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Original Article

Acute unilateral leg vibration exercise improves contralateral neuromuscular performance

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Abstract

Objectives: To examine the post-exercise cross-transfer effects of acute whole body vibration (WBV). **Methods:** Seventeen healthy male volunteers (20.8±1.2 y) performed three unilateral vibration conditions in a randomized order: 1) WBV-50 Hz [high amplitude]; 2) WBV-30 Hz [low amplitude]; and 3) a control no WBV condition (Sham) applied to the dominant leg. Each condition involved maximal voluntary isometric contractions (MVC) followed by three leg press explosive repetitions (40% MVC) with non-dominant and dominant legs; which were conducted prior to and post vibration (immediately; 2 min and 5 min). Surface electromygraphy (sEMG) of the vastus lateralis (VL) and medial gastrocnemius (MG) were measured throughout each condition. **Results:** A condition x leg x time interaction effect was detected (p=0.001) where 50 Hz-High in the stimulated leg enhanced mean velocity at post-2 min compared to 30 Hz-Low and Sham, remaining elevated at post-5 min. Similarly, 50 Hz-High in the non-stimulated leg increased mean velocity at post-immediately and post-2 min compared to 30 Hz-Low and Sham. There were no changes in sEMG of VL and GM in the stimulated and non-stimulated post-conditions. **Conclusion:** WBV (50 Hz) can augment cross-transfer in neuromuscular performance. WBV could provide an alternate method of unilateral training to promote cross education explosive strength.

Keywords: Sinusoidal Vibration, Electromyography, Power, Vibration Exercise, Cross-education

Introduction

Whole-body vibration (WBV) exercise has become a popular health and fitness tool over the past decade. Typically, WBV exercise involves intermittent exposures to a vibration stimulus while performing traditional body weight exercises such as squats or lunges on a ground-based platform. Several WBV studies have demonstrated that higher frequencies of vibration combined with higher amplitudes result in increased muscle activity[1-3], suggesting an increased stimulus. Because of the increasing popularity, much research has been performed to understand both if WBV exercise is beneficial for users and if so how WBV is resulting in these benefits.

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An early suggestion was that WBV exercise improved neuromuscular function[4-7], though whether these include increases in muscle strength remains equivocal[5,8]. However, WBV exercise has demonstrated acute increases in strength following a WBV exposure suggesting a degree of neuromuscular potentiation[9-11]. Performing exercises on a synchronously (uniform vertical vibrations) oscillating platform induces short and rapid changes in muscle fibre length stimulating reflexive muscle contractions in a response akin to monosynaptic reflexes[12-14]. This response results in an increase in muscle activity[1,2,15,16], enhanced excitability of the cortical motor pathway, as well as modulation of intracortical circuits[17]. The mechanical vibration stimulus may also affect skin and joint receptors that provide sensory input to the gamma motor system increasing the sensitivity and responsiveness of the muscle spindle to further mechanical perturbations[18-20]. Though several studies have investigated the potential of WBV to improve subsequent performance[21-24], it is not well understood whether unilateral exposure to WBV will cause improvements in performance of the other leg.

Recently, it was demonstrated that 3 weeks of unilateral training (3 sessions per week) with the addition of WBV (35 Hz, 2.5 mm) did not further augment the cross-transfer of strength compared to the same training without WBV[25]. While this suggests that 9 sessions over 3 weeks was not sufficient to induce an adaptation they only employed one vibration frequency over the 3 weeks and utilized large external loads that may have diminished the stimulus generated by the WBV platform. Therefore, before more training studies are performed, it seems practical to examine if there is an acute cross-transfer effect with WBV exposure. The practical importance of the effects of WBV on the cross-transfer of strength are also clinically important in rehabilitation settings for individuals with compromised capacity to use/train one limb due to injury or limb immobilization following surgery[25-27]. Thus, the aim of this study was to analyze the potential post-exercise cross-transfer effects of WBV by muscle activity and neuromuscular performance of explosive repetitions after WBV exposure (30 s duration) to determine if WBV exposure has a residual effect on contralateral leg. It was hypothesized that WBV would potentiate the neuromuscular system by improving neuromuscular performance of explosive movements.

Materials and methods

Experimental design

This study investigated whether 30 s of WBV exposure during a one-legged static semi-squat would benefit muscle performance in the non-exposed contralateral leg. Muscle activity and neuromuscular performance of leg press explosive repetitions at 40% MVC were measured before, immediately (within 30 s), 2, and 5 min post-WBV exposure. Three different exercise conditions were performed in a randomized order (independent variables): 1) 50 Hz with high amplitude (50 Hz-High), 2) 30 Hz with low amplitude (30 Hz-Low), and 3) no WBV (Sham). All exercise conditions were separated by at least 2 days and were conducted at the same time of day to account for daily biorhythms. Thus, at the end of the experimental phase, all the participants had been tested for the three conditions. The participant's dominant leg was defined by their preference for kicking.

Participants

Seventeen undergraduate male students participated in the study (20.8±1.2 y, 179.7±0.2 cm, 76.0±8.5 kg, mean±SD). Each participant performed all 3 conditions to minimize inter-individual variance in neuromuscular response and 15 of the 17 participants indicated right leg dominance. All participants were recreationally active (physically active) but none were involved in a systematic exercise-training program at the time of data collection or for at least 2 months prior to the study. All participants were experienced with free-weight resistance exercises and training leading to failure. Prior to data collection participants were informed of the requirements associated with participation and provided written informed consent. Exclusion criteria were diabetes, epilepsy, gallstones, kidney stones, cardiovascular diseases, joint implants, recent thrombosis, as well as musculoskeletal problems. Participants were encouraged to maintain their dietary, sleeping, and drinking habits during participation in the study. One week before the testing sessions, subjects attended two familiarization sessions. The research project was conducted according to the Declaration of Helsinki and was approved by the University Review Board for use of Human Subjects.

Vibration equipment

The vibration stimulus consisted of commercial platform (Power Plate® Next Generation pro 5, Power Plate North America, Northbrook, Illinois, USA) that produced synchronous (uniform) tri-planar oscillations[28]. The acceleration of the vertical sinusoidal oscillations (z-axis) was measured using a uni-axial accelerometer in accordance with ISO2954 (Vibration meter VT-6360, Hong Kong, China). Vibration platform settings included a frequency of 50 Hz with the peak-to-peak displacement of 2.51 mm (High) or a frequency of 30 Hz with peak-to-peak displacement of 1.15 mm (Low). Measured accelerations were 100.6±0.24 $m \cdot s^{-2}$ (at 50 Hz) and 20.44±0.34 $m \cdot s^{-2}$ (at 30 Hz). During all conditions, subjects wore the same athletic shoes to standardize the damping of the vibration because of the footwear[16].

Neuromuscular performance measurement

During all experimental sessions, participants performed isometric MVC trials at 60º-knee flexion followed by dynamic explosive contraction at 40% MVC on an adapted horizontal leg press machine (Nautilus Strength System S912, Vancouver, Canada) unilaterally on non-dominant and dominant legs. For the isometric MVC trials, participants were instructed to contract as 'hard' and 'fast' as possible for ~3 s. They repeated this 3 times for each leg separated by 20 s followed by the other leg. A digital load cell (HCB200K100, Kern & Sohn GmbH, Balingen, Germany) attached to the Nautilus equipment cable was used to measure the parameters of each MVC repetition. Participants then rested for 5 min before performing 3 dynamic explosive contractions at 40% of their MVC for each leg separated by 20 s of rest where participants were again instructed to extend their knee(s) as 'fast' and hard as possible for 3 s. The main investigator provided verbal cues to ensure correct execution was maintained through all testing. The neuromuscular performance of each explosive repetition were monitored by a rotary encoder (Globus Real Power, Globus, Codogne, Italy) linked to the highest load plate on the machine. The rotary encoder recorded the position of the load plate within an accuracy of 0.1 mm and time events with an accuracy of 0.001 s. Mean velocity for each repetition was analysed. Velocity was determined using software provided by the rotary encoder as described previously[29,30].

Surface electromyographic activity (sEMG)

Muscle activity of the vastus lateralis (VL) and medial gastrocnemius (MG) muscles were measured using sEMG[2,15,16,31,32]. Prior to electrode placement, the area was shaved and cleaned with isopropyl alcohol to reduce skin impedance. The electrodes were placed over the midbelly of the muscle parallel to the direction of the fibres according to recommendations by the SENIAM project (Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles)[33].

The double differential technique was used to detect myo-

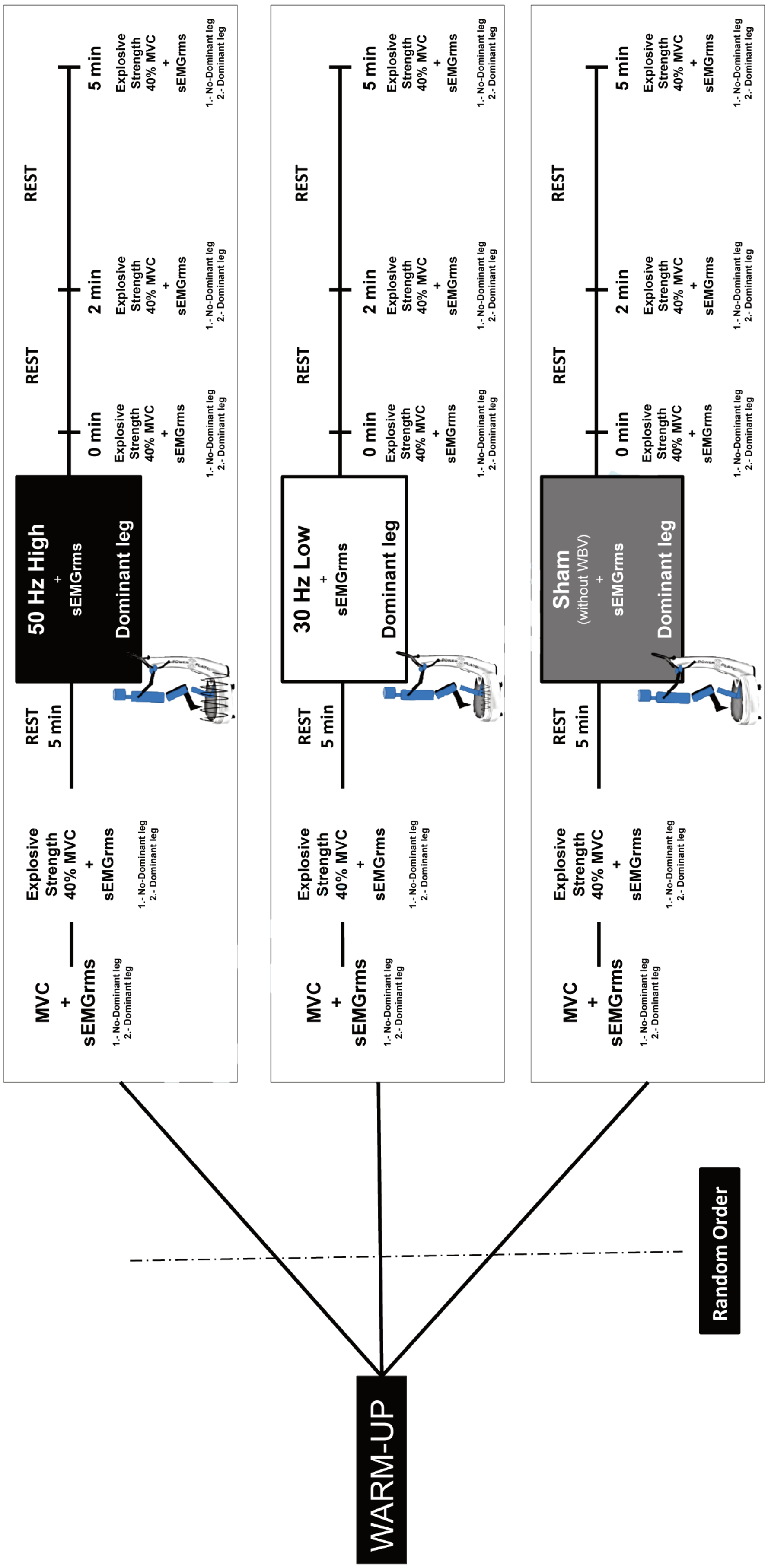
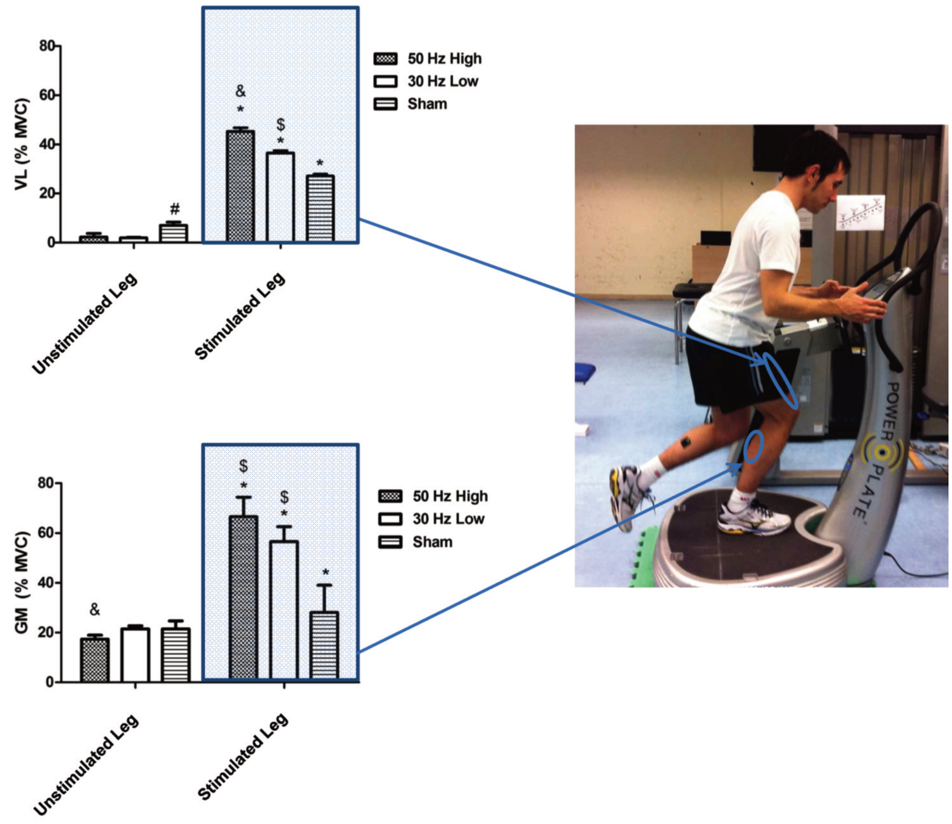


Figure 1. Experimental design.



* Statistically significant between legs (p<0.001)

Statistically significant from 50 Hz High and 30 Hz Low (p<0.001).

& Statistically significant from Sham and 30 Hz Low (p<0.001).

$ Statistically significant from Sham (p<0.001).

Figure 2. sEMGrms of vastus lateralis (VL) and gastrocnemius medialis (GM) during unilateral WBV stimulation.

electric raw signals. The surface electrodes were connected to a 16-bit AD converter (Trigo™ Wireless System, Delsys Inc., Boston, MA, USA). Raw EMG signals were pre-amplified close to the electrodes (signal bandwidth of 20-450 Hz) and sampled at 4000 Hz and stored on a laptop. sEMG data analysis was performed using specific software (Delsys EMGworks Analysis 4.0. Delsys Inc. Boston, Massachusetts, USA). sEMG data was averaged by root mean square (rms) in order to obtain averaged amplitude of the sEMG signal. The sEMGrms values post-WBV of explosive 40% MVC test was normalized relative to maximum peak obtained in pre-WBV testing. For data analysis during WBV, only 20 s of the test condition were utilized (from 5 s to 25 s), which were normalized relative to MVC during the isometric test[1,2,15,16].

Protocol

In all experimental sessions, participants began with a warm-up consisting of 5 minutes of low-resistance (75 W) cycling on an ergometer. Each participant performed three separate conditions: 1) WBV-50 Hz [high amplitude]; 2) WBV-30 Hz [low amplitude]; and 3) a control no WBV condition (sham). Each session (Figure 1) was performed in random order beginning with the isometric MVC and dynamic explosive contractions at 40% MVC followed by 5 min rest. The experimental treatment then initiated with unilateral WBV stimulation on a vibration platform where participants were instructed to place their dominant foot in the middle of the platform and maintain a single-leg static squat at 60º knee flexion for 30 s, (knee fully extended=0º), which was measured by manual goniometer. The non-stimulated (non-dominant) leg remained off the platform behind the participant (Figure 2) and for balance the participants were allowed to touch the handrails. The time delay between exposure condition and post-testing was no longer than 5 seconds in duration.

Statistical analysis

The normality of the data was checked and subsequently confirmed with the Shapiro-Wilk test. Dependent variables were evaluated with a three-way repeated measures analysis of variance (ANOVA) on time x condition x leg. When a sig-

	Mean Velocity	VL sEMG$_{rms}$	GM sEMG$_{rms}$
Condition	p=0.091; n²=0.139	**p=0.029; n²=0.224**	p=0.717; n²=0.030
Leg	**p=0.002; n²=0.465**	p=0.121; n²=0.163	p=0.298; n²=0.098
Time	**p=0.002; n²=0.264**	p=0.367; n²=0.072	p=0.610; n²=0.053
Condition*Leg	p=0.088; n²=0.141	p=0.575; n²=0.039	p=0.420; n²=0.076
Condition*Time	**p<0.001; n²=0.244**	p=0.139; n²=0.107	p=0.255; n²=0.108
Leg*Time	p=0.159; n²=0.101	p=0.115; n²=0.130	p=0.158; n²=0.144
Condition*Leg*Time	**p=0.001; n²=0.208**	p=0.850; n²=0.031	**p=0.029; n²=0.187**

Table 1. Summary of the main effects analyzed with the ANOVAs for the dependent variables.

	50Hz-High		30Hz-Low		Sham	
	Non-Stimulated	**Stimulated**	**Non-Stimulated**	**Stimulated**	**Non-Stimulated**	**Stimulated**
Pre	0.296±0.01	0.315±0.01	0.288±0.02	0.299$^{\$}$±0.01	0.285±0.02	0.302±0.01
Post-Immediately	0.312$^{*\#}$±0.01	0.325*±0.01	0.289±0.02	0.288$^{*\&}$±0.01	0.279±0.02	0.303±0.02
Post 2 min	0.309*±0.01	0.329*±0.01	0.289±0.02	0.306±0.01	0.288±0.02	0.309±0.02
Post 5 min	0.302±0.01	0.331*±0.01	0.282*±0.02	0.296$^{\&}$±0.01	0.288±0.02	0.285*±0.02

$ - Statistically significant between leg for experimental sessions (p<0.05).
* - Statistically significant from Pre at the same leg and experimental session (p<0.05).
& - Statistically significant from Post 2 min at the same leg and experimental session (p<0.05).
# - Statistically significant from Post 5 min at the same leg and experimental session (p<0.05).

Table 2. Pre and post times of mean velocity (m·s^{-1}) for the three conditions.

nificant F-value was achieved, pairwise comparisons were performed using the Boferroni post hoc procedure. The level of significance was fixed at p≤0.05. The intraclass correlation coefficients (ICC's) were calculated for both the peak and mean velocity of the three explosive dynamic contractions at 40% MVC for each leg to determine test-retest reliability. The ICC's were greater than 0.92 indicating a high level of reproducibility in assessing the dependent variables was achieved. Values are expressed as mean±SEM and effects sizes were measured by partial Eta square (η^2).

Results

The summary of the 2-way and 3-way interactions as well as the main effects analyzed with the ANOVAs for the dependent variables are given in Table 1.

Neuromuscular performance

A main effect of the leg was observed indicating that the stimulated leg produced a faster mean velocity than the non-stimulated leg (p=0.002). Likewise, a time effect was significant where post-2 min produced the greatest change in mean velocity compared to other time points (pre, post-immediately and post-5 min, p=0.002). A significant interaction effect of condition and time (p<0.001) was observed indicating that 50Hz-High at post-2 min produced the greatest increase in mean velocity (Table 2). A condition x leg x time interaction effect was detected (p=0.001) where 50Hz-High of the stimulated leg enhanced mean velocity at post-2 min compared to 30Hz-Low and Sham and remained elevated at post-5 min. Likewise, 50Hz-High in the non-stimulated leg increased mean velocity at post-immediately and post-2 min compared to 30Hz-Low and Sham. The percentage of change for mean velocity is shown in Figure 3.

Muscle activity during unilateral WBV stimulation

WBV significantly increased sEMG VL and GM activity during exposure compared to Sham in the stimulated leg compared to the non-stimulated leg, where during 50Hz-High exposure significantly increased sEMG VL more than during 30Hz-Low exposure. There was no significant difference in the enhanced sEMG GM between the 50Hz-High and 30Hz-Low exposures (Figure 2).

Muscle activity post-WBV Exposure

There were no significant changes reported for sEMG of VL and GM post-WBV exposure indicating EMG was not enhanced sufficiently in either the stimulated and non-stimulated post-conditions (Figure 3). However, there was a significant condition effect for such that the Sham condition significantly increased (p<0.05) sEMG VL compared to 30 Hz (Table 3). A condition x leg x time interaction effect was noted where

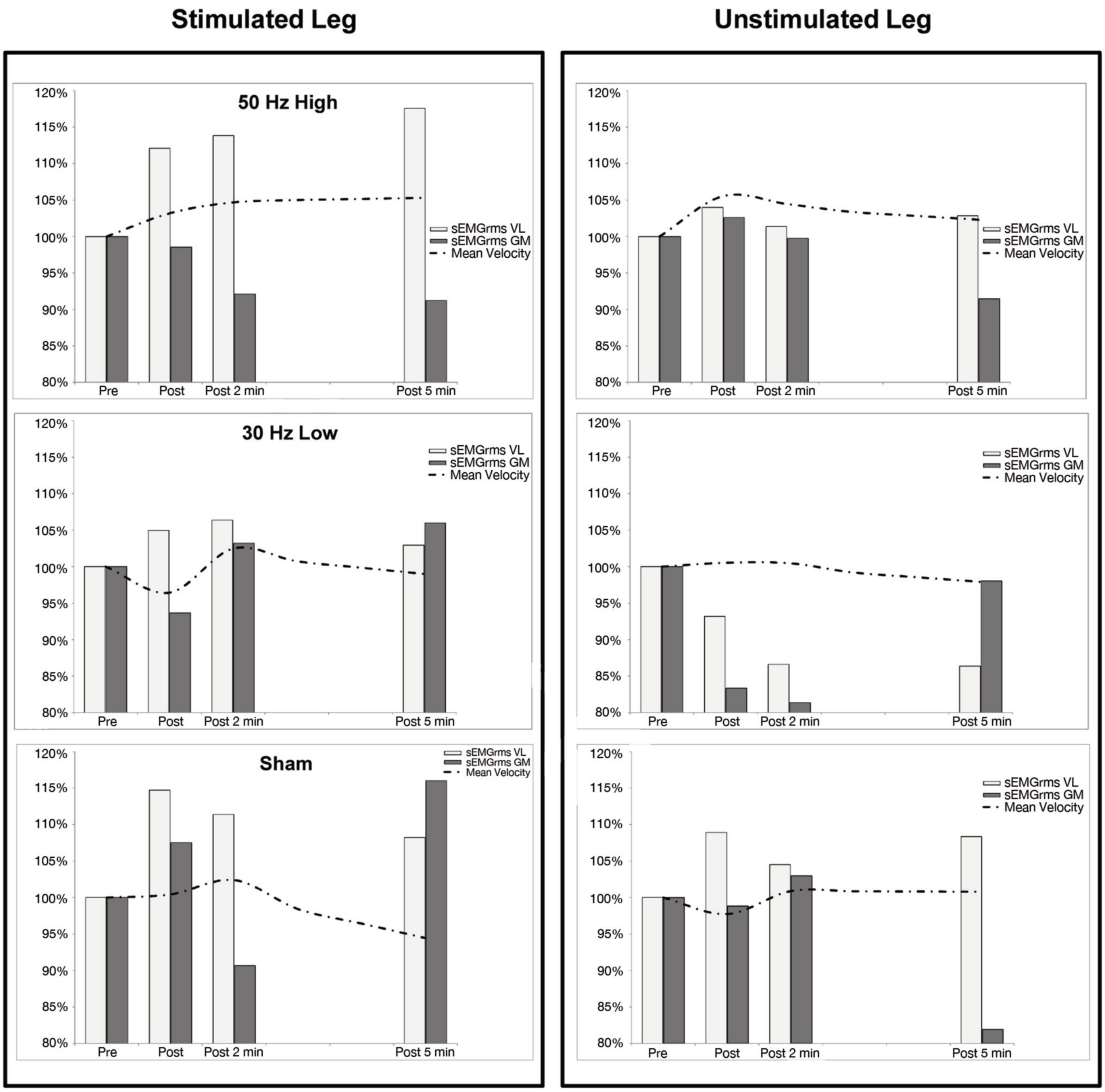


Figure 3. Percent of change for mean velocity and sEMG of vastus lateralis (VL) and gastrocnemius medialis (GM).

sEMG GM of the non-stimulated leg was significantly reduced ($p<0.05$) at post-5 min from 30Hz-Low compared to Sham (Table 4).

Discussion

The major finding of this study was that an acute WBV (50Hz) bout of 30 s augments cross-transfer in neuromuscular performance of explosive power parameters. To optimise muscle power from synchronous vibration platforms, such as the one used in this study, it has been advocated that higher WBV frequencies of 45-50 Hz at a fixed amplitude can significantly increase sEMG during exposure and acute power characteristics post-exposure compared to lower WBV frequencies of 20-35 Hz[1-3]. Similarly, 50Hz-High used in this current study elicited a significantly higher level of sEMG activity during WBV exposure in the VL compared to 30Hz-Low and Sham and both 30Hz-Low and 50Hz-High increased sEMG during exposure in the GM compared to Sham. According to Ronnestad[3] 50 Hz vibration frequency may provide a greater excita-

	50Hz-High		30Hz-Low		Sham	
	Non-Stimulated	**Stimulated**	**Non-Stimulated**	**Stimulated**	**Non-Stimulated**	**Stimulated**
Pre	100.0±0.0	100.0±0.0	100.0±0.0	100.0±0.0	100.0±0.0	100.0±0.0
Post Immediately	104.0±9.0	112.1±5.5	93.2±9.2	105.0±7.5	108.9±5.1	114.7±6.5
Post 2 min	101.4±9.0	113.8±7.0	86.6±7.0	106.4±10.3	104.5±5.4	111.4±5.2
Post 5 min	102.8±9.0	117.6±7.0	86.4±5.9	102.9±10.6	108.3±5.6	108.2±6.5

Table 3. Pre and post times of $sEMG_{rms}$ VL (%) for the three conditions.

	50Hz-High		30Hz-Low		Sham	
	Non-Stimulated	**Stimulated**	**Non-Stimulated**	**Stimulated**	**Non-Stimulated**	**Stimulated**
Pre	100.0±0.0	100.0±0.0	100.0±0.0	100.0±0.0	100.0±0.0	100.0±0.0
Post Immediately	102.6±7.6	98.6±5.8	83.4±11.1	93.7±4.4	98.8±11.2	107.5±10.3
Post 2 min	99.8±8.0	92.1±9.1	81.4±6.8	103.2±4.7	103.0±10.4	90.7±4.4
Post 5 min	91.5±7.6	91.2±9.8	98.0±14.2	106.0±5.1	81.9±10.1	116.0±5.4

Table 4. Pre and post Times of $sEMG_{rms}$ GM (%) for the three conditions.

tory stimulus to the motoneuron pool than a lower WBV frequency due the quadriceps relying on optimising a motor unit discharge rate of 50-60 impulses per second to reach maximum force[34].

Previously, it has been reported that following acute WBV power and strength performance is enhanced in bilateral countermovement vertical jump[11,35,36], bilateral squat power performance[23], unilateral knee isokinetic torque[37,38] and unilateral isometric knee extension force[36]. Significant increases (5-7%) in velocity have also been observed during single-leg press loads (70-130 kg) after unilateral WBV exposure (10 x 60 s)[10]; which is consistent with our muscle velocity enhancement (3-5%) of the stimulated and non-stimulated leg following 50 Hz-High.

It has been well documented that 'cross education' or 'cross training effect' enhances strength in the untrained contralateral limb from unilateral resistance training that relies on training specificity of the homologous muscles[39,40]. Many cross education studies have used various unilateral resistance training methods and loading parameters to elicit changes in contralateral strength[41], which have been attributed to neural adaptations[40]. It has been suggested that WBV elicits a neural potentiation effect similar to that of resistance training[42] due to its ability to increase acute strength parameters[9-11]. During WBV, the loading parameter is altered by adjusting the acceleration (vibration frequency and amplitude), which differs from conventional strength training the weight lifted is altered to modify the neuromuscular effects. In the current study the stimulus of 50 Hz-High significantly enhanced velocity (4-5%) in the non-stimulated leg; indicating that WBV can effectively induce cross education in the contralateral limb. To our knowledge, no other studies have reported a cross-transfer effect following acute WBV. However, Goodwill and Kidgell[25] investigated the short-term effect of 9 training sessions (3 per week, for 3 weeks) on unilateral resistance training with WBV and without WBV. They reported a significant increase in 1RM squat strength of 52.4% and 35.4% in the untrained leg with WBV and without WBV respectively indicating that the addition of WBV did not significantly augment muscle strength more effectively than resistance training alone. The discrepancy between these results[25] and our current data may be explained by WBV stimulus employed. Our current results used a higher frequency WBV stimulus (50 Hz) compared to a lower frequency in previous work (35 Hz)[25]. Perhaps a higher frequency is necessary to augment the cross-transfer of strength. Moreover, we used a relatively light external resistance (40% MVC) compared to much heavier loads (>75% 1-RM)[25] which may have altered the WBV stimulus (diminished the acceleration generated). Further, we applied WBV during explosive movements compared to a much slower contraction (3 sec concentric and 4 sec eccentric phases) in the work by Goodwill and Kidgell[25] that may also help explain our conflicting results. Our work also demonstrates an acute positive effect which may not be present after repeated WBV exposures[25], thus future research is warranted to clarify if these methodological differences are responsible for the divergent results.

From a review of resistance training studies, the extent of cross education appears on average to increase contralateral strength by 7.6%[39]), which is comparable with the current findings of a velocity improvement (3-5%) in the stimulated leg following 50 Hz-High. Likewise, a similar magnitude gain of 4-5% in velocity was also observed in the non-stimulated leg (50 Hz-High), which is in agreement with previous literature that strength transfer to the untrained limb is proportional to the strength gain observed in the trained limb[39,41]. This augmentation of cross-transfer effects on strength could be clinically important in rehabilitation settings for individuals with compromised capacity to use/train one limb due to injury or limb immobilization following surgery[25-27].

One purported characteristic of cross education in the untrained leg indicates that it is likely to occur in the absence of muscle activity, cross sectional area growth, and muscle enzyme activity[40,43]. In cross education studies, it has been observed that sEMG remains inactive in the untrained limb during resistance training of the contralateral limb[44,45]. This was also evident in the present study; following WBV-50 Hz quiescent sEMG activity accompanied a muscle velocity gain suggesting modifications in neural control. Currently, there is no consensus on the mechanisms of cross education, however the likely candidates to eliciting neural modifications could be the cortical and spinal areas[26,40] that are responsible for excitatory responses of the appropriate cortex area during voluntary contractions[46]. Evidence suggests that the cross-transfer of resistance training could be due to supraspinal rather than spinal mechanisms[47]. Moreover, strength gained in an untrained leg may coincide with enhanced agonist activation[48], reduced antagonist activation[49], or increased synergist activation[50]. However, the level of contribution from the central nervous system remains speculative and requires further investigation.

Although WBV mechanisms are still being debated, it is thought that WBV causes a rapid reflex and stretch-shortening[14] where a temporal association exists between EMG activity and muscle contractile displacement[51] that is likely to involve the tonic vibration reflex (TVR)[13,14], thereby activating the muscle spindles and enhancing the excitatory drive reflex of the alpha motor neurons[8]. Additionally, WBV may have a positive influence on motor cortex excitability and voluntary drive. Recently, it has been observed when acute WBV was applied to the lower-body during or between resistance training sets it significantly increased upper body performance[52,53]. Likewise, Mileva et al.[17], reported increased corticospinal excitability and alteration of intracortical processes during WBV. The aforementioned studies indicate that the WBV facilitatory effects may influence the excitatory state of the peripheral and central structures of the brain, which could facilitate subsequent voluntary contractions. Contrary, Goodwill and Kidgell[25] reported a decrease in intracortical inhibition following 3 weeks of combined leg squat resistance and WBV training and although corticomotor excitability increased with the WBV combined training it was not significant to that of conventional leg squat resistance training. The authors acknowledge that various physiological pathways may be responsible for mediating different effects during and post-WBV.

While the results from the current study are important in the area of WBV literature it is not without its limitations. We only used healthy young males so our extrapolation of the present data to different participant populations should be made with caution. We did not measure any synergistic or antagonistic muscles involved, nor did we measure muscle force production, which could have further clarified some of the results. Further, our current study only used 2 WBV stimuli (low frequency, low amplitude and high frequency, high amplitude) and only tested neuromuscular performance at 40% of MVC of explosive muscle contractions so further research is warranted on other WBV stimuli and other types of muscle contractions.

In conclusion, the present study documents for the first time a cross-education effect following acute WBV-50 Hz, as demonstrated by the enhancement in muscle velocity from explosive unilateral leg press. This increase in explosive power and neuromuscular performance combined with the quiescent sEMG activity during and following WBV suggests neural drive was responsible for such an effect. However, the likely candidate mechanism of corticospinal and intracortical processes to explaining cross education for explosive movements requires additional research. The implications of this research could be beneficial in the rehabilitation field; often an injury can lead to a period of immobilisation and compromises neural function. However, WBV could provide an alternate method of unilateral training to promote cross education strength in reducing the functional loss of the affected limb.

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