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Weight Bearing through Lower Limbs in a Standing Frame with and without Arm Support and Low-Magnitude Whole Body Vibration in Men and Women with Complete Motor Paraplegia

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Abstract

Objective—To determine the proportion of body weight (BW) borne through the lower limbs in persons with complete, motor paraplegia using a standing frame, with and without support of their arms. We also examined the effect of low-magnitude whole body vibration on loads borne by the lower extremities.

Design—Vertical ground reaction forces (GRF) were measured in 11 participants (6 men and 5 women) with paraplegia of traumatic origin (injury level T3 to T12) standing on a low-magnitude vibrating plate using a standing frame. GRF were measured in four conditions: 1) no vibration with arms on standing frame tray; 2) no vibration with arms at side; 3) vibration with arms on tray; 4) vibration with arms at side.

Results—GRF with arms on tray, without vibration, was 0.76 ± 0.07 BW. With arms at the side, GRF increased to 0.85 ± 0.12 BW. With vibration, mean GRF did not significantly differ from no-vibration conditions for either arm positions. Oscillation of GRF with vibration was significantly different from no-vibration conditions ($p < 0.001$) but similar in both arm positions.

Conclusion—Men and women with paraplegia using a standing frame bear the majority of their weight through their lower limbs. Supporting their arms on the tray reduces the GRF by ~10% BW. Low-magnitude vibration provided additional oscillation of the load-bearing forces and was proportionally similar regardless of arm position.

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Keywords

Spinal Cord Injury; Paraplegia; Standing Frame; Ground Reaction Forces; Vibration

INTRODUCTION

Passive standing is widely used in both acute and chronic spinal cord injury (SCI) care. While a tilt table is often used to initiate a standing regimen, a standing frame is preferred for the long term, and suitable for home use. Despite widespread acceptance among clinicians and patients alike, psychological well-being is the most consistent benefit that has been demonstrated from passive standing (1–3). Nonetheless, interest persists in the benefits of standing for lower limb stretching and improving and/or maintaining bone mass after paralysis. However, in order to better understand whether a standing intervention would be of potential merit, it would be useful to quantify what actual loads are being borne through the lower extremities of individuals with SCI while standing, as it is these loads that are expected to have an effect on the prevention of soft tissue contractures and bone loss. Such loads have been determined in persons with SCI at varying degrees of tilt when using a tilt table, although not at a fully upright position (4). Nevertheless, this information would not likely be directly translatable to loads experienced when using a standing frame, due to the full body contact that occurs with the tilt table or to the potential effect of arm support when using a standing frame. To our knowledge the proportion of body weight borne through the lower extremities in men and women with SCI using a standing frame has not been determined to date, and was the primary goal of our study.

Connective tissue progressively shortens or elongates to achieve a position of rest. Spasticity can speed the progression, unless opposed by equal or greater force (5). Frequent repetition of stretch opposing a contracture has been historically considered optimal, but in recent years, slow prolonged stretch, such as during passive standing, has been observed to provide greater soft tissue lengthening (6). However, the optimal amount of force, duration and frequency needed to lengthen soft tissue is unknown. A recent Cochrane review by Katalinic et al reported that the different stretching modalities that have been studied to date do not prevent contractures in those with neurologic injuries or illnesses (7). Only one study included in their analyses evaluated weight bearing as a mode of stretch in a SCI population, and it was effective (8). Regardless, improved strategies are necessary for the prevention and treatment of contractures and require further study, particularly in those with SCI. Whether passive standing in a standing frame will be useful as an intervention remains to be determined, but knowledge on the loads achievable would be ideal.

Improving bone mass, or preventing its loss, following SCI has been an increasingly high priority. Significant bone loss in the first two years after SCI has been well documented, and presumed to be primarily due to loss of load-bearing by the skeleton (1,9). Prevention or reduction of this bone loss through passive standing would seem an obvious intervention based on Wolff's Law (10), yet initiation of passive standing in those with chronic SCI has not yet been proven to alter bone density (11). A single study has suggested that passive standing using a standing frame early following acute SCI for at least 1 hour a day, 5 days per week, may be beneficial in reducing bone loss (1). Nevertheless, optimal frequency of passive standing for bone health following either acute or chronic SCI remains undetermined.

In both lower extremity stretching and loading of bone, the vertical force generated by gravity, and its ground reaction force (GRF), are key components of the “dose” of standing. It has been assumed that the standing frame bears some portion of the GRF, attenuating the

load-bearing effect on the individual, but the amount is unknown. Clinical observation indicates most SCI patients prefer to rest their arms on the standing frame tray for comfort and stability. The effect of arm position on load borne through lower extremities is also unknown. Elucidating how much force is borne through the lower extremities of a paralyzed person in a standing frame would facilitate research into optimal dosing of standing frame use, and allow clinicians to provide better advice to their patients, both with respect to safety as well as efficacy.

Recently, there has been increasing interest in the benefits of adding whole body vibration while standing in persons with SCI, either through a high-magnitude ($\geq 1g$, where g = Earth's gravitational field, or 9.8 m/s^2) or a low-magnitude ($< 1g$) vibrating plate. Whole body vibration offers another potential low risk attempt to provide additional mechanical stimuli to the soft tissues and bones of individuals with limited mobility from various neurologic conditions, including SCI (4,12–16). The mechanical stimulation from vibration, in the form of the vertical oscillation signal, is considered to be anabolic to bone (17,18). Preliminary data suggest that high-magnitude whole body vibration, delivered as four consecutive sessions involving 45 seconds of vibration followed by 1 minute of seated rest in some SCI studies, may improve spasticity and reduce bone loss in those with SCI (13–15). Low-magnitude vibration, which has been reported to be of benefit to bone density in children with disabilities and women, (19–21), may be better suited for use in combination with current passive standing regimens proposed for those with SCI, as it is usually administered in one 10 minute session of vibration. Asselin et al (4) recently evaluated the combination of passive standing and low-magnitude whole body vibration in individuals with SCI using a tilt table, with arms strapped to their side. They demonstrated greater axial vibration signal transmission at steeper angles of tilt (4). The vertical oscillation signal while standing on a low-magnitude vibrating plate with a standing frame would thus be expected to also be well transmitted. While we would not anticipate arms resting on the tray of a standing frame to influence the vertical oscillation signal, the effect is not known. If attenuated, then the anabolic effect of vibration to bone would likely be diminished. It also is unknown whether the vibration stimulus would have any influence on the degree to which an individual may use their arms for more support when resting on the standing frame tray, thereby changing the GRF. Thus, determining whether the vertical oscillation signal remains consistent with and without the support of arms when using a standing frame, and how different the mean GRF is between each arm position when vibration is used, would be of clinical relevance.

In this study, we sought to determine the percentage of body weight borne through the lower extremities in men and women with complete motor paraplegia as measured by the GRF while in a standing frame with arms resting on the tray of the frame and then at the side. We hypothesized that the GRF would be lower with arms resting on the tray, but sought to quantify the reduction in GRF in this position. We also investigated the effect of low-magnitude whole body vibration on GRF while using a standing frame and whether the use of arms resting on the tray attenuates the observed vertical oscillation signal. We hypothesized that the vertical oscillation signal would not be attenuated but be proportionally similar, regardless of arm position.

METHODS

Study Participants

Men and women between the ages of 20 and 50 years with a traumatic, complete motor paraplegia (American Spinal Injury Association (ASIA) Impairment Scale type A or B) (22) for at least 2 years were recruited from the clinical practice of an academic SCI center and with assistance from the EasyStand company. Study participants were completely unable to

come to a stand without bracing or a standing frame. Persons with a history of long bone fracture since onset of SCI, existing pressure ulcer greater than stage 2, lower extremity contractures, or inability to tolerate passive standing for any reason were excluded. Subjects could have been previously using a standing frame regularly or not. The study was approved by the Institutional Review Board and all subjects provided written informed consent to participate. Our final study participants included 6 men and 5 women with traumatic SCI (level of injury T3 to T12) whose time since injury ranged from 2 to 26 years.

Ground Reaction Force Measurements

During a single study visit, subjects underwent vertical GRF measurement while standing in a standing frame. Subject body mass (kg) was measured for comparison to vertical GRF. Each subject was weighed in their wheelchair, and then the wheelchair alone, with the difference being the body mass of the subject. A low-magnitude vibrating plate (Juvent Medical, Somerset, NJ; model Juvent 1000) was placed on a previously zeroed 6-component force platform (Advanced Mechanical Technology, Inc., Watertown, MA; model BP400600). The commercially available vibrating plate provided a 0.3g, 34 Hz vertical sinusoidal movement adjusted to compensate for the user's body mass. An EasyStand standing frame (Altimate Medical, Morton, MN) was placed with the frame legs straddling the force platform and vibrating plate. Subjects were placed in the standing frame with the assistance of a physical therapist with hips and knees extended and bare feet flat on the vibrating plate surface (Figures 1A–1B). Abdominal binding and compressive leg wraps were applied prior to standing as deemed necessary by the study participant and therapist to ensure orthostatic homeostasis during the data collection. Reflective markers were placed on the right leg over the lateral proximal femur and lateral distal fibula to calculate the sagittal plane knee flexion angle with a 10 camera motion capture system (EvaRT software, Motion Analysis Corporation, Santa Rosa, CA).

GRFs were measured with subjects' arms resting on the tray of the standing frame and then at the subjects' side, with and without the vibration source active for each position (Figures 1A–1B). For each of these four test conditions, five-second data recordings were made initially and then at one minute intervals for five minutes thereafter. Test condition order was the same for each subject. Subjects were asked to remain still and look forward during the data collection, but postural adjustments between test conditions were permitted. Total time in the standing frame was approximately 25 minutes for each subject. GRF was collected at 600 Hz, and time-synched to the marker location data which was captured at 60 Hz with the motion capture software.

Analyses

Vertical GRFs were calculated with custom programming (Matlab, Mathworks, Natick, MA). For all four test conditions, the mean and standard deviation (SD) over each five-second epoch of the vertical GRF signal was calculated. Additionally, the mean of the maxima and minima of the vertical oscillation signal from the vibrating plate were determined. All GRF measures were expressed as a percent of subject body weight (BW), measured in kg, after subtracting the weight of the vibrating plate from the total measured vertical GRF. Approximate average knee flexion angle for each five-second trial was determined using the included angle function in the motion capture software.

A two factor ANOVA with repeated measures on the two independent factors (vibration [on/off] and arm position [on tray/at side]) was performed using SAS (SAS Institute Inc., Cary, NC). Significance was set at $p < 0.05$.

RESULTS

We recruited 12 subjects, but the weight of one participant could not be accurately determined, so we analyzed data from 11 subjects (6 males and 5 females), all of whom were Caucasian. Their mean age $\pm$ standard deviation (SD) was 40 ± 8 years (age range: 25 to 50 years) and mean body mass index (BMI) was 22.2 ± 3.8 kg/m². The mean time since injury was 11 ± 8 years (range: 2 to 26 years). There were 5 subjects who had flaccid paraplegia and the remainder had spastic paraplegia. Three subjects had a high paraplegia (T3 to T5) while 8 had a lower injury (T6 to T12).

Ground Reaction Forces and Arm Position in Standing Frame

Mean vertical GRF at baseline with the arms resting on the tray and without the vibration source active was 0.76 ± 0.07 BW, (range: 0.64–0.85 BW). With arms hanging at the side and no vibration, baseline mean vertical GRF increased to 0.85 ± 0.12 BW (range: 0.64–0.95 BW). Arm position did have a significant effect on GRF ($p=0.027$), being approximately 10% lower when the arms were resting on the tray when compared to being at the side. Data at baseline and over the 5 minute trial period are presented in Figures 2A–2B.

Mean GRF did change slightly over the 5-minute trial period, decreasing to 0.75 ± 0.09 BW and 0.81 ± 0.15 BW for arms on the tray and arms at the side, respectively. In the arms on tray position, there was about an equal number of subjects who had an increase in load as subjects who had a decrease, and the change in load over time was not statistically significant ($p=0.08$). In the arms at the side position, the load magnitude decreased over time and was statistically significant ($p=0.03$). The mean decrease in GRF observed in either situation, however, was small, being less than 4% BW.

Ground Reaction Forces and Low-magnitude Vibration

The baseline mean GRF with addition of vertical oscillation from the low-magnitude vibrating plate did not significantly differ from the no-vibration conditions for either arms on the tray or arms at the side (0.76 ± 0.08 BW, range: 0.59–0.85 BW, and 0.86 ± 0.10 BW, range: 0.63–0.98 BW, respectively). Data at baseline and over the 5 minute trial period are presented in Figures 2A–2B. However, the vertical oscillation was evident when examining the raw signal (Figures 3A–3B). Mean maximum and minimum GRF over the baseline 5-second epochs were 0.78 ± 0.09 BW and 0.74 ± 0.08 BW, respectively, for arms on the tray, while they were 0.88 ± 0.10 BW and 0.84 ± 0.10 BW, respectively, for arms at the side.

As expected, variability (SD over the five-second collections) of the GRF signal was significantly larger for the vibration compared with the no-vibration conditions ($p<0.001$) (Figures 4A–4B). Arm position in the vibration conditions did not result in additional differences in variability compared with the no-vibration trials (Figures 4A–4B).

Approximate knee flexion position did not change significantly over time in any of the four test conditions. Results did not appear to be affected by tone or injury level as assessed in ANOVA models.

DISCUSSION

To our knowledge, this is the first study to quantify load borne through the lower extremities in men and women with complete motor paraplegia using a standing frame. The results indicate that the majority (~85%) of body weight is borne through the plantar surface of the feet, as measured by a GRF plate, when subjects are supported by a standing frame, arms by their side, with near full hip and knee extension and neutral ankle dorsiflexion. A ten percent reduction in GRF was identified when subjects rested their arms on the standing frame tray.

However, participants in this study preferred resting their arms on the tray for stability and comfort. Nevertheless, a large proportion of their body weight (~75%) was still borne through the lower extremities even though their arms were resting on the tray and this did not significantly change over the 5 minute period examined. We also found that mean GRF, for either arm position, did not differ when the vertical oscillation was active from the low-magnitude vibrating plate. Furthermore, the magnitude of the vertical oscillation signal was similar whether arms were resting on the tray or at the side.

There are other options for weight bearing through the lower extremities in individuals with SCI, such as a tilt table or standing wheelchairs. However, there have been limited studies determining the actual amount of body weight borne through the lower extremities with these devices. Asselin et al, (4) did show that percentage of body weight borne through the lower extremities in SCI subjects increased from 22% at 15 degrees of tilt on a tilt table to 46% at 45 degrees of tilt. The study did not examine subjects in a fully upright position so comparisons to a standing frame are not possible. Maximum load bearing may be less on a tilt table due to increased friction from full body contact with the tilt table. Also, inconsistent strapping mechanisms for preventing anterior translation of the tibia (knee flexion) make attaining full vertical position difficult. To our knowledge, no study has quantified the load borne through the lower extremities of those with SCI using a standing wheelchair. Clinical experience has shown that it is more challenging to achieve full hip and knee extension in a standing wheelchair than in a standing frame. In such situations, more weight is translated anteriorly into the tibia and posteriorly at the pelvis rather than axially.

In our study, we found that a low-magnitude whole body vibrating plate, in conjunction with a standing frame, allowed for a mean 2% body weight variation both above and below the mean GRF, and this variation was not attenuated when the arms were used for support in the standing frame. Asselin et al (4), using a similar low-magnitude whole body vibrating plate, showed that the vibration signal was translated through the axial skeleton as measured using an accelerometer in the mouth at various inclines on the tilt table. Subjects showed a greater translation of vibration with increased load-bearing corresponding to increased degree of tilt. One would therefore also expect transmission of vibration through the axial skeleton when standing vertical in a standing frame, although we did not measure this in our study.

Ideally, it would be clinically relevant to evaluate all standing devices available for paraplegics in order to see which one provides the greatest amount of load-bearing through the lower extremities. Nevertheless, the choice of such devices will also depend on other clinical considerations and include the following practical concerns: 1) Can a person independently get in and out of the standing device? 2) How rapidly can the person come out of standing device if they experience negative side effects like orthostatic hypotension? 3) How convenient is standing for this person (can they have the equipment at home, or do they need to go to a medical facility to use the device)? 4) How affordable is it to purchase this equipment for home use?

Passive standing is a relatively easy physical activity that may reduce the risk of secondary medical complications after SCI, such as pressure ulcers and has been shown to improve the perception of well-being in those with SCI (2,3). Nonetheless, while passive standing has been used as a treatment for spasticity as well as an intervention to prevent contractures and reduce bone loss in SCI, the data to support such recommendations remain limited to date. In a within-subject randomized trial, Ben et al (8) evaluated the effect of standing on ankle mobility in persons who had SCI for 12 months or less. Subjects stood using a tilt table supported in single leg stance with one foot on a wedge and the contralateral ankle being used as a control (8). After a 12 week period, the mobility of the control ankle decreased by a mean of 4.90 degrees, while the experimental ankle decreased by a mean of 0.85 degree

(mean difference 4.05 degrees, 95% CI: 1.60, 6.50) (8). Whether passive standing in a standing frame, where load-bearing would be expected to be greater, would offer greater improvement in ankle mobility is unknown and warrants further study.

Kunkle et al (11) assessed the effects of standing on six males with varying levels and completeness of paralysis. Each subject stood using a standing frame for 45 minutes twice daily for 5 months (11). There was no reported reduction of spasticity, contracture or bone loss at completion of the study (11). However, subjects did indicate improvement in how they felt in terms of their overall health with passive standing (11). Of note, this study included only six subjects who were a mean of 19 years after SCI and had no control group for comparisons (11). In contrast, among 27 subjects with SCI, Alekna et al did show a reduction in bone loss after both 12 and 24 months of passive standing in a standing frame for 1 hour or more a day, at least 5 days per week, when compared with non-randomized controls with SCI who did not stand regularly (1). Study subjects were all within 2 years of SCI (1). Further studies are thus needed to determine the benefits of passive standing on bone density, particularly in those with chronic SCI. Our data would also suggest that studies using a standing frame should consider whether arms are to be supported on the tray or not in their study design, although the reduction in GRF with arms supported is effectively small.

The use of whole body vibration to prevent spasticity and bone loss in SCI is also of increasing interest. Sensory stimulation in the form of vibration to tendons or muscle has been reported to activate modulatory systems which decrease the amplitude of the Hoffman-reflex, increases in which have been implicated in spasticity following SCI (15). Indeed, preliminary data suggest high-magnitude whole body vibration may have benefits on spasticity and function after SCI (14,15). Increasing evidence also indicate that mechanical stimuli that affect bone metabolism are transmitted to bone at the cellular level through alterations in fluid flow or fluid shear forces and changes in intramedullary pressure in the porous spaces of bone (lacuna-canalicular network) (23,24). Whole body vibration has been reported to provide mechanical stimuli in the form of vertical oscillation adequate to increase fluid flow in bone and a strongly osteogenic signal, at least with low-magnitude vibration (17,18). In animal studies, high- and low-magnitude whole body vibration is anabolic to bone (25,26). Whole body vibration, either with high-or low-magnitude vibration, also appears to have modest benefits on bone density in humans (27), but studies to date are limited in those with SCI (13). Most whole body vibration protocols have involved administration at least 3 to 5 days per week. Protocols studying high-magnitude whole body vibration in SCI populations have involved short periods of vibration (45 seconds) followed by 1 minute of seated rest, given in 4 consecutive sessions (14,15). Low-magnitude whole body vibration is administered as one, sometimes two, 10 minute sessions in a day. Thus, the combination of passive standing regimens using a standing frame with low-magnitude vibration is a potentially attractive management approach in those with SCI, but further work is needed on determining the optimal dosing and both the risks and benefits of such an intervention. Our data suggest that the vertical oscillation signal from a low-magnitude vibrating plate translates to a mean 4% body weight variability across the mean GRF when using a standing frame, irrespective of arm position, in men and women with chronic SCI. Whether low-magnitude vibration will have a positive effect on muscle or bone parameters in those with SCI, while using a standing frame, needs to be studied.

Our study population was limited to those with paraplegia resulting from traumatic spinal cord injury, but could potentially be extrapolated to others with neurological diseases causing lower limb paralysis including stroke, multiple sclerosis, or traumatic brain injury. It is unknown if the limb loads would be less among individuals with tetraplegia. However, it would be unlikely that those with tetraplegia would stand with their arms unsupported. Our

subjects with high paraplegia, although able to stand in the standing frame, felt less secure with their arms at their sides, even though joint angle data did not suggest any “sagging” during the testing period. We also selected only subjects with near normal hip and knee extension. Knee or hip flexion contractures would likely change the alignment relationship of the GRF vector with respect to the limb axial direction, and may result in an attenuation of total load borne by the lower limbs. It may also be useful to evaluate those with acute SCI, prior to the majority of bone and muscle loss (28), since the center of mass moves cephalad as a result of this loss. Differences in limb loading, however, are likely to be small, and may not have clinical significance.

We have identified that men and women with complete motor paraplegia bear the majority of their body weight through their lower limbs when using a standing frame, irrespective of arm position. Supporting the arms on the standing frame tray reduces the GRF by about 10% of body weight. Low-magnitude vibration was found to add to the variability of load-bearing in a standing frame, and was unaffected by arm position. Further research is needed in light of these data to determine the effect of frequency and duration of standing, with and without the effects of low-magnitude vibration, on the soft tissues and bone mass in individuals with SCI.

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Figure 1. Setup of subjects standing on a low-magnitude vibrating plate using a standing frame with arms resting on the standing frame tray (Panel A) and hanging at the sides (Panel B). The force measurement platform is located below the vibrating plate.

Figure 2.

Box plots depicting the median ground reaction forces (GRF) as a proportion of body weight (BW), and interquartile range (25th to the 75th percentiles represented as the box) with whiskers representing the 5th and 95th percentiles, measured over 5 seconds at baseline and

at each minute for 5 minutes without low-magnitude vibration (=N) and with low-magnitude vibration (=Y). Panel A represents data collected with arms resting on the standing frame tray. Panel B represents data collected with arms hanging at sides.

Figure 3.
Raw data collected on one subject over 5 seconds with arms resting on tray and at side without low-magnitude vibration (Panel A) and with low-magnitude vibration (Panel B).

Figure 4.

Box plots depicting the median standard deviation (SD), a measure of variability, of the ground reaction forces as a proportion of body weight (BW) and interquartile range (25th to

the 75th percentiles represented as the box) with whiskers representing the 5th and 95th percentiles, as measured over 5 seconds at baseline and at each minute for 5 minutes without low-magnitude vibration (=N) and with low-magnitude vibration (=Y). Panel A represents data collected with arms resting on the standing frame tray. Panel B represents data collected with arms hanging at sides.