past few years. Recently, a systematic review by Liao et al.[22] revealed inadequate evidence to refute or support the clinical application of WBV therapy in enhancing motor function in the stroke population, primarily because of the conflicting results reported.[22] It seems that more foundational issues have to be more thoroughly investigated before further randomized controlled efficacy studies are conducted.[22] One of these issues pertains to how different WBV intensities affect the extent of neuromuscular activation, and how the muscle response to different WBV intensities varied with different exercises performed (i.e., static Vs dynamic exercises). Liao et al.[23,24] demonstrated that EMG amplitude in four major leg muscle groups, namely, gastrocnemius (GS), and tibialis anterior (TA), biceps femoris (BF), vastus lateralis (VL) muscles, was significantly augmented by applying WBV (by up to 6.5-25.0%) during various static exercises among individuals with chronic stroke, and that the muscle response to WBV was quite similar in both the affected and unaffected lower limb. However, the extent to which leg EMG activity is enhanced by WBV during dynamic exercises in individuals with stroke has never been investigated. This is an important issue because dynamic muscle strength is impaired after stroke, and is strongly correlated with gait performance, balance and activity participation.[25,26] Therefore, dynamic exercises are also often used in WBV training.[27-29]

The current study aimed to examine the EMG response in the VL, BF, TA and GS of both legs during exposure to different WBV intensities while performing various dynamic exercises among individuals with chronic stroke. The hypotheses were: 1) Higher WBV intensity would lead to greater EMG amplitude of the tested muscles during different dynamic exercises; 2) The change in EMG amplitude caused by WBV was associated with the dynamic exercise performed; 3) The effects of WBV on EMG amplitude on the affected and unaffected side would be similar.

Methods

Study design

A one-group experimental study with cross-over design was undertaken to examine the neuromuscular activation of bilateral VL, BF, TA and GS among individuals with chronic stroke during exposure to various WBV intensities when simultaneously performing different dynamic exercises.

Participants

Between June 2013 and March 2014, participants with stroke were recruited from a stroke patient organization in the community via convenience sampling. The following eligibility criteria had to be met for inclusion: diagnosis of hemispheric stroke in chronic stage (i.e., onset >6 months ago), community-dwelling, having motor impairment in the affected leg, as demonstrated by the total leg and foot score ≤13 based on the Chedoke-McMaster Stroke Assessment (Impairment Inventory),[30] and capable of performing the six dynamic exercises (Figure 1) specified in this study. Exclusion criteria included low back pain, spinal diseases, severe cardiovascular conditions (e.g., cardiac pacemaker), peripheral vascular disease, severe musculoskeletal conditions (e.g. rheumatoid arthritis), vestibular dysfunctions, kidney or bladder stones, or pregnancy. We obtained written informed consent from each participant before any data collection took place. Ethics approval was obtained from the Institutional Review Board of the university, and the Declaration of Helsinki were followed in all experiments.

Sample size calculation

A previous study showed that WBV significantly augmented EMG amplitude of the GS muscle in the affected leg, yielding large effect sizes (f=0.46-0.93).[23] Assuming a medium to large effect size (f=0.35), and after accounting for a 10% attrition rate, we aimed to recruit a minimum of 27 participants to yield a power of 90% at a significance level of 0.05.

WBV intensities

All participants underwent a single session of WBV on a vibration platform (Jet-Vibe System, Danil SMC Co. Ltd., Seoul, Korea) that delivered uniform synchronous oscillations at frequencies of 20-55Hz with fixed amplitudes associated with each frequency. We used synchronous WBV in this study, as intended to induce higher level of neuromuscular activation than side-alternating WBV.[31] All experiments were conducted in a university exercise performance laboratory.

All participants were exposed to three WBV conditions: 1) low-intensity WBV [20 Hz frequency with 0.60mm amplitude, peak acceleration: 0.96*g*, where g represents Earth's gravity at 9.8m/s];[32] 2) high-intensity WBV [30Hz, 0.44mm, 1.61*g*]; and 3) no WBV (Table 1). The sequence of WBV intensity was randomized via drawing ballots. A tri-axial accelerometer was used to verify the output of the WBV device (Model 7523A5; Dytran Instruments Inc., Chatsworth, CA).

Exercise conditions

Participants performed six different dynamic exercises for each WBV intensity (Figure 1). Before actual EMG data collection took place, participants were given the opportunity to practice the exercises until they were able to perform them accurately and consistently. A metronome was used in conjunction with verbal commands to guide the rhythm during each dynamic exercise (1.5-second down and 1.5-second up). Each exercise was 45 seconds in duration for each repetition, and 3 repetitions were performed.[12] A 10-second pause was given between each trial of the same exercise. A rest of 1 minute in duration was given after the 3 repetitions were completed. In addition, after all 6 exercises for a particular WBV intensity had been completed, another rest of 5 minutes in duration was given. The sequence of the 6 exercises was determined randomly by drawing ballots prior to actual EMG measurement. An electro-goniometer (Type XM180, Penny and Giles Biometric Ltd, Blackwood, Gwent, UK) was used to monitor the knee angle changes during exercises. Participants were asked to hold onto the handrail of the vibration machine gently for maintaining equilibrium only.

Measurement of neuromuscular activation

Surface EMG was recorded form the VL, BF, TA and GS on both sides during exposure to the three WBV protocols. Following skin preparations, bipolar bar electrodes were attached to the skin atop the respective muscles (Bagnoli EMG system, Delsys, Inc., Boston, MA, USA), according to standardized guidelines.[33] The ground electrode was placed on the head of the fibula in the affected lower limb.

All participants underwent maximal voluntary contraction (MVC) testing for the four muscle groups on each side in sitting. The hip and knee joints were placed in 90° flexion. For each muscle, three MVCs were attempted, with an interspersed 1-minute break between each attempt. For each muscle, the peak EMG amplitude of each trial was averaged to yield the mean. This mean value was then used to normalize the EMG data acquired from the WBV exercise trials. Analysis of the EMG data generated from the three MVC trials demonstrated very good test-retest reliability ($ICC_{2,1}$=0.85-0.98).

EMG data analysis

A sampling rate of 1000Hz was used (Bagnoli-8, DelSys, Inc., Boston, MA, USA) and the EMG data stored directly to hard disk for offline analysis. A20-500Hz band-pass Butterworth filter was used to process the EMG signals (LabView software version 7.0, National Instruments Corp., Austin, TX, USA). To eliminate the noise arising from the frequencies generated by the vibration platform, the harmonic frequencies (i.e., 20Hz, 30Hz and 60Hz) were selectively removed from the data (MyoResearch XP, Master Package version 1.06 software, Noraxon USA, Inc., Scottsdale, AZ, USA).[23] After full-wave rectification of the signals, the EMG root mean square (EMG_{rms}) was then computed in 100-ms windows around each data point.[11] For all trials, the data acquired during the middle 30 seconds were selected for computation of the EMG_{rms} values.[12] The EMG_{rms} was normalized to the peak EMG amplitude recorded in MVC (i.e., %MVC). For each unique combination of WBV intensity and dynamic exercise, the data of the three trials were averaged to provide the mean EMG_{rms} (in %MVC) for subsequent analysis.

Statistical analyses

The dependent variable was normalized EMG_{rms} measured from the four muscles in both legs. Four separate 3-way repeated measure ANOVA models (three WBV intensities; six exercises; paretic leg Vs non-paretic leg) were utilized to examine the EMG data of the four leg muscles respectively (IBM SPSS software version 20.0, IBM Statistics, Armonk, NY). This was followed by contrast analysis with Bonferroni correction if the ANOVA model generated significant results. A significance level of $P<0.05$ was used.

Results

Demographics

Thirty participants (9 women; mean±SD age: 56.8±10.1 years) completed all experimental procedures (Figure 2). Overall, the participants had moderate motor impairment (median Chedoke-McMaster Stroke Assessment lower extremity score=7, interquartile range=6.8-9) (Table 2).

Three-way ANOVA

The intensity × exercise× side interaction was not significant for the VL ($F_{5.496,150.344}=0.642$, $P=0.683$), BF ($F_{4.460,156.628}=1.073$, $P=0.376$), TA ($F_{3.672,94.615}=1.277$, $P=0.285$), and GS ($F_{2.888,138.914}=1.098$, $P=0.353$), suggesting that the interaction of all three factors (i.e., intensity, exercise, and side) did not determine the EMG responses. The following sections would address the three hypotheses of the study.

Main effect of vibration intensity

The effect of WBV intensity for the VL ($F_{1.634,1708.653}$=7.497, P=0.003), BF ($F_{1.354,2942.099}$=41.283, P<0.001), TA ($F_{1.584,625.499}$=15.639, P<0.001), and GS ($F_{1.282,5532.252}$=27.522, P<0.001) were all statistically significant, suggesting that increased WBV intensity led to an increase in neuromuscular activation of these muscles (i.e., hypothesis 1). Post-hoc analysis revealed that in both legs, imposing either low-intensity or high-intensity WBV stimulation during dynamic exercise resulted in significantly greater EMG activity compared with the corresponding exercises when no WBV was added (P<0.05). The EMG amplitude induced by the high-intensity protocol was also significantly greater than that induced by the low-intensity protocol for all (P<0.05) tested muscles except the VL (P>0.05) (Table 3).

Intensity by exercise interaction

The TA ($F_{4.809,254.511}$=2.794, P=0.021) and GS ($F_{4.410,283.364}$=2.636, P=0.032) showed a significant WBV intensity × exercise interaction, suggesting that the muscle responses to the three WBV intensities were associated with the specific dynamic exercises performed (Table 3) (i.e., hypothesis 2). However, such interaction effect was not found in the VL ($F_{5.923,197.072}$=0.720, P=0.632) and BF ($F_{3.780,278.255}$=1.956, P=0.110).

Intensity by side interaction

The intensity × side interaction was significant for the GS ($F_{1.179,2326.829}$=10.501, P=0.002) and BF ($F_{1.206,1242.577}$=14.931, P<0.001) (Table 3), indicating that the two sides showed different responses to WBV (Fig. 3). The intensity × side interaction effect for the VL ($F_{1.371,340.150}$=2.501,

P=0.112) and TA ($F_{1.761,75.630}$=2.918, P=0.069) did not quite reach statistical significance.

Discussion

This is the first report of acute effects of different WBV intensities on neuromuscular activation during different dynamic exercises in individuals with stroke. The key findings were that: 1) Adding WBV to dynamic exercise caused a significant increase in EMG amplitude of leg muscles, and higher WBV intensity was associated with more pronounced increase in EMG amplitude of the BF, TA and GS muscles; 2) The augmentation of EMG activity evoked by WBV was exercise-dependent in the TA and GS; and 3) The EMG response to WBV in the GS and BF of the affected leg was greater than the corresponding muscles of the unaffected leg.

Effect of WBV intensity

Our first hypothesis was confirmed, since the EMG amplitude was significantly augmented by the imposed WBV across all tested muscle groups. With the exception of the VL muscle, the high-intensity WBV protocol led to greater level of neuromuscular activation when compared with the other two WBV conditions (Table 3). Therefore, our findings are generally well aligned with previous investigations on healthy adults, which also demonstrated that a higher WBV intensity would result in more pronounced increase in EMG amplitude.[2,10,11,14,31,34-36] The actual degree of increase in EMG amplitude induced by WBV differed across various studies, primarily due to differences in WBV protocols (e.g., types of vibration, frequency, and amplitudes), exercise (e.g., type of exercise, additional load, and duration), processing methods of raw EMG data, and characteristics of the participants (e.g., stroke Vs able-bodied, severity of stroke impairment, etc.).

Liao et al. [23,24] used the same WBV intensities as the present study to investigate the neuromuscular activation of leg muscles during static exercise among individuals after chronic stroke. Their report showed that the EMG amplitude of the BF, VL, TA and GS muscles on the affected side was significantly increased up to 25.0%, 11.5%, 13.5%, and 20.2%MVC respectively by adding WBV. In this study, we found an increase of EMG amplitude up to8.9%, 4.5%, 3.7%, and 10.7% MVC in the corresponding muscles. The results thus indicated that the influence of superimposed WBV on EMG amplitude was less remarkable during dynamic exercise than static exercise.[23] Whether the two WBV protocols used here would induce more gain in muscle strength in addition to the dynamic leg exercise protocol after a longer intervention period would need to be further tested.

The present study demonstrated that the EMG amplitude of the BF, TA and GS during the high-intensity WBV protocol was significantly greater than the low-intensity WBV protocol during dynamic exercises. However, the actual difference in EMG amplitude induced by the two protocols used here was only around 2-3%MVCand 1-2%MVC for the affected and unaffected sides respectively. This was similar to what was found in previous studies that investigated EMG response in individuals with stroke during static exercise.[23,24] Further increasing the intensity from 0.96*g* to 1.61*g* led to only modest increase in EMG amplitude, highlighting that the relationship between EMG response and increasing WBV intensity was not linear.

WBV intensity by exercise interaction

The intensity by exercise interaction was found to be significant in the TA and GS muscles, thus partly confirming our second hypothesis. It indicated that neuromuscular activation of these two muscles was exercise-dependent. In particular, the WBV-induced muscle activity for the TA and GS was substantially less with the dynamic backward weight-shift and dynamic forward weight-shift exercise respectively (Figure 3 C and D). This was likely related to the relatively high EMG amplitude during these exercises in the control condition where no WBV was applied.

In contrast, the VL and BF muscles did not show any intensity by exercise interaction (Table 3). Some previous studies investigated the WBV intensity by exercise interaction effects in healthy adults but the results were inconsistent.[13,14,37] For instance, in the study by Di Giminiani et al.,[37] different vibration frequencies did not seem to influence the EMG responses during various exercises. On the other hand, Roelantset al.[14] identified a more substantial increase in EMG activity of the VL muscle when one-leg-squat exercise was performed simultaneously when WBV was applied, as opposed to high-squat and low-squat exercise. Recently, Liao et al.[23,24] found a similar WBV intensity by exercise interaction in the VL, BF, TA and GS muscles of both legs during static exercises in individuals with stroke. The greater neuromuscular activity in the GS and TA induced by WBV relative to the VL and BF muscles found in this study may be related to the attenuation of WBV signals as they were transmitted from the feet upward to other parts of the body. The energy of WBV signals may be attenuated by the muscles of the shank (TA and GS) before reaching the thigh (VL and BF), and therefore the difference in effective intensity of WBV delivered to the regions above the knee among the three WBV conditions may be less.

Comparison of WBV-induced EMG responses between affected and unaffected legs

The third hypothesis was partly confirmed as there was a significant intensity by side interaction in the BF and GS, but not the VL and TA. It is clear from Figure 3 that the WBV-induced augmentation of EMG amplitude of the BF and GS was more remarkable in the affected leg than the corresponding muscles in the unaffected leg, indicating possible preferential activation of the affected side by WBV. The lack of significant results in the VL and TA muscles could be due to inadequate statistical power. Indeed, the corresponding p-values obtained were not remote from the level of significance, at 0.112 and 0.069 respectively. Significant results might have been obtained had greater sample size been used. Overall, it seems that there may be preferential activation of the leg muscles on the affected side by WBV during dynamic exercises. This is in discordance with the findings of two previous reports, which showed similar EMG responses to WBV in the affected and unaffected lower extremities during static exercises in individuals with stroke.[23,24] The dynamic exercises, requiring controlled movements at a specified pace, are more challenging than static exercises, which involve only the maintenance of particular postures. Perhaps the participants preferentially used the stronger unaffected leg during the more challenging dynamic exercises, resulting in much higher EMG activity levels in the unaffected leg relative to the affected leg in the control condition. Consequently, the percent increase in EMG activity induced by WBV would be more pronounced in the affected leg than the unaffected leg.

Study limitations

First, our findings may not be generalized to acute or subacute individuals with stroke because the participants were all individuals with chronic stroke in the present study. Second, we only compared the neuromuscular activation among three WBV conditions. The EMG response to WBV intensities higher than 1.61*g* is unknown. Finally, this study only evaluated the EMG activity during exposure to WBV when performing different dynamic exercises, and was not designed to examine whether the WBV intervention would translate into long-lasting changes in muscle activation or functional performance following a training period of longer duration.

Conclusions

In summary, the WBV protocols used in this study caused only a modest increase in EMG amplitude of the leg muscles on both the affected and unaffected sides during dynamic exercises, although the response in the paretic leg seemed to be greater. The WBV-induced muscle activation was dependent on the choice of intensity, exercise, and their interaction. These factors should be considered when prescribing WBV intervention to individuals with stroke.

Clinical messages

- Higher WBV intensity was associated with more pronounced increase in EMG amplitude of the BF, TA and GS.
- The WBV-induced EMG activity was exercise-dependent in the TA and GS.
- The EMG response to WBV in the GS and BF was greater on the affected side than the unaffected side.

Conflict of interest

The authors declare that there is no conflict of interest.

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Table 1. Whole-body vibration (WBV) testing protocol

WBV Condition	Frequency (Hz)	Amplitude (mm)	Peak Acceleration (*g*)	Duration/exercise (second)
No-WBV	0	0	0	45
Low-intensity WBV	20	0.60	0.96	45
High-intensity WBV	30	0.44	1.61	45

WBV= whole body vibration; *g*= I unit of Earth's gravity ($9.8 m/s^2$)

Table 2. Characteristics of participants (n=30)

Variable	Value[*]
Basic demographics	
Age, year	56.8 ±10.1
Sex, men/women, n	21/9
Body Mass Index, kg/m^2	24.7±3.7
Required walking aid for outdoor mobility, none/cane/quadrupod, n	9/17/4
Stroke characteristics	
Time since stroke onset, year	5.2±3.4
Type of stroke, ischemic/hemorrhagic/unknown, n	14/12/4
Side of hemiparesis, left/right, n	10/20
CMSA Lower Extremity Composite Score (out of 14), median (IQR)	7(6.75-9)
Abbreviated Mental Test Score (out of 10)	9.2±1.0
Paretic knee Modified Ashworth Scale of spasticity score (0–4)[†]	
0/1/1.5/2/3/4, n	18/7/4/0/1/0
Median (IQR)	(0-1)
Paretic ankle Modified Ashworth Scale of spasticity score (0–4)	
0/1/1.5/2/3/4, n	2/8/9/10/1/0
Median (IQR)	1.5 (1-2)
Co-morbid conditions	
Hypertension, n	18
High cholesterol, n	15
Diabetes mellitus, n	4
Medications	
Antihypertensive agents, n	
Beta-blockers, n	18
Calcium channel blockers, n	5
Angiotensin converting enzyme inhibitors, n	4
Hypolipidemic agents, n	15
Antidiabetic agents, n	4
MVC EMGrms (μV)	
Paretic leg VL	301.8±159.8
Non-paretic leg VL	444.0±185.6
Paretic leg GS	218.5±182.0
Non-paretic leg GS	356.5±133.4
Paretic leg BF	187.3±136.6
Non-paretic leg BF	456.2±193.9
Paretic leg TA	369.2±243.2
Non-paretic leg TA	654.8±274.4

[*]Mean±SD presented for continuous variables.
[†]Modified Ashworth Scale is a 6-point ordinal scale. The category 1+ was converted to 1.5 for statistical analysis.
BF=biceps femoris; CMSA = Chedoke–McMaster stroke assessment; EMG=electromyography; GS= gastrocnemius; IQR= interquartile range; MVC= maximum voluntary contraction; VL= vastus lateralis; rms=root mean square; TA=tibialis anterior

Table 3. Effect of whole-body vibration (WBV) intensity on neuromuscular activation

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}†	*P*-value	F_{df}†	*P*-value	Mean difference‡ (95% CI)	*P*-value §	Mean difference (95% CI)	*P*-value	Mean difference (95% CI)	*P*-value
VL	$0.72_{5.92,171.7}$	0.632	$7.50_{1.63,47.38}$	0.003*	2.4 (0.2, 4.6)	0.011*	2.9 (1.4, 4.3)	<0.001*	0.5 (-1.8, 2.7)	0.593
BF	$1.96_{3.78,109.61}$	0.110	$41.28_{1.35,39.28}$	<0.001*	2.9 (1.8, 4.0)	<0.001*	3.9 (2.4, 5.3)	<0.001*	1.0 (0.2, 1.7)	0.008*
TA	$2.79_{4.81,139.46}$	0.021*	$15.64_{1.58,45.94}$	<0.001*	1.0 (0.3, 1.7)	<0.001*	1.9 (0.8, 2.9)	<0.001*	0.8 (0.07, 1.6)	0.010*
GS	$2.64_{4.41,127.88}$	0.032*	$27.52_{1.28,37.18}$	<0.001*	4.0 (2.3, 5.6)	<0.001*	5.3 (2.8, 7.8)	<0.001*	1.3 (0.02, 2.7)	0.018*

*Statistically significant (*P*<0.05)
†Greenhouse-Geisser epsilon adjustment was used to generate the F-score, degrees of freedom and P-values due to violation of the sphericity assumption.
‡ EMG magnitude expressed as percent maximal voluntary contraction (%MVC)
§The p-values for the contrast analysis are Bonferroni corrected values.
BF=biceps femoris; CI=confidence interval; df=degrees of freedom; GS= gastrocnemius; TA=tibialis anterior; VL= vastus lateralis; WBV=whole-body vibration

Figure. 1 Exercise protocol

For exercise A-E below, the feet were placed at shoulder width, and the trunk was in upright position.

A. Dynamic semi-squat (DSS): Bilateral knees flexion and extension at a range between 10° and 45°.

B. Dynamic deep squat (DDS): Bilateral knees flexion and extension at a range between10° and70°.

C. Dynamic forward weight shift (DFWS): Bilateral knees maintained at 10° flexion, leaning body forward so that the heels came off the platform as much as possible, then return to original position.

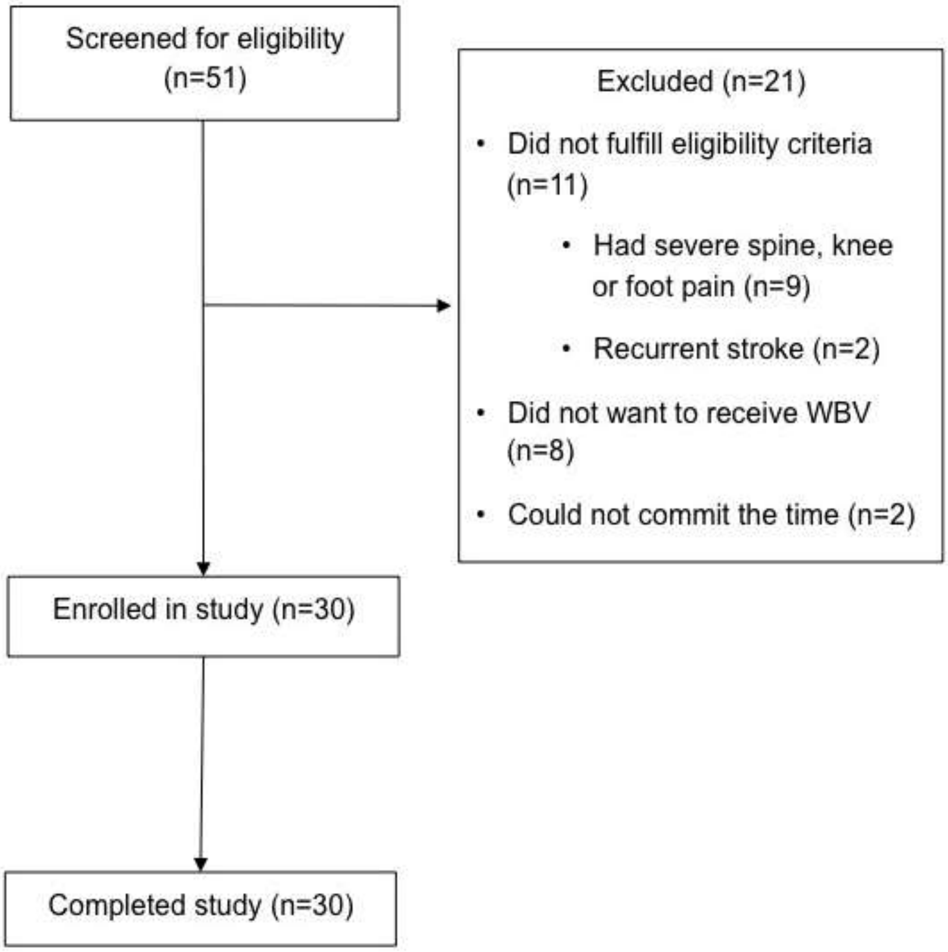
D. Dynamic backward weight shift (DBWS): Bilateral knees maintained at 10° flexion, leaning body backward so that the forefoot came off the platform as much as possible, then return to original position.

E. Dynamic weight shift side to side (DWSSTS): Bilateral knees maintained at

10° flexion, shirting body weight onto the affected side, and then shifting onto the unaffected side.

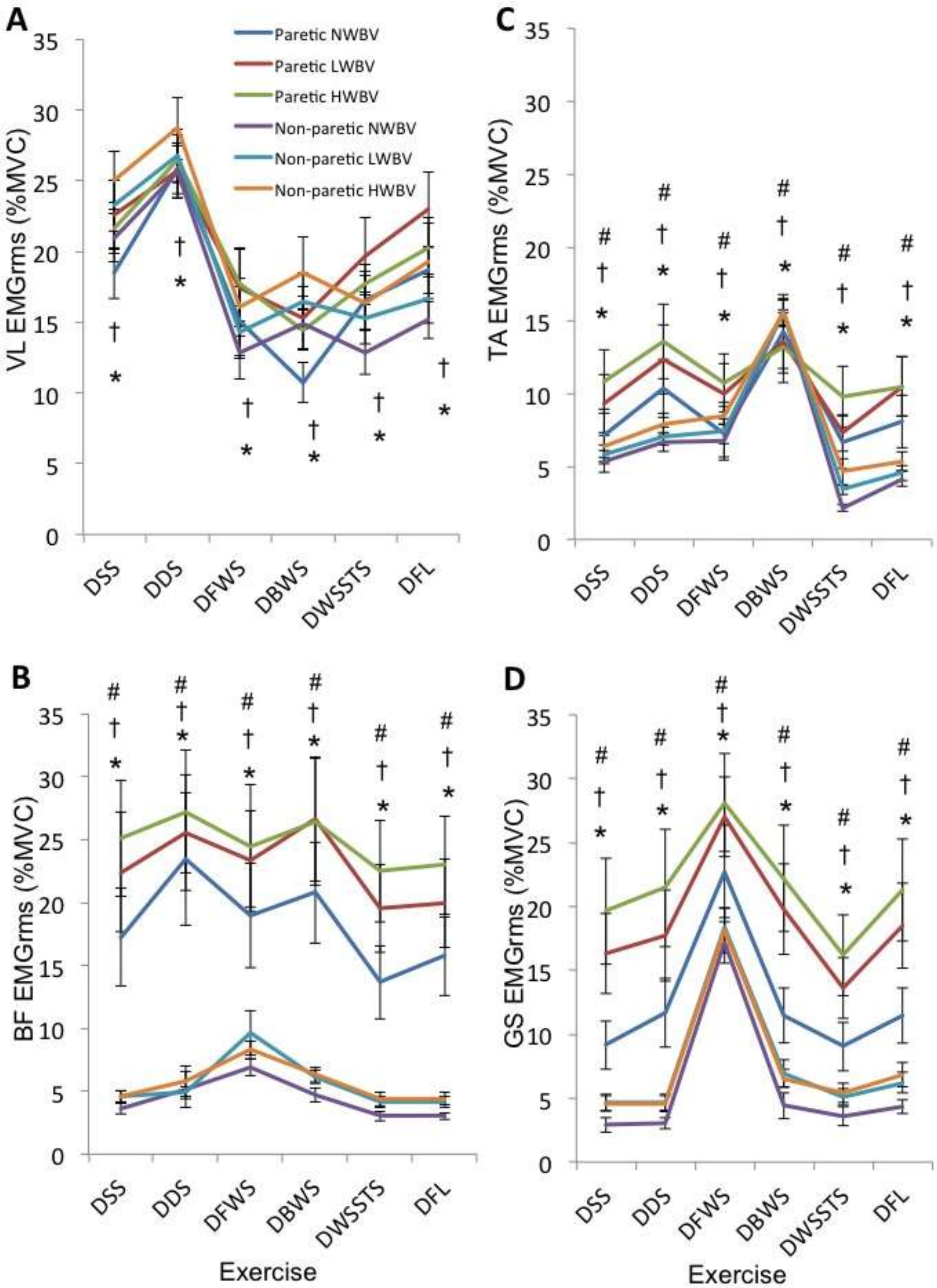
F. Dynamic forward lunge (DFL): Leaning body forward and weight shifting onto the affected leg as much as possible, flexion and extension of the affected knee at a range between10° and45°. Repeat after switching the positions of the two legs.

Figure 2. Study flow chart.



Thirty individuals with stroke completed all experiments.

Figure 3. Normalized EMG amplitude in different WBV and exercise combinations



The normalized EMG$_{rms}$ of the VL (Figure 3A), BF (Figure 3B), TA (Figure 3C), and GS (Figure 3D) in each WBV and exercise condition is expressed as %MVC. The error bars denote 1 standard error of the mean. Six dynamic exercises were performed while undergoing three different WBV conditions: dynamic semi-squat (DSS), dynamic deep squat (DDS), dynamic forward weight shift (DFWS), dynamic backward weight shift (DBWS), dynamic weight shift side to side (DWSSTS) and dynamic forward lunge (DFL). * denotes significant difference between low-intensity WBV and control condition (i.e., no WBV). † indicates significant difference between high-intensity WBV protocol and control condition. # denotes significant difference between the high-intensity and low-intensity protocols. The results were significant if P<0.002 due to Bonferroni adjustment.