Variation in Neuromuscular Responses during Acute Whole-Body Vibration Exercise

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[1]Wyle Laboratories, Inc., Houston, TX; [2]Human Performance Laboratory, University of Houston, Clear Lake, TX; [3]Laboratory of Integrated Physiology, University of Houston, TX; [4]Department of Physical Therapy, Hardin-Simmons University, Abilene, TX; and [5]Human Adaptations and Countermeasures Division, National Aeronautics and Space Administration, Houston, TX

ABSTRACT

ABERCROMBY, A. F. J., W. E. AMONETTE, C. S. LAYNE, B. K. MCFARLIN, M. R. HINMAN, and W. H. PALOSKI. Variation in Neuromuscular Responses during Acute Whole-Body Vibration Exercise. *Med. Sci. Sports Exerc.*, Vol. 39, No. 9, pp. 1642–1650, 2007. **Purpose:** Leg muscle strength and power are increased after whole-body vibration (WBV) exercise. These effects may result from increased neuromuscular activation during WBV; however, previous studies of neuromuscular responses during WBV have not accounted for motion artifact. **Methods:** Sixteen healthy adults performed a series of static and dynamic unloaded squats with and without two different directions of WBV (rotational vibration, RV; and vertical vibration, VV; 30 Hz; 4 mm$_{p-p}$). Activation of unilateral vastus lateralis, biceps femoris, gastrocnemius, and tibialis anterior was recorded using EMG. During RV and VV, increases in EMG relative to baseline were compared over a range of knee angles, contraction types (concentric, eccentric, isometric), and squatting types (static, dynamic). **Results:** After removing large, vibration-induced artifacts from EMG data using digital band-stop filters, neuromuscular activation of all four muscles increased significantly ($P \leq 0.05$) during RV and VV. Average responses of the extensors were significantly greater during RV than VV, whereas responses of the tibialis anterior were significantly greater during VV than RV. For all four muscles, responses during static squatting were greater than or equal to responses during dynamic squatting, whereas responses during eccentric contractions were equal to or smaller than responses during concentric and isometric contractions. Neuromuscular responses of vastus lateralis, gastrocnemius, and tibialis anterior were affected by knee angle, with greatest responses at small knee angles. **Conclusions:** Motion artifacts should be removed from EMG data collected during WBV. We propose that neuromuscular responses during WBV may be modulated by leg muscle cocontraction as a postural control strategy and/or muscle tuning by the CNS intended to minimize soft-tissue vibration. **Key Words:** ELECTROMYOGRAPHY, POSTURE, STRENGTH, DAMPING, REFLEX

Whole-body vibration exercise (WBV) may enhance muscle strength adaptations associated with traditional neuromuscular training or rehabilitation (7,21). The potentially beneficial effects of WBV are caused by the transmission of mechanical, sinusoidal vibrations throughout the body via the feet. Isometric leg extensor strength has been reported to increase by 3.2% at 2 min after a single 4-min WBV session, returning to baseline strength levels 60 min later (23). Chronic exposure to WBV (three sessions per week, for 2–6 months) has been reported to elicit increases in isometric (16.6%, 24.4%) and isokinetic (8.3%, 9.0% at 100 = Is$_{j1}$) knee extensor strength similar to those observed after moderate-intensity resistance training programs (dynamic leg-press and leg-extension exercises (10–20 RM, 3× wk^{-1}) of the same duration and frequency (12,19).

Others have speculated that increased muscle strength and power after WBV results from increased neuromuscular activation during WBV, which subsequently induces adaptations similar to resistance training (1,4,5,12). Specifically, it has been suggested that Ia-afferent–mediated myotatic reflex contractions may partially explain the increases in leg extensor strength after WBV (12,18,21). Applying a vibration stimulus directly to a muscle or muscle tendon stimulates Ia-afferents, inducing a myotatic reflex contraction referred to as the tonic vibration reflex (TVR) (6,14,20). Measurement of TVR and neuromuscular activation is complicated by the common presence of artifacts in EMG data, which result from electrode/cable motion and nearby electrical noise. It is not known whether WBV elicits TVR; however, if neuromuscular responses to WBV are modulated by Ia-afferents, then the magnitude of muscle activation during WBV should be influenced by Ia-afferent

sensitivity. Changes in relaxed muscle length alter intrafusal fiber tension and, thus, Ia-afferent sensitivity, such that tension increases in a lengthening muscle and decreases in a shortening muscle (15,17,27). The amount of muscle stretch and, thus, the amount of Ia-afferent stimulation, induced during each cycle of vibration may also increase as knee angle increases (2). We hypothesized that the changes in muscle length voluntarily induced during dynamic squatting would alter intrafusal fiber tension and Ia sensitivity such that responses to WBV would be greater in magnitude during eccentric contractions than during isometric and concentric contractions. We also hypothesized that greater knee joint compliance at larger knee angles would result in greater transient muscle stretch during each vibration cycle, and that the increased Ia-afferent stimulation would result in greater responses at larger knee angles.

A novel aspect of the present study is that we included a filtering procedure to remove vibration artifacts from within our EMG data to prevent misinterpretation of neuromuscular responses to WBV. A second unique aspect of the present study is that we examined a number of different parameters in an effort to identify optimal conditions, which maximize neuromuscular responses to WBV. We hypothesized that, for the vastus lateralis, biceps femoris, gastrocnemius, and tibialis anterior muscles, 1) neuromuscular activation (EMGrms) would increase significantly during two different directions of WBV; 2) EMGrms enhancement during two different directions of WBV would differ significantly among isometric, concentric, and eccentric muscle contraction types, with responses being greatest during eccentric contractions and smallest during concentric contractions; 3) EMGrms enhancement during two different directions of WBV would differ significantly during static and dynamic squatting exercises; 4) EMGrms enhancement during two different directions of WBV would increase significantly with increases in knee angle; and 5) vibration direction would not significantly affect the responses to WBV in hypotheses 1–4. The purpose of this study was to quantify the effects of postural variation and vibration direction on neuromuscular responses to WBV after removing EMG artifacts by digital filtering.

METHODS

Approach to the problem and experimental design. A single-group repeated-measures study design was employed in which the neuromuscular activation (EMGrms) of four leg muscles were the dependent variables. The independent variables were vibration (WBV vs baseline), contraction type (eccentric vs concentric vs isometric), knee angle (10–15, 16–20, 21–25, 26–30, and 31–35°), and vibration direction (rotational vibration, RV; and vertical vibration, VV). The study design was fully crossed, with the exception of the isometric contraction conditions, which were performed only at knee angles of approximately 16–20° during WBV and baseline conditions.

For analysis purposes, exercise type (static vs dynamic squatting) was also included as an independent variable; for each vibration direction during baseline and vibration conditions, responses during dynamic squatting were calculated as the average responses during eccentric and concentric contractions at all knee angles, whereas responses during static squatting were identical to those during the isometric condition.

Subjects and study design. Nine male (32.7 ± 7.0 yr; 177.8 ± 2.8 cm; 85.8 ± 7.9 kg) and seven female (32.7 ± 8.3 yr; 164.7 ± 7.8 cm; 67.2 ± 11.3 kg) subjects were recruited through the NASA–Johnson Space Center human test subject facility. All subjects passed an Air Force Class III physical and were screened for contraindications to WBV exposure. Exclusion criteria included a history of back pain, acute inflammations in the pelvis and/or lower extremity, acute thrombosis, bone tumors, fresh fracture, fresh implants, gallstones, kidney or bladder stones, any disease of the spine, peripheral vascular disease, or pregnancy. Written informed consent was obtained for each subject, and all procedures were approved by the institutional review boards at NASA–Johnson Space Center and at the University of Houston.

Vibration conditions. Subjects were exposed to WBV at 30 Hz and 4-mm peak-to-peak (4-mm$_{p-p}$) amplitude using a Power Plate (Power Plate North America LLC, Culver City, CA) and a prototype Galileo 2000 (Orthometrix, Inc., White Plains, NY) WBV platform. The Power Plate platform (VV) vibrates in a predominantly vertical direction with 4-mm$_{p-p}$ amplitude. The Galileo 2000 (RV) rotates about an anteroposterior horizontal axis such that positioning the feet farther from the axis of rotation results in larger-amplitude vibration. In addition to the mediolateral component of the vibration force, RV also differs from VV because of the asynchronous nature of the RV, whereby unilateral force is applied alternately to the left and right foot. The result is an asymmetric perturbation of the legs during RV exposure. Conversely, the VV platform translates vertically under both feet at the same time, which results in simultaneous and symmetrical movement of both sides of the body during VV exposure. In this study, VV was applied with 4-mm$_{p-p}$ amplitude at 30 Hz with the subjects' feet 20.6 cm apart. During RV at 30 Hz, subjects' feet were in the anatomical position, 10.3 cm from the axis of rotation corresponding to vibration amplitude of 4-mm$_{p-p}$ and a distance of 20.6 cm between left and right feet. The appropriate toe and heel positions were marked on each platform to ensure consistency of foot position and orientation between platforms and among trials. During testing sessions, subjects wore the same type of sports socks to standardize any damping of vibration attributable to footwear. Subjects did not wear shoes during testing. To minimize unwanted foot movement during vibration, fine-grade sandpaper with adhesive backing was attached to the vibration platforms, which improved traction between the subjects' socks and the platform.

Postural conditions. After instrumentation, a test operator demonstrated the slow dynamic squatting movement

and the static squatting posture to be performed with and without vibration during the testing protocol. A) *Dynamic squat*: starting from an upright posture with approximately 5° knee flexion, subjects slowly squatted until approximately 40° of knee flexion was achieved. After holding the 40° knee flexion posture for 2 s, subjects slowly returned to the starting posture. To control the angular velocity of the flexion and extension movements, a test operator used a metronome at 60 bpm concurrently with verbal commands, such that both the flexion and extension phases of movement each lasted 4 s with a 2-s pause between phases. The limited range of knee flexion angles was chosen to allow unsupported squatting during WBV without inducing loss of stability. B) *Static squat*: subjects stood with an upright posture while maintaining 20° knee flexion. A test operator instructed subjects on achieving 20° knee flexion. Subsequent analysis of kinematic data indicated that the average knee angle actually achieved during the static condition was 18.5 ± 3.0°.

Before commencing data collection, test operators instructed subjects on the appropriate foot placement on each platform as described above. Subjects were given the following instructions to be followed during all data-collection trials: stand with head and eyes forward; stand with equal weight on each foot; stand with weight distributed over the whole of each foot; stand with arms outstretched with palms facing down; and do not touch the handrail during data collection unless support is required.

The squat movement and postural instructions were practiced with and without vibration before data collection, until a consistently smooth movement was achieved. During this process, subjects were exposed to more no than approximately 30 s of each vibration condition before data collection. All conditions were performed twice, and the average EMG and acceleration values were calculated for each condition. Trials were repeated if subjects touched the handrail or if their feet moved noticeably from the required positions.

Baseline (nonvibration; BL) trials preceded each vibration trial. The order in which the vibration platforms were presented and the order of static and dynamic trials were balanced among all subjects to control for any possible confounding effects of muscular fatigue or adaptation to the WBV.

Safety and fatigue. In consideration of the possible effects of fatigue, the duration of each trial was limited to no longer than 15 s in length, with a cumulative WBV exposure for each subject of less than 3 min during a 90-min protocol. Each vibration trial was separated by at least 1 min. Throughout the testing protocol, subjects were asked to rate their perceived exertion using Borg's 20-point rating of perceived exertion scale (3). No subjects reported exertion as being *somewhat hard* (13 on the 6–20 scale) or greater. During and after the testing protocol, subjects were instructed to report any discomfort to the test operators or the responsible physician at the human test subject facility. During testing, one subject experienced itchiness in both feet because of mild erythema. Symptoms were relieved quickly after the subject walked around the laboratory, and no other adverse effects were reported during or after testing. After symptoms resolved, the protocol continued without incident, and the subject's data were included in the analysis.

Knee flexion angles. Unilateral position data from the lateral malleolus, fibular head, and greater trochanter were recorded using an optoelectronic motion-analysis system (Optotrak 3020, Northern Digital, Inc., Waterloo, Canada). Position data were sampled at 400 Hz using NDI Toolbench software. The Optotrak camera unit was positioned to view subjects in the sagittal plane. Knee angles were calculated using the angle between ankle, knee, and hip kinematic markers in the saggital plane. Small oscillations in calculated knee angles during each vibration cycle were not interpreted because of the potentially confounding effect of vibration of the soft tissues to which position markers were attached. Data from all trials were visually inspected. Because some subjects did not squat to fully 40°, only data from knee angles between 10° and 35° were analyzed. All data from static (18.5°) trials were analyzed. In the subsequent interpretation of results, knee-ankle flexion was interpreted as eccentric contraction of the vastus lateralis and gastrocnemius and concentric contraction of biceps femoris and tibialis anterior, whereas knee-ankle extension was associated with concentric contraction of the vastus lateralis and gastrocnemius and eccentric contraction of the biceps femoris and tibialis anterior. Muscle contractions were considered isometric during the static squatting condition.

Neuromuscular activation. Surface EMG was recorded from vastus lateralis, lateral biceps femoris, lateral gastrocnemius, and tibialis anterior in all 16 subjects during all conditions. Bipolar bar electrodes (99.9% Ag, 10-mm length × 1-mm width, 10-mm spacing; CMRR: > 80 dB; model DE2.1, DelSys, Inc., Boston, MA) were applied to lightly abraded, washed skin over the respective muscle belly, parallel to the pennation angle. A ground electrode was placed over the tibial tuberosity. EMG electrodes and cables were secured to subjects' skin with medical tape. Signals were amplified (1000×), filtered (20–450 Hz band pass; Bagnoli-8, DelSys, Inc., Boston, MA), and sampled at 2000 Hz synchronously with kinematic data, using a 16-bit Optotrak Data Acquisition Unit II and NDI Toolbench software (Northern Digital, Inc., Waterloo, Canada).

Data processing was performed using MATLAB version 7.0 (The Mathworks, Inc., Natick, MA). Spectral analysis of EMG data was performed by dividing each signal into overlapping segments, which were then windowed using a 1024-sample Hanning window. Short-term frequency content of each segment was computed using a 4096-sample fast Fourier transform (FFT) with sections overlapping by 1000 samples. Inspection of resulting spectrograms from each muscle indicated the presence of significant motion artifacts not only at the fundamental excitation frequency (30 Hz) but also, to a lesser degree, at integer multiples of

the excitation frequency. The excessive EMG signal power at these frequencies is attributable to vibration of the EMG electrodes and cables at the excitation frequency and at the associated harmonic frequencies. When the signal power at each frequency was averaged across an entire trial, it was evident that the magnitude of the signal at the excitation and harmonic frequencies greatly exceeded the signal power at all other frequencies (Fig. 1).

Digital band-stop filters were implemented to eliminate motion artifacts at the exact excitation frequency of each platform and also at integer multiples of the excitation frequencies up to 450 Hz, to ensure that all motion artifacts were removed from the EMG signals. Filters were applied to EMG data from all baseline and vibration conditions using direct–form II second-order sections implementation: for $N = 1:15$, band-stop filters were applied at Nf_v, where f_v is the fundamental vibration frequency; 17th-order Chebyshev type II; stop-band $= (Nf_v) \pm 1$ Hz; $f_{pass1} = (Nf_v) - 1.5$ Hz, $f_{pass2} = (Nf_v) + 1.5$ Hz; minimum 100-dB stop-band attenuation, maximum 0.01-dB pass-band ripple. In addition to the antialiasing filter, a digital band-pass filter was implemented: 20–450 Hz band-pass; 18th-order Chebyshev type II; $f_{stop1} = 17$ Hz, $f_{stop2} = 500$ Hz; minimum 60-dB stop-band attenuation; maximum 0.01-dB pass-band ripple.

Motion artifacts caused by harmonic vibration at 60 Hz (at $2f_v$) would coincide with any line interference that may have arisen from nearby electrical equipment and power lines. Comparison of the frequency content of EMG data before and after the filtering procedure indicated that artifacts were successfully removed from EMG signals without excessive loss of overall signal power (Fig. 1).

After filtering, bias was calculated and removed from each EMG signal, after which the data were rectified and
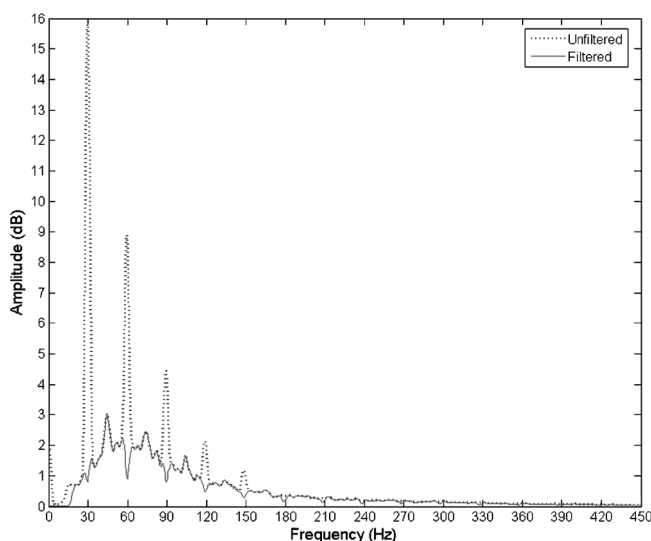

FIGURE 1—Typical mean frequency content of vastus lateralis EMG signal during a VV condition before and after removal of artifacts by filtering with Chebyshev type II band-stop filters. Motion artifacts are apparent in unfiltered data at the excitation frequency (30 Hz) and at the associated harmonic frequencies.

the root mean square (EMGrms) was calculated in 100-ms windows around every data point. For each subject, EMGrms of each muscle was then calculated for all levels of the independent variables, thereby quantifying neuromuscular activation under all conditions. Because EMGrms values were being compared with equivalent baseline (no vibration) squatting conditions, normalization relative to maximal voluntary contractions was unnecessary.

Statistical analysis. The dependent variables in all statistical tests were EMGrms, measured from vastus lateralis, biceps femoris, gastrocnemius, and tibialis anterior. Before statistical analyses, data were examined (probability–probability plot) to evaluate the assumption of normality. A fourth-root transformation was applied to data to decrease skewedness and kurtosis. To correct for violations of the sphericity assumption as indicated by Mauchly's test, the Huynh–Feldt correction was used to adjust the degrees of freedom in the repeated-measures ANOVA. For the tests of hypotheses 1–4, repeated-measures ANOVA were used to test the effects of interest within each vibration direction. In all tests, the vibration main effect and its interactions were evaluated to test the hypotheses, because enhancement of EMGrms above baseline levels was of interest; absolute EMGrms values were not compared among different conditions. The statistical significance of differences in the effects between vibration directions (hypothesis 5) was tested using interactions in repeated-measures ANOVA in which vibration direction (D) was included as a factor.

The average knee angle during isometric conditions was $18.5 \pm 3.0°$. Therefore, to evaluate the effect of contraction type independently of knee angle, only EMGrms data from eccentric and concentric conditions between 16 and 20° were used in the comparison with the isometric conditions. A $2 \times 3 \times 2$ repeated-measures ANOVA was calculated for each muscle, with vibration (VB), contraction type (CT), and vibration direction (D) as factors with repeated measures. The VB $\times$ CT $\times$ D interaction was used to evaluate whether the effects of contraction type on neuromuscular responses differed between vibration directions (hypothesis 5). Separate 2×3 (VB $\times$ CT) repeated-measures ANOVA were used to evaluate the effect of contraction type (VB $\times$ CT interaction; hypothesis 2) within each vibration direction. Paired t-tests were used to compare the mean differences between baseline and vibration neuromuscular activation for eccentric, concentric, and isometric conditions during each vibration direction for descriptive purposes.

When comparing the average neuromuscular responses between static and dynamic exercise types (ET; hypothesis 3), data from eccentric and concentric conditions at all knee angles (dynamic squatting) were averaged and compared with data from isometric conditions (static squatting) using 2×2 (VB $\times$ ET) repeated-measures ANOVA for each vibration direction. Because data from all knee-angle and contraction-type conditions were included, the vibration main effects from the VB $\times$ ET repeated-measures ANOVA were used to evaluate whether neuromuscular activation

was increased, on average, during WBV on each vibration platform (hypothesis 1). Three-way (VB × ET × D) repeated-measures ANOVA were used to determine whether the effects of vibration and exercise type differed between the two vibration directions (VB × D and VB × ET × D interactions; hypothesis 5).

The role of knee angle (KA) in neuromuscular responses to each vibration direction (hypothesis 4) was assessed using 2 × 5 (VB × KA) repeated-measures ANOVA, using only data from dynamic conditions (10–35°). The VB × KA × D interaction from separate repeated-measures ANOVA compared the effect of knee angle between the two vibration directions (hypothesis 5). After the two-way repeated-measures ANOVA, polynomial contrasts were used to evaluate trends in response variation with respect to knee angle (hypothesis 4). Although not explicitly required by our hypotheses, paired t-tests were used to compare all baseline EMGrms values with the associated EMGrms values measured during vibration, thereby enabling evaluation of neuromuscular responses at each knee angle for all eccentric, concentric, and isometric conditions.

Initially, gender (G) was included as a between-subjects factor in the repeated-measures ANOVA used to test the hypotheses; however, the VB × G interaction and all higher-order interactions involving VB and G were non-significant for all muscles. Therefore, male and female data were grouped for further analysis. In all tests, $P \leq 0.05$ was considered significant. Statistical analysis was performed using SPSS 13.0 for Windows (SPSS, Inc., Chicago, IL). For descriptive purposes, percent increases between vibration and baseline conditions were calculated using untransformed data.

RESULTS

Effect of vibration. When averaged over all knee angles and contraction types, neuromuscular activation of all four muscles increased significantly during RV and during VV. The average magnitude of neuromuscular responses differed significantly between the two vibration directions in the vastus lateralis, gastrocnemius, and tibialis anterior, such that average responses of the extensors (vastus lateralis and gastrocnemius) were significantly greater during RV than VV, whereas responses of the tibialis anterior were significantly greater during VV than RV. The percentage increases in untransformed EMGrms associated with the significant VB main effects in all conditions are given in Table 1.

Effect of exercise type. Neuromuscular responses of all four muscles to both vibration directions were greater during static squatting than during dynamic squatting, with only two exceptions: there was no significant difference in response magnitude between static and dynamic squat conditions in the biceps femoris during RV or in the tibialis anterior during VV. The effect of exercise type on responses to vibration differed significantly between platforms in these

TABLE 1. Percent increases above baseline EMGrms during rotational vibration (RV) and vertical vibration (VV) for dynamic (eccentric and concentric combined, all knee angles), static (isometric, 18.5 ± 3.0° knee angle), eccentric (16–20° knee angle), and concentric (16–20° knee angle) conditions.

| | Percent EMGrms Increase Above Baseline | | | | | | | |
| | Dynamic | | Static (Isometric) | | Eccentric | | Concentric | |
Muscle	RV	VV	RV	VV	RV	VV	RV	VV
Vastus lateralis	26	NS	103	77	26	30	26	NS
Biceps femoris	30	NS	10	9	NS	NS	48	NS
Gastrocnemius	106	34	151	132	123	40	89	29
Tibialis anterior	57	145	328	223	50	28	63	261

NS, no statistically significant difference from baseline.

two muscles. The only muscle in which neuromuscular responses were greater during VV than during RV was the tibialis anterior, though only during dynamic squatting. Dynamic and static responses were greater during RV than VV in all other instances, with the exception of static squatting responses in the biceps femoris and gastrocnemius, which did not significantly differ between RV and VV.

Effect of contraction type. Neuromuscular responses of all four muscles to both vibration directions were significantly affected by contraction type, with only two exceptions: responses of the biceps femoris and gastrocnemius were not significantly affected by contraction type during RV. When knee angles were between 16 and 20°, neuromuscular responses in isometrically contracting muscles were significantly greater than responses in muscles that were contracting eccentrically or concentrically. The only two exceptions were the tibialis anterior during VV and the biceps femoris during RV, where responses during concentric contractions were greater than static and eccentric responses. The vibration × contraction-type effect differed significantly between platforms only in the vastus lateralis and the tibialis anterior. The filtered untransformed EMGrms for each muscle under all conditions including isometric contractions are shown as means ± standard error in Figures 2–5.

Effect of knee angle. Neuromuscular responses of the vastus lateralis, gastrocnemius, tibialis anterior, but not biceps femoris, were significantly affected by changes in knee angle during both vibration directions. Significant within-subjects linear contrasts confirmed that, contrary to our hypothesis, the magnitude of neuromuscular responses above baseline was greatest at small knee flexion angles for vastus lateralis, gastrocnemius, and tibialis anterior, and that response magnitudes decreased as knee angle increased. Responses of the biceps femoris to either direction of vibration were not significantly affected by changes in knee angle. The effect of knee angle on neuromuscular response magnitudes differed significantly between RV and VV only in the tibialis anterior, which reflects the noticeably different responses of the tibialis anterior to RV and VV, particularly when considered over the full range of concentric contractions (Fig. 5). The asterisks in Figures 2–5 indicate the specific conditions in which neuromuscular activation was significantly increased above baseline.

APPLIED SCIENCES

DISCUSSION

To our knowledge, this is the first study to determine the effects of static and dynamic squatting, muscle contraction type (eccentric, concentric, isometric), vibration direction (RV, VV), and motion artifact removal on measured neuromuscular responses to WBV in the same group of subjects. The key findings were that 1) motion artifacts must be removed from EMG data collected during WBV at the excitation frequency and also at the associated harmonic frequencies; 2) neuromuscular activation (EMGrms) of vastus lateralis, biceps femoris, gastrocnemius, and tibialis anterior increased significantly during RV and VV; 3) EMGrms enhancement during RV and VV differed significantly among isometric, concentric, and eccentric muscle contraction types, with most responses being greatest during isometric contractions; 4) EMGrms enhancement during RV and VV was significantly greater during static squatting than during dynamic squatting exercises in most instances; 5) EMGrms enhancement during RV and VV differed significantly with changes in knee angle; and 6) vibration direction significantly affected EMGrms enhancement during WBV.

Spectral analysis of our unfiltered data reveals large EMG artifacts during WBV, which is contrary to reports in the literature that anchoring of EMG cables and electrodes will prevent motion artifacts (8). Despite securing EMG electrodes and cables during data collection, the localized peaks in signal power in unfiltered EMG data at 30 Hz and integer multiples thereof (Fig. 1) indicates the presence of
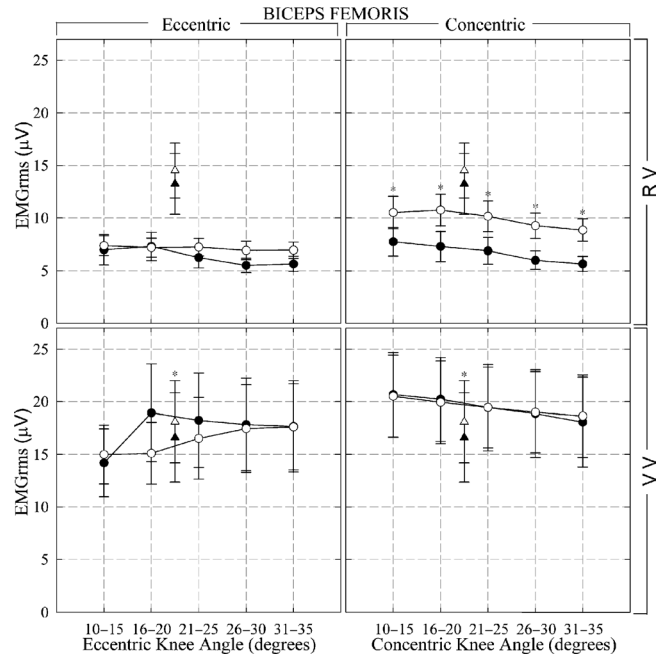
FIGURE 3—Mean ± SE of filtered, untransformed EMGrms for eccentric, concentric, and isometric contractions of biceps femoris during RV and VV compared with no vibration (baseline). ● Concentric/eccentric baseline; ○ concentric/eccentric vibration; ▲ isometric baseline; △ isometric vibration. * Vibration significantly greater than at baseline ($P \leq 0.05$).
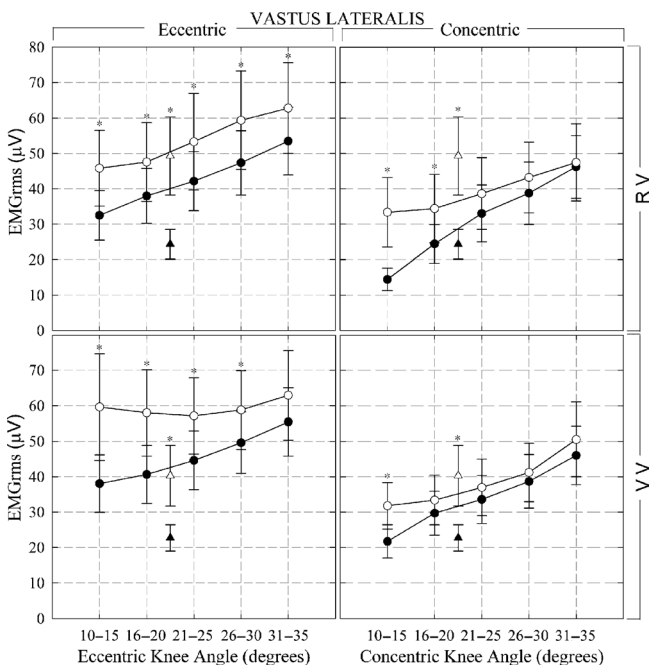
motion artifacts caused by vibration of the EMG electrodes and cables. Although the signal power at the excitation and harmonic frequencies also reflect actual motor-unit firing, the signal power of the true EMG signal is not expected to be significantly greater at these frequencies compared with adjacent frequencies, because the power at any given frequency is a function of action potential–conduction velocity and not motor unit–firing frequency. Thus, to the extent that action potentials are being conducted within a muscle at the velocities associated with the vibration and harmonic frequencies, the application of band-stop filters will result in an underestimation of the true magnitude of the neuromuscular responses to WBV. However, if band-stop filters are not applied, then motion artifacts will cause an overestimation of muscle activation during WBV but not during baseline conditions. The more conservative approach of applying digital band-stop filters allows the assertion that increases in EMG reflect true increases in neuromuscular activation.

We hypothesized that the changes in muscle length voluntarily induced during dynamic squatting (16–20°) would alter intrafusal fiber tension and Ia sensitivity such that responses to WBV would be greater in magnitude during eccentric contractions than during isometric and concentric contractions. We also hypothesized that greater knee joint compliance at larger knee angles would result in greater transient muscle stretch during each vibration cycle, and that the increased Ia-afferent stimulation would result in greater responses at larger knee angles. Our data did not support either hypothesis; responses were greatest during

FIGURE 2—Mean ± SE of filtered, untransformed EMGrms for eccentric, concentric, and isometric contractions of vastus lateralis during RV and VV compared with no vibration (baseline). ● Concentric/eccentric baseline; ○ concentric/eccentric vibration; ▲ isometric baseline; △ isometric vibration. * Vibration significantly greater than at baseline ($P \leq 0.05$).
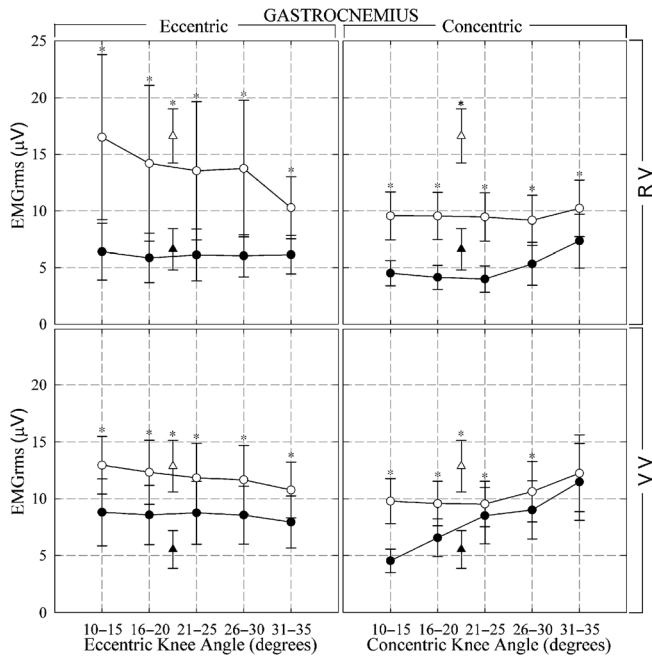
FIGURE 4—Mean ± SE of filtered, untransformed EMGrms for eccentric, concentric, and isometric contractions of gastrocnemius during RV and VV compared with no vibration (baseline). ● Concentric/eccentric baseline; ○ concentric/eccentric vibration; ▲ isometric baseline; △ isometric vibration. * Vibration significantly greater than at baseline ($P \leq 0.05$).

isometric and concentric contractions, and responses decreased as knee angle increased. It is possible that alpha–gamma coactivation during voluntary muscle contractions altered the relationship between muscle length and intrafusal fiber-tension previously documented in relaxed muscles. TVR response magnitudes in humans are affected by simultaneous contraction of muscle groups elsewhere in the body (28). It follows that variation in neuromuscular responses during WBV may be the result of involuntary TVR response magnitudes being modulated as the voluntary activation of muscles varies during the different phases of squatting and different directions of vibration.

Leg extensor muscles (vastus lateralis and gastrocnemius) may be more affected than the flexors: the triceps surae and quadriceps muscles are stretched as the upward motion of the vibration platform imposes ankle dorsiflexion and knee flexion. Because the feet are not attached to the WBV platform, plantarflexion and knee extension are not caused by the movement of the platform, and may result from the elastic properties of muscle and from myotatic muscle contractions in the triceps surae and quadriceps muscles. All of these factors may contribute to a greater enhancement of muscle activation in the vastus lateralis and gastrocnemius compared with the biceps femoris and tibialis anterior. Although the percent increases in EMGrms indicate that, overall, the biceps femoris does indeed show the least responsiveness to WBV, the tibialis anterior was, in fact, the most responsive of the four muscles during both directions of vibration.

Another possible explanation for the above finding is that increased leg neuromuscular activation reflects a postural control strategy that is adopted during WBV rather than myotatic reflex contractions. Increased activation of tibialis anterior in conjunction with deactivation of hamstrings muscles has been previously reported as a postural control response to rapid leg flexion (11); the findings of Carpenter et al. (9,10) also support the concept of a systemic postural control strategy rather than myotatic reflexive contractions in each muscle. Our data show that neuromuscular responses (vastus lateralis, gastrocnemius, and tibialis anterior) were larger at small knee angles than at large knee angles. As described above, it is possible that this effect may be mediated by the presence of a postural control mechanism. We have speculated elsewhere that small knee angles are associated with a greater postural anxiety than are large knee angles (2).

Increased muscle activation during WBV may serve to minimize the potentially damaging vibration of muscles and other soft-tissues via muscle tuning (24–26). We have previously reported that head acceleration during WBV increases as knee angles increase above 30° (2). Increased baseline muscle activation at large knee angles may affect joint compliance and/or the capacity to damp vibrations via muscle tuning. It has previously been reported that the damping coefficient of elbow flexor muscles increases as joint angular velocity increases (16). Thus, the extent of neuromuscular activation required to damp vibrations should be greatest during isometric contractions. This is consistent with our observation that the magnitude of
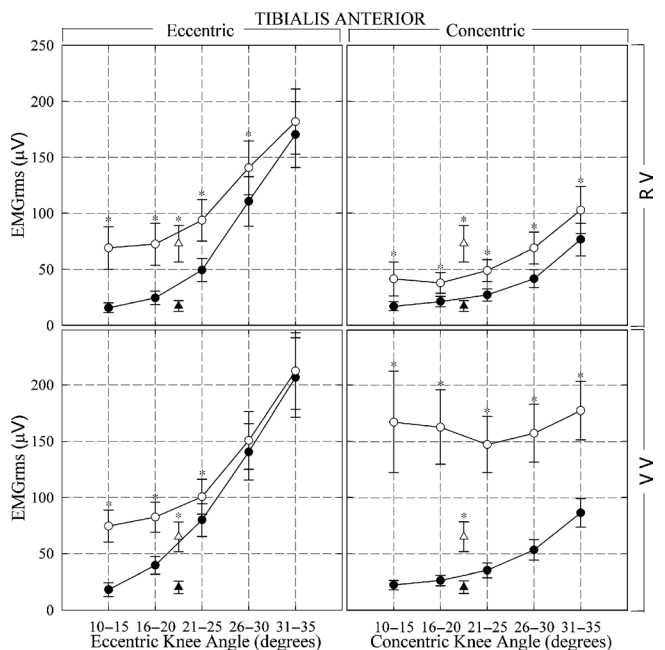

FIGURE 5—Mean ± SE of filtered, untransformed EMGrms for eccentric, concentric, and isometric contractions of tibialis anterior during RV and VV compared with no vibration (baseline). ● Concentric/eccentric baseline; ○ concentric/eccentric vibration; ▲ isometric baseline; △ isometric vibration. * Vibration significantly greater than at baseline ($P \leq 0.05$).

enhancement during isometric contractions was greater than that during eccentric and concentric contractions (16–20°) in all muscles and conditions except for biceps femoris during RV and tibialis anterior during VV.

Because vibration energy is dissipated by the ankle and knee joints and, possibly, by the muscles of the shank and thigh, the proximity of a muscle to the vibration stimulus might also affect the magnitude of muscle-tuning responses to WBV; if the proportion of vibration energy transmitted to soft-tissues is less in the thigh than in the shank, then a lesser degree of muscle activation will be required to damp the vibrations in the thigh. Our data indicate that the responses of the distal muscles were indeed larger than those for proximal muscles. This finding could also be a result of a postural control mechanism in which distal muscles are preferentially activated, as has been suggested by Slijper et al. (22), who observed increased cocontraction of distal muscles as a postural control mechanism employed by the CNS under conditions of postural instability.

From the results of our study, we suggest that static (18.5 ± 3.0° knee flexion) rather than dynamic (10–35° knee flexion) squatting during WBV exercise will maximize enhancement of leg extensor activation, and that, on average, leg extensor responses to RV will exceed responses to VV. Our data from dynamic squatting across a range of knee angles indicate that enhancement of neuromuscular activation is generally greatest at small knee angles and decreases as knee angle increases. Static squatting data were collected only at 18.5 ± 3.0°. Future research should compare neuromuscular responses to WBV between static and dynamic squatting conditions at other knee angles, to determine the optimal posture for neuromuscular enhancement during vibration, and to determine whether static conditions result in greater enhancement at a range of knee angles.

Our data show significantly different neuromuscular responses to the two different vibration directions. We have described tonic vibration reflex, postural control strategies, and muscle tuning as potential mechanisms of neuromuscular enhancement during WBV. These potential mechanisms are not mutually exclusive. Compared with VV, the asymmetric and nonvertical forces associated with RV may induce different degrees of muscle stretch, postural challenge, and/or tissue vibration in the leg muscles, each of which could contribute to the different neuromuscular responses. Although our study did not investigate performance changes after RV and VV, it follows that differing acute neuromuscular responses between vibration directions may be associated with differing chronic adaptations. Further studies are required to compare the effectiveness of RV and VV in eliciting performance improvements.

In all instances, neuromuscular responses were measured relative to baseline levels where baselines were measured in the same conditions, without vibration, immediately before the vibration condition. Although some variability was expected and observed between baseline conditions, Figure 2 shows that baseline EMGrms of the biceps femoris before VV was two to three times greater than the corresponding baseline EMGrms before RV. We suggest that this unexpected difference is attributable to a difference in the designs of the RV and VV platforms. The baseline squats were performed while standing on the respective vibration platform with the vibration turned off. The RV platform did not move perceptibly while subjects performed their baseline squats. Conversely, the design of the VV platform meant that some unmeasured but perceptible movement of the platform occurred while subjects performed their baseline squats on the platform. Although the magnitude of the VV platform movement in baseline conditions was very small, it may have been sufficient to elicit increased neuromuscular activation of the biceps femoris during VV baseline conditions to correct for displacements of the center of mass.

The findings of the present study support the further investigation of mechanisms of neuromuscular responses to WBV. Interestingly, we found that certain conditions associated with WBV may result in the adoption of different postural control strategies, which may, in turn, explain the effects that have been attributed to WBV. More research is needed to examine other mechanisms that may underlie the physiological responses and adaptations to WBV, and how these responses and adaptations may differ among people with abnormal muscle tone and soft-tissue tightness. Future studies of WBV should include controls for motion artifacts as well as differences in postural control strategies.

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