Research article

Effect of whole-body vibration on lower-limb EMG activity in subjects with and without spinal cord injury

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Objective: Traumatic spinal cord injury (SCI) results in substantial reductions in lower extremity muscle mass and bone mineral density below the level of the lesion. Whole-body vibration (WBV) has been proposed as a means of counteracting or treating musculoskeletal degradation after chronic motor complete SCI. To ascertain how WBV might be used to augment muscle and bone mass, we investigated whether WBV could evoke lower extremity electromyography (EMG) activity in able-bodied individuals and individuals with SCI, and which vibration parameters produced the largest magnitude of effect.

Methods: Ten male subjects participated in the study, six able-bodied and four with chronic SCI. Two different manufacturers' vibration platforms (WAVE® and Juvent™) were evaluated. The effects of vibration amplitude (0.2, 0.6 or 1.2 mm), vibration frequency (25, 35, or 45 Hz), and subject posture (knee angle of 140°, 160°, or 180°) on lower extremity EMG activation were determined (not all combinations of parameters were possible on both platforms). A novel signal processing technique was proposed to estimate the power of the EMG waveform while minimizing interference and artifacts from the plate vibration.

Results: WBV can elicit EMG activity among subjects with chronic SCI, if appropriate vibration parameters are employed. The amplitude of vibration had the greatest influence on EMG activation, while the frequency of vibration had lesser but statistically significant impact on the measured lower extremity EMG activity.

Conclusion: These findings suggest that WBV with appropriate parameters may constitute a promising intervention to treat musculoskeletal degradation after chronic SCI.

Keywords: Whole-body vibration, Spinal cord injury, Electromyography, Musculoskeletal health, Osteoporosis

Introduction

Individuals who sustain a spinal cord injury (SCI) experience a number of complications, including atrophy and the degradation of their musculoskeletal system.[1,2] These reductions in muscle mass, bone mineral density, and bone architecture are predominantly attributed to the lack of mechanical stimuli to the muscles and of loading the limbs below the level of injury.[3] It has been shown that 6 weeks post-injury subjects with motor complete SCI experience an 18–46% decline in the average cross-sectional area of their muscles compared to controls, and that this decline continues at 24 weeks post-injury.[4] This steep decline in muscle mass and volume has further implications on metabolic rates and energy expenditure patterns, increasing the risk of cardiovascular disease and reducing insulin sensitivity.[1,3] There is a concurrent 50% decline in bone mass of the hip and knee regions in the first 12–18 months post-injury, which results in a lifetime increased risk of fragility fracture.[5] The muscle–bone theory suggests that declines in muscle and bone mass could be closely linked.[6] Therefore, rehabilitation interventions that can counteract muscle atrophy may also have significant clinical implications for limiting osteoporosis. Current rehabilitation

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interventions including functional electrical stimulation (FES) cycle ergometry, body-weight-supported treadmill training, and passive standing have failed to demonstrate substantial sustained increases in lower extremity muscle and bone mass among patients with chronic SCI.[1,7,8]

Whole-body vibration (WBV) is commonly used as an exercise or therapeutic tool with numerous purported benefits for the musculoskeletal system in both able-bodied (AB) and clinical populations.[9–19] In most instances of WBV therapy, participants perform static or dynamic, loaded or unloaded squat exercises with WBV, which results in improved lower-limb neuromuscular performance including increased muscle strength and/or power[9,11,12] and improved walking function.[14] In most cases, positive training effects after WBV exercise have been reported in the AB population and elite athletes, but WBV therapy has also been shown to have positive effects on walking speed and cadence in individuals with incomplete SCI[14] and in improving muscle strength in patients who have had a stroke.[11] This positive training response or therapeutic effect can be attributed to the ability of WBV to induce additional muscle activity beyond the natural muscle activity elicited during applied motor tasks.[20–25,25–31] For example, Roelants *et al.*[25] reported that the muscle activity measured by electromyography (EMG) of lower-limb muscles during various squat tasks increased with WBV compared to the same activities without WBV (increases between 39.9 ± 17.5 and $360.6 \pm 57.5\%$, depending on the muscle selected and type of exercise). WBV is thus an appealing alternative for reducing or treating musculoskeletal degradation after SCI. However, in all the aforementioned studies, the participants voluntarily stood on a WBV plate during the training or therapy, which is not possible for a majority of individuals with paralysis of their lower-limb muscles following SCI. For subjects with motor complete injuries and an inability to voluntarily activate their lower extremity muscles, we have incorporated a standing frame which can be combined with one of the two vibration plates, allowing individuals with SCI who cannot stand independently to stand on the WBV device.[32] However, in this scenario, the lower-limb muscles of the subject are in a resting condition without any visible or palpable voluntary muscle activity while in a passive standing posture. No study to date has investigated whether WBV can induce muscle activity in the lower extremity muscles, when WBV is applied to resting muscles in standing posture, i.e. to individuals who are passively standing on the WBV platform.

The underlying mechanisms by which WBV affects EMG and enhances neuromuscular performance have yet to be established. However, it is strongly believed that increases in muscle activity, i.e. the presence of EMG, during WBV can be attributed to tonic vibration reflexes or stretch reflexes.[13,29] Improvements in muscle strength and power post-vibration can in turn be attributed to the increased muscle activity and increased gravitational loading of the musculoskeletal system as a result of vibration, leading to subsequent neurogenic/morphological adaptation[13] and/or changes in concentrations of hormones, such as testosterone, cortisol, and growth hormone.[15,28] Although the increment of EMG is likely due to tonic vibration reflexes, there is currently a lack of evidence as to what extent vibration to relaxed muscles during passive loading may be able to elicit muscle activity among spinal cord intact participants and individuals with SCI.[33,34]

Thus, the purpose of this study was to investigate whether WBV would elicit EMG activity in individuals with SCI and AB subjects when the subjects are secured in a standing posture using a standing frame attached to either the WAVE® or Juvent™ WBV plate. In addition, we examined the effects of specific vibration parameters (frequency and amplitude of vibration) and posture of the subjects when exposed to WBV, to determine the impact of each variable on lower-limb EMG activation. The goal was to establish the vibration parameters and posture that elicited the greatest lower extremity muscle EMG activity when subjects in a standing frame are exposed to WBV. We hypothesized that since higher frequencies and amplitudes of vibration result in larger magnitudes of vibration, these vibration parameters would bring about greater EMG activation of the lower-limb muscles to counteract the imposed mechanical stimulus. Regarding posture during WBV, we hypothesized that the more erect postures (knees straight), would allow greater transmission of vibrations,[32] thereby resulting in greater EMG activation.

Materials and methods

Study subjects

Ten adult male subjects were recruited for the study, six AB and four with chronic SCI (>1 year post-injury). The details of the subject inclusion and exclusion criteria and training, which was provided prior to initializing the study, can be found elsewhere in Alizadeh-Meghrazi *et al.*[32] A breakdown of the subject demographic and impairment characteristics are shown in Table 1. This study was approved by the Research Ethics Board of the Toronto Rehabilitation Institute,

Table 1 The breakdown of the demographic characteristic of the participating subjects

AB				SCI				
Subject	Age	Height (cm)	Weight (kg)	Subject	Age	Height (cm)	Weight (kg)	Injury
A	41	174	74	I	30	188	79	C6 AIS A
B	29	179	75	J	38	173	76	C7 AIS C
C	24	180	66	K	27	185	77	T9 AIS A
D	35	180	74	L	50	170	75	L1 AIS A
E	22	170	62					
F	22	171	76					
Mean	28.83	175.67	71.17	Mean	36.25	179.00	76.75	
STD	7.78	4.59	5.74	STD	10.28	8.83	1.71	

and all applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed.

WBV platforms and setup

Two commercially available vibration platforms were used: (1) WAVE® (WAVE Manufacturing Inc., Windsor, Ontario, Canada); and (2) Juvent™ (Juvent Medical Inc., Somerset, NJ) in conjunction with a standing frame EasyStand 5000 (Altimate Medical Inc., Morton, MN) (Fig. 1). The WAVE® platform generated larger magnitude vibrations (>1 g) than the Juvent™ platform, which is designed to deliver low-magnitude vibrations (<1 g). The specifications and performance evaluation test results for each plate and the WBV platform/standing frame setup details are reported in a prior publication.[32]

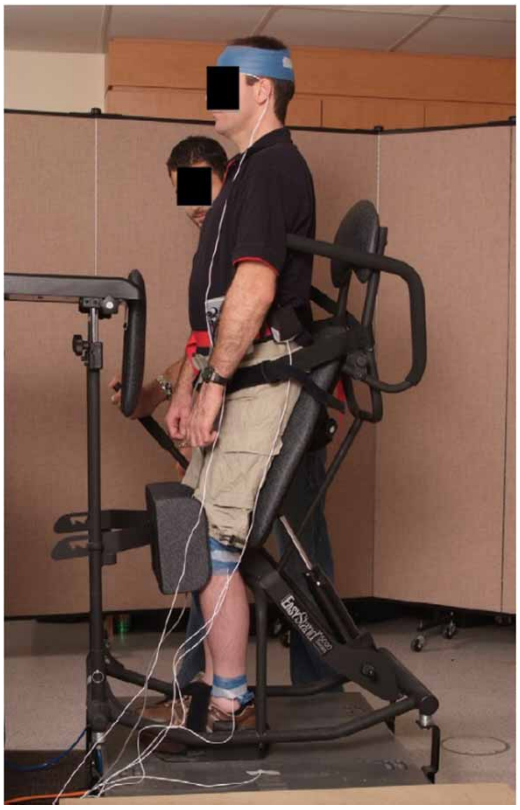

Figure 1 The WAVE® vibration platform and the standing frame (experimental setup). Reproduced from Alizadeh-Meghrazi *et al.*[32]

Experiment and vibration protocol

Testing was performed on 2 days, where the subjects were randomly allocated to exposure to either the WAVE® or Juvent™ platform each day. All subjects were provided with the same shoes to eliminate footwear variability. In the case of the WAVE® platform, all combinations of the following parameters were used: (1) vibration frequencies of 25, 35, and 45 Hz; (2) two vibration amplitude settings, which we measured using a laser displacement measuring tool (LK-500; Keyence Co., Osaka, Japan) to correspond to peak-to-peak displacements of ~0.6 and 1.2 mm; and (3) knee angles of 140°, 160°, and 180°. The 180° posture was used only in the AB subjects, because it was observed during testing that this posture induced strong extensor spasms for those with an upper motor lesion and a strong extensor synergy at the knee and ankle (three of four subjects with SCI) and vibrations to the head, and there was a concern that it might produce adverse events (nausea, headaches, foot, or ankle injuries) in the subjects with SCI. In the case of the Juvent™ platform, all combinations of the following parameters were used: (1) vibration frequencies of 25, 35, and 45 Hz; (2) constant power setting of 28; and (3) knee angles of 140°, 160°, and 180°. The vibration amplitude of the Juvent™ was measured to be ~0.2 mm; because the amplitude was lower than in the WAVE® platform, the 180° posture was used for both AB and subjects with SCI on this plate. The knee angle was chosen at random with subsequent testing of frequency and amplitude at that knee angle, as shown in Table 2. Subjects were asked to remain relaxed during WBV to minimize voluntary movement in their lower limbs during each bout of WBV. Note that when standing (while supported by the standing frame), there was almost no visible or

Table 2 The breakdown of the combinations of tested conditions on each platform

WAVE®			Juvent™	
Posture	Frequency (Hz)	Amplitude (mm)	Posture	Frequency (Hz)
140°	25	0.6	140°	25
		1.2		35
	35	0.6		45
		1.2	160°	25
	45	0.6		35
		1.2		45
160°	25	0.6	180°	25
		1.2		35
	35	0.6		45
		1.2		
	45	0.6		
		1.2		
180° (AB only)	25	0.6		
		1.2		
	35	0.6		
		1.2		
	45	0.6		
		1.2		

palpable muscle activity in the subjects' lower extremity muscles even for AB individuals (see also Masani *et al.*[35]). Subsequently, EMG recordings were performed 1 minute after initiation of WBV, and were recorded for a 20-second interval for each test condition. Recordings were also collected in each posture with and without WBV, in order to provide baseline information. Further details on the experiment and vibration protocol can be found in the work of Alizadeh-Meghrazi *et al.*[32]

Data collection and analysis

In order to quantify muscle activity during WBV, surface EMG was acquired using an EMG system AMT-8 (Bortec Biomedical Ltd, Calgary, Alberta, Canada) with an amplifier gain of 2000, a frequency bandwidth of 10–1000 Hz, and a common mode rejection ratio of 115 dB (at 60 Hz). Bipolar silver–silver chloride surface disposable electrodes were employed (10 mm diameter, 18 mm inter-electrode distance) and placed over the tibialis anterior (TA), soleus (SO), gastrocnemius medialis (GM), rectus femoris (RF), and vastus lateralis (VL) muscles of the subject's right lower limb. The electrodes and their pre-amplifiers were taped to the leg, and wrapped with pre-wrap to reduce the movement artifact stemming from the vibration. In order to quantify the increase in EMG activity due to WBV, baseline measures were taken before exposure to WBV. For the AB subjects, recordings were obtained in sitting, active standing (normal standing with knees straight, erect posture), and passive standing postures (standing with the aid of the standing frame). For subjects with SCI, recordings were obtained in sitting and passive standing postures.

Data were recorded with a data acquisition unit PowerLab 16SP (ADInstruments, Dunedin, New Zealand) at a sampling rate of 2000 Hz. The recorded data were then analyzed in MATLAB (R2008a, Mathworks, Natick, MA, USA). When recording EMG during WBV exposure, a motion artifact component was picked up by the electrodes. This artifact was visualized by computing the power spectral density (PSD) of the raw EMG data. It was confirmed that the artifact occurs at the vibration frequency and approximately around its harmonics. The most commonly used filters for removal of the motion artifact are bandstop and notch filters.[23,24,29,30] These methods were tested for their effectiveness in removing the motion artifact from the raw EMG signal, but present flaws that significantly influenced the magnitude of EMG. First, the magnitude of the signal removed from the raw EMG was dependent on the size of the motion artifact spike in the PSD plot. This issue created inconsistencies in the magnitude of the filtered signal from case to case, which would affect the tabulated EMG magnitudes and influence the comparison of different conditions when determining the effect of various parameters on EMG activation. Secondly, the vibration frequency and its harmonics, which were used to pinpoint the center of the filters, were not consistent and did not follow the form "$n\omega_o$", where n is an integer representing the order of the harmonic and ω_o is the frequency of vibration (25, 35, or 45 Hz). The peaks would occur in a frequency band ± 7.5 Hz of $n\omega_o$ and this was sensitive to the parameters used in computing the PSD. This issue created a deviation between the observed center of the harmonic and the theoretical value, affecting the magnitude of the filtered signal.

In order to address the issue of motion artifact in the EMG, a new filtering method was devised that overcomes the two flaws present when using bandstop or notch filters. The new method first determined the frequency of the motion artifact through examination of the PSD. Bands of ± 7.5 Hz around the frequency of vibration and each of its theoretical harmonics ($n\omega_o$) were then surveyed to identify the frequency with the highest power in each case. The ± 7.5 Hz range used to survey these frequencies was established based on the initial observation that the harmonics do not exactly fall at $n\omega_o$, and after sensitivity testing and visual inspection established that ± 7.5 Hz is the optimal survey band for detection of all deviated centers of frequency (± 2.5, 5, and 10 Hz bands were also tested). Frequencies up to 300 Hz were examined and the rest of the signal was

omitted. This 300 Hz ceiling was based on the typical bandwidth of EMG recordings (EMG peaks between 100 and 200 Hz), which suggests that the rest of the signal (>300 Hz) would not provide any useful information.[36] Once the artifact frequencies were determined, the PSD was set to zero within a ±1.5 Hz band around each of those frequencies. Therefore, each specific vibration regiment (combination of frequency, amplitude, and posture) had its unique filter, and since the EMG activation during WBV was compared to the EMG activation during baseline conditions (sitting, passive standing, and standing), the filter was also applied to the baseline data. This ensured consistency in signal manipulations on a case-by-case basis and allowed us to quantify changes in EMG activation from the baseline conditions to WBV. However, this method did not allow us to compare variations in EMG activation between different WBV regimens, i.e. 180° – 45 Hz – 1.2 mm vs. 160° – 25 Hz – 0.6 mm, since: (1) each signal had a unique filter which eliminated a different magnitude of the signal; and (2) higher frequency vibration regiments result in the elimination of fewer bands of signal (up to 300 Hz, 25 Hz = 12 bands, 35 Hz = 8 bands, 45 Hz = 6 bands). To circumvent this issue, the EMG power for each condition was normalized to the number of non-zeroed points of the PSD plot (<300 Hz). In other words, since the PSD had a different number of entries for each condition, depending on the identified and removed artifact frequencies, the total power in each spectrum was divided by its number of remaining entries. This normalized power would allow us to compare different vibration regiments and determine the effect of each variable (frequency, amplitude, and posture) on EMG activation.

To assess the effect of the test condition variables (frequency, amplitude, and posture) on EMG activation on different muscles, repeated measures analysis of variance (RMANOVA) and two-tailed paired *t*-tests were performed to establish the effect of each of the variables on the outcome measures. A P-value of 0.05 was considered statistically significant for all analyses. When multiple paired *t*-tests were performed, Bonferroni correction was applied to the P-value, to account for the number of comparisons ($\text{P-value}_{adj} = 0.05/c$, where "*c*" is the number of paired *t*-tests). The SCI and AB groups were assessed in different pools. All statistical analyses were performed with SPSS (version 17.0, SPSS Inc., Chicago, IL, USA). Because the WAVE® platform provided amplitude control whereas the Juvent™ platform did not, the two devices were analyzed separately for their effects on EMG activation.

Results

WAVE® EMG results

Two-tailed paired *t*-tests of EMG activation of baseline conditions, sitting vs. passive standing, in the AB group revealed that for most muscles there was no statistically significant difference except for two cases. The two cases where sitting and passive standing showed significant differences were (1) TA, knee angle of 180°, (2) GM, knee angle of 160°; upon further analysis of the EMG signals in these two conditions, we observed that the difference in the means was due to a single outlier whose active and passive standing recordings were very similar, and therefore concluded that this subject had unknowingly been performing voluntary contractions. Therefore, we assumed that among the AB participants muscle activity during the passive standing condition was equivalent to that during the sitting condition. The same *t*-tests in the SCI group revealed no significant differences between EMG levels of passive standing and sitting. Based on these results, we used the sitting EMG activity of each participant as the baseline to compare against EMG activity during exposure to WBV. Fig. 2 illustrates the variations in EMG activation in the AB group while using the WAVE® device, as a function of the vibration and posture parameters, and provides the passive sitting data for comparison. EMG activity from active standing is also shown in order to provide context for activity elicited by the WBV. Fig. 3 provides the analogous data for the SCI group, though in this case, no active standing data are available, and therefore only the sitting data are used for comparison.

Comparison of WBV and sitting conditions as a function of vibration frequency

Among the AB participants for the five recorded muscles, in vibration regimens where the frequency of vibration was 25 Hz, 16 out of 30 conditions showed significantly larger EMG activation compared to sitting EMG levels. The same is observed with the 35 and 45 Hz vibration regimens, where 16 and 21 conditions demonstrated greater EMG activity, respectively. Among the participants with SCI, the three frequencies 25, 35, and 45 Hz resulted in 14, 12, and 10 out 20 conditions of increased EMG activation, respectively, compared to sitting baseline EMG levels.

In the AB group, zero, one, and four conditions were found where the WBV elicited significantly greater EMG activity than active standing, for the 25, 35, and 45 Hz vibration conditions, respectively. Figs. 2 and 3 detail which comparisons were significant. The large standard deviations are due to the expected variability in recording EMG signals from different subjects,

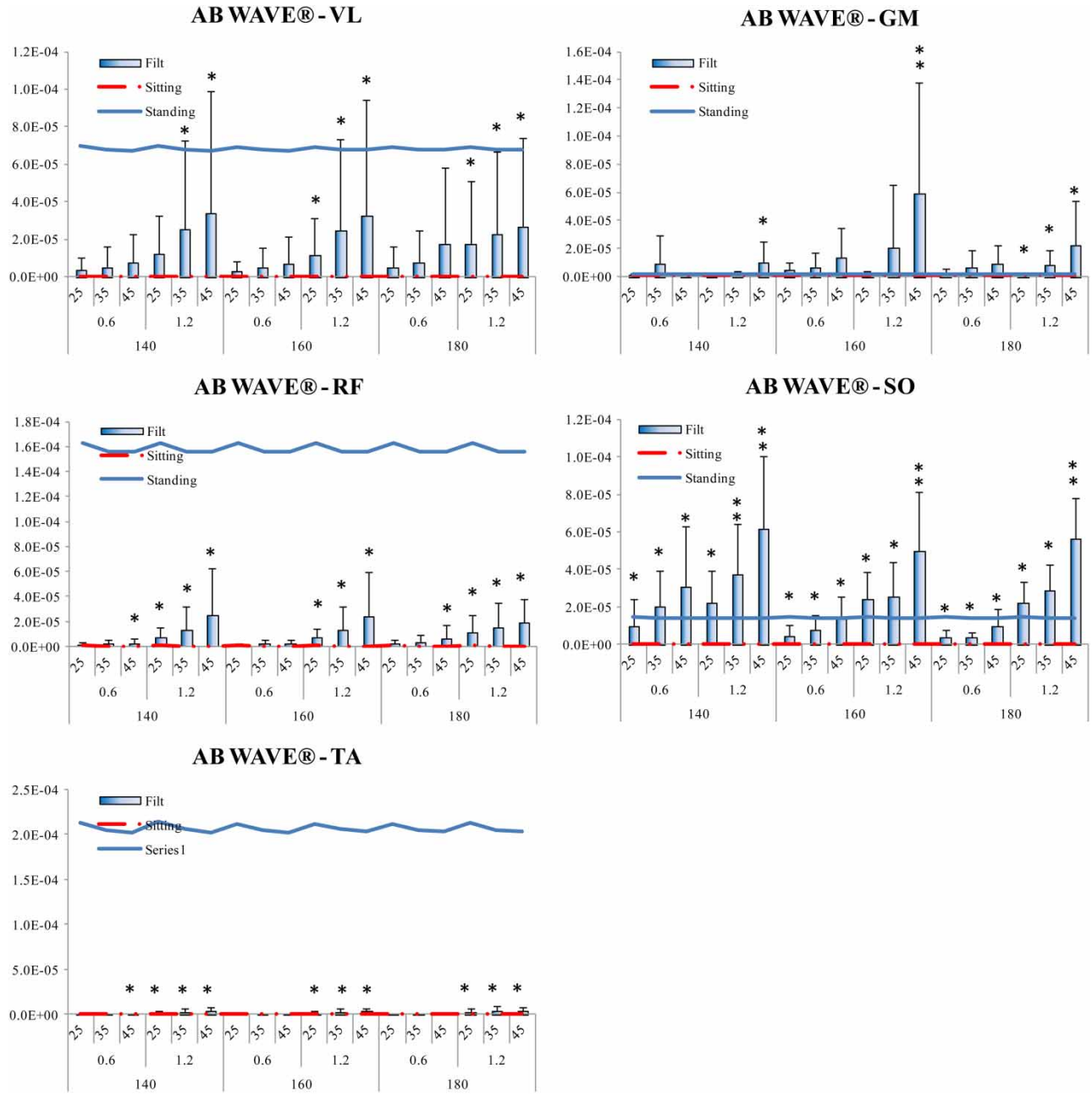

Figure 2 Mean + standard deviation of EMG power for each muscle in AB individuals using the WAVE® platform, as a function of the vibration and posture parameters (frequency of 25, 35, or 45 Hz; amplitude of 0.6 mm or 1.2; knee angle of 140°, 160°, or 180°). Activation levels recorded during passive sitting are provided (red dotted line) for comparison with the vibration-induced activity. A single asterisk (*) denotes WBV-induced activity that is significantly greater than sitting levels, whereas a double asterisk denotes induced activity that is significantly greater than active standing levels. VL, vastus lateralis; GM, gastrocnemius medialis; RF, rectus femoris; SO, soleus; TA, tibialis anterior.

given that our processing methodology was based on a raw rather than normalized EMG signal.

Comparison of WBV and sitting conditions as a function of vibration amplitude

Regarding the effect of the amplitude of vibration in the AB group, with amplitudes of 0.6 and 1.2 mm, 12 and 41 conditions out of 45, respectively, showed significant differences compared to sitting EMG activity. In the SCI group, amplitudes of 0.6 and 1.2 mm led to significant activation in 13 and 23 conditions out of 30, respectively.

In contrast, in the AB group, zero and five conditions were found where the WBV elicited significantly greater EMG activity than active standing, for amplitudes of 0.6 and 1.2 mm, respectively.

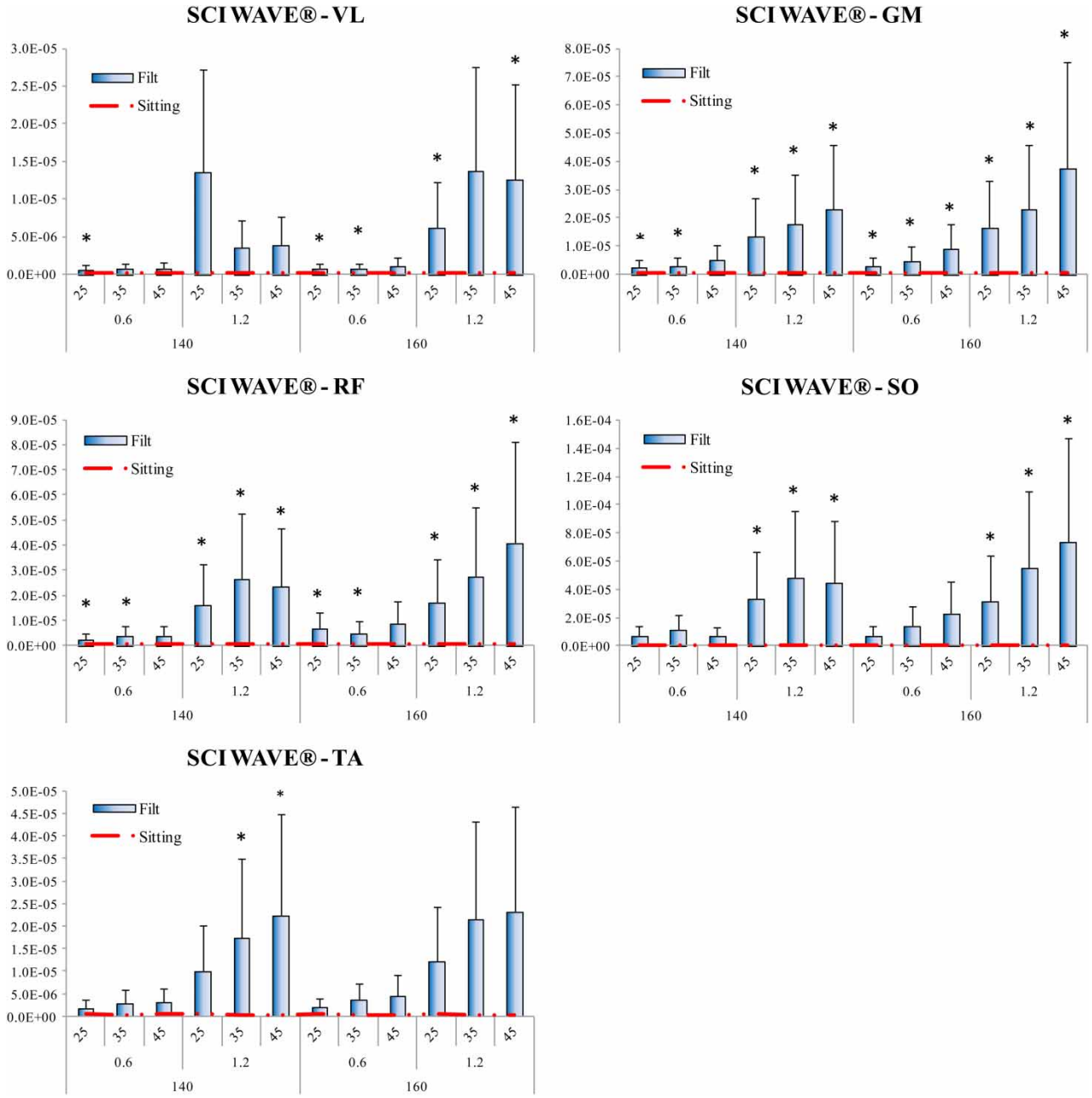

Figure 3 Mean + standard deviation of EMG power for each muscle in individuals with SCI using the WAVE® platform, as a function of the vibration and posture parameters (frequency of 25, 35, or 45 Hz; amplitude of 0.6 or 1.2 mm; knee angle of 140° or 160°). Activation levels recorded during passive sitting are provided (red dotted line) for comparison with the vibration-induced activity. An asterisk (*) denotes WBV-induced activity that is significantly greater than sitting levels. VL, vastus lateralis; GM, gastrocnemius medialis; RF, rectus femoris; SO, soleus; TA, tibialis anterior.

Comparison of WBV for different vibration conditions

The RMANOVA of the normalized EMG data for the AB group revealed that variations in posture did not generate any statistically significant difference in EMG activation in any muscle or for any vibration conditions. In contrast, variations in the frequency and amplitude of vibration generated significant differences in WBV EMG activation in all tested muscles. Among the participants with SCI, the pattern was very similar: variations in posture did not generate significant differences in EMG activation, whereas variations in the frequency of vibration affected EMG activation levels in all muscles except VL. Variations in the amplitude of vibration in the SCI group resulted in a significant difference in the activation of the GM and RF muscles. In summary, on the WAVE® platform, EMG activation

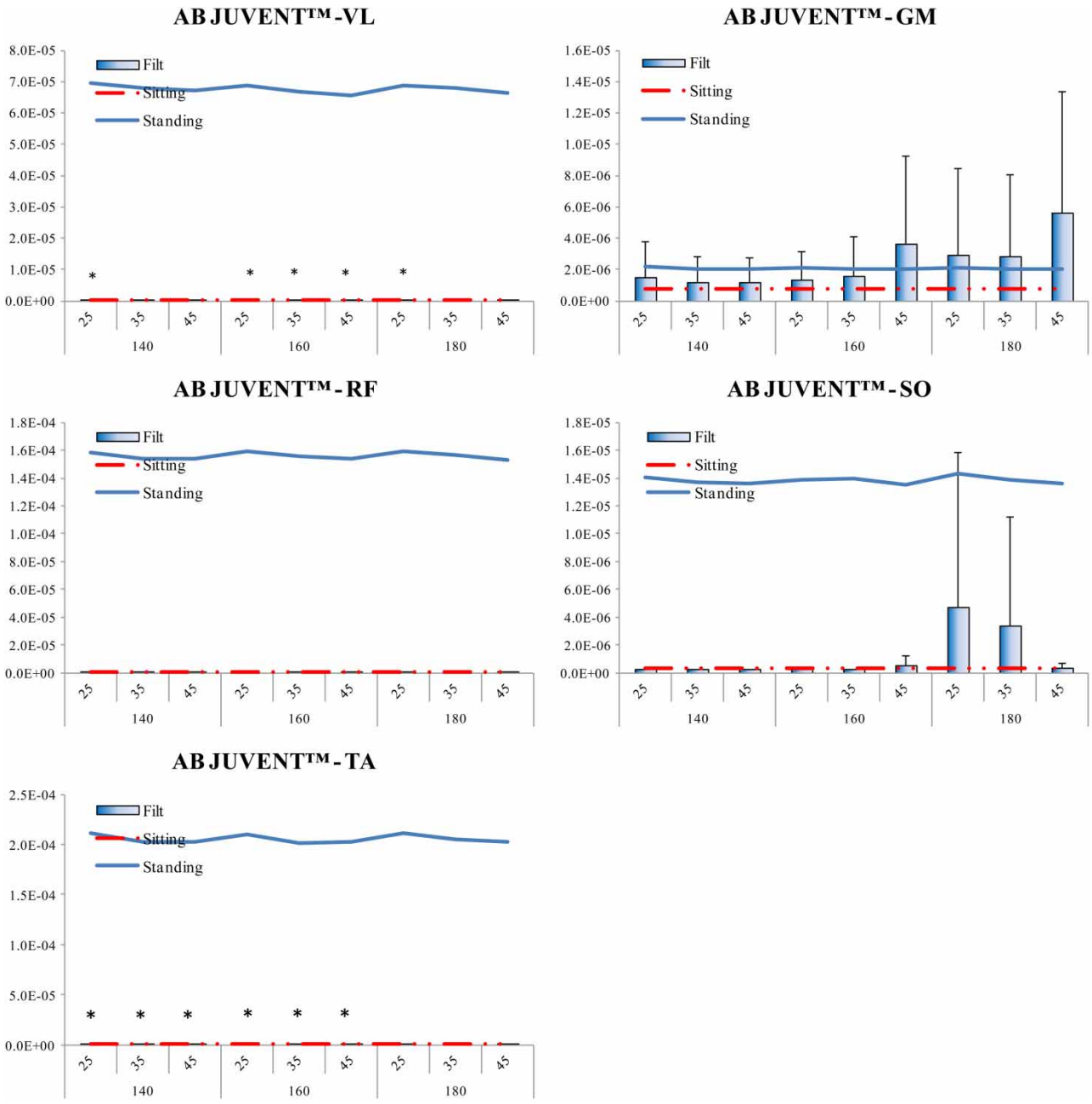

Figure 4 Mean + standard deviation of EMG power for each muscle in AB individuals using the Juvent™ platform, as a function of the vibration and posture parameters (frequency of 25, 35, or 45 Hz; knee angle of 140°, 160°, 180°; amplitude was 0.2 mm in all cases). Activation levels recorded during passive sitting are provided (red dotted line) for comparison with the vibration-induced activity. An asterisk (*) denotes WBV-induced activity that is significantly greater than sitting levels. VL, vastus lateralis; GM, gastrocnemius medialis; RF, rectus femoris; SO, soleus; TA, tibialis anterior.

was modulated by the vibration parameters (frequency and amplitude) but not by the posture of the subject.

Juvent™ EMG results

In the AB group, a total of 11 out of 45 conditions showed significant EMG activation compared to sitting (all muscles, postures, and frequencies combined), and 0 conditions showed significant activation compared to active standing. Fig. 4 details which comparisons were significant. In the SCI group, no significant EMG activation was observed, for any muscles or settings. The RMANOVA of the normalized EMG data collected while using the Juvent™ device did not reveal any significant differences for any factors (posture, frequency, or amplitude), in either the AB (Fig. 4) or SCI group (Fig. 5).

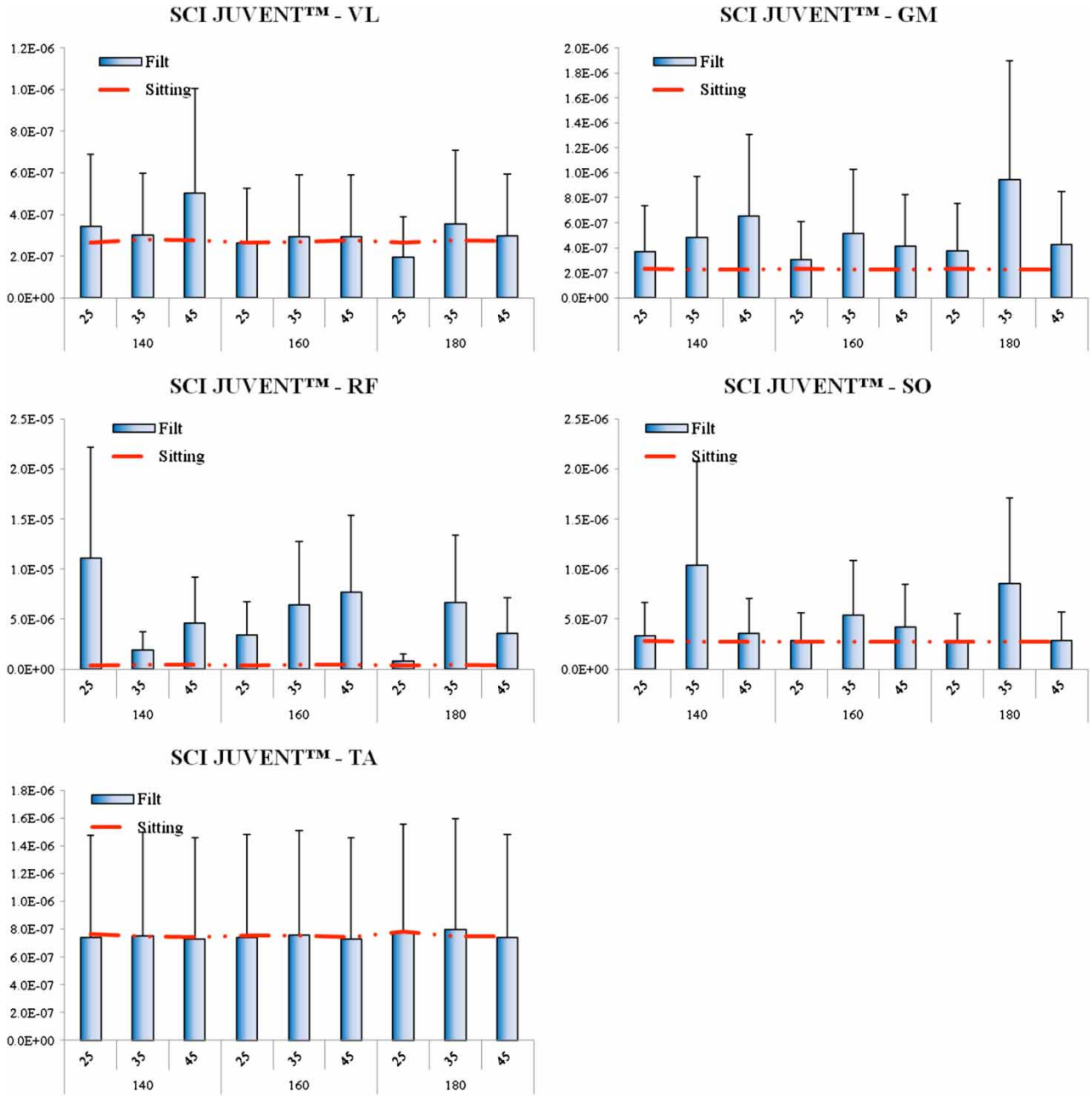

Figure 5 Mean + standard deviation of EMG power for each muscle in individuals with SCI using the Juvent™ platform, as a function of the vibration and posture parameters (frequency of 25, 35, or 45 Hz; knee angle of 140°, 160°, 180°; amplitude was 0.2 mm in all cases). Activation levels recorded during passive sitting are provided (red dotted line) for comparison with the vibration-induced activity. An asterisk (*) denotes WBV-induced activity that is significantly greater than sitting levels. VL, vastus lateralis; GM, gastrocnemius medialis; RF, rectus femoris; SO, soleus; TA, tibialis anterior.

Discussion

The ability of WBV to evoke EMG activation in resting lower-limb muscles was investigated. EMG activity was successfully produced in both AB subjects and subjects with SCI, providing the first demonstration that WBV can induce activation even in resting muscles with low levels of tonic reflex activity. On the other hand, our results also showed that EMG activity is only observed if specific vibration parameters are employed. With appropriate vibration parameters, WBV can induce muscle activity in the resting muscle at the same level as what is observed during standing for anti-gravity muscles. In particular, increasing the amplitude of vibration had the most noticeable impact on EMG activation, with high vibration amplitudes producing measurable EMG increases in the greatest number of

muscle and parameter combinations. The frequency of vibration was also found to have a statistically significant impact on EMG activation in the RMANOVA analysis, but examination of Figs. 2 and 3 shows that varying the frequency alone was most often not sufficient to produce activation significantly greater than the passive sitting level, if the amplitude of vibration was low; in other words, frequency was not in itself sufficient to bring about significant activation. Overall, the vibration parameters that could most reliably elicit EMG activation were the combination of 45 Hz frequency and 1.2 mm amplitude, in both groups of subjects, with posture not found to be playing a significant role.

The parameter dependence of the EMG activation effect is well exemplified by our comparison of the two vibration platforms. The WAVE® platform provided the higher vibration of the two devices, and was responsible for all of the results described in the previous paragraph. In contrast, the Juvent™ platform, which uses lower vibration magnitudes, was able to produce EMG activation in fewer cases than the WAVE® in the AB subjects. More importantly, the Juvent™ platform failed to elicit EMG activation in any of the subjects with SCI, regardless of the muscle or parameter combination employed, suggesting that this device is of little interest for clinical applications of WBV requiring muscle activation in SCI.

In addition to the vibration parameters, the ability of WBV to elicit EMG activity was influenced by the muscles under consideration. In the AB group, the SO, medial gastrocnemius, and to a lesser extent VL, which are so-called anti-gravity muscles, displayed EMG activity that was comparable to that observed during active standing. TA was the muscle least activated by WBV, with activation levels far below those observed during active standing. When considering clinical application of the study results, it is therefore worth taking into consideration that the patterns of activity produced by WBV may be dissimilar from the physiological patterns of activity during standing.

In addition to direct benefits on the muscles, such as increased strength, tone, and reduced spasticity, the successful production of EMG activity in subjects with SCI implies that WBV could potentially be beneficial for promoting maintenance or accrual of bone mass after injury, as the forces exerted by the muscles on the bones induce morphological adaptation, in accordance to the muscle–bone theory.[6] Our results therefore suggest that the clinical application of WBV to prevent or treat musculoskeletal degradation after SCI warrants further investigation.

There have been a number of new emerging therapies for treatment of musculoskeletal degradation after SCI.[37] Recent investigations (http://www.clinicaltrials.gov) have tried to capitalize on the muscle–bone unit theory through the presumed synergistic effects of the WBV mechanical stimuli of muscle and bone with pharmacological interventions for bone including recombinant parathyroid hormone (PTH) (NCT 01225055) or passive standing with recombinant PTH (NCT 00826228). In the future, investigators should carefully consider the specificity of vibration parameters for treatment effects, and weigh the relative merits of continuous vs. intermittent vibration, and the need for continuous variation in the frequency and intensity of WBV stimuli throughout the intervention, when emulating the variation in mechanical stimuli among those able to weightbear and participate in instrumental activities of daily living (sit to stand, walk on a slope, jump, descend stairs, etc.). Although, the application of the muscle–bone theory is most appealing for treatment of patients with motor complete SCI, WBV effectiveness is likely to be greatest among those with some preservation of voluntary lower extremity muscle activity, as the muscle–bone unit likely requires active contraction of the muscle in addition to electrophysiological activation in response to WBV, to elicit the desired changes in bone quality. A detailed understanding of the physiological connections between muscle mass and bone quality across impairment subgroup (AIS A vs. AIS C) will become increasingly important, as muscle density and bone turnover will likely emerge as predictors of WBV therapeutic effectiveness.

Although a number of previous studies have examined EMG responses during WBV.[20–31] the EMG analyses that they employed were not well suited to accurately remove the vibration noise without compromising the quality of the EMG data. As a result, the EMG measures reported thus far in the literature cannot be regarded as wholly reliable. Our proposed approach improves on previous methods using a two-step approach. First, the frequencies of the vibration artifact and each of its harmonics are identified individually on a case-by-case basis for each recording, ensuring that the correct information is removed. Second, rather than quantifying the activation based on a filtered version of the EMG signal, we relied directly on the PSD of the recording. This allowed us to focus the information being removed, and therefore impact the EMG signal less than if traditional filtering had been used.

The main limitation of our study is the overlap of the EMG recordings and vibration artifacts with the vibration frequency and its associated harmonics.

Further, the periodic signal eliminated in our analysis may not be a motion artifact but an EMG signal induced by stretch reflex.[29] In order to minimize the impact of this interference, we have proposed a signal processing methodology that allowed us to isolate the EMG activity unlike in prior published studies. The analysis presented here allowed us to quantify the variations in EMG activity under different vibration conditions. On the other hand, because our method operates on the power spectrum directly rather than on a filtered signal, it precludes us from analyzing the EMG in the time domain, and its usefulness is thus likely to be limited to WBV studies. The second limitation of this work is that we cannot exclude the possibility that the subjects had some involuntary leg muscle contractions. This issue is of particular concern for the AB subjects, but may to a lesser extent affect the results of subjects with SCI. In the standing frame, activities in lower-limb muscles have previously been observed to automatically disappear even in AB subjects.[35] Therefore, we do not expect involuntary contractions to have been responsible for the significant portion of the observed EMG activity, but the possibility is not completely excluded. Although the sample size for our study was small, the size of the effects observed suggests that our results will be robust and applicable to a larger population. Nevertheless, our conclusions are specific to the range of vibration parameter values explored in this study: different amplitudes and frequencies of vibration or different subject postures could result in different effects.

Conclusion

WBV was administered to adult male subjects and subjects with chronic SCI and AB subjects. Vibration and posture parameters were varied, and EMG activity on two manufacturers' plates was recorded using a novel methodology designed to minimize the impact of the vibration artifact. WBV is capable of eliciting lower extremity EMG activity, not only in AB subjects' resting muscles but also in subjects with chronic SCI, among whom a majority of subjects with SCI had motor complete injuries and an inability to voluntary contract their lower extremity muscles. For SO and the medial gastrocnemius, WBV can induce activity in the resting muscle at the same level, to the levels observed during standing. Importantly, the power of the recorded EMG signal was crucially dependent on the vibration parameters, confirming that the choice of vibration platform and parameters is of paramount importance for any clinical application of WBV. Among the parameters studied here, 45 Hz vibration with an amplitude of 1.2 mm was the most reliable combination of WBV parameters to elicit EMG activity, in both AB subjects and subjects with chronic SCI.

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Disclaimer statements

Contributors MAM, KM, and DGS participated in the collection of the data. MAM conducted the signal processing. MAM, KM, and JZ analyzed the data and drafted the manuscript. MRP and BCC obtained funding for the project and participated in the design of the study. All authors reviewed and provided input into the manuscript.

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Conflicts of interest None.

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References

1 Giangregorio L, McCartney N. Bone loss and muscle atrophy in spinal cord injury: epidemiology, fracture prediction, and rehabilitation strategies. J Spinal Cord Med 2006;29(5):489–500.
2 Shields RK. Muscular, skeletal, and neural adaptations following spinal cord injury. J Orthop Sports Phys Ther 2002;32(2):65–74.
3 Giangregorio LM, Craven B, Webber CE. Musculoskeletal changes in women with spinal cord injury: a twin study. J Clin Densitom, 2005;8(3):347–51.
4 Castro MJ, Apple DF, Jr, Hillegass EA, Dudley GA. Influence of complete spinal cord injury on skeletal muscle cross-sectional area within the first 6 months of injury. Eur J Appl Physiol Occup Physiol 1999;80(4):373–8.
5 Craven BC, Robertson LA, McGillivray CF, Adachi JD. Detection and treatment of sublesional osteoporosis among patients with chronic spinal cord injury: proposed paradigms. Top Spinal Cord Inj Rehabil 2009;14(4):1–22.
6 Totosy de Zepetnek JO, Craven BC, Giangregorio LM. An evaluation of the muscle-bone unit theory among individuals with chronic spinal cord injury. Spinal Cord 2012;50(2):147–52.

7 Craven BC, Lynch CL, Eng JJ. Bone health following spinal cord injury. In: Eng JJ, Teasell RW, Miller WC, Wolfe DL, Townson AF, Hsieh JTC, Connolly SJ, Noonan VK, Loh E, McIntyre A (eds.) Spinal cord injury rehabilitation evidence version 5.0. Vancouver; 2014, pp. 1–37. http://www.scireproject.com

8 Chang KV, Hung CY, Chen WS, Lai MS, Chien KL, Han DS. Effectiveness of bisphosphonate analogues and functional electrical stimulation on attenuating post-injury osteoporosis in spinal cord injury patients – a systematic review and meta-analysis. PLoS ONE 2013;8(11):e81124.

9 Blottner D, Salanova M, Püttmann B, Schiffl G, Felsenberg D, Buehring B, *et al.* Human skeletal muscle structure and function preserved by vibration muscle exercise following 55 days of bed rest. Eur J Appl Physiol 2006;97(3):261–71.

10 Cardinale M, Wakeling J. Whole body vibration exercise: are vibrations good for you? Br J Sports Med 2005;39(9):585–9.

11 Tihanyi J, Di Giminiani R, Tihanyi T, Gyulai G, Trzaskoma L, Horváth M. Low resonance frequency vibration affects strength of paretic and non-paretic leg differently in patients with stroke. Acta Physiol Hung 2010;97(2):172–82.

12 Bosco C, Colli R, Introini E, Cardinale M, Tsarpela O, Madella A, *et al.* Adaptive responses of human skeletal muscle to vibration exposure. Clin Physiol 1999;19(2):183–7.

13 Wilcock IM, Whatman C, Harris N, Keogh JWL. Vibration training: could it enhance the strength, power, or speed of athletes. J Strength Cond Res 2009;23(2):593–603.

14 Ness LL, Field-Fote EC. Whole-body vibration improves walking function in individuals with spinal cord injury: a pilot study. Gait Posture 2009;30(4):436–40.

15 Kvorning T, Bagger M, Caserotti P, Madsen K. Effects of vibration and resistance training on neuromuscular and hormonal measures. Eur J Appl Physiol 2006;96(5):615–25.

16 Rehn B, Lidstrom J, Skoglund J, Lindstrom B. Effects on leg muscular performance from whole-body vibration exercise: a systematic review. Scand J Med Sci Sports 2007;17(1):2–11.

17 Delecluse C, Roelants M, Verschueren S. Strength increase after whole-body vibration compared with resistance training. Med Sci Sports Exerc 2003;35:1033–41.

18 Totosy de Zepetnek JO, Giangregorio LM, Craven BC. Whole-body vibration as potential intervention for people with low bone mineral density and osteoporosis: a review. J Rehabil Res Dev 2009;46(4):529–42.

19 Sayenko DG, Masani K, Alizadeh-Meghrazi M, Popovic MR, Craven BC. Acute effects of whole body vibration during passive standing on soleus H-reflex in subjects with and without spinal cord injury. Neurosci Lett 2010;482(1):66–70.

20 Hazell TJ, Jakobi JM, Kenno KA. The effects of whole-body vibration on upper-and lower-body EMG during static and dynamic contractions. Appl Physiol Nutr Metab 2007;32(6): 1156–63.

21 Eckhardt H, Wollny R, Müller H, Bärtsch P, Friedmann-Bette B. Enhanced myofiber recruitment during exhaustive squatting performed as whole-body vibration exercise. J Strength Cond Res 2011;25(4):1120–5.

22 Coza A, Nigg BM, Dunn JF. Effects of vibrations on gastrocnemius medialis tissue oxygenation. Med Sci Sports Exerc 2011; 43(3):509–15.

23 Hazell TJ, Kenno KA, Jakobi JK. Evaluation of muscle activity for loaded and unloaded dynamic squats during vertical whole-body vibration. J Strength Cond Res 2010;24(7):1860–5.

24 RPollock RD, Woledge RC, Mills KR, Martin FC, Newham DJ. Muscle activity and acceleration during whole body vibration: effect of frequency and amplitude. Clin Biomech 2010;25(89): 840–6.

25 Roelants M, Verschueren SMP, Delecluse C, Levin O, Stijnen VRE. Whole-body-vibration-induced increase in leg muscle activity during different squat exercises. J Strength Cond Res 2006;20(1):124–9.

26 Fratini A, La Gatta A, Bifulco P, Romano M, Cesarelli M. Muscle motion and EMG activity in vibration treatment. Med Eng Phys 2009;31(9):1166–72.

27 Wakeling JM, Nigg BM, Rozitis AI. Muscle activity damps the soft tissue resonance that occurs in response to pulsed and continuous vibrations. J Appl Physiol 2002;93(3):1093–103.

28 Bosco C, Iacovelli M, Tsarpela O, Cardinale M, Bonifazi M, Tihanyi J, *et al.* Hormonal responses to whole-body vibration in men. Eur J Appl Physiol 2000;81(6):449–54.

29 Ritzmann R, Kramer A, Gruber M, Gollhofer A, Taube W. EMG activity during whole body vibration: motion artifacts or stretch reflexes? Eur J Appl Physiol 2010;110(1):143–51.

30 Abercromby AFJ, Amonette WE, Layne CS, McFarlin BK, Hinman MR, Paloski WH, *et al.* Variation in neuromuscular responses during acute whole-body vibration exercise. Med Sci Sports Exerc 2007;39(9):1642–50.

31 Cardinale M, Lim J. Electromyography activity of vastus lateralis muscle during whole-body vibrations of different frequencies. J Strength Cond Res 2003;17(3):621–4.

32 Alizadeh-Meghrazi M, Masani K, Popovic MR, Craven BC. Whole-body vibration during passive standing in individuals with spinal cord injury: effects of plate choice, frequency, amplitude, and subject's posture on vibration propagation. PMR 2012;4(12): 963–75.

33 LZaidell LN, Mileva KN, Sumners DP, Bowtell JL. Experimental evidence of the tonic vibration reflex during whole-body vibration of the loaded and unloaded leg. PLoS ONE 2013;8(12):e85247.

34 Hortobágyi T, Rider P, Devita P. Effects of real and sham whole-body mechanical vibration on spinal excitability at rest and during muscle contraction. Scand J Med Sci Sports 2014. doi: 10.1111/sms.12219.

35 Masani K, Sayenko DG, Vette AH. What triggers the continuous muscle activity during upright standing? Gait Posture 2013;37(1): 72–7.

36 Komi PV, Tesch P. EMG frequency spectrum, muscle structure, and fatigue during dynamic contractions in man. Eur J Appl Physiol Occup Physiol 1979;42(1):41–50.

37 Battaglino RA, Lazzari AA, Garshick E, Morse LR. Spinal cord injury-induced osteoporosis: pathogenesis and emerging therapies. Curr Osteoporos Rep 2012;10(4):278–85.