Whole-Body Vibration During Passive Standing in Individuals With Spinal Cord Injury: Effects of Plate Choice, Frequency, Amplitude, and Subject's Posture on Vibration Propagation

Milad Alizadeh-Meghrazi, MASc, Kei Masani, PhD, Milos R. Popovic, PhD, PEng, Beverley Catharine Craven, MD

Background: To date, few pharmacologic or rehabilitation interventions for sublesional osteoporosis (SLOP) or low bone mass of the hip and knee regions after spinal cord injury (SCI) have produced significant or sustained increases in lower extremity bone mineral density. Whole body vibration (WBV) is a potential intervention for the prevention and/or treatment of SLOP.

Objective: To identify the optimal WBV conditions (ie, plate, frequency, amplitude, and subject posture) among men with chronic SCI during passive standing and facilitate the implementation and future evaluation of the efficacy of WBV and passive standing for prevention and treatment of SLOP in men with SCI.

Design: This phase 0 device development study assessed the lower extremity propagation characteristics of WBV in men with and without SCI by using a variety of a priori specified plates, frequencies, amplitudes, and postures that facilitate lower extremity vibration absorption while minimizing vibration propagation to the head.

Setting: A tertiary SCI rehabilitation center in Toronto, Canada.

Participants: Healthy men with chronic paraplegia (n = 5) and those without SCI (n = 7), ages 20-50 years, weight 68-113 kg, and height 168-188 cm.

Interventions: An EasyStand standing frame (Altimate Medical Inc, Morton, MN) was fitted onto 2 commercially available vibration platforms: WAVE (WAVE Manufacturing Inc, Windsor, Ontario, Canada) and Juvent (Juvent Medical Inc, Somerset, NJ). Accelerometers were attached to the participants’ forehead, hip, knee, and ankle to measure vibration propagation. Vibration parameters evaluated were posture (knee angles of 140°, 160°, and 180° [180° for Juvent only]), vibration frequency (25 Hz, 35 Hz, and 45 Hz), and vibration amplitude (0.6 mm and 1.2 mm [WAVE only]). The subjects were exposed to all combinations of posture, frequencies, and amplitudes during the experiments (total parameter combinations: 12 WAVE and 9 Juvent).

Main Outcome Measurements: Peak-to-peak vibration and transmissibility of vibration were recorded and computed for each accelerometer at the tested locations.

Results: Variations in frequency generated the most noticeable changes in propagation characteristics, followed by variations in knee angle and amplitude.

Conclusions: WBV therapy delivered with use of the WAVE platform with a knee angle of 140°, plate frequency of 45 Hz, and amplitude of 1.2 mm met our a priori criteria for the “optimal WBV condition.” Future studies should evaluate the therapeutic efficacy of the WAVE platform by using these parameters to maintain or augment bone mass among persons with SCI and SLOP.

PM R 2012;4:963-975

INTRODUCTION

Whole-body vibration (WBV) therapy has been proposed as a therapeutic intervention to prevent bone mineral density (BMD) decline or to treat established osteoporosis. Several animal and human studies in the field of osteoporosis management have evaluated WBV as...
a therapeutic intervention [1-5]. Animal studies have verified enhancements in BMD and bone formation rates as a result of WBV. Human studies of WBV have focused on improving bone mass and the architecture of weight-bearing bones, predominantly of the spine or lower extremities [2,6-8].

The underlying mechanisms by which WBV affects BMD and enhances bone turnover rates are still unclear. Wolff’s Law [9-12], Utah’s Paradigm (Mechanostat Theorem) [13,14], and the Mechanotransduction Theorem [15,16] provide potential explanations about how WBV influences BMD. Wolff’s Law purports that bones adapt their microarchitecture to the loading to which they are exposed such that the strain the bone cells experience is minimized. These adaptations are thought to be site-dependent and proportional to the magnitude, type, and duration of the mechanical load [17-19]. The biological effects of specific loading stimuli remodeling, which, in turn, helps maintain bone structure [17-19]. Thus before considering implementation of WBV and passive standing as therapy for the prevention or treatment of sublesional osteoporosis (SLOP), it is crucial to establish the degree of loading and WBV vibration parameters most likely to enhance bone mineral content and skeletal strength without adverse effects.

SLOP is a disease process unique to persons with spinal cord injury (SCI). It is characterized by excessive lower extremity bone resorption and a subsequent increased risk of lower extremity fragility fracture [20]. Typically at 12-18 months after injury, BMD of the hips, distal femur, and proximal tibia are 28%, 37%-43%, and 36%-50%, respectively, below that of age-matched peers [21-26]. The declines in the lower extremity predominantly occur in metaphyseal-epiphyseal areas of the proximal and distal femur (hip and knee) and proximal tibia (knee) regions [27-29]. Fracture fractures develop in 25%-46% of patients with chronic SCI [30,31], with the fractures primarily of the distal femur and proximal tibia region; these fractures typically result in increased morbidity and attendant care requirements [32]. SLOP is thought to result from the combined effects of immobilization and impairment (ie, muscle atrophy and adipose tissue accumulation due to inactivity) after SCI [27,33]. However, analysis of recent data suggests that hormonal changes and immune-mediated mechanisms also contribute [33].

Current interventions for treatment of SLOP include pharmacologic and nonpharmacologic therapies. Several systematic reviews describe and evaluate the therapeutic efficacy of bisphosphonates therapy [34] and nonpharmacologic interventions, including body-weight-support treadmill training, passive standing, and functional electrical stimulation [35,36]. To date, no single intervention has been associated with a significant and/or sustained increases in BMD or associated reductions in fracture risk among patients with SCI and SLOP. A single case study and a feasibility study have examined the implementation of WBV in the SCI population to treat SLOP [37,38]; however, the investigators did not report the criteria and rationale for selecting the device or vibration parameters studied. Several investigators reported the propagation characteristics of WBV through the body among able-bodied subjects, whereas others have developed biomechanical models that account for the transmission characteristics of vibration [39-44]. A review of these prior studies identified the following variables as having an important influence on vibration propagation:

- subject posture, namely the knee angle;
- frequency of vibration;
- amplitude of vibration; and
- the type of vibration platform (vertical versus oscillating).

Although these studies addressed important WBV parameters, they did not examine the influences of these parameters on WBV propagation. The choice of WBV parameters determines the therapeutic benefits and the frequency and severity of adverse effects. The objective of this study was to determine the effects of plate choice, subject posture, plate frequency, and plate amplitude on the vibration propagation characteristics through the body to identify an optimal combination of vibration parameters to maximize lower extremity vibration propagation while minimizing WBV adverse effects, particularly the discomfort and adverse effects associated with vibration at the head. This objective assumes that imparting the greatest tolerable amounts of vibration to the lower extremities emulates the biomechanical forces associated with weight bearing, which have proven effective in treating osteoporosis in other patient populations.

**METHODS**

**Subjects**

Able-bodied men without SCI (n = 7) and men with chronic SCI (n = 5), ages 20-50 years and with a maximum weight of 115 kg, were recruited for participation. Inclusion criteria for the subjects with SCI were >1 year after injury and C2-T10 American Spinal Injury Association Impairment Scale A-D. Demographic and impairment characteristics of subjects are shown in Table 1. Subjects were excluded if they reported a history of any of the following contraindications to WBV exposure: uncontrolled autonomic dysreflexia, untreated or-thostatic hypotension, seizure disorder, migraine headaches, rheumatoid arthritis, kidney stones, arrhythmias, valvular heart disease, cochlear implants, deep vein thrombosis, spondylolisthesis, joint implant, diabetes, gallstones, pacemaker, pregnancy, or cancer. In addition, subjects with SCI were excluded for contraindications of the use of the standing frame: bilateral heterotopic ossification of the hip or knee region, nonunion fracture of the lower extremity, planter flexion contractures >20°, or combined hip and knee flexion contractures >30°. Nonambulatory subjects completed a postural retraining program to ensure safety during data
collection [45]. This study was approved by the research ethics board at the Toronto Rehabilitation Institute, and subjects’ informed consent was obtained.

Procedures

To assess the effects of WBV on persons with SCI, setups were devised that allowed passive standing and partial weight bearing on the WBV platforms. The EasyStand 5000 (ultimate Medical Inc, Morton, MN) was retrofitted to each vibration platform. Advantages of this standing frame included commercial availability, adjustable knee angles, and ease of transferring patients (Figure 1).

Two modified commercially available vibration platforms were used: WAVE (WAVE Manufacturing Inc, Windsor, Ontario, Canada) and Juvent (Juvent Medical Inc, Somerset, NJ). The WAVE platform consisted of a high-grade tensile steel plate (75 × 90 × 25 cm) actuated by 2 motors that have offset masses attached to their rotating shafts. The WAVE platform was customized with the addition of 2 motors. On-site laser measurements of platform amplitude resulted in choosing 0.6 and 1.2 mm amplitudes for this study. The WAVE plate frequency spans the range of 20-50 Hz, with adjustable frequency and amplitude in 1-Hz increments. Testing demonstrated that the WAVE platform accurately adjusted output parameters regardless of the user’s body weight.

The Juvent platform consisted of an aluminum plate (34 × 36 × 8 cm) actuated by a linear solenoid. A single-spring, 4-point suspension system stabilized and distributed the vibration evenly to the plate. An RS-232 computer port interface and software were provided by the manufacturer for the Juvent platform to allow computer control over output parameters: frequencies of 10-99 Hz and power settings of 1-28. The power settings determined the amount of energy sent to the solenoid, which, in return, set the vibration intensity and amplitude. Contrary to the WAVE, the Juvent did not adjust for subject weight. Based on the subject weight inclusion criteria, a power setting of 28 was chosen.

On-site performance evaluations were conducted with 3 persons with the modified WAVE and Juvent plates. Testing took place with the aid of a laser displacement measuring tool (LK-500; Keyence Co, Osaka, Japan) and 5 uniaxial accelerometers (3041A2; Dytran Instruments Inc, Chatsworth, CA). The results for the WAVE verified that the magnitude of the output vibration from the platform was independent of the subject’s weight. However, in the case of the Juvent, the magnitude of the output vibration varied with the subject’s weight. For the purposes of this study, we tested frequencies of 25 Hz, 35 Hz, and 45 Hz on both plates after completing a review of the literature that examined the potential of WBV to treat osteoporosis [46].

All the subjects were provided with the same Crocs shoes (Crocs Inc, Longmont, CO) to eliminate footwear variability. During data recording intervals, the subjects were asked to remain erect and still, with their arms laid on top of the EasyStand’s tray, which was aligned with their xiphoid process in the erect posture. This trunk posture resulted in a hip joint angle of approximately 120°.

The 2 platforms were tested on separate days, with the order of platforms alternating between subjects. Twelve combinations of vibration frequency (25 Hz, 35 Hz, and 45 Hz), vibration amplitudes (0.6 mm and 1.2 mm), and knee angles (140° and 160°) were used with the WAVE device. The 180° knee angle was not evaluated on the WAVE because it was deemed hazardous as a result of the propagation of high-magnitude vibration to the head. Nine combinations of vibration frequency (25 Hz, 35 Hz, and 45 Hz), and knee angles (140°, 160°, and 180°) were used with the Juvent device at a constant power setting of 28. For each device, the subjects were exposed systematically to varying vibration parameters (Table 2) for 2 minutes at a time. The order of knee angle was chosen at random.

Uniaxial, low-mass, high-sensitivity accelerometers (3041A2; Dytran Instruments) were used to quantify vibration at the plate and the subject’s ankle (lateral malleolus), knee (ca-

### Table 1. Demographic characteristics of participating subjects

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age</th>
<th>Height, cm</th>
<th>Weight, kg</th>
<th>Subject</th>
<th>Age, y</th>
<th>Height, cm</th>
<th>Weight, kg</th>
<th>NLI*</th>
<th>ASIA†</th>
<th>Hip BMD Z-Score‡</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>41</td>
<td>174</td>
<td>74</td>
<td>H</td>
<td>42</td>
<td>178</td>
<td>79</td>
<td>C5-C6</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>29</td>
<td>179</td>
<td>75</td>
<td>I</td>
<td>30</td>
<td>188</td>
<td>79</td>
<td>C6</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>24</td>
<td>180</td>
<td>66</td>
<td>J</td>
<td>38</td>
<td>173</td>
<td>76</td>
<td>C7</td>
<td>C</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>35</td>
<td>180</td>
<td>74</td>
<td>K</td>
<td>27</td>
<td>185</td>
<td>77</td>
<td>T9</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>23</td>
<td>185</td>
<td>100</td>
<td>L</td>
<td>50</td>
<td>170</td>
<td>75</td>
<td>L2</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>22</td>
<td>170</td>
<td>62</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>22</td>
<td>171</td>
<td>76</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mean (SD) 28.00 ± 7.44 179.75 ± 4.50 78.50 ± 14.82 37.40 ± 9.26 178.80 ± 7.66 77.20 ± 1.79

SCI = spinal cord injury; NLI = neurologic level of injury; ASIA = American Spinal Injury Association; BMD = bone mineral density; SD = standard deviation.

*Based on the international standards for classification of SCI.

†ASIA Impairment Scale.

‡The number of SDs below the young adult mean.
pitulum fibulae), hip (tuberculum iliacum), and forehead. Placement and alignment of the accelerometers ensured that vertical accelerations were recorded. At the knee, because the accelerometer was attached to the capitulum fibulae and the subjects were in the standing frame, the positioning of the knee support and placement of the seat were such that it ensured that the subject’s calf would be orthogonal to the plate, bringing about the vertical alignment of the attached accelerometer. The skin was cleaned and prepared with a Cavilon Barrier (3M, St Paul, MN), adhesive, and double-sided tape before application of the accelerometer. Accelerometers were then secured with tape and covered with prewrap (Figure 1).

**Outcome Measures**

Accelerometry data were recorded with a PowerLab data acquisition unit (ADInstruments, Sydney, Australia) at a sampling rate of 2000 Hz; the unit was connected to a personal computer. Data recording began 1 minute after initiation of each 2-minute vibration parameter and lasted for 20 seconds. Data were then analyzed in MATLAB (Mathworks, Natick, MA). The signals were band-pass filtered with a Butterworth filter between 10-50 Hz to eliminate noise and undesirable motion artifacts such as lower extremity spasticity or unanticipated subject repositioning. The maximum and minimum points of each single cycle of vibration were identified, and the peak-to-peak amplitude of acceleration (P-P) was computed. The computed P-Ps were averaged over each 20-second signal duration. Transmissibility (TRANS) of the vibration at each measurement location was computed and defined as P-P at each location divided by the P-P of the plate in each test condition. The quantified measures of these vibrations, P-P and TRANS, provided information regarding the amount of vibration at each anatomic location and the propagation level, respectively.

**Statistical Analysis**

Statistical analysis for the WAVE and Juvent platforms was conducted independently. Data collected on the WAVE device were analyzed with 5-way mixed factorial analysis of variance (ANOVA) with one factor not repeated (subject group) and 4 factors repeated (accelerometer location, posture, frequency, amplitude). Data from the Juvent platform were analyzed through 4-way mixed factorial ANOVA with 1 factor not repeated (subject group) and 3 factors repeated (accelerometer location, posture, and frequency). Post hoc analysis was carried out with paired $t$-tests with Bonferroni correction for each level. Significance was set at $P < .05$. All analyses were performed with SPSS version 17.0 (SPSS Inc, Chicago, IL).

To assess the effect of the test condition variables (ie, subject group, accelerometer location, posture, frequency, and amplitude of vibration) on the outcome measures (P-P and TRANS), factorial ANOVA was performed. In addition,

**Table 2. Breakdown of the combinations of vibration parameters tested for each platform**

<table>
<thead>
<tr>
<th>Posture</th>
<th>WAVE</th>
<th>Frequency, Hz</th>
<th>Amplitude, mm</th>
<th>Juvent</th>
<th>Frequency, Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>140°</td>
<td>25</td>
<td>0.6</td>
<td>1.2</td>
<td>140°</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>0.6</td>
<td>1.2</td>
<td>160°</td>
<td>25</td>
</tr>
<tr>
<td>160°</td>
<td>25</td>
<td>0.6</td>
<td>1.2</td>
<td>180°</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>0.6</td>
<td>1.2</td>
<td></td>
<td>45</td>
</tr>
<tr>
<td>45</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>45</td>
<td>45</td>
</tr>
</tbody>
</table>
repeated measures ANOVA (RMANOVA) and 2-tailed paired t-tests were performed to establish the effect of each of the variables on the outcome measures. A P value of .05 was considered statistically significant for all analyses. For the paired t-tests, Bonferroni correction was applied to the P value to account for the number of comparisons (P value_adj = .05/c, where “c” is the number of paired t-tests).

For the WAVE platform, a 5-way factorial ANOVA (factors of subject group, accelerometer location, posture, frequency, and amplitude) was applied. After confirming that no subject group differences existed (see Results), the able-bodied and SCI groups data were pooled for subsequent analyses. After that, a 3-way RMANOVA (factors of posture, frequency, and amplitude) with paired t-tests and Bonferroni correction for each level of the factors was applied at each accelerometer location. In the case of analyses for each subject group separately, a 3-way RMANOVA (factors of posture, frequency, and amplitude) were applied for each subject group at each accelerometer location.

For the Juvent platform, a 4-way factorial ANOVA (factors of subject group, accelerometer location, posture, and frequency) was applied. After confirming that there was no group difference and when pooling the able-bodied and SCI groups, a 2-way RMANOVA (factors of posture and frequency) with paired t-tests with Bonferroni correction for each level of the factors was applied at each accelerometer location. In the case of analyses for each subject group separately, a 2-way RMANOVA (factors of posture and frequency) also was applied for each subject group at each accelerometer location. All analyses were performed with SPSS version 17.0.

RESULTS

The frequency and severity of positive and adverse effects that the subjects experienced during these WBV regimens are reported elsewhere [47]. In general, the WAVE plate produced higher magnitude accelerations, which resulted in the subjects reporting more vibration effects compared with the Juvent plate. No statistically significant effects were found between the able-bodied and SCI subgroups on the outcome measures with the WAVE (P-P, P = .970; TRANS, P = .942) and Juvent (P-P, P = .210; TRANS, P = .051) platforms. Thus in subsequent analyses, data for able-bodied (n = 7) and SCI (n = 5) subjects were pooled (n = 12).

WAVE Accelerometer Results

A typical 1-second window of the filtered vibration output file from the WAVE is shown in Figure 2, which clearly demonstrates that vibration is reduced as it travels away from the plate through the body segments.

Figure 2. Sample accelerometer data output file for the WAVE vibration platform for subject A. The test condition is for a knee angle of 160°, 35 Hz frequency, and 1.2 mm amplitude of vibration. The 5 graphs from top to bottom show how the vibration propagates through the body at the specified locations.

P-P Results

The P-P results for the WAVE are shown in Figure 3. The frequency of vibration has a strong effect on P-P at each accelerometer location (F = 192.472, P < .001). When the posture and amplitude of vibration were considered constant, the higher frequencies created greater P-P at the plate. At the ankle, 35 and 45 Hz vibrations were not significantly different in the magnitude of P-P, whereas 25-Hz vibration generated significantly smaller P-P for all test cases. At the knee, the effect of frequency was not significant for a knee angle of 160°; however, at 140°, the lower frequencies resulted in significantly larger P-P (P-P_{25} > P-P_{35} > P-P_{45}) (P < .05). At the hip, P-P was not significantly different among the frequency groups. At the head, no significant difference was found between 25 and 35 Hz on P-P measurement. On the contrary, 45 Hz vibration consistently generated a smaller P-P at the head compared with 25 Hz and 35 Hz vibrations.

The effect of vibration amplitude on P-P at each accelerometer location was significant at the plate and ankle, with the higher amplitude vibrations generating a larger P-P throughout (when posture and frequency were held constant) (F = 317.496, P < .001) (Figure 3). At the knee and hip, however, P-P was not significantly different between the 2 amplitudes. At the head, the pattern was similar to that seen at the plate and the ankle, where the larger amplitude created a significantly larger P-P in all cases except at 140° and 25 Hz.
The effect of posture (knee angle) on P-P was not deemed significant ($F_{/H11005}/H11005/0.266, P_{/H11005}/H11005/.606$). Once the groups were separated, the 4-way RMANOVA revealed that posture showed a more dominant effect in the able-bodied group ($F_{/H11005}/H11005/31.844, P_{/H11021}/H11021/.001$) compared with the SCI group ($F_{/H11005}/H11005/0.036, P_{/H11005}/H11005/.850$). Because of these results, the effects of posture on P-P were only analyzed for the able-bodied group ($n_{/H11005}/H11005/7$), in which paired $t$-tests with the Bonferroni correction examined the effects of 2 knee angles of 140° and 160° on P-P at each accelerometer location. Variations in posture created significant differences in P-P recordings at the plate, where the more erect knee angle generated greater P-P ($P_{P_{160°}>P_{P_{140°}}}$). At the ankle, 140° generated a significantly smaller P-P at 25 Hz compared with 160°; however, for the other 3 frequencies, the differences were not statistically significant. At the knee and hip, variations in knee angle created statistically significant differences with 45 Hz vibration, where 160° had a greater P-P compared with 140°. At the head, the P-P for a knee angle of 160° was significantly greater than that of a knee angle of 140° for all test cases.

### TRANS Results

The TRANS results are shown in Figure 4. TRANS is also strongly affected by the frequency of vibration ($F_{/H11005}/H11005/8.292, P_{/H11021}/H11021/.001$). At the ankle, TRANS at 25 Hz demonstrated an amplification effect for the knee angle of 140° (TRANS > 1); also, TRANS at 25 Hz was significantly larger for the knee angle of 140°, followed by 35 Hz and 45 Hz. For the knee angle of 160°, TRANS at 25 Hz and 35 Hz were not significantly different, but TRANS at 45 Hz was significantly lower than the other 2 frequencies. At the knee, hip, and head, a consistent pattern was present, in which the smaller frequency generated significantly larger TRANS compared with the next frequency for all test cases ($TRANS_{25} > TRANS_{35} > TRANS_{45}$).

The effect of amplitude on TRANS was significant ($F_{/H11005}/H11005/13.785, P_{/H11021}/H11021/.001$). At the ankle at 25 Hz, the 2 amplitudes were not significantly different. In contrast, at 35 Hz and 45 Hz, TRANS at 0.6 mm was significantly larger than at 1.2 mm. At the knee, TRANS at 0.6 mm was significantly larger for all test cases, except at 160° and 35 Hz. At the hip, no
differences were found. At the head, TRANS at 0.6 mm was significantly larger for all cases, except at 160° and 25 Hz.

The effect of variations in posture on TRANS was significant ($F_{[H11005]}^{362.050}$, $P_{[H11021]}^{34.454} < .001$). Contrary to what was seen with P-P, the effect of frequency on TRANS was not significant. At the ankle and knee, TRANS was significantly larger for 140° compared with 160°, except at 45 Hz and 0.6 mm. At the hip, no significant difference was found between 140° and 160° except at 45 Hz, where 160° generated a larger TRANS than 140°. At the head, TRANS at 160° was significantly larger than 140° for all test cases.

**Juvent Accelerometer Results**

**P-P Results.** The P-P results for the Juvent platform are shown in Figure 5. Frequency had a strong effect on P-P recordings ($F = 362.050$, $P < .001$). The results show that, at the plate, 35 Hz vibration created a significantly larger P-P, followed by 45 Hz and 25 Hz. At the ankle and knee, the smaller knee angles created larger P-Ps for all test cases, except at 45 Hz between 140° and 160°. At the hip, posture did not create any significant differences in P-P. At the head, the larger knee angle generated larger P-Ps for all test cases (P-P_{180} > P-P_{160} > P-P_{140}).

**TRANS Results.** The TRANS results are shown in Figure 6. Frequency had a strong effect on TRANS ($F = 34.454$, $P < .001$). At the ankle, the only significant difference was observed at a knee angle of 140°, where 45 Hz generated significantly smaller TRANS than did 35 Hz. At the knee and the hip, 25 Hz generated larger TRANS than the other 2
frequencies; the difference between 35 Hz and 45 Hz was only significant at 140°, where 45 Hz generated significantly smaller TRANS than did 35 Hz. At the head, the smaller frequency generated a significantly larger P-P for all test cases, except at 140° between 25 Hz and 35 Hz. Posture also had a strong effect on TRANS ($F_{11005} = 18.004$, $P < .001$). At the ankle, the smaller knee angle generated significantly larger TRANS, except at 45 Hz between 140° and 160°. At the knee, 180° created significantly smaller TRANS than the other knee angles for all test cases. At the hip, posture did not create any differences in TRANS. At the head, the larger knee angles created larger TRANS for all test cases, except at 35 Hz between 140° and 160°.

**WAVE Versus Juvent Accelerometer Results**

To compare the WAVE and Juvent platforms, RMANOVA with paired $t$-tests with Bonferroni correction were performed on the P-P recordings at the head and on the TRANS recordings at the ankle, knee, and hip. For the paired $t$-tests at each accelerometer location, the following 3 factors were compared: WAVE 0.6 mm, WAVE 1.2 mm, and Juvent.

**P-P Results.** At the head, the 2 amplitudes of the WAVE platform (0.6 mm; 0.652 g; 1.2 mm; 0.871 g) generated significantly larger P-P compared with the amplitude of the Juvent platform (0.098 g); for both tests, $P < .001$.

**TRANS Results.** At the ankle, at 25 Hz, no significant differences were found between WAVE and Juvent platforms in TRANS for the 3 tested factors; however, for the other 2 frequencies, the smaller magnitude vibrations generated significantly larger TRANS ($\text{TRANS}_{\text{Juvent}} > \text{TRANS}_{\text{WAVE 0.6}} > \text{TRANS}_{\text{WAVE 1.2}}$). At the knee, the smaller magnitude vibrations generated greater TRANS, except at 25 Hz between WAVE 0.6 mm and the Juvent. At the hip, only at 140° were significant differences present, where the TRANS of the Ju-
vent platform was significantly larger than the WAVE platform 1.2 mm.

**DISCUSSION**

**Assessment of the Tested WBV Parameters**

An objective of this project was to select the combination of vibration parameters (frequency and amplitude) that would help achieve the highest vibration absorption in the lower extremities while minimizing vibration propagation to the head. The assumption that the highest absorption of vibration in the lower extremities would be beneficial to the bones is based on our interpretation of Wolff’s Law [12,48], the Utah Paradigm [14,49], and published data [50] that describe the relationship between strain threshold and the number of loading cycles necessary to increase BMD. In the case of patients with SCI and low bone mass of the hip and knee regions and impaired mobility, propagation of vibration in the lower extremities where bone mass is low is key to identifying a therapy that is likely to be effective when it is evaluated in future prospective intervention studies. In prior studies that investigated WBV among animals and human subjects, magnitude and frequency appear to have the greatest impact on WBV therapeutic efficacy [51]. In this study, we examined the impact of frequency, amplitude, and posture on lower extremity vibration propagation.

**Effect of Frequency**

For both WAVE and Juvent platforms, the greatest levels of vibration attenuation (the lowest TRANS) in the lower extremities (ankle and knee) occurred with the vibration frequency of 45 Hz. Similarly, the magnitude of vibration that propagated to the head was lowest at 45 Hz vibration. Platform frequencies of 25 Hz uniformly created the greatest propagation of vibration to the head, which results in negative feedback from subjects. The factorial ANOVA results confirm that frequency was the most influential variable that affects P-P and TRANS for all test conditions and platforms. A potential study limitation is our limited choice of device frequencies studied. Our results are consistent with previ-
ously published work [39,44], which demonstrated a similar relationship between frequency and vibration propagation among able-bodied subjects, although previous investigators did not study passive standing or vibration propagation to the head. The observed relationships between device frequency, P-P, and TRANS should hold true with alternate frequencies among vertical sinusoidal vibration platforms. Given the importance of frequency on lower extremity vibration propagation, it is of utmost importance that investigators confirm the frequency output of a platform via on-site testing before data acquisition [52].

**Effect of Amplitude**

Few studies published to date have investigated the influence of platform amplitude and subject posture on vibration propagation. With regard to the amplitude of vibration, 0.6 mm with the WAVE platform best satisfied the requirements of our study. A comparison between the TRANS of 0.6 mm vibration with 1.2 mm vibration on the WAVE platform showed that they are similar in propagation profile. However, when comparing the P-P at the head, 0.6 mm produced smaller vibrations at the head compared with the 1.2 mm amplitude. High levels of vibration at the head can produce headache, dizziness, and nausea [53-55]; therefore a 0.6-mm vibration amplitude at 45 Hz is a safer choice for applying WBV to subjects with SCI while optimizing vibration propagation. Although the Juvent platform does not allow for amplitude selection, the TRANS profiles of the WAVE and Juvent devices appear similar in Figures 4 and 6, respectively.

**Effect of Posture**

The final variable evaluated in this study was the subject’s knee angle during WBV and passive standing. Knee angle was the second most influential factor on P-P and TRANS for both platforms. Two knee angles, 140° and 160°, were tested for the WAVE device, and 180° was considered only with the Juvent platform. Of these knee angles, the 140° knee angle was optimal based on our a priori criteria. In most cases, the P-P at the head was smallest, with a knee angle of 140°. However, increases in knee angle (greater flexion) resulted in reductions in lower extremity TRANS, presumably because of absorption of vibration at the knee. A prior study showed reductions in TRANS among able-bodied subjects with changes in knee flexion by comparing TRANS in free standing with the knees extended (180° versus squatting 160°) [56]. We did not measure the changes in lower extremity loading on the platform with varying knee angles of subjects in the standing frame. The degree of lower extremity loading may vary with the different knee postures because of the concurrent use of the passive standing frame to maintain an upright posture. Further exploration of the interrelationships of posture, P-P, and TRANS is needed. For the purpose of this study, emphasis was given to the level of P-P at the head rather than the TRANS of the lower extremities; hence the smaller P-P at the head for a knee angle of 140° was deemed the decisive factor over the smaller TRANS.

**Comparison of WAVE and Juvent Platforms**

The Juvent platform, unlike the WAVE platform, did not provide control over the amplitude of vibration, and the magnitude of the platform was dependent on the subject’s weight. Second, in most scenarios, the lower extremity attenuation of vibration was larger with the Juvent platform compared with the WAVE platform. When comparing the P-P at the head, the Juvent platform produced smaller vibrations followed by WAVE 0.6 mm. However, the vibrations produced by the Juvent platform were variable (0.01-0.33 g) but consistently <1.0 g, and close to an order of magnitude smaller than the output from the WAVE platform. These differences in magnitude accounted for the lower measured P-P for the Juvent platform compared with the WAVE platform across test conditions. Although the magnitude of the WAVE platform was higher than the Juvent platform, we thought that the magnitudes were sufficiently low to be safe and chose between the devices based on our a priori criteria.

**Alternatives to WBV With Passive Standing**

Asselin et al [37] have proposed a WBV setup for persons with SCI that uses a vertical vibration platform attached to a tilt table; they demonstrated that, the higher the tilt angle, the greater the loading on the bones and the higher the transmissibility. In the current study, we propose a WBV device setup with a passive standing frame that an individual can use to erect themselves into a standing posture and remain standing on the platform during WBV. The current study results suggest that our strategy has greater potential for therapeutic efficacy compared with the WBV platform with a tilt table. First, a person with SCI can independently transfer into the standing frame and assume the posture appropriate for WBV therapy. Second, passive standing allows the subject’s weight to load the bones. With our device setup, up to 100% of the subject’s body weight can be used to load the bones during WBV, whereas with the tilt-table setup, the maximum tilt angle was 45°, which allowed a maximum load of 70% of the person’s body weight [37]. The higher the dynamic loading, the higher the strain rate on the bones, which, in turn, increases the level of bone formation [17-19]. Third, changes in posture allowed us to regulate how much vibration was transmitted to the head. Increased vibration at the head causes dizziness and nausea and, with prolonged exposure, is hazardous and may contribute to device rejection or poor adherence to WBV [54].
Potential Benefits of WBV for Persons With SCI

The objective of this study was to determine the ideal combination of WBV parameters from a preselected set of vibration parameters (frequency, amplitude, and posture) that facilitates lower extremity vibration absorption, while minimizing vibration propagation to the head. This ideal combination of WBV parameters has a potential to maximize the “osteogenic effects” in the lower extremities of persons with chronic SCI and SLOP. Future studies should investigate the efficacy of WBV for treatment of SLOP by using these parameters. However, it must be noted that, in addition to the potential for enhancing osteoblast activity, the potential benefits of WBV also include muscle activation.

Results of several studies have indicated the presence of electromyographic activity, specifically in the lower extremities, during exposure to WBV [57-59]. The advantage in potentially stimulating muscles and improving their strength and cross sectional area with WBV in persons with SCI also may play a role in further improving BMD. One prior study investigated the decline and recovery of bone and muscle upon paralysis on the calf muscle of rats induced by Botox (Allergan, Inc, Irvine, CA) [60]. The results demonstrated that, subsequent to paralysis, losses in muscle mass and bone mass appear. However, upon recovery from paralysis, the cortical bone demonstrated improvements, whereas the trabecular bone did not demonstrate improvements. These results indicate that, upon activation of the muscles of the lower extremities from WBV, the potential exists for improvements in cortical bone. Future intervention studies should measure electromyographic activation and both muscle and bone responses to WBV therapy [61]. This study is a device development study akin to a phase 0 trial, designed to speed up the development of promising devices by establishing very early on whether the device behaves in human subjects as expected from animal or preclinical biomechanical studies.

Technical Limitations

This study has some technical limitations. First, we used the uniaxial accelerometer and placed the accelerometer vertically via visual inspection. Use of uniaxial versus triaxial accelerometers may have produced measurement errors, because the direction of the measured acceleration could have deviated from vertical. Second, the accelerometer was attached to the skin overlying a bony prominence rather than on the bone. Thus the soft tissue between the bone and the accelerometer may have produced some measurement errors, and the effects of the soft tissue cannot be estimated. Third, we only measured 3 frequencies (25 Hz, 35 Hz, and 45 Hz) for each plate, although the frequencies selected were those most commonly used in clinical practice. Fourth, whole-body vibration can induce activation of lower limb muscles, which likely resulted in variation in the measured acceleration, because acceleration likely varies with induced muscle activity among subjects.

CONCLUSION

The primary aim of this study was to inform the development and implementation of WBV therapy for persons with SCI and SLOP. A passive standing frame and 2 vertical oscillation platforms (WAVE and Juvent) were evaluated by using specific platform frequencies and amplitudes to determine their effects on lower extremity and head vibration propagation of subjects in a variety of postures. Our results have shown that 45 Hz vibration met both of the a priori specified criteria for greatest attenuation of vibration in the lower extremities while minimizing vibration to the head. Assessment of the accelerometer results (P-P and TRANS) illustrated that 45 Hz, 0.6 mm vibration on the WAVE platform with 140° knee angle best suits the criteria for development and implementations of WBV and passive standing for treatment of persons with SCI and SLOP.

WBV is a rehabilitation technique with the potential to treat SLOP after SCI. Although numerous studies have investigated the potential of WBV therapy for persons with osteoporosis [2,3,8,62] to date, no study has rigorously examined the interplay of vibration frequency, amplitude, and the individual’s posture among people with SCI. To our knowledge, this is the first study of its kind that investigates the effects of these factors within the SCI population while providing clear indications about which vibration parameters and body postures should be used to maximize the vibration effects on lower extremity and limit discomfort and risk during WBV. The results of this study are intended to inform the design of future phase II and III intervention studies to evaluate the efficacy of WBV and passive standing for treatment of SLOP after SCI. The ability to generalize the results is limited to the specific vertical oscillation platforms and combinations of vibration parameters tested.

ACKNOWLEDGMENTS

We thank Julia Totosy de Zepetnek, Jude Delparte, Stephanie Hadi, and Cameron Moore for their assistance with data collection and subject retention. We also thank Drs Lora Giangregorio, Lidan You, and Alan Morris for their technical assistance and scientific contributions.

REFERENCES

2. Verschueren SMP, Roelants M, Delecouse C, Swinnen S, Verschueren D, Boonen S. Effect of 6-month whole body vibration training on hip density, muscle strength, and postural control in post meno-


This CME activity is designated for 1.0 AMA PRA Category 1 Credit™ and can be completed online at me.aapmr.org. Log on to www.me.aapmr.org, go to Lifelong Learning (CME) and select Journal-based CME from the drop down menu. This activity is FREE to AAPM&R members and $25 for non-members.

CME Question
The authors did not intend to evaluate which of the following?

a. weight bearing vibration (WBV) frequency
b. WBV amplitude
c. WBV efficacy
d. WBV devices

Answer online at me.aapmr.org