

Effect of whole-body vibration on quadriceps spasticity in individuals with spastic hypertonia due to spinal cord injury

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Abstract. *Purpose:* Individuals with spinal cord injury (SCI) often have involuntary, reflex-evoked muscle activity resulting in spasticity. Vibration may modulate reflex activity thereby decreasing spasticity. This study suggests feasibility of using whole-body vibration (WBV) to decrease quadriceps spasticity in individuals with SCI.

Methods: Participants were individuals ($n = 16$) with spastic quadriceps hypertonia due to chronic SCI (> 1 year). Quadriceps spasticity was measured by gravity-provoked stretch (Pendulum Test) before (initial) and after (final) a 3 day/week, 12-session WBV intervention. In addition, differences between immediate (immediate post-WBV) and delayed (delayed post-WBV) within-session effects were quantified. Finally, we assessed response differences between subjects who did and those who did not use antispastic agents.

Results: There was a significant reduction in quadriceps spasticity after participation in a WBV intervention that persisted for at least eight days. Within a WBV session, spasticity was reduced in the delayed post-WBV test compared to the immediate post-WBV test. The WBV intervention was associated with similar changes in quadriceps spasticity in subjects who did and those who did not use antispastic agents.

Conclusions: Vibration may be a useful adjunct to training in those with spasticity. Future studies should directly compare the antispastic effects of vibration to those of antispastic agents.

Keywords: Spinal reflex, human movement system, rehabilitation, stretch reflex, reflex modulation, Pendulum Test

1. Introduction

In individuals with disorders of the central nervous system, there are multiple consequences of disrupted communication between the brain and spinal cord. Among these is the loss of descending modulation of spinal reflex circuitry. The consequence of this disrupted modulation is spastic hypertonia with increased reflex excitability and disordered motor output (i.e., spasticity, clonus, spastic gait patterns) that contribute to impaired motor function. The loss of presynaptic

inhibition has been suggested by the increased amplitude of the Hoffman reflex (H-reflex; the electrical analogue of the stretch reflex) in individuals with spasticity (Burke and Ashby, 1972; Calancie et al., 1993). Peripheral sensory input in the form of localized vibration applied to specific muscle tendons may activate modulatory systems (Butler et al., 2006; Calancie et al., 1993; Perez et al., 2004) that produce effects similar to those of the descending modulatory pathways. Localized vibration to the tendon or muscle belly suppresses the amplitude of the H-reflex in both non-disabled individuals and in individuals with spasticity (Calancie et al., 1993). While the depression is not as effective in those with spasticity as in non-disabled individuals, the depression of the H-reflex during vibration in individuals with spasticity suggests vibration may modulate the

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excitability of the underlying neural circuits (Burke and Ashby, 1972; Calancie et al., 1993). Further evidence for the modulatory influence of vibration in reflex activity in individuals with SCI, is offered by studies in our lab wherein tendon vibration was associated with improved reciprocal inhibition, with effects of a single session persisting up to 15 minutes after vibration was removed (Perez et al., 2004).

Whole-body vibration (WBV) has become popular in fitness centers with a myriad of benefits ascribed to its use. The research literature lends support to several of these claims with findings that WBV may be associated with increased muscle strength, (Delecluse et al., 2003; Fagnani et al., 2006; Mahieu et al., 2006; Roelants et al., 2004; Torvinen et al., 2002a; van den, 2006) flexibility (Cochrane and Stannard, 2005; Fagnani et al., 2006; Mahieu et al., 2006), and performance measures such as jump ability (Torvinen et al., 2002b; Torvinen et al., 2002a; Torvinen et al., 2003; Roelants et al., 2004; Cormie et al., 2006; Cochrane et al., 2004). In addition to indications that WBV has an effect on these movement-related variables, there are also reports that WBV may have beneficial effects on some aspects of function in older individuals (Verschuere et al., 2004; Bogaerts et al., 2007; Kawanabe et al., 2007), as well as in some clinical populations (Ahlborg et al., 2006; Tihanyi et al., 2007; van Nes et al., 2004; van Nes et al., 2006; Jackson et al., 2008).

In individuals with chronic stroke, a single session of WBV has been shown to be associated with improvements in balance function with effects persisting 45 minutes (van Nes et al., 2004). In individuals with acute stroke, improvements in balance and scores on tests of functional independence were found to be associated with a 6-week intervention of WBV. These improvements were observed both immediately after the 6-week intervention and at follow-up testing 6 weeks after the intervention, however, these changes were similar to those attained by subjects randomized to an alternate intervention group (van Nes et al., 2006). In another study designed to rule out the possible influence of merely standing in a squat position, individuals with subacute stroke were randomized into a group receiving a single session of WBV while performing a static squat or a group that only performed static squatting. The WBV group had an increase in maximal voluntary strength and reduction of the antagonistic hamstring muscle activity during eccentric contraction of the quadriceps muscle compared to no change in the squat-only group (Tihanyi et al., 2007). In adults with spastic diplegia due to cerebral palsy, WBV has been

shown to be associated with improvements in muscle strength and reductions in spasticity of the knee extensor muscles (Ahlborg et al., 2006). In individuals with multiple sclerosis, WBV has been associated with improvements in knee muscle performance (Jackson et al., 2008). Evidence of the effects of WBV in individuals with SCI is limited. In individuals with SCI who were unable to stand without long-leg braces, a case series reported in a published abstract found that the use of WBV evoked reflex-induced standing, and subsequently some of the individuals were able to progress to walking (Gianutsos et al., 2000).

The purpose of this study was to determine whether WBV decreases spasticity in subjects with spastic hypertonia due to chronic, motor-incomplete SCI. Our goal was to quantify the effect of WBV on quadriceps muscle spasticity in these subjects as preliminary data for a planned randomized, controlled study, and to identify the characteristics of those subjects likely to benefit from this intervention. Subjects were tested before and after participation in a 3 day/week, 12-session intervention of WBV, as well as weekly at two post-vibration time intervals following a vibration session. These weekly post-vibration testing sessions were considered important as lower extremity spasticity frequently interferes with function and mobility in individuals with SCI (Scivoletto et al., 2008), therefore quantifying the timecourse of effects following a single WBV session may offer support for the use of WBV as a pre-training adjunct for functional and mobility training. Finally, we assessed differences in response to the WBV intervention between subjects who used antispastic agents and those who did not. If antispastic agents are capable of reducing spasticity to the fullest extent possible, then no further WBV-induced reduction in spasticity would be anticipated in those who used these agents. We hypothesized that there would be a reduction in quadriceps spasticity after a 12-session intervention of WBV, that the within-session effects would be such that less spasticity would be observed in the immediate post-WBV test compared to the delayed post-WBV test, and that the subjects who reported daily use of antispastic agents would experience a smaller reduction in quadriceps spasticity associated with the WBV intervention compared to those who reported no use of antispastic agents.

2. Materials and methods

2.1. Subjects

Seventeen subjects (3 women, 14 men; age 28–65) with SCI enrolled in the study. All subjects underwent

Table 1
Demographics of participants

Subject	Gender	Age	Injury level	LEMS Scores	Antispastic agents	Primary daily assistive device
1	M	41	C5	25	Tizanidine	Wheelchair
2	F	42	C4	23	Baclofen	Wheelchair
3	M	60	C6	17	Baclofen	Wheelchair
4	M	48	C5	33	None	Wheelchair
5	M	56	C5	38	Baclofen	Wheelchair
6*	F	60	T4	34	Baclofen	Wheelchair
7	M	43	T8	26	None	Personal Transporter
8	M	54	T4	36	None	Wheelchair
9	M	34	T4	29	None	Wheelchair
10	M	42	C4	24	Baclofen	Wheelchair
11	M	41	T6	23	None	Wheelchair
12	M	53	T7	34	None	Walker
13	M	42	C4	23	Baclofen	Wheelchair
14	M	43	T7	42	None	Wheelchair
15	M	58	C6	31	None	None
16	M	65	C3	36	None	Wheelchair
17	M	28	C4	39	Baclofen	Wheelchair

Subject 6 was excluded from analysis due to initial first swing excursion (FSE) values > 96 degrees indicating no spasticity (i.e., equivalent FSE values are observed in non-disabled individuals) (Stillman and McMeeken, 1995). LEMS = lower extremity motor scores represent the sum of the motor scores for the 5 key muscles of both legs graded according to ASIA guidelines (American Spinal Injury Association, 2002) prior to the WBV intervention.

clinical examination prior to testing. Subject inclusion criteria was motor incomplete, chronic (≥ 1 year duration) SCI, and ability to stand with no more than moderate assistance. Exclusion criteria was a lack of quadriceps spasticity as defined by the Pendulum Test first swing excursion value (see Data analysis) equivalent to that of non-disabled subjects (96 degrees) (Stillman and McMeeken, 1995). One subject who was screened was excluded due to not demonstrating quadriceps spasticity as defined by the exclusion criteria. Therefore, sixteen subjects (2 women, 14 men; age 28–65) with spastic hypertonia due to SCI were tested. American Spinal Injury Association (ASIA) motor and sensory scores (American Spinal Injury Association, 2002), and ASIA Impairment Scale (AIS) classification (Marino et al., 2003) were evaluated by a physical therapist who was not otherwise involved in the study. All subjects had injuries that were classified as either AIS C or AIS D. Subjects with injuries classified as AIS C have sensory and some motor function preserved below the neurological level, but more than half of the key muscles below the neurological level are unable to move the limb segment against gravity. Subjects with injuries classified in the AIS D have sensory and motor function preserved, but at least half of the muscles are able to move the limb segment against gravity (American Spinal Injury Association, 2002). All subjects had asymmetrical lower extremity motor scores, the weaker extremity was designated as the test leg. Information about daily

use of medications and assistive devices for mobility was recorded. Seven subjects reported daily use of antispastic agents, while nine subjects reported no use of these medications.

Demographic data for the subjects is given in Table 1. All subjects gave written and verbal informed consent for participation in a protocol approved by the Human Subjects Research Office at the University of Miami, Miller School of Medicine. All subjects were instructed to maintain their pre-enrollment exercise and medication habits until completion of the study.

2.2. WBV Intervention

Subjects participated in an intervention consisting of WBV (Power Plate; Northbrook, IL) 3 days per week for 4 weeks. Each session included four, 45-second bouts with one minute of seated rest (without vibration) between bouts according to previously published protocols (van Nes et al., 2004; van Nes et al., 2006). The sequence of procedures for a single session of WBV is illustrated in Fig. 1. During each WBV bout, subjects stood on the vibration platform with knees slightly flexed (approximately 30 degrees from full extension). Vibration was delivered at 50 Hz with a vertical displacement of 2–4 mm (depending on subject weight).



Fig. 1. Procedure for a single session of whole-body vibration (WBV).

2.3. Testing procedure

The Pendulum Test was used to measure quadriceps spasticity (i.e., responsiveness of the spinal stretch reflex to quadriceps muscle stretch). The Pendulum Test allows the application of a consistent, gravity-provoked stretch to assess responsiveness of the knee extensor muscles to rapid stretch. The test was performed according to previously published protocols (Fowler et al., 2000; Stillman and McMeeken, 1995), which have shown this test to be a reproducible (Bohannon, 1987; Katz et al., 1992) measure of quadriceps spasticity. In individuals with SCI, the Pendulum Test has been validated (Nance, 1994), shown to correlate well with clinical measures of spasticity (Nance, 1994), and has been used to quantify the decrease in quadriceps spasticity associated with pharmacological intervention (Nance et al., 1994; Nance, 1994). In individuals with quadriceps spasticity due to SCI, the test-retest variability is 5 degrees of difference in first swing excursion (FSE; see Data Analysis) values between tests performed 8 weeks apart (Nance et al., 1994).

The Pendulum Test was performed with the subject in a semi-reclined position on a treatment table, with the hip in neutral [180 degrees]. Reflective markers were placed on the weaker lower extremity at the greater trochanter, the lateral knee joint line, and the lateral malleolus. Kinematic data associated with the Pendulum Test was collected at 60 Hz using an 8-camera, 3D motion capture system (Peak Motus[®] Software, Peak Performance, Centennial, CO) in a calibrated test space. The test was performed by an experimenter not otherwise involved in the data analysis (Fowler et al., 2000; Stillman and McMeeken, 1995). The examiner grasped the heel of the test leg to extend the knee, and the leg was dropped.

2.4. Testing protocol

Five Pendulum Tests, with at least 30 seconds of rest between, were performed in each test set. A test set was captured both prior to the start of the 12-session intervention (*initial test*) and following the 12-session intervention (*final test*). This arrangement allowed us to assess the overall influence of the 12-session WBV intervention. Once each week, following a session of

WBV, two test sets were captured: the first test set was captured within five minutes following the vibration session (*immediate post-WBV test*), and the second test set was captured approximately fifteen minutes after the WBV session (*delayed post-WBV test*). This test arrangement allowed us to assess the within-session timecourse of the effects of WBV on quadriceps spasticity. To avoid lower extremity use or weight bearing that might confound the influence of the WBV in the immediate post-session period, following the last vibration bout for that session, the subject sat on a wheeled, padded table that was located next to the WBV platform, and was then wheeled into the 3D motion capture area for the immediate post-WBV test set. During the time between the immediate post-WBV test and the delayed post-WBV test, a support was placed under the subject's legs to maintain the knees in the extended position (limiting passive stretch of the knee extensors) and the subject rested quietly for 10 minutes. After 10 minutes, the testing procedure was repeated for the delayed post-WBV test set.

Following the final WBV session, all subjects returned within 8 days for the final test session. Thirteen of the subjects returned for the final test session within 4 days of the final WBV session and three were tested 6–8 days after the WBV intervention. The data acquired for the subjects tested within 4 days was compared to that of that acquired from subjects tested 6–8 days after the WBV intervention to obtain a sense of the persistence of the effect of the WBV intervention.

2.5. Data analysis

FSE of the weaker leg was the primary outcome measure of interest and an increase in FSE was interpreted as a decrease in spasticity. For each Pendulum Test, we assessed change in the anatomical knee angle (i.e., 0 degrees = full knee extension). FSE was defined as the angle at which the swinging leg first reversed direction from flexion to extension indicating the point in the knee range of motion at which a reflex contraction of the quadriceps caused the knee to extend. The initial and final knee angles associated with the Pendulum Test in one subject are illustrated in Fig. 2 (arrows indicate initial and final FSE values). The number of oscillations (OSC) was determined by graphing the knee joint

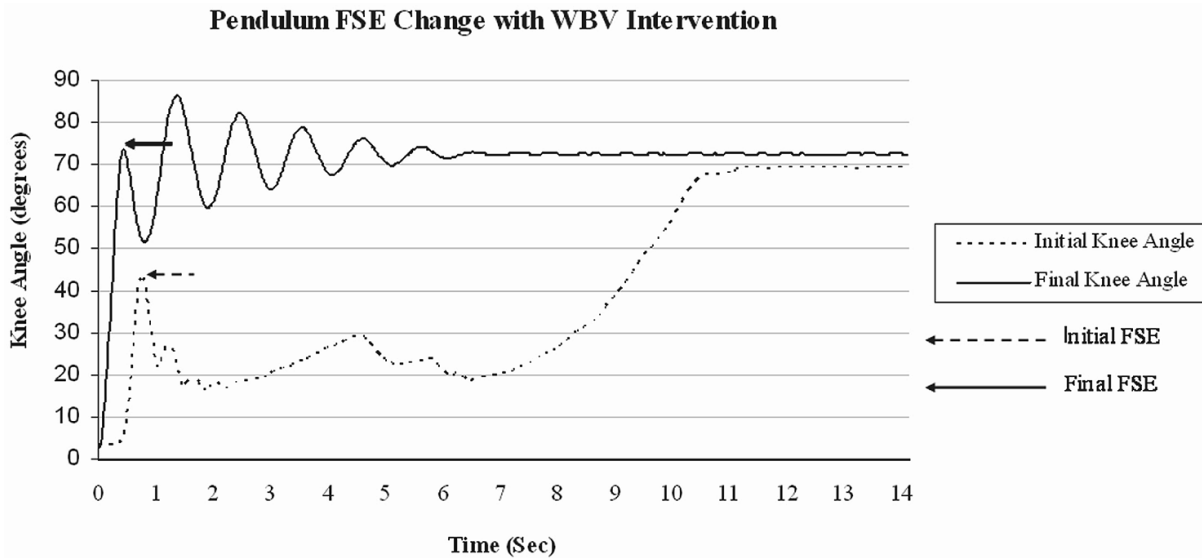


Fig. 2. Changes in quadriceps spasticity in response to a 12-session whole-body vibration (WBV) intervention in an example subject. The first swing excursion (FSE) is marked for the initial (dashed trace) and final tests (solid trace), wherein an increase in FSE suggests a decreased responsiveness to quadriceps stretch (i.e., decreased spasticity).

angle and summing the number of peaks before the leg returned to the resting knee angle. The number of oscillations completed prior to returning to the rest position has been shown to be a useful indicator of whether or not spasticity is present (Fowler et al., 2000), but is not sensitive to differences in amount of spasticity (Boczko and Mumenthaler, 1958; Wartenberg, 1951). Because the usefulness of OSC values to quantify severity of spasticity in individuals with SCI has not previously been determined, we quantified the change in OSC associated with the 12-session intervention of WBV. For each set of five tests, the mean of the five FSE and OSC was calculated and used for all statistical tests.

To classify those subjects likely to obtain maximum benefit from the WBV intervention, the criterion of a FSE increase of greater than 10 degrees (i.e., a change greater than two times the expected FSE measurement variability in this population) was established. To classify those subjects likely to obtain moderate benefit from the WBV intervention the criterion of a FSE increase between 6–10 degrees was established (i.e., a change greater than the expected FSE measurement variability but by less than two times). Finally, to classify those subjects likely to obtain least benefit from WBV, the criteria of an increase in FSE of 5 degrees or less was established (i.e., a change within the range of expected FSE variability). To assess the possible impact of prolonged or repetitive squatting on the measures of interest, data from one subject (subject 7), who

stood in a slight squat for long periods on a Segway Personal Transporter (Bedford, NH) that he used for daily mobility, was considered separately.

2.6. Statistical analysis

Statistical Analysis Software 9.1.3 (Cary, NC) was used for all statistical analyses. One-tailed, paired t-tests were used to compare initial and final FSE values and to compare initial and final OSC values; significance was set at $\alpha = 0.05$. One-tailed, paired t-tests were also used to compare each of the four weekly immediate and delayed post-WBV FSE values; a Bonferroni correction to adjust the alpha level for these five pair-wise comparisons resulted in an adjusted value of $\alpha = 0.01$. A Pearson correlation was used to assess the relationship between the initial FSE value and WBV-related change in FSE value. The pooled standard deviation and Cohen's *d* was used to calculate the effect size of the change in FSE associated with use of the WBV intervention.

To verify that there were no pre-intervention differences in spasticity in subjects who did and those who did not use antispastic agents, a one-tailed, independent sample t-test was used to compare the initial FSE values between the two groups. To determine whether there were differences in responsiveness to WBV between these two groups, a repeated-measures ANOVA was performed to identify any time x group interaction in the initial and final FSE values of those subjects who did and those who did not use antispastic agents.

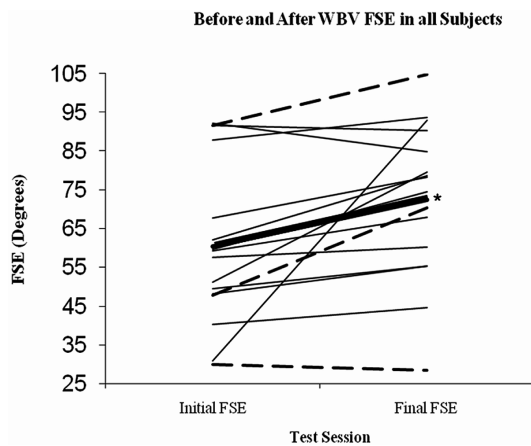


Fig. 3. Change in first swing excursion (FSE) values associated with the 12-session whole-body vibration (WBV) intervention. Change in FSE values for all subjects (thin lines) and group mean change (thick line). Group mean initial (60.42 ± 5.2 degrees) and final FSE values (72.47 ± 5.0 degrees) were significantly different (*), indicating a decreased responsiveness to stretch associated with the intervention. Change in FSE values were similar for those individuals ($n = 3$; dashed lines) for whom the final test as administered 6–8 days after the final WBV session.

3. Results

The 12-session intervention of WBV was found to be associated with a statistically significant increase in FSE from initial to final test (initial FSE = 60.42 ± 5.2 degrees; final FSE = 72.47 ± 5.0 degrees; $p = 0.005$) that was considered a moderate effect size ($d = 0.61$), indicating that there was a reduction of quadriceps spasticity. The initial and final FSE values for each of the subjects is illustrated in Fig. 3. There was not a statistically significant change in OSC ($p = 0.195$). There was a fair, inverse correlation (Portney and Watkins, 2008) between the initial FSE value and the WBV-related change in FSE value ($r = -0.44$) suggesting that those individuals who had a smaller initial FSE value had a greater change in FSE. Seven of the 16 participants met the criterion for maximum benefit from WBV, with a FSE increase exceeding 10 degrees (initial FSE = 58.65 ± 7.11 degrees; final FSE = 82.74 ± 4.53 degrees). Four of the participants met the criterion for moderate benefit with a FSE increase of 6–10 degrees (initial FSE = 61.17 ± 9.25 degrees, final FSE = 68.06 ± 9.02 degrees). Five of the participants met the criterion for least benefit, having an increase in FSE of 5 degrees or less (initial FSE = 62.3 ± 12.86 degrees; final FSE = 61.63 ± 11.73 degrees), suggesting that this group of subjects were not likely to benefit from WBV.

Comparisons of the weekly immediate and delayed post-WBV FSE values identified a significant within-session difference for week 1 ($p = 0.005$), week 2 ($p = 0.006$), and week 4 ($p = 0.006$). This indicates that in the post-vibration period, quadriceps spasticity was lower after a delay of 15 minutes compared to immediately after the vibration. The difference in the FSE for the within-session post-WBV tests for week 3 was not statistically significant ($p = 0.039$). Values of the initial and final FSE, and weekly immediate and delayed post-WBV FSE values are illustrated in Fig. 4.

There was no significant difference between the initial FSE values of subjects who did and those who did not use antispastic agents ($p = 0.198$). There was no significant time \times group interaction between the initial and final FSE values of those subjects who reported daily use of antispastic agents and those who reported no use of antispastic agents ($p = 0.221$), indicating that the effects of WBV in subjects who use antispastic agents are similar to those who do not. The initial and final FSE values for the groups of subjects who did and did not use antispastic agents are illustrated in Fig. 5.

The data from thirteen subjects who had their final test session within 1–4 days of the final intervention session were compared to that of the three subjects who had their final intervention session 6–8 days after the final intervention session. The mean change for each of these was 12.05 ± 4.04 degrees and 11.47 ± 18.31 degrees, respectively (dashed lines in Fig. 3 show FSE values for the latter subjects). The similarities between FSE values suggest that the effects of the WBV intervention persist for at least 6–8 days.

The data from one subject (subject 7), who used a personal transporter for daily mobility and always maintained a slight, standing squat while riding the device, was examined individually. The change in FSE for this subject was 8.73 degrees. This was within the range of the mean change in FSE exhibited by the other subjects (12.05 ± 4.04 degrees), and met the criterion for moderate benefit, suggesting that this subject obtained benefit from WBV above that of standing in a squat posture.

There were no adverse effects associated with participation in the 12-session WBV intervention in any of the subjects. Many subjects indicated they would like to continue with these sessions and would be interested in participating in future studies involving WBV.

4. Discussion

Our results indicate that use of WBV is associated with decreased quadriceps spasticity in individu-

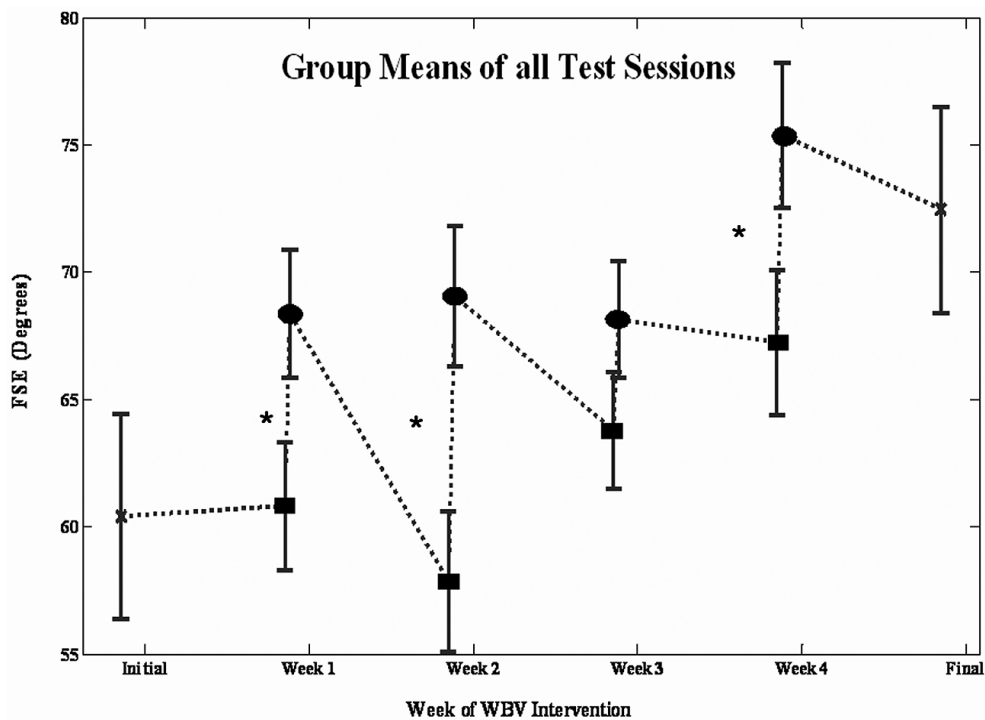


Fig. 4. Within-session comparisons of weekly immediate and delayed post-WBV FSE values for the 12-session intervention. Delayed post-WBV FSE values (circles) were significantly different (as indicated by asterisk [*]) from immediate post-WBV values (squares) and for weeks 1 (7.07 ± 2.39 degrees), 2 (8.73 ± 3.02 degrees), and 4 (8.13 ± 2.87 degrees). The difference for week 3 (4.35 ± 2.29 degrees) was not statistically significant.

als with spastic hypertonia due to SCI, as measured by an increase in the knee angle at which a stretch to the quadriceps first elicits a reflex muscle contraction (i.e., the FSE). While definitive conclusions cannot be drawn from this study which lacked a control group, these results compare favorably with published results of changes in spasticity associated with use of antispastic agents. A mean change in FSE of 11.7 ± 5.3 degrees is reported to be associated with a 7-week course of tizanidine in individuals with SCI (Nance et al., 1994), this change is similar to the mean change of 12.1 ± 5.2 degrees we observed with 4 weeks of WBV. The reduction in quadriceps spasticity we observed in individuals with SCI is consistent with evidence of reduced knee extensor spasticity associated with WBV intervention in individuals with spastic diplegia due to cerebral palsy (Ahlborg et al., 2006).

We identified a fair, inverse correlation between the initial FSE values and WBV-related change in FSE values that suggests that those who have a greater amount of spasticity prior to the WBV intervention experienced the most reduction in spasticity with WBV. Having found this relationship, the data were examined to identify characteristics of subjects who obtained most benefit

versus those who obtained least benefit from the WBV. While there were some trends, no clear differences between groups in terms of subject characteristics were identified. Six of the seven subjects in the group meeting the criterion for most benefit had an initial FSE value of 30–68 degrees. Conversely, two of the five subjects in the group that obtained least benefit had an initial FSE value greater than 90 degrees. Since non-disabled individuals have FSE of approximately 96 degrees (Stillman and McMeeken, 1995) this may suggest that individuals must have reasonable amount of spasticity in order to benefit from the spasticity-reducing effects of WBV. However, the three remaining subjects in the group that obtained least benefit had FSE values that were within the range of those observed in the group obtaining most benefit from the WBV. Other factors that were considered included ASIA lower extremity motor scores, level of injury, chronicity of injury, and age. None of these factors were associated with magnitude of the response to WBV.

In agreement with other studies that have quantified the severity of spasticity (Fowler et al., 2000), we did not observe a significant difference in the number of oscillations of the swinging leg (i.e., the OSC) between

Influence of antispastic agents use on effects of WBV

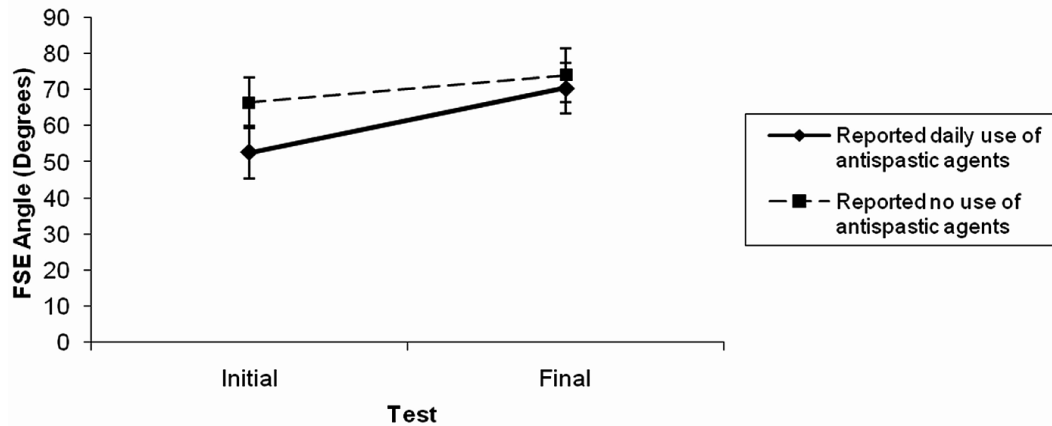


Fig. 5. Influence of antispastic agent use on response to spasticity-reducing effects of whole-body vibration (WBV). There was no difference in the effect of a 12-session WBV intervention in individuals who used antispastic agents and those who did not.

the initial and final tests. The number of swing oscillations has been found to be useful only in distinguishing between non-disabled individuals and clinical populations with spasticity (Fowler et al., 2000). Therefore the OSC appears not to be sufficiently sensitive to detect changes quadriceps spasticity in a sample of individuals with spastic hypertonia due to SCI.

We hypothesized that WBV would be associated with a reduction in quadriceps spasticity immediately following a WBV session and this reduction would decay with time. However, data from weekly test sessions suggests that following a session of WBV the reduction in quadriceps spasticity is greater following a delay of 15 minutes than when tested within 5 minutes following a WBV session (see Fig. 4). Others have reported WBV-related effects that persist following a single session, as improvements in balance have been shown to persist for up to 45 minutes after a session of WBV (van Nes et al., 2004). In individuals with SCI, recent evidence suggests that spasticity has a negative affect on walking performance (Scivoletto et al., 2008). Therefore, our results may suggest that for individuals with SCI in whom spasticity interferes with function or mobility, WBV may be a useful intervention. Further, WBV may be a valuable adjunct to training, a suggestion that should be investigated via studies that combine WBV and training. To determine the time duration of the effects of WBV, future investigators should acquire post-WBV data at later time points to identify the time at which the within-session effects associated with WBV reach a plateau.

Known neurophysiologic mechanisms are likely to underlie the outcomes observed in this study. Vibration is known to elicit both excitatory and inhibitory influences on spinal reflex activity, resulting in a phenomenon called "the vibration paradox." Excitatory influences in the form of a tonic vibration reflex (TVR) give rise to a tonic muscle contraction from activation of muscle spindle afferents in the vibrated muscle. Vibration also activates inhibitory influences, thought to be due to presynaptic inhibition (Eccles et al., 1962; Gillies et al., 1969; Schieppati and Crenna, 1984; Schieppati, 1987) or depletion of neurotransmitter (Ashby et al., 1987; Faist et al., 1994; Hultborn et al., 1996; Katz, 1999; Kohn et al., 1997; Nielsen et al., 1995), that result in a reduction of the excitatory Ia influences on the homonymous motoneuron (Desmedt, 1983). It is possible that the vibration-induced excitatory influences continue for a short time after the WBV, resulting in a transient increase in spasticity (observed in the immediate post-WBV test). Similarly, vibration-induced inhibitory influences may have a delayed onset, resulting in a later within-session reduction in spasticity (observed in the delayed post-WBV test). Theoretically, it would be the long-term persistence of these inhibitory influences that resulted in the overall spasticity-reducing effects of the WBV observed following the 12-week intervention period.

Our data suggests that there was a progressive decrease in spasticity each week of the WBV intervention. Therefore, it is likely that the repetitive use of the afferent stimulus in the form of WBV induces persistent plastic changes in the neural circuits related to spinal

reflex excitability (Field-Fote, 2004). This view is further supported by the decrease in quadriceps spasticity observed in the three individuals in whom the final test session was administered 6–8 days following the last WBV session. The reduction in spasticity was evident up to 6–8 days after the WBV intervention, as the final test values of these individuals was within the range of that obtained for subjects who were tested within four days. Future studies should consider follow-up testing intervals to characterize persistence of the effects of WBV beyond the 8 days examined in our study.

This persistence of the reflex-modulating effects following application of afferent stimulus has been identified in prior studies from our laboratory. In a preliminary study in non-disabled individuals, a single session of WBV resulted in a significant decrease in the Ia-mediated reflex circuit (as measured by the size of the normalized H-reflex amplitude; H/M ratio) (Beekhuizen et al., 2004). Our group has also shown short-term changes in reflex modulation following electrical stimulation in non-disabled individuals (Perez et al., 2003), and following localized tendon vibration in individuals with SCI (Perez et al., 2004). In individuals with chronic, motor-incomplete SCI, localized tendon vibration applied to the tibialis anterior tendon results in improved efficacy of reciprocal inhibition to the soleus muscles. Reflex modulation was greatest 5 minutes after the vibration was removed, and remained depressed relative to pre-vibration values for minutes thereafter (Perez et al., 2004).

We hypothesized that individuals who used antispastic agents would not be as responsive to the spasticity-reducing effects of WBV as those who did not use antispastic agents. We expected that the medication would have reduced spasticity to the maximum extent possible and therefore, that these individuals would experience a smaller relative reduction in quadriceps spasticity. Contrary to our hypothesis, we found that individuals who used antispastic agents experienced similar reductions in quadriceps spasticity as those who did not use such medication. These results are consistent with a prior study demonstrating that localized tendon vibration causes a reduction of the excitatory Ia influences on the homonymous motoneuron even after use of antispastic agents (Nance et al., 1994). In a study of individuals with spastic hypertonia due to chronic SCI who were not previously using antispastic agents, administration of antispastic agents for 3 weeks resulted in an increase in the vibration-induced inhibition of the H-reflex as measured by the vibration inhibition index (i.e., the H-reflex amplitude during vibration

as a proportion of the H-reflex amplitude without vibration) (Nance et al., 1994). These findings suggest that WBV decreases spasticity even in individuals who routinely use antispastic agents. Tizanidine (Nance et al., 1994), baclofen (Nance, 1994), and cyproheptadine (Nance, 1994) have all been associated with improvements in quadriceps spasticity in individuals with SCI. Given that the reduction in spasticity we observed was similar to those reported for individuals with SCI who used tizanidine (Nance et al., 1994) these findings warrant further investigation via a randomized, controlled study to compare interventions of WBV and antispastic medication that may support WBV as an alternative to pharmacological intervention for reducing spasticity.

Tension in the quadriceps muscle due to the slight squat that the subjects maintained during the WBV bouts may activate Ib fibers, which are classically thought to activate a homosynaptic inhibitory circuit. For this reason, we considered the possibility that the squat position, rather than the WBV, was responsible for the reduction in quadriceps spasticity. However, in a subject who habitually stood for hours each day in a semi-squat position while riding a personal transporter, the results of WBV were similar to those of subjects who habitually sat in a wheelchair for mobility. This suggests that the effects observed are not likely due to the influence of squatting alone (in the absence of WBV). Our results are consistent with evidence in subjects with stroke in whom more normal motor output was observed in subjects that received WBV, which were not observed in control subjects who only performed a static squat (Tihanyi et al., 2007). However, while individuals with stroke and the subject in our study who used the personal transporter were community ambulators, the majority of our subjects primarily used a wheelchair. Because results associated with WBV may differ depending on the level of walking function, future studies should consider comparing WBV to static, squatting alone in individuals who use a wheelchair as their primary means of mobility.

5. Implications for function

These results support the use of WBV as an intervention to decrease quadriceps spasticity in individuals with SCI. With a 12-session intervention of WBV, we found significant decreases in quadriceps spasticity. In individuals in whom spasticity interferes with function, WBV may represent an approach to decreasing spasticity. Furthermore, the effect of vibration on spasticity

persists for several days, suggesting that WBV may be useful prior to motor rehabilitation interventions to enhance the effects of training. Future studies should investigate whether WBV could be an effective substitute for antispastic agents in some individuals.

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