Single-dose effects of whole body vibration on quadriceps strength in individuals with motor-incomplete spinal cord injury

Rick Bosveld¹, Edelle C. Field-Fote^{2,3}

¹Department of Biomedical Engineering, University of Twente, Enschede, Netherlands, ²Shepherd Center – Crawford Research Institute, Atlanta, GA, USA, ³The Miami Project to Cure Paralysis, University of Miami Miller School of Medicine, Miami, FL, USA

Context: Paresis associated with motor-incomplete spinal cord injury (SCI) impairs function. Whole body vibration (WBV) may increase strength by activating neuromuscular circuits.

Objective: We assessed effects of a single session of WBV on lower extremity strength in individuals with motor-incomplete SCI.

Design: A single-session blinded randomized controlled trial.

Setting: Rehabilitation research laboratory.

Participants: Subjects ($n = 25$; age 49.7 ± 12.5 years) had chronic SCI (>1 year) and were able to stand for at least 45 seconds.

Interventions: Subjects were randomized either to WBV ($n = 13$) consisting of four 45-second bouts with 1-minute intervening rest periods (frequency: 50 Hz, amplitude: 2 mm) or to sham electrical stimulation ($n = 12$).

Outcome measures: Maximal voluntary isometric quadriceps force was measured with a fixed dynamometer. A modified Five-Time-Sit-To-Stand (FTSTS) test was used to assess functional lower extremity strength. Measures were made at pre-test, immediate post-test, and delayed post-test 20 minutes later.

Results: At immediate post-test, change in voluntary isometric force in the WBV group was 1.12 kg greater than in the sham group. The within-group change for the WBV group was significant with a moderate effect size ($P = 0.05$; $ES = 0.60$). No force-related changes were observed in the sham group. The modified FTSTS scores improved in both groups, suggesting that this measure was subject to practice effects.

Conclusion: Evidence from the present study suggests that even a single session of WBV is associated with a meaningful short-term increase in quadriceps force-generating capacity in persons with motor-incomplete SCI. The multi-session use of WBV as part of a strengthening program deserves exploration.

Keywords: Lower extremity, Rehabilitation, Spinal cord injuries, Strength, Vibration

Introduction

Individuals with spinal cord injury (SCI) commonly have impaired lower extremity strength, resulting from damage to descending spinal pathways that innervate the lower motor neurons in the spinal cord. Loss of this descending control impairs voluntary motor activation and function of the muscles below the level of injury. Previous research has shown that lower extremity strength is an important predictor of walking function in individuals with motor-incomplete SCI.^{1–3} Therefore,

an important part of rehabilitation for individuals with motor-incomplete SCI should focus on the improvement of lower extremity strength.⁴

Conventional strength exercises are often difficult for individuals with SCI to perform, due to their physical limitations and the limited availability of adapted equipment. Whole body vibration (WBV) stimulation could offer an approach to strength training that is physically less demanding than conventional strength training. The vibratory stimulation an individual receives while standing on a WBV platform evokes reflex contractions of the lower extremity muscles, presumably by activating the type Ia sensory fibers.⁵ These sensory fibers are highly

Correspondence to: Edelle Carmen Field-Fote, Director of Spinal Cord Injury Research, Shepherd Center–Crawford Research Institute, 2020 Peachtree Rd NW, Atlanta, GA 30309. E-mail: edelle_field-fote@shepherd.org

sensitive to changes in length of the muscle, and standing on the WBV platform evokes repeated rapid, small-amplitude stretch to the muscles of the lower extremity. The evoked reflex contractions are thought to augment the voluntary drive to the motor units that comes from voluntary effort, and thereby increase the excitability of the muscles. For this reason strengthening protocols involving WBV stimulation incorporate some form of active muscle contraction, be it concentric, eccentric or isometric in nature.⁶⁻⁸

In healthy individuals and in individuals with neurological impairments, WBV stimulation has shown to increase lower extremity strength. Rehn *et al.*⁹ conclude in their systematic review on the effects of WBV stimulation on lower extremity strength in healthy individuals that older and untrained individuals benefit the most from WBV stimulation. They showed that there is moderate to strong evidence that long-term WBV stimulation (more than 10 sessions) increases lower extremity strength and moderate evidence that a single session of WBV stimulation increases lower extremity strength. In a systematic review of the effects of WBV stimulation in individuals with multiple sclerosis, Parkinson's disease, cerebral palsy and stroke, Del Pozo-Cruz *et al.*¹⁰ concluded that there is some evidence of increased lower extremity strength due to long-term WBV stimulation.

Beyond the effects on strength that have been observed with multisession WBV interventions, there are studies that have assessed the impact of a single session of WBV stimulation. Jackson *et al.*¹¹ showed an increase in isometric quadriceps and hamstring muscle strength in individuals with multiple sclerosis. In this study, subjects stood on the WBV platform for 30 seconds with a vibration amplitude of 6 mm and vibration frequency of 26 Hz. In individuals with stroke who received a single session of WBV stimulation consisting of six 60-second bouts with a vibration amplitude of 5 mm and frequency of 20, Tihanyi *et al.*¹² found an increase of 36.6% in isometric quadriceps strength. These results suggest that even a single session of WBV can have a meaningful effect on lower extremity strength.

Despite encouraging evidence for the value of WBV stimulation for improving lower extremity strength in neurological populations, no studies have assessed the effects of WBV stimulation on lower extremity strength in individuals with SCI. To determine whether WBV stimulation has potential to increase lower extremity strength in persons with motor-incomplete SCI, we investigated the effects of a single session of WBV stimulation on isometric strength and functional strength of

the quadriceps muscles. Based on prior evidence we hypothesized that a single session of WBV would be associated with a greater change in quadriceps strength compared to sham stimulation.

Methods

Subjects and setting

All subjects were recruited from the Miami Project To Cure Paralysis research volunteer registry. Inclusion criteria were chronic (>1 year post injury) motor-incomplete SCI (American Spinal Injury Association Impairment Scale classification C or D).¹³ To be included subjects were required to have a score of at least 16/40 on the SCIM II mobility subscale,¹⁴ and the ability to stand with minimal assistance for at least 45 seconds. The study was performed at the Miami Project to Cure Paralysis, University of Miami Miller School of Medicine. All subjects provided verbal and written informed consent before participating in the study, which was approved by the Human Subjects Research Office of the University of Miami.

Study design

A blinded randomized sham-controlled trial was used to investigate the effects of a single session of WBV stimulation on quadriceps strength. Subjects were randomly assigned to either the WBV group or a sham stimulation group. A random number generator was used to create the randomization order. The random allocation sequence was stored in sealed numbered envelopes by a member of the laboratory staff who was not otherwise involved in the study, and subjects were allocated to group by another member of the laboratory staff. Both subjects allocated to the WBV group, and those allocated to the sham stimulation group received a single session of the respective intervention. Testing was performed before (pre-test), immediately after (immediate post-test) and 20 minutes after (delayed post-test) the intervention. All tests were performed by the same examiner who was blinded to the subjects' group allocation.

Interventions

WBV stimulation: The single session of WBV stimulation (Power Plate; Northbrook, IL, USA) consisted of four 45-second bouts of vibration (primarily vertical) with a frequency of 50 Hz and amplitude on the high-amplitude setting (unloaded peak-to-peak amplitude of approximately 2 mm) with 1 minute of seated rest between bouts. If subjects perceived the high-amplitude setting to be too intense (one subject), the amplitude was changed to the low-amplitude setting (unloaded peak-

to-peak amplitude ≈ 1 mm). Subjects stood on the WBV platform in a slight squat position (≈ 30 degrees of hip and knee flexion) during each bout of vibration. This protocol is based on a protocol that has previously been used in our lab and others.^{15–18}

Sham stimulation: The sham stimulation protocol was included in the study to control for effects of simply standing on the WBV platform, which may potentially drive neural activation in a population for whom standing is not a habitual activity. During the sham stimulation, subjects stood on the WBV platform in the same posture and for the same duration/intervals as those in the WBV stimulation but with the vibration turned off. The sham stimulation intervention was performed by placing stimulating electrodes on the medial and lateral tibial plateaus of each leg. The stimulation intensity was turned on and intensity increased until the subject indicated he/she could feel the electrical stimulation. Subjects were instructed that the stimulation would remain ‘on’ but the intensity would be reduced to below the sensory threshold. In fact the stimulation was turned ‘off’. While prior studies have suggested that there is no influence of electrical stimulation when intensity is below sensory threshold,^{19,20} we were concerned that in the presence of SCI the lesion may have impaired transmission to the supraspinal centers and prevented the subject from feeling the stimulation but there still may be an effect of the stimulation at the spinal level. As with the WBV stimulation intervention, the sham stimulation intervention included four 45-second standing bouts with one minute of seated rest between bouts.

Outcome measures

Maximal voluntary isometric quadriceps force was assessed using a dynamometer mounted to a fixed frame; this has been shown to be a reliable method to measure maximal voluntary isometric force.^{21,22} During the strength test the subjects were seated facing the dynamometer on a padded table with a backrest. Both the knee and hip angle of the subject were positioned at 90 degrees with the pelvis in neutral position. The thighs and upper body were stabilized with straps. The test leg of the subject was placed in contact with the padded dynamometer just proximal to the level of the malleoli. The subjects were asked to maintain their arms crossed in front of their chest. To familiarize the subjects with the procedure, the subject was instructed to perform the isometric knee extension movement one time with sub-maximal force. Subjects were then asked to extend the knee of the test leg and exert maximal force against the dynamometer. This

procedure was repeated three times for each leg. Values for the left and right leg were summed to obtain a composite score. The average of the three trials was used for analysis.

A modified version of the Five Times Sit-To-Stand (FTSTS) test was used to assess functional lower extremity muscle strength. The FTSTS test has been used and validated to measure lower extremity muscle strength in different populations.^{23–26} While the FTSTS test has been validated for use in individuals with SCI,²⁶ the individuals with SCI for whom the test was validated were community ambulators. Conversely, many subjects in our study used a wheelchair as their primary means of mobility, and in pilot testing only a few were able to perform the standard FTSTS test. For this reason we used a modified version of the FTSTS test wherein the sitting platform was elevated to a normalized height. During the modified FTSTS test subjects were seated on a padded table with the table height adjusted to 85% of their lower extremity length, measured from the malleolus to the greater trochanter. This approach was derived from pilot testing wherein it was determined that this was the minimum height of the sitting platform from which the majority of subjects were able to perform the sit-to-stand maneuver without resorting to use of the upper extremities for assistance. Subjects were instructed to cross their arms in front of their chest and place their feet comfortably underneath them. The sit-to-stand maneuver was performed once, for familiarization purposes, before testing. Subjects were then asked to stand up and sit down five times as fast as possible. An assistant stood nearby to provide balance support if needed in order to provide a safe environment and ensure subject confidence. The outcome value of interest was the time required to complete this modified FTSTS test.

Statistical analysis

Baseline equivalence of age, time post injury, and baseline values of quadriceps strength and modified FTSTS were evaluated using unpaired *t*-tests. To determine whether the modified FTSTS test could be used as a measure of quadriceps strength, Pearson correlation coefficients were calculated to assess the relationships between maximal voluntary isometric quadriceps force (measured with the fixed dynamometer) and functional lower extremity strength (measured with the modified FTSTS test), and the relationship between baseline force and change in force. To investigate the differences in effects of the WBV stimulation and sham stimulation a general linear mixed model was used on both outcome

measures. The fixed effects were group (WBV versus Sham) and time (pre-test, post-test, and delayed post-test). The means and standard errors of the outcome measures were calculated from the linear mixed model parameters and were adjusted for effects of all variables in the model and sample sizes. Contrasts were used to make planned comparisons between groups at each time and among times within group. For this single-session study, analyses wherein $P \leq 0.05$ were considered to have achieved statistical significance, and analyses wherein $P > 0.05$ but ≤ 0.10 (i.e. 10% or less probability of having occurred by chance) were considered to have approached statistical significance. Effect sizes were based on the absolute value of the difference in means divided by the pooled standard deviation. An effect size of 0.20 was considered a small effect, an effect size of 0.50 a moderate effect and an effect size of 0.80 a large effect.²⁷ SAS 9.3 statistical software (SAS Institute, Inc., Cary, NC, USA) was used for all analyses.

Results

Subjects

Twenty-five subjects (20 males) with chronic motor-incomplete SCI participated in the study. An overview of the demographics of the subjects is shown in Table 1. A flow diagram of subject recruitment, randomization and participation is shown in Figure 1.

One participant (subject 3) was withdrawn due to inability to complete the four bouts of standing on the vibrating platform. In one instance a participant (subject 19) was not able to tolerate the high-amplitude vibration, and therefore low-amplitude vibration setting was used in this case. The group demographics at baseline were equivalent in term of mean [SD] age (WBV: 51.0 [12.1] years, sham: 48.3 [13.3] years; $P = 0.59$), and time post injury (WBV: 11.2 [9.8] years; sham: 9.9 [7.4] years; $P = 0.72$). The groups also demonstrated baseline equivalence for initial mean (SE) values of quadriceps strength (WBV: 18.46 [2.4] kg, sham: 18.43 [2.4] kg; $P = 0.97$) and time to complete the modified FTSTS (WBV: 15.26 [1.45] sec, sham: 16.50 [1.46] sec; $P = 0.18$). Despite the equivalence of the groups at baseline, within groups was a large range in the quadriceps force-generating capacity (WBV group range = 12.6–38.4 kg; sham group range = 3.5–51.4 kg).

Concurrent validity of the modified FTSTS test

Moderate correlations between maximal voluntary isometric quadriceps force and modified FTSTS test scores were shown for the pre-test scores ($r = -0.59$, $P < 0.01$), the immediate post-test scores ($r = -0.51$, $P = 0.01$) and the delayed post-test scores ($r = -0.52$, $P < 0.01$). These correlation values support the concurrent validity of the modified FTSTS as a functional measure of strength.

Table 1 Demographics of subjects

Group	Subject	Sex	Age (years)	Level of injury	Years Post injury
WBV	1	M	61	T4	28
Sham	2	M	27	T2	7
WBV	3	F	60	C5	12
WBV	4	M	48	T6	9
Sham	5	M	36	C6	19
WBV	6	M	56	C5	9
Sham	7	F	69	T4	11
Sham	8	M	61	T7	8
Sham	9	M	50	T12	16
WBV	10	M	45	T12	5
Sham	11	M	57	C3	24
Sham	12	M	49	C2	1
WBV	13	M	59	C4	5
Sham	14	M	29	C5	10
WBV	15	M	65	C2	2
Sham	16	M	61	C5	5
Sham	17	M	37	T9	1
Sham	18	F	51	C6	15
WBV	19	M	55	C4	35
WBV	20	M	57	C7	2
WBV	21	M	33	C1	7
Sham	22	M	52	C4	2
WBV	23	M	34	C5	7
WBV	24	M	61	C5	12
WBV	25	F	29	T10	12

Figure 1 CONSORT diagram summarizing numbers of subjects recruited and randomized to each of the two study arms.

Effects of WBV and sham stimulation on composite maximal isometric quadriceps strength

For the composite maximal isometric quadriceps strength measure, the difference in mean ($\pm$ se) change between pre-test and immediate post-test for the WBV group and the sham group was 1.41 ± 3.3 and 0.29 ± 3.3 kg, respectively. This between-groups difference approached significance ($P = 0.10$). The between-groups difference in mean change between pre-test and delayed post-test was not significant ($P = 0.82$) (Fig. 2).

Within the WBV group, the difference in maximal isometric quadriceps strength was significant for the pre-test versus immediate post-test comparison ($P = 0.05$) with a moderate effect size ($ES = 0.6$), but this effect did not persist to the time of the delayed post-test ($P = 0.28$). There were no within-group changes in the sham group (for comparison of pre-test to immediate and delayed post-test, $P = 0.68$ and 0.40 , respectively); all effect sizes were small. No correlations were found between baseline strength and change in strength measured at the immediate post-test for either the WBV group ($r = 0.16$, $P = 0.64$) or the sham group ($r = -0.13$, $P = 0.68$; Fig. 3).

Effects of WBV and sham stimulation on modified FTSTS

For the functional lower extremity strength measure, the difference in mean ($\pm$ se) change between pre-test and immediate posttest for the WBV group and the sham group was -1.74 ± 2.1 sec and -1.48 ± 2.1 sec, respectively; this time difference between groups approached

significance ($P = 0.10$). The between-groups difference in mean change between pre-test and delayed post-test was not significant ($P = 0.32$; Fig. 4).

Within the WBV group, the difference in time to complete the modified FTSTS approached significance with

Figure 2 Effects over time of WBV stimulation and sham stimulation on maximal voluntary isometric quadriceps force. Means $\pm$ SE are shown. The asterisk (*) indicates the between-groups difference at the time of post-test approached significance ($P = 0.10$), the within-group change in the WBV group was significant ($P = 0.05$).

Figure 3 Change in force was not associated with baseline force for either the WBV (●) or the sham (+) group. The correlation between baseline maximal quadriceps force and change in force measured at the immediate post-test for the WBV group ($r = 0.16$, $P = 0.64$) and the sham group ($r = -0.13$, $P = 0.68$) is illustrated.

moderate effect sizes for the comparison between pre-test versus immediate post-test ($P = 0.06$; $ES = 0.56$) and between pre-test versus delayed post-test ($P = 0.07$; $ES = 0.53$). The comparison of pre-test to delayed post-test was significant in this group, with a

Figure 4 Effects over time of WBV stimulation and sham stimulation on functional lower extremity strength. Means $\pm$ SE are shown.

moderate effect size ($P = 0.04$; $ES = 0.63$), while the comparison of pre-test to immediate post-test was not significant and had a small effect size ($P = 0.12$, $ES = 0.48$). However, these differences may indicate practice effects as the results for the sham group were similar.

Discussion

To our knowledge, this study is the first to investigate the effects of a single session of WBV on quadriceps strength in individuals with other motor-incomplete SCI. Prior investigators have identified single-session effects on strength-related measures in persons with other neurological deficits.^{11,12} Given that persons with motor-incomplete SCI have significant impairments of muscle strength, which has a negative impact on performance of motor behaviors, even small improvements in strength may be of value.

Our results indicate that the composite measure of quadriceps force was stable, as there was no change in this measure in the sham group. However, the measure of functional lower extremity strength (FSTST) appears to be susceptible to practice effects, as the sham group improved in this measure between the first performance (pre-test) and the third performance (delayed post-test) of this assessment. For this reason the discussion will focus on composite maximal voluntary isometric quadriceps force. Despite the apparent influence of practice effects on the modified FTSTS test, the correlation between this measure and the maximal voluntary isometric force measures acquired using the dynamometer was strong, suggesting that the modified FTSTS is a reasonable measure of functional strength for persons with motor-incomplete SCI who have limited walking function. The finding that there was no correlation between baseline measures of maximal isometric force and change in force indicates that participants experienced improvement in quadriceps strength regardless of degree of strength impairment.

The effects of a single session of WBV stimulation have been investigated in other neurological populations. Tihanyi *et al.*¹² found a significant difference between the effects of a single session of WBV stimulation and the effects of a sham stimulation (standing on platform without vibration) on maximal voluntary isometric quadriceps torque of the affected leg in individuals with stroke measured immediately after the intervention. While Jackson *et al.*¹¹ did not find a significant increase in maximal voluntary isometric quadriceps torque and hamstring torque immediately after a single session of WBV stimulation in individuals with MS, they did find torque values that were consistently higher until 20 minutes after WBV stimulation. In

both the study of Tihanyi *et al.*¹² and Jackson *et al.*¹¹, subjects were higher functioning than the subjects in the present study. Because WBV stimulation is thought to increase lower strength via mechanisms of neural adaptation,⁸ a reduced effect of WBV stimulation may be due to more severe neurological impairment in our study sample.

The parameters of the WBV stimulation protocol could also have influenced the outcomes of our study. The single session of WBV stimulation of the present study consisted of four 45-second bouts (frequency: 50 Hz, amplitude: 2 mm or 1 mm) with one minute rest between bouts, this protocol has been shown to increase lower extremity strength in trained and untrained healthy adults.²⁸ WBV stimulation protocols with high frequency and low amplitude vibration have been associated with muscle fatigue and consequently a decrease in power output.^{29,30} This could explain the large inter-subject variability between the effects of the single session of WBV stimulation observed in the present study. Indeed some subjects reported that they perceived the WBV stimulation as fatiguing. In the study of Tihanyi *et al.*¹² the WBV stimulation protocol consisted of six 1-minute bouts (frequency: 20 Hz, amplitude: 5 mm) with 2-minute rest periods between bouts. This protocol might have resulted in less fatigue and consequently a larger increase of maximal voluntary isometric quadriceps force in individuals with motor-incomplete SCI.²⁹ Jackson *et al.*¹¹ used a WBV stimulation protocol consisting of one 30-second bout of WBV stimulation (frequency: 26 Hz, amplitude: 6 mm). One 30-second bout might not have been sufficient WBV stimulation to significantly increase maximal voluntary isometric quadriceps and hamstrings torques. Therefore, it seems that finding the optimal vibration amplitude, frequency and duration for each individual may be important to fully exploit the potential of WBV stimulation.

Practical implications

The results from the present study indicate that a single session of WBV stimulation increased quadriceps strength in individuals with motor-incomplete SCI but the increase only approached significance compared to a sham stimulation. However, large inter-subject variability between the effects of the single session of WBV stimulation was observed. On that account, a single session of WBV stimulation might have a beneficial effect on quadriceps strength for some individuals with motor-incomplete SCI. The minimal clinically important difference for changes in quadricep strength or sit-to-stand testing has not been defined. However,

based on our results, there may be value in the use of WBV as part of a strengthening program. Alternatively, given that WBV stimulation serves to condition the spinal circuits, it may represent a means of priming these circuits in preparation for training-related effects associated with, for example, locomotor training.

Limitations

The sample size of this study was modest and there was considerable variability among subjects in terms of baseline functioning. It is possible that these factors limited our ability to identify significant between-group effects of WBV using this parallel-group design. Likewise, while we identified no correlation between baseline values of quadriceps strength and the amount of change in strength, it is possible that such a relationship may be observed with a larger sample. Finally, we assessed the outcomes associated with a single session of WBV that was delivered at a pre-specified frequency, amplitude, and exposure duration; no conclusions can be drawn regarding whether these parameters were optimal.

Conclusion

In individuals with motor-incomplete SCI, a single session of WBV stimulation was associated with larger effect on maximal quadriceps force compared to sham stimulation. However, these improvements in strength did not generalize to performance of a functional task for which quadriceps activity is required. The results of this study provide preliminary evidence for the value of WBV to improve strength in this population, but more work is needed to assess the influence of other protocols, including multi-session interventions.

Disclaimer statements

Contributors We thank Kris Arheart, PhD, for assistance with statistical methods and analyses.

Conflicts of interest The authors declare no conflicts of interest.

Ethics approval The protocol was approved by the Human Subjects Research Office of the University of Miami Miller School of Medicine, and conforms to the guidelines of the Helsinki Declaration of 1975, as revised in 2000.

Funding This study was supported by The Miami Project to Cure Paralysis.

References

- 1 Kim CM, Eng JJ, Whittaker MW. Level walking and ambulatory capacity in persons with incomplete spinal cord injury: relationship with muscle strength. *Spinal Cord* 2004;42(3):156–62.

- 2 Waters RL, Yakura JS, Adkins R, Barnes G. Determinants of gait performance following spinal cord injury. *Arch Phys Med Rehabil* 1989;70(12):811–8.
- 3 Crozier KS, Cheng LL, Graziani V, Zorn G, Herbison G, Ditunno JF, Jr. Spinal cord injury: prognosis for ambulation based on quadriceps recovery. *Paraplegia* 1992;30(11):762–7.
- 4 Ditunno PL, Patrick M, Stineman M, Ditunno JF. Who wants to walk? Preferences for recovery after SCI: a longitudinal and cross-sectional study. *Spinal Cord* 2008;46(7):500–6.
- 5 Ritzmann R, Kramer A, Gruber M, Gollhofer A, Taube W. EMG activity during whole body vibration: motion artifacts or stretch reflexes? *Eur J Appl Physiol* 2010;110(1):143–51.
- 6 Eklund G, Hagbarth KE. Normal variability of tonic vibration reflexes in man. *Exp Neurol* 1966;16(1):80–92.
- 7 Ronnestad BR, Ellefsen S. The effects of adding different whole-body vibration frequencies to preconditioning exercise on subsequent sprint performance. *J Strength Cond Res* 2011;25(12):3306–10.
- 8 Rittweger J, Mutschelknauss M, Felsenberg D. Acute changes in neuromuscular excitability after exhaustive whole body vibration exercise as compared to exhaustion by squatting exercise. *Clin Physiol Funct Imaging* 2003;23(2):81–6.
- 9 Rehn B, Lidstrom J, Skoglund J, Lindstrom B. Effects on leg muscular performance from whole-body vibration exercise: a systematic review. *Scand J Med Sci Sports* 2007;17(1):2–11.
- 10 Pozo-Cruz B, Adsuar JC, Parraca JA, Pozo-Cruz J, Olivares PR, Gusi N. Using whole-body vibration training in patients affected with common neurological diseases: a systematic literature review. *J Altern Complement Med* 2012;18(1):29–41.
- 11 Jackson KJ, Merriman HL, Vanderburgh PM, Braehler CJ. Acute effects of whole-body vibration on lower extremity muscle performance in persons with multiple sclerosis. *J Neurol Phys Ther* 2008;32(4):171–6.
- 12 Tihanyi TK, Horvath M, Fazekas G, Hortobagyi T, Tihanyi J. One session of whole body vibration increases voluntary muscle strength transiently in patients with stroke. *Clin Rehabil* 2007;21(9):782–93.
- 13 Kirshblum SC, Waring W, Biering-Sørensen F, Burns SP, Johansen M, Schmidt-Read M, *et al*. Reference for the 2011 revision of the International Standards for Neurological Classification of Spinal Cord Injury. *J Spinal Cord Med* 2011;34(6):547–54.
- 14 Catz A, Itzkovich M, Steinberg F, Philo O, Ring H, Ronen J, *et al*. The Catz-Itzkovich. SCIM: a revised version of the Spinal Cord Independence Measure. *Disabil Rehabil* 2001;23(6):263–8.
- 15 Ness LL, Field-Fote EC. Whole-body vibration improves walking function in individuals with spinal cord injury: a pilot study. *Gait Posture* 2009;30(4):436–40.
- 16 Ness LL, Field-Fote EC. Effect of whole-body vibration on quadriceps spasticity in individuals with spastic hypertonia due to spinal cord injury. *Restor Neurol Neurosci* 2009;27(6):621–31.
- 17 van Nes IJ, Geurts AC, Hendricks HT, Duysens J. Short-term effects of whole-body vibration on postural control in unilateral chronic stroke patients: preliminary evidence. *Am J Phys Med Rehabil* 2004;83(11):867–73.
- 18 van Nes IJ, Latour H, Schils F, Meijer R, van Kuijk A, Geurts AC. Long-term effects of 6-week whole-body vibration on balance recovery and activities of daily living in the postacute phase of stroke: a randomized, controlled trial. *Stroke* 2006;37(9):2331–5.
- 19 Conforto AB, Kaelin-Lang A, Cohen LG. Increase in hand muscle strength of stroke patients after somatosensory stimulation. *Ann Neurol* 2002;51(1):122–5.
- 20 Conforto AB, Cohen LG, dos Santos RL, Scaff M, Marie SK. Effects of somatosensory stimulation on motor function in chronic cortico-subcortical strokes. *J Neurol* 2007;254(3):333–9.
- 21 Bohannon RW. Test-retest reliability of hand-held dynamometry during a single session of strength assessment. *Phys Ther* 1986;66(2):206–9.
- 22 Ford-Smith CD, Wyman JF, Elswick RK, Jr, Fernandez T. Reliability of stationary dynamometer muscle strength testing in community-dwelling older adults. *Arch Phys Med Rehabil* 2001;82(8):1128–32.
- 23 Bohannon RW. Alternatives for measuring knee extension strength of the elderly at home. *Clin Rehabil* 1998;12(5):434–40.
- 24 Bohannon RW. Muscle strength and muscle training after stroke. *J Rehabil Med* 2007;39(1):14–20.
- 25 Ng S. Balance ability, not muscle strength and exercise endurance, determines the performance of hemiparetic subjects on the timed-sit-to-stand test. *Am J Phys Med Rehabil* 2010;89(6):497–504.
- 26 Poncumhak P, Saengsuwan J, Kamruecha W, Amatachaya S. Reliability and validity of three functional tests in ambulatory patients with spinal cord injury. *Spinal Cord* 2013;51(3):214–7.
- 27 Cohen J. Statistical power analysis for behavioral sciences. Hillsdale: Erlbaum; 1987. p. 40.
- 28 Ronnestad BR. Acute effects of various whole-body vibration frequencies on lower-body power in trained and untrained subjects. *J Strength Cond Res* 2009;23(4):1309–15.
- 29 Cardinale M, Lim J. The acute effects of two different whole body vibration frequencies on vertical jump performance. *Med Sport* 2003;56:287–92.
- 30 Rittweger J, Beller G, Felsenberg D. Acute physiological effects of exhaustive whole-body vibration exercise in man. *Clin Physiol* 2000;20(2):134–42.