Vibration Exposure and Biodynamic Responses during Whole-Body Vibration Training

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ABSTRACT

ABERCROMBY, A. F. J., W. E. AMONETTE, C. S. LAYNE, B. K. MCFARLIN, M. R. HINMAN, and W. H. PALOSKI. Vibration Exposure and Biodynamic Responses during Whole-Body Vibration Training. *Med. Sci. Sports Exerc.*, Vol. 39, No. 10, pp. 1794–1800, 2007. **Purpose:** Excessive, chronic whole-body vibration (WBV) has a number of negative side effects on the human body, including disorders of the skeletal, digestive, reproductive, visual, and vestibular systems. Whole-body vibration training (WBVT) is intentional exposure to WBV to increase leg muscle strength, bone mineral density, health-related quality of life, and decrease back pain. The purpose of this study was to quantitatively evaluate vibration exposure and biodynamic responses during typical WBVT regimens. **Methods:** Healthy men and women ($N = 16$) were recruited to perform slow, unloaded squats during WBVT (30 Hz; 4 mm$_{p\text{-}p}$), during which knee flexion angle (KA), mechanical impedance, head acceleration (Ha$_{rms}$), and estimated vibration dose value (eVDV) were measured. WBVT was repeated using two forms of vibration: 1) vertical forces to both feet simultaneously (VV), and 2) upward forces to only one foot at a time (RV). **Results:** Mechanical impedance varied inversely with KA during RV (effect size, η_p^2: 0.668, $P < 0.01$) and VV (η_p^2: 0.533, $P < 0.05$). Ha$_{rms}$ varied with KA (η_p^2: 0.686, $P < 0.01$) and is greater during VV than during RV at all KA ($P < 0.01$). The effect of KA on Ha$_{rms}$ is different for RV and VV (η_p^2: 0.567, $P < 0.05$). The eVDV associated with typical RV and VV training regimens (30 Hz, 4 mm$_{p\text{-}p}$, 10 min·d^{-1}) exceeds the recommended daily vibration exposure as defined by ISO 2631-1 ($P < 0.01$). **Conclusions:** ISO standards indicate that 10 min·d^{-1} WBVT is potentially harmful to the human body; the risk of adverse health effects may be lower during RV than VV and at half-squats rather than full-squats or upright stance. More research is needed to explore the long-term health hazards of WBVT. **Key Words:** ISO 2631-1, ESTIMATED VIBRATION DOSE VALUE, MECHANICAL IMPEDANCE, HEAD ACCELERATION, RISK

Whole-body vibration training (WBVT) has been shown to elicit beneficial effects including improvements in isometric/dynamic leg muscle strength (18,22), bone mineral density (BMD) (20,22), back pain (12,17), health-related quality of life, and decreased fall risk (5). However, the proposed benefits of WBVT are equivocal (16), and it is possible that deleterious side effects of WBVT exist (6,7,19). It is well accepted that chronic whole-body vibration (WBV), which is unintentional vibration exposure resulting from an individual's chosen occupation has been reported to have a number of negative side effects that are known to disturb normal physiology and structure in the back, digestive, reproductive, visual, and vestibular systems (4,9,14,21). For example, operators of off-road vehicles, tractors, helicopters and armored vehicles are frequently exposed to high-magnitude vibration for prolonged durations. The resulting vibration of the spinal column is believed to cause intervertebral disc displacement, spinal vertebrae degeneration, and osteoarthritis (9,14,21), and vibration that is transmitted through the spinal column to the head may induce hearing loss, visual impairment, vestibular damage, and can even induce brain hemorrhaging at very high vibration magnitudes (2,8,9,11). Quantitative techniques exist to quantify the severity of occupational WBV exposures and relate those WBV exposures to health risks; however, we are unaware of any previous attempts to apply these techniques to WBVT.

Vibration exposure may be quantified using estimated vibration dose value (eVDV, ISO 2631-1) (10), which is calculated using direction, frequency, magnitude, and duration of the vibration applied to a human and amalgamated into a single metric. The eVDV is classified as potentially harmful if it exceeds an ISO upper limit of 17.

The potential for negative side effects associated with WBV can also be assessed by measuring head and spine acceleration and mechanical impedance (9). Relative apparent mass magnitude (RAMM) is a measure of relative mechanical impedance; increased RAMM is associated with decreased joint compliance, which increases the body's absorption of vibration energy (9,15). Joint compliance limits transmission of vibration energy to the head and upper body (13).

A combination of eVDV, head acceleration, and RAMM measurements are useful in quantitatively defining the risk of negative side effects for a given dose of WBVT. Thus, we hypothesized that: 1) RAMM would vary inversely with knee flexion angle (KA), 2) root mean square (RMS) head acceleration (Ha_{rms}) would be greater during VV than during RV, 3) Ha_{rms} during RV and VV would vary inversely with KA, 4) the direction of platform vibration (RV vs VV) would significantly affect the relationship examined in hypothesis 3, and 5) the eVDV associated with typical RV and VV training regimens (30 Hz, 4 mm$_{p-p}$, 10 min·d^{-1}) would exceed the recommended daily vibration exposure as defined by ISO 2631-1. The purpose of this study was to quantitatively evaluate and compare the severity of vibration exposure during typical WBVT regimens using two different directions of vibration.

METHODS

Approach to the problem and experimental design. A single-group study design with repeated measures was employed in which Ha_{rms}, RAMM, and eVDV were the dependent variables. The independent variables were KA (10–15, 16–20, 21–25, 26–30, and 31–35°) and vibration direction (RV vs VV).

Subjects and study design. Nine male (32.7 ± 7.0 yr; 178 ± 2.8 cm; 85.8 ± 7.9 kg) and seven female (32.7 ± 8.3 yr; 167 ± 7.8 cm; 67.2 ± 11.3 kg) subjects were recruited through the NASA–Johnson Space Center Human Test Subject Facility. All subjects were screened for contraindications to vibration 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.

Each subject participated in a single data-collection session, consisting of exposure to each of two different directions of WBV: rotational vibration (RV) and vertical vibration (VV). After a 15-s exposure to each vibration direction for familiarization, subjects performed dynamic squats during each of the two vibration conditions while Ha_{rms}, RAMM, eVDV, and KA were measured. Each subject performed two 15-s dynamic squats on each

vibration platform, separated by 60 s with 5 min of rest between vibration directions, for a total vibration duration of 30 s on each vibration platform. The order in which vibration directions were presented was balanced among all subjects, to control for any possible confounding effects of muscular fatigue or adaptation to the WBV. Although biodynamic responses to WBV are likely to vary with exposure duration, this effect was not investigated directly in this study. The estimated effect of exposure duration on the likelihood of deleterious health effects in this study was based on the time dependence incorporated within the eVDV calculation in ISO 2631-1 (10).

Vibration conditions. Subjects completed WBVT at 30 Hz and 4-mm peak-to-peak (*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) WBVT platform. The Power Plate platform (VV) vibrates in a predominantly vertical direction with 4-mm$_{p-p}$ amplitude (Fig. 1). 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 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, 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. During RV at 30 Hz, subjects' feet were positioned 10.3 cm from the axis of rotation corresponding to 4-mm$_{p-p}$ amplitude. The same stance width was used during VV. The appropriate foot positions were marked on each platform to ensure consistency between platforms and among trials. During
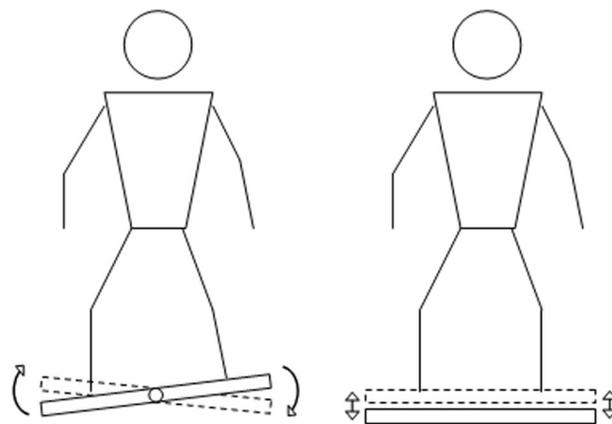

FIGURE 1—Comparison of rotational vibration (RV, *left*) and vertical vibration (VV, *right*). Platform displacements are exaggerated for demonstrative purposes.

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.

Posture conditions. After instrumentation, a test operator demonstrated the slow dynamic squatting movement to be performed during the testing protocol. Starting from an upright posture with 5° knee flexion, subjects slowly squatted until 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 the flexion and extension phases of movement each lasted 4 s, with a 2-s pause between phases. The limited range of KA was chosen to allow unsupported squatting during WBVT without inducing loss of balance.

Before commencing data collection, test operators instructed subjects on the appropriate foot placement on each platform, as described above. Subjects were given 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 was practiced before data collection until a consistently smooth movement was achieved. All conditions were performed twice, and the average head and platform acceleration values were calculated for each KA (described below). Trials were repeated if subjects touched the handrail or if their feet moved noticeably from the required positions.

Safety and fatigue. To minimize fatigue, each trial was limited to a maximum of 15 s in duration, and each vibration trial was separated by at least 1 min. The cumulative exposure to WBVT, including data collection and practice trials, did not exceed 3 min for any subject.

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 *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 from mild edema. Symptoms were relieved quickly after the subject walked around the laboratory. No other adverse effects were reported during or after testing.

Knee flexion angles. Unilateral position data from the lateral malleolus, lateral tibial head, and greater trochanter were recorded using an optoelectronic motion-analysis system (Optotrak 3020, Northern Digital, Inc., Waterloo, Canada; RMS error: ± 0.1 mm). Position markers were also attached to each WBVT platform to measure displacement immediately anterior to the right foot of each subject. Position data were sampled at 400 Hz using NDI Toolbench software. The Optotrak camera unit was positioned to view subjects in the sagittal plane. KA was calculated using the angle between ankle, knee, and hip kinematic markers in the sagittal plane. Data from all trials were visually inspected. Because some subjects did not squat to fully 40°, only data from KA between 10 and 35° were analyzed.

Head and platform acceleration. Triaxial accelerations of each WBVT platform and the head of each subject were measured using miniature triaxial accelerometers (EGAXT3, Entran Devices, Inc., Fairfield, NJ). A 25g accelerometer was attached to each WBVT platform immediately anterior to the right foot of the subject, in accordance with the ISO 2631-1 standards for the evaluation of whole-body vibration (10). A 5g accelerometer was attached to a custom-made plastic bite-bar, which measured subjects' head acceleration when held firmly between the teeth. Accelerometers were powered on 1 h before commencing data collection, to ensure a constant accelerometer temperature during testing. Signals were 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). Accelerometer data were digitally low-pass filtered before further processing (40 Hz low pass; 10th-order Butterworth; f_{pass} = 40 Hz, f_{stop} = 100 Hz; minimum 50-dB stop-band attenuation; maximum 0.01-dB pass-band ripple).

Instantaneous triaxial head and platform accelerations were expressed as a root sum square, a_{rss}, to reflect the overall magnitude of acceleration for each subject at each instant during each trial. For all a_{rss} data points, RMS values were calculated to yield measures of RMS head acceleration (Ha_{rms}) and RMS platform acceleration (Pa_{rms}) that reflected the mean power of head and platform accelerations. RMS acceleration is the ISO 2631-1 recommended measure of sinusoidal vibration magnitude. RMS values were calculated using a 250-ms moving window with successive windows overlapping by 249 ms.

Mechanical impedance. Apparent mass magnitude (AMM) is a measure of mechanical impedance defined as the ratio of force to acceleration. When the peak force applied by the platform during each cycle of vibration is constant but unknown, the reciprocal of platform acceleration magnitude defines a measure of RAMM that will vary in direct proportion to variation in actual AMM. Because the subsequent analysis required within-subject comparisons only and did not compare vibration directions, measurement of vibration force was unnecessary. For all conditions, RAMM of each WBVT platform was calculated

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as the reciprocal of Pa_{rms}. For each subject, the average values of Ha_{rms}, Pa_{rms}, and RAMM were calculated for each of the 5° increments between 10 and 35°, and these mean values were used in the subsequent statistical analysis.

eVDV. eVDV was calculated according to the procedures defined by ISO 2631-1 (10). RMS platform acceleration was calculated in each orthogonal axis and was averaged across all KA. RMS acceleration values were then weighted according to the frequency-weighting coefficients defined in ISO 2631-1. In this process, RMS acceleration values in each axis are multiplied by specific coefficients, such that values were adjusted to more closely reflect the health hazard posed to the human body. Coefficients are defined by ISO 2631-1 on the basis of the frequency and the direction of vibration being applied to the body, both of which are known to affect the likelihood of the vibration causing bodily harm. Coefficients of $W_k = 0.426$ (cephalocaudal axis) and $W_d = 0.067$ (anteroposterior and mediolateral axes) were applied to yield frequency-weighted RMS accelerations in each axes (a_{wx}, a_{wy}, and a_{wz}) for RV and VV platforms. The rotational motion of the RV platform meant that the coordinate system of the accelerometer rotated with respect to the gravity vector during RV; however, the amount of rotation was calculated as approximately ± 1.1°, which corresponds to a maximum overestimate in true vertical and horizontal accelerations of less than 0.02%. Thus, comparison between RV and VV using the weighting coefficients defined by ISO 2631-1 was considered valid.

eVDV was calculated as follows: $eVDV = 1.4 a_w T^{1/4}$, where a_w is the frequency-weighted RMS acceleration and T is the duration of daily vibration exposure in seconds. When combining accelerations in multiple directions a_w is replaced by the vibration total value, $a_v = (k^2_x a^2_{wx} + k^2_y a^2_{wy} + k^2_z a^2_{wz})^{1/2}$, where k_x, k_y, and k_z are multiplying factors defined in ISO 2631-1 (11). For evaluation of health effects, $k_x = 1.4$, $k_y = 1.4$, and $k_z = 1$. The average eVDV across all subjects was computed for each vibration direction for durations up to 1000 s·d^{-1}.

ISO 2631-1 specifies that vibration during sitting or standing should be measured at the interface between the vibrating surface and the human. Although weighting coefficients are defined in ISO 2631-1 for WBV during standing, their use in the evaluation of health effects of WBV exposure during standing is not recommended, because research on pathological responses to WBV is limited primarily to vibration of the head and upper body during sitting (10). It follows that relating eVDV during standing to ISO health guidelines is only valid if the calculated eVDV reflects the actual severity of upper-body vibration. Because the legs serve to damp mechanical energy, particularly at larger angles of knee flexion (13,23), the vibration at the interface (feet) does not necessarily represent the vibration of the upper body. The ratio between the vibration magnitude of the spinal column and the feet can be expressed as foot-to-spine transmissibility (FST). By calculating eVDV for a range of FST values, a calculation of eVDV is achieved that reflects the amount of upper-body vibration, provided that the approximate value of FST is known (see Discussion). Accordingly, eVDV was calculated for FST values up to 1.1, under the assumption of equal FST in all axes: measured acceleration values in each axis were multiplied by coefficients of 0.05 to 1.1, and eVDV was then calculated as described above.

The average values of a_v used in the calculation of eVDV for RV and VV platforms were 22.48 and 16.75 m·s^{-2}, respectively. Data were processed using MATLAB version 7.0 (The Mathworks, Inc., Natick, MA).

Statistical analysis. Before statistical analysis, acceleration data were examined (probability–probability plot) to evaluate the assumption of normality, which was satisfied. 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 (RM) ANOVA.

A 5 × 2 (knee angle × direction) RM ANOVA was performed to evaluate the hypothesis that Ha_{rms} is affected by KA, by vibration direction (D), and by their interaction (KA × D). For each direction, a one-way RM ANOVA was performed to test the hypothesis that RAMM would decrease as knee flexion increased. Effects were tested using the multivariate criterion of Wilks' Λ. Follow-up polynomial contrasts were used to statistically test the quadratic trends in Ha_{rms} means during RV and VV. Bonferroni-adjusted paired t-tests compared Ha_{rms} between RV and VV conditions. One-sample t-tests were conducted to evaluate whether the mean eVDV values (at FST = 1) for each direction were significantly different from 17, the upper limit of the ISO 2631-1 health caution zone (10). In all tests, $P \leq 0.05$ was considered significant. Statistical analyses were performed using SPSS 13.0 for Windows (SPSS, Inc., Chicago, IL).

RESULTS

Means and standard errors of RAMM and Ha_{rms} with respect to KA are displayed in Figures 2 and 3, respectively. The stick figures indicate the squatting position at the smallest and largest knee angles. The RAMM data are normalized to the maximum RAMM for each vibration direction.

Results of the one-way RM ANOVA indicate significant effects of knee angle on RAMM during RV (Wilks' $\Lambda = 0.332$, $F = 6.05$, $P = 0.007$, $\eta_p^2 = 0.668$) and during VV (Wilks' $\Lambda = 0.467$, $F = 3.42$, $P = 0.044$, $\eta_p^2 = 0.533$).

Results of the RM ANOVA for RMS head acceleration indicate significant main effects of knee angle (Wilks' $\Lambda = 0.314$, $F = 6.57$, $P = 0.005$, $\eta_p^2 = 0.686$), direction (Wilks' $\Lambda = 0.235$, $F = 48.94$, $P < 0.001$, $\eta_p^2 = 0.765$), and a significant knee angle × direction interaction (Wilks' $\Lambda =$
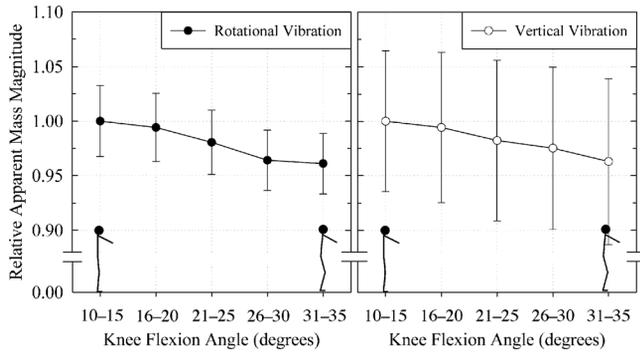
FIGURE 2—Relative apparent mass magnitude (RAMM) variation with respect to knee flexion angle during rotational vibration and vertical vibration. Data are normalized to the maximum RAMM for rotational and vertical vibration. *Stick figures* indicate the squatting position at the smallest and largest knee angles.

0.433, $F = 3.93$, $P = 0.029$, $\eta_p^2 = 0.567$). Follow-up polynomial contrasts indicate significant quadratic trends in Ha$_{rms}$ data through the range of knee angles during RV ($F = 24.43$, $P < 0.01$, $\eta_p^2 = 0.620$) and VV ($F = 26.34$, $P < 0.01$, $\eta_p^2 = 0.515$).

The eVDV calculated for a 10-min daily exposure at 30 Hz and 4-mm$_{p-p}$ amplitude was significantly greater than 17, the upper limit of the ISO 2631-1 health caution zone, for RV ($t(15) = 30.95$, $P < 0.01$) and for VV ($t(15) = 14.19$, $P < 0.01$). Figures 4 and 5 show the mean eVDV for each vibration direction calculated for daily exposures between 60 and 1000 s and an FST of 0.05–1.1.

The RMS root sum square accelerations of the RV and VV platforms averaged across all KA were 58.5 and 39.9 m·s^{-2}, respectively. The difference was attributable in part to the mediolateral component of the RV platform motion. Furthermore, inspection of platform-displacement data revealed that, once loaded, VV amplitude was approximately 0.5 mm (± 0.1 mm) lower than RV amplitude as
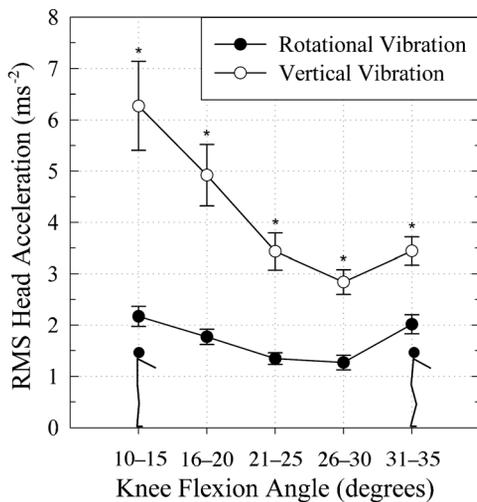
measured by optoelectronic motion-capture markers attached to each platform. However, in the only direct comparison between the two modalities, Ha$_{rms}$ was significantly greater during VV than during RV. Thus, the difference in vibration magnitudes was not a confounding factor; the only effect may have been to underestimate the size of the difference in Ha$_{rms}$ between VV and RV.

DISCUSSION

To our knowledge, this is the first study to quantitatively evaluate vibration exposure and biodynamic responses during WBVT. The key findings were that, during WBVT with slow dynamic squatting from 10 to 35° KA, 1) RAMM during RV and VV varies inversely with KA, 2) Ha$_{rms}$ is greater during VV than during RV, 3) Ha$_{rms}$ during RV and VV varies inversely with KA, 4) the effect of KA on Ha$_{rms}$ is different for RV and VV, and 5) the eVDV associated with typical RV and VV training regimens (30 Hz, 4 mm$_{p-p}$, 10 min·d^{-1}) exceeds the recommended daily whole-body vibration exposure as defined by ISO 2631-1.

Our present findings regarding RAMM and KA are consistent with those of Lafortune et al. (13), who report that a decrease in mechanical impedance was associated with decreased transmission of mechanical energy to the head. We found that WBVT with a knee flexion angle of 10–15° was associated with the greatest RAMM and, thus, the greatest transmission of mechanical energy transmitted to the upper body and head. On the basis of ISO health standards, this suggests that the use of small knee flexion angles during WBVT increases the likelihood of negative side effects and should, therefore, be avoided.

Damping of mechanical energy by the legs is achieved by compliance of ankle, knee, and hip joints, and also by the

FIGURE 3—Mean ± SE of RMS head acceleration variation with respect to knee flexion angle for rotational vibration and vertical vibration. * VV significantly greater than RV ($P \leq 0.01$). *Stick figures* indicate the squatting position at the smallest and largest knee angles.
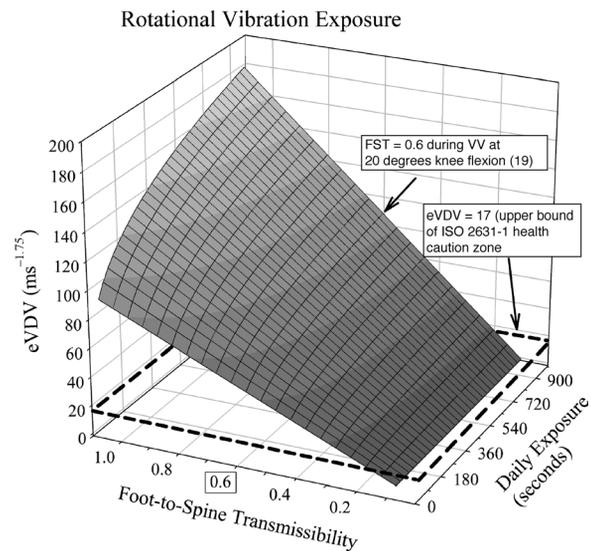

FIGURE 4—Estimated vibration dose value (eVDV) with respect to daily exposure duration and foot-to-spine transmissibility for rotational vibration. The upper limit of the ISO 2631-1 health caution zone is eVDV = 17.

Vertical Vibration Exposure

FST = 0.6 during VV at
20 degrees knee flexion (19)

eVDV = 17 (upper bound
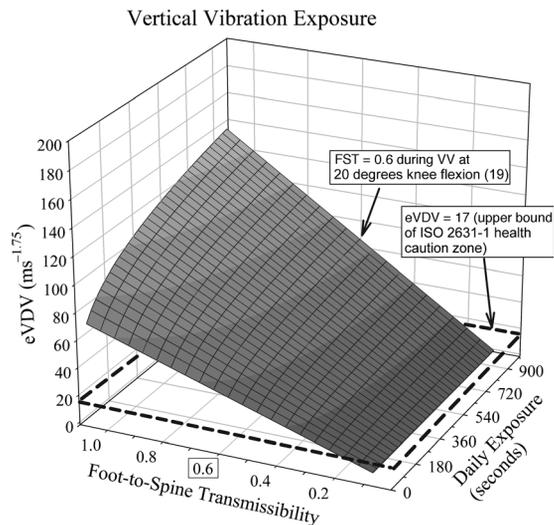of ISO 2631-1 health
caution zone)

FIGURE 5—Estimated vibration dose value (eVDV) with respect to daily exposure duration and foot-to-spine transmissibility for vertical vibration. The upper limit of the ISO 2631-1 health caution zone is eVDV = 17.

modulation of leg muscle activation in a process known as *muscle tuning* (13,23). Contrary to our hypothesis, the relationship between KA and Ha_{rms} was not linear. Ha_{rms} decreased as KA increased from 10 to 30°. When KA increased beyond 30°, Ha_{rms} also increased, which we interpreted as an indication that the ability of legs to damp mechanical vibration energy decreased when KA was greater than 30°. Whereas the effectiveness of joint compliance in damping mechanical energy increases with KA up to at least 40° (13), we have suggested elsewhere that the contribution of leg muscles to the dissipation of mechanical energy via muscle tuning during WBVT may decrease as KA increases (1). Increased Ha_{rms} above 30° KA might also result from the increased baseline neuro-muscular activation affecting joint compliance.

We also found that the transmission of vibration mechanical energy to the upper body and head was 71 to 189% greater during vertical than rotational vibration, which may be attributed to damping of vibration energy by rotation of the pelvis during RV, because of the alternating upward forces being applied to the left and right feet during RV. Others have reported temporary decrements in visual acuity (11) and visual–motor tracking perform-ance (24) during low-magnitude VV ($Pa_{rms} \leq 2.5$ ms^{-2}, 8–80 Hz) while sitting. Reports of torn utricular otolithic membranes, abnormal semicircular canals, and fatal brain hemorrhaging caused by head vibration in monkeys demonstrate the importance of avoiding unnecessary head vibration (9). Our present findings suggest that head vibration during WBVT is minimized by using RV and by squatting with 26–30° KA.

Greater variability was found in Ha_{rms} during VV than in RV; however, decreased variability during VV as Ha_{rms} decreased suggests that this may be the result of a floor effect whereby variability decreases as Ha_{rms} approaches

zero. It is possible that a floor effect was also responsible for the larger RAMM variability during VV than in RV, but this cannot be evaluated from our data, because absolute AMM values were not measured.

Some intersubject variability in the vibration magnitude of each platform was observed but could not be explained by body mass or height differences among subjects when examined statistically using RM analysis of covariance ($P > 0.05$). Although body mass is expected to affect the magnitude of platform vibration, it is likely that intersubject variability in posture, anthropometry, body mass distributions, and possibly other physical characteristics of the human body not measured in this study contributed to the observed intersubject differences in platform vibration magnitude.

We found that the vibration stimulus in both VV and RV exceeded ISO 2631-1 health guidelines; however, because subjects experienced WBVT during standing rather than sitting, these values are overestimates of the true vibration dose values to which the upper body was exposed. To account for posture, we calculated eVDV for RV and VV for FST values between 0.05 and 1.10. This range was chosen on the basis of what others have reported (19). We relied on the literature because we were unable to accurately quantify spine acceleration, because of the invasive nature of this measurement. Rubin et al. (19) measured FST by surgically implanting pins into the greater trochanter and into the spinous process of the L4 vertebrae of five human subjects. They report that FST at 30-Hz VV was approx-imately 0.70 with knees locked and approximately 0.60 with 20° knee flexion. In the present study, VV was associated with a lower vibration total value than RV; however, our findings suggest that VV had a higher FST and, therefore, a higher eVDV.

After adjustment for the ameliorating effect of the legs, the ISO health guidelines' upper limit for eVDV was still exceeded during 10 min of RV or VV when FST was greater than 0.10. This evaluation of WBVT according to ISO 2631-1 represents the first quantification of the potential for regular WBVT protocols to cause harm, and it demonstrates the need for caution and prescreening when using WBVT for the intended improvement of health or performance. ISO health guidelines on WBV exposure were developed to assess the chronic exposure of healthy individuals to vibration on a daily basis. Thus, this comparison may not be useful for assessing the adverse health effects from infrequent WBVT. Furthermore, biodynamic responses to WBV are likely to change as subjects become fatigued; this was not measured in the present study because the protocol was designed to minimize subjects' vibration exposure. For the purposes of comparison between vibration directions, fatigue was also minimized by exposing subjects to short durations, and any possible confounding fatigue effect was controlled for by balancing the order in which subjects experienced each vibration direction.

This study investigated vibration exposure and biody-namic responses only at 4-mm$_{p\text{-}p}$ amplitude and 30-Hz

frequency, and these results cannot be assumed to generalize to other frequencies and amplitudes. Both platforms can be operated at different frequencies (RV: 5–30 Hz; VV: 30–50 Hz) and at different vibration amplitudes (RV: 1–14 mm$_{p\text{-}p}$; VV: 2 or 4 mm$_{p\text{-}p}$). Although we have found that RV may pose less health risk than VV at 30 Hz and 4 mm$_{p\text{-}p}$, it is possible that RV may pose the greater health risk when the feet are positioned further from the axis or rotation, which would result in vibration amplitudes of up to 14 mm$_{p\text{-}p}$. Future research in the area of WBVT should attempt to develop a new standard for the assessment of the adverse health effects associated with intermittent use of WBVT as a treatment or rehabilitation modality.

In summary, the least hazardous WBVT protocols are theoretically those involving low mechanical impedance, low head acceleration, and low eVDV, although such conditions are not necessarily the most effective in terms of inducing the desired training outcome. Our key finding was that short-duration exposures to rotational vibration at small knee flexion angles (26–30°) have the lowest risk of negative side effects on the basis of head acceleration and mechanical impedance. WBVT health risk cannot be accurately calculated using ISO health standards, because of the intermittent nature of WBVT as a treatment modality. More research is needed to develop a new method of assessing negative side effects when the WBV is intermittent.

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