Cover

November 20, 2014

Title:

Effect of balance exercise in combination with whole-body vibration on muscle activity of the stepping limb during a forward fall in older women: a randomized controlled pilot study

Short title:

Effect of whole-body vibration on the balance recovery step

Akira Ochi [a, b)], Tomokazu Abe [a)], Kazumasa Yamada [a)], Satoko Ibuki [b)], Hiroshige Tateuchi [b)], Noriaki Ichihashi [b)]

[a]Division of Physical Therapy, Faculty of Care and Rehabilitation, Seijoh University: 2-172 Fukinodai, Toukai-City, Aichi 476-8588, Japan

[b]Department of Physical Therapy, Human Health Sciences, Graduate School of Medicine, Kyoto University: 53, Kawahara-cho, Shogoin, Sakyo-ku, Kyoto 606-8507, Japan

Corresponding Author

Akira Ochi

Tel: +81-52-601-6986 (direct line)

Fax: +81-52-601-6245

Email: ochi@seijoh-u.ac.jp

Highlights

- The effects of balance training on the ability to regain balance were examined.
- The effect of whole-body vibration (WBV) added to standard balance exercise was examined.
- Older women participated in balance exercise and WBV for 12 weeks.
- Balance exercise improved step length, and adding WBV increased step velocity.
- Step performance changes manifested as increased EMG activity in the stepping leg.

Key words: Balance recovery, Electromyography, Whole-body vibration, Training, Older women, Tether-release

Abbreviations: BF, biceps femoris; BW, body weight; EMG, electromyography; GC, lateral head of the gastrocnemius; ICC, intra-class correlation; MVC, maximal voluntary contraction; RF, rectus femoris; STE, standard balance exercise group; TA, tibialis anterior; TUG, timed up-and-go; VAS, vastus lateralis; WBV, whole body vibration

1. Introduction

Falls can result in serious injuries, leading to bone fractures and, in some cases, long-term disability. Most falls occur while walking on an even surface, followed by transfers while rising from a chair or while climbing stairs. Falls on an even surface are caused by an unexpected loss of balance such as slipping, tripping, or stumbling (Roudsari et al., 2005). After an unexpected loss of balance, the immediate response is to take a step to recover balance and avoid falling. One experimental approach to examine the ability to recover balance after a forward fall is the tether-release method (Hsiao-Wecksler, 2000), in which the participant is required to recover balance from a supported, forward-leaning posture after a sudden release of the cable providing the support. Earlier studies using this method showed that older women had poor stability performance, shorter step length, and slower step speed after unexpected disturbances compared with young people and older men (Wojcik et al., 1999; Wojcik et al., 2001). In addition, older women with poor stability performance also had lower hip extension strength and produced less knee and ankle joint peak power during stepping (Carty et al., 2012). These results suggest that exercise interventions for older women need to target improvements in step performance, such as step length and step velocity, and lower limb muscle strength, power, and coordination, all of which are essential to improve stability performance in older women. Indeed, stepping behavior during a forward loss of balance and physiological profile assessment results were found to be independent predictors of a future fall in elderly individuals; hence, it can be assumed that exercise interventions designed to improve stepping behavior may protect against future falls (Carty et al., 2014).

A few studies have demonstrated that training in a laboratory using an unpredictable perturbation, such as a waist pull or altered base of support, improved compensatory stepping reaction for balance recovery in the elderly (Rogers et al., 2003; Mansfield et al., 2010; Grabiner et al., 2012). However, it is unclear whether training to improve a specific disturbance problem will help an individual avoid all potential falls in daily life. Therefore, more general training is recommended to improve stability performance and decrease falls in elderly individuals. Arampatzis et al. (2011) and Aragao et al. (2011) demonstrated that exercise for dynamic stability control and trampoline exercise in the elderly improved stability performance using the tether-release method (i.e., the participants were able to better recover balance from a more forward-leaning posture after the training). Because it improved step velocity and hip moment generation, the authors suggested that reinforcement of dynamic stability was caused by neuromuscular coordination upgraded to create a joint moment in the appropriate time element. However, these intervention studies used the stability performance index focusing on kinematic measurements, and no study to date has investigated changes in electromyography (EMG) activity, which serves as a neuromuscular parameter. Improvement of stability performance during balance recovery is also thought to be correlated with changes in lower-limb EMG activity, as individuals with poor stability performance counterparts recruit a lower proportion of the available motor unit pool during balance recovery compared to those with good stability performance (Cronin et al., 2013).

The age-related loss of strength, power, and functional strength is termed as dynapenia (Clark and Manini, 2008), and has a negative influence on physical performance, which increases the risk of falling. Strength, power, and functional strength training are the most effective intervention methods for elderly individuals who have dynapenia. In recent years, whole-body vibration (WBV) has been the focus of attention as a method that can promote muscle strength, power, and balance control improvements in the elderly (Sitjà-Rabert et al., 2012; Osawa et al., 2013). The mechanisms by which WBV promotes muscle strength and power are not clear, but WBV increases lower limb EMG activity during induced stretch reflexes (Ritzmann et al., 2010) and improves lower limb power, which affects vertical jump performance (Russo et al., 2003; Raimundo et al., 2009). Therefore, WBV is a valid exercise mode of sensorimotor training for increasing power, strength, and functional strength in elderly individuals (Rogan et al., 2014a; 2014b). Because WBV-based training is economical, takes less time, and is convenient, its use is considered most suitable for nursing home residents. Adding WBV to a balance training program might improve step performance during a simulated forward fall by enhancing lower limb muscle strength and power. The effect of balance training on changes in EMG activity during the balance recovery step induced by a simulated fall is currently unknown, but could provide insight into differences between WBV and standard balance exercise on functional enhancement of the balance recovery step.

This study is a randomized controlled pilot trial based on a prospective intervention. The purpose was to examine the effect of balance exercise combined with WBV on step performance and lower limb EMG activity during a forward loss of balance. It was hypothesized that adding WBV training would improve step performance and enable balance recovery during a forward balance loss to a greater extent than balance training only, and that this improvement would be reflected in the EMG activity of the stepping leg.

2. Methods

2.1. Design and participants

This study involved two randomized groups in a parallel-group controlled pilot trial, which was conducted from August to December 2012. Twenty healthy older women residents were recruited from two nursing homes using advertising literature. The inclusion criteria were as follows: aged ≥ 65; dwelling in a nursing home; able to walk independently (without a cane); willing to participate in group exercise classes; and minimal, if any, auditory or visual impairment. Potential participants with central nervous system disorders, severe cardiovascular disease, advanced cognitive impairment, any history of major trauma, rheumatoid or osteoarthritis, or other major systematic diseases were excluded. Further exclusion criteria were any new medications during the study (e.g. against joint pain), limited range of motion in the legs affecting stepping, severe kyphosis, or pain in the trunk or lower limbs. Written informed consent was obtained from each participant in the trial in accordance with the Declaration of Human Rights, Helsinki, 1975. This research was approved by the Ethical Review Board of Kyoto University Graduate School of Medicine, Kyoto, Japan.

Participants were stratified by age and were allocated to two groups by simple randomization using a computer-generated sequence: 10 participated in standard exercise plus WBV and 10 participated in standard exercise without vibration (STE). As it was not possible to blind the subjects to the two types of exercise, on the first day of evaluation, the group assignment was orally reported to participants by nursing home staff not involved in the study. Evaluation and both types of exercise were performed in the waiting lounge of the respective nursing homes.

2.2. Training protocol

Each group exercised 3 d/week for 12 weeks × ~30 minutes/session, and all participants finished the experiment. The home-program intervention was conducted according to an individual schedule for each group.

Participants performed five minutes of limb stretching before training as a warm-up. Following a five-minute break, WBV performed the vibration exercise in a standing position. In each session, vibration was provided by a commercially available device (Galileo 2000, Novotec GmbH, Pforzheim, Germany). The participants stood with their feet shoulder-width apart on the board, which produced side-alternating oscillations of the whole body. WBV received three-minute vibration stimuli. During the vibrations, the participant performed a half squat, heel rise, and toe up on the WBV platform. Weight shift training was also performed on the WBV platform, including anterolateral and posterolateral weight shifting without stepping while reaching forward and laterally. Frequency, amplitude, and maximum acceleration parameters were set at 10 Hz, 3 mm, and 11.8 ms^{-2} during the first week, and increased to 21 Hz, 7 mm, and 121.9 ms^{-2} in the 12th week, respectively. Load progressions of the vibratory stimuli were increased by 1 Hz every week. STE performed the same exercises as WBV on the floor without vibration stimuli.

The training protocol for both groups included an exercise aimed to increase step length and other balance exercises. The exercise to increase step length included large and small steps, fast and slow steps, and single spontaneous steps in anterior–posterior and medial-lateral directions. The participant was required to flex the knees deeply at foot contact. Other balance training consisted of standing on one leg, tandem standing, walking with very small and large steps, and hopping or landing. All training was supervised by the nursing home staff. All session time (minutes) and training days were recorded by the participant.

2.3. Evaluation of physical function characteristics

The physical function characteristics and balance recovery after simulated forward falls were examined before and after the 12 weeks of intervention.

The walking speed, timed up-and-go (TUG) test time, and maximum isometric knee extension strength of the dominant leg were recorded as indices of physical function. Participants were asked to perform walking trials at their maximum speed over a 12-m walkway. The examiner measured the time for the middle 10 m. Following instruction, a single trial was conducted, and walking speed (m/s) was calculated. A Chapman dominant leg test was performed to define the dominant leg (Chapman et al., 1987). Maximum isometric muscle strength was determined using a hand-held dynamometer (μTas MT-1, ANIMA, Inc., Japan) with a fixation band during maximal isometric contraction of the quadriceps in the dominant leg with both the knee and hip joints flexed to 90°.

The test-retest inter-day reliability for evaluating physical function characteristics was estimated using intra-class correlation (ICC). The ICCs for the function characteristics were as follows: 0.73 (95% CI: 0.45–0.88) for the walking speed, 0.93 (95% CI: 0.84–0.97) for the TUG, and 0.62 (95% CI: 0.26–0.83) for the maximum isometric muscle strength. These ICCs indicated substantial to almost perfect reliability.

2.4. Evaluation of step performance during balance recovery

The tether-release method was conducted as described previously for evaluation of the balance recovery from a simulated forward fall (Ochi et al., 2014). Briefly, it involves positioning the participant in a static forward-leaning posture using a horizontal tether that is subsequently released after a randomly determined time delay. Participants stood barefoot with feet shoulder-width apart and were tilted forward, keeping their feet flat on the ground, until a specified percentage of the participant's body weight (BW) was recorded on a load cell (EM-554, Noraxon USA Inc., Scottsdale, AZ) placed in series with an inextensible cable. One end of the cable was attached to a safety harness worn by the participant at the pelvic level, and the other end was attached to a metal pole that allowed height adjustment. The release switch was custom-made from a car seatbelt buckle and installed between the cable and a metal pole. The angle of the forward lean was controlled by adjusting the cable length. For safety, a shock-absorbent lanyard was attached at the participant's upper back and to a support beam on the research facility ceiling. Foot switches were attached to the heel and ball of both feet (EM-556, Noraxon USA Inc., Scottsdale, AZ). Foot-off was determined as the timing when both the heel and ball of the foot of the stepping leg was off the ground, and the subsequent foot contact was determined as the timing of foot contact during the step. It was also confirmed that the stance foot remained in contact with the ground prior to release. A three-dimensional motion capture system (MA 2000 Systems, ANIMA Inc., Japan) was used to measure step length, kinematic parameters of the stepping leg, and trunk angle in the sagittal plane, with four cameras operating at 120 Hz. The trajectories of 12 reflective markers were tracked; the markers were attached bilaterally to the acromion, iliac crest, greater trochanter, knee joint, malleolus lateralis, and head of the fifth metatarsal.

The participant was asked to lean forward against the tether and step forward once with the predetermined stepping leg to regain balance as quickly as possible after tether release. Following achievement of the prescribed posture and cable force (± 2% body weight; BW), the cable was released at a random time interval (2–10 s) by disengaging a release switch located in series with the cable. In the first pre-intervention trial, the tension on the load cell achieved through forward leaning was set to 9% of the participant's BW, and the load was then increased by 3% of BW after every fifth successful recovery of balance. The maximum cable tension from which all participants could recover with a single step was 21% of BW, thus 20% of BW was used for all subsequent assessments. After three practices, five successful steps were measured for each participant, and the last three data sets were analyzed.

2.5. Determination of leg muscle activity during balance recovery

Electrical activity of the rectus femoris (RF), vastus lateralis (VAS), biceps femoris (BF), tibialis anterior (TA), and lateral head of the gastrocnemius muscle (GC) of the stepping leg were examined by surface EMG. The skin superficial to these muscles was prepared so that skin resistance was < 5 kΩ, and disposable electrodes were attached with paste at 2-cm intervals parallel to the muscle fibers in reference to the motor points of each muscle (Ambu, Blue sensor N-00-S, Denmark, 30 mm × 22 mm). The ground electrode was attached 5 cm superior to the patella superficial to the vastus medialis. Distances and angles from bone landmarks and electrode positions were recorded for the each participant, so that the electrode could be identically positioned for the pre- and post-evaluations. Muscle activity was measured with a Telemyo 2400 EMG system (Noraxon USA Inc., Scottsdale, AZ) using the bipolar stepping method. The EMG was band-pass-filtered with a frequency setting of 10–500 Hz. The load cell and foot switch output were synchronized with the EMG. The EMG, foot switch, and load cell data were uploaded at a sampling frequency of 1,500 Hz.

EMG activity was recorded from the five muscles during maximal voluntary contractions (MVC). The MVCs of the GC and the TA were performed with maximal isometric ankle plantar flexion and dorsiflexion at 0°. Similarly, the MVCs of the RF, VAS, and BF were performed during maximal isometric knee extension and flexion with the knee flexed at 90°. Strong verbal encouragement was provided to promote maximal effort. The EMG data from the MVCs were used to normalize the EMG amplitude (% MVC) during the postural tasks. The MVCs were recalculated for the post-training measurement.

2.6. Data analysis

The EMG data was analyzed using Myoresearch version 2.1. The spatiotemporal parameters of balance recovery were determined from the EMG, load cell, foot switch, and motion capture data. The time of cable release was defined as the moment when the load cell reading dropped two standard deviations (SD) below the average value during the 1 s before release. Balance recovery was divided into two phases as follows: 1) lift-off time: from tether release until foot-off of the stepping limb; 2) step time: from foot-off until foot contact. Step length was defined as the distance between the malleolus lateralis of the stance leg and stepping leg at foot contact and was normalized to each participant's height (% height). The step velocity (m/sec) was calculated from the step time and step length. Step length and velocity were the main outcomes in this study because these are important characteristics for regaining balance from a forward fall and are the factors that discriminate the risk of falling in elderly individuals (Cronin et al., 2013; Ochi et al., 2014). The trunk angle was defined as the angle from absolute vertical to a line connecting the two acromion markers to the greater trochanter markers and was obtained during initial lean before tether release and at foot contact.

The raw EMG data were full-wave rectified and band-pass filtered at 20–500 Hz with second-order Butterworth characteristics. The temporal aspects of the EMG responses, i.e. the onset time and first peak during the recovery step, were assessed. Onset latency was defined as the time between tether release and the instant that EMG amplitude exceeded the mean pre-release EMG by two standard deviations for at least 200 ms. To normalize muscle activity during balance recovery, EMG signals were root-mean-square-integrated at 50 ms. The EMG first peak was determined as the time point when EMG peak amplitude appeared during the period between cable-release to foot contact. BF and GC have two peaks of muscle activity, one during the lift-off time and one just before foot contact (**Fig. 1.**). Therefore, the EMG first peak of BF and GC from the lift-off time were derived. EMG data during the stepping movement were expressed relative to the mean integrated EMG during the 1-s period surrounding the peak EMG amplitude phase of the respective MVC. The peak-normalized EMG, onset and peak timing were indexed to reflect stepping behavior (Thelen et al., 2000; Cronin et al., 2013; Ochi et al., 2014); these EMG profiles were determined as secondary outcomes in this study.

2.7. Statistical analysis

The normality of all distributions was confirmed using the Shapiro-Wilk test. A twofactor repeated-measures ANOVA with time (pre vs. post) and intervention groups as factors was used to examine the intervention effects on physical function and analyzed spatiotemporal parameters, including EMG data from the balance recovery task. Significant interactions were further analyzed by using post-hoc paired and unpaired t-tests using a Bonferroni adjustment. The significance level for all comparisons was set at $\alpha = 0.05$.

3. Results

3.1. Adherence to the study protocol

Table 1 summarizes the anthropometric data for the 20 participants who completed the study. No significant differences between WBV and STE were observed in any of the characteristics examined, including age, height, and weight. During the 12-week intervention phase, 36 exercise sessions were scheduled and performed. Both groups had an overall attendance rate of 99% over the 12 weeks. The training volume was evenly distributed between WBV and STE. No health problems, including cardiovascular or musculoskeletal complications, occurred during training sessions or testing. No adverse event that prevented progress occurred due to the intervention.

3.2. Effects of intervention on physical function

After the 12-week intervention phase, walking speed (time effect: $F_{1,18} = 5.24$, $p < 0.05$, $\eta^2 = 0.19$), TUG ($F_{1,18} = 4.78$, $p < 0.05$, $\eta^2 = 0.16$), and maximum knee extension strength ($F_{1,18} = 5.73$, $p < 0.05$, $\eta^2 = 0.27$) were significantly improved in both groups (**Table 1**). No significant difference in improvement between WBV and STE was observed.

3.3. Effects of intervention on step performance during balance recovery

Spatio-temporal variables such as step performance in pre- and post-intervention in both groups are shown in **Table 2**. There was no significant difference in lift-off time or step time between the two groups or between interventions. A significant time effect was observed for step length, which was significantly longer at post-intervention in both groups ($F_{1,18}$ = 4.51, $p < 0.05$, $\eta^2 = 0.20$). Further, there was a significant group × time interaction in step velocity ($F_{1,18}$ = 5.18, $p < 0.05$, $\eta^2 = 0.07$); a significant post-training increase was found in WBV by a post-hoc test (WBV pre- vs. post-training, $p < 0.05$). For both the trunk angle at initial lean and at foot contact, significant effects for groups or interventions were not found.

3.4. Changes in EMG activation during balance recovery

No pre- and post-intervention statistical differences were observed between groups for EMG onset or timing of first-peak EMG. The EMG onset and timing of first-peak EMG amplitude are shown in **Table 3**. The normalized EMG pattern was similar between pre- and post-intervention for all muscles in both groups (see **Fig. 1.**). A significant time effect was observed for peak normalized EMG (% MVC) for RF ($F_{1,18}$ = 10.59, $p < 0.01$, $\eta^2 = 0.34$) and BF ($F_{1,18}$ = 5.33, $p < 0.05$, $\eta^2 = 0.23$), but not for VAS and TA (**Fig. 2.**). Significant group × time interactions in GC activity were observed ($F_{1,18}$ = 5.23, $p < 0.05$, $\eta^2 = 0.09$), and a significant post-training increase was found only in WBV by a post-hoc test (WBV pre- vs post-training, $p < 0.05$; **Fig. 2.**).

4. Discussion

After the 12-week intervention, both groups showed improvements in physical function such as walking speed, knee extension strength, and the TUG test. In addition, a longer step length during a simulated forward fall was observed post-intervention, which was reflected in increased EMG activity in the RF and BF muscles in the stepping leg. Compared to an equal amount of training, the combination of balance training and WBV did not improve physical function. However, WBV improved balance recovery from a forward fall, resulting in a higher step velocity and increased EMG peak activity of the GC muscle, which is involved with ankle action immediately before foot-off. This is the first report showing changes in lower limb EMG activity during balance recovery from a forward fall before and after balance exercise with the addition of WBV.

WBV has been shown to have a beneficial effect on mobility and dynamic balance in elderly individuals compared to typical exercise in several studies (Rogan et al., 2011). On the other hand, no significant improvement in walking score was reported (Lam et al., 2012). Bruyere et al. (2005) reported that WBV training, compared with typical physiotherapy, decreased fall risk and improved gait score and TUG performance in elderly nursing home residents. This is in contrast to the present study, as there were no differences in improvements in walking speed or TUG performance between WBV and STE. Baselines walking speed and TUG performance in the present study were better compared to those in the study of Bruyere et al. (2005); this may explain the lack of effect of WBV on physical function. In a recent study, Rogan et al. (2014b) reported that stochastic resonance WBV can be used for training elderly individuals who have marked physical limitations, equivalent to the “frail and/or prefrail” level, as classified by the Physical Performance Classification for Elderly. WBV is the most likely effective method that can improve the physical performance and general health status, especially in frail older adults (Zhang et al., 2014). However, the participants in this study may potentially have had physical function that was initially too high; therefore, the additional effect of WBV may have been diminished.

Arampatzis et al. (2011) reported that exercise focusing on dynamic stability improved stability performance and increased step velocity in elderly individuals, and the balance exercise program in the current study was similar to those focusing on dynamic stability used in that particular study (Arampatzis et al., 2011). General exercise for dynamic stability may be effective in improving step performance during balance recovery in the elderly; this is partially supported by the present data. However, improvements in stability performance were unclear, as the tether traction was constant in the pre- and post-intervention periods. Traction of 20% BW was used during the balance recovery test, but this was close to the pre-intervention limit of balance recovery using a single step, whereas step length extended in both groups after the intervention. As the participants were able to take a longer step when needed, it is assumed that participants had enhanced balance recovery ability, even though the tested task was the same. This assumption is supported by the finding that both young and elderly women showed a dramatic increase in single-step balance recovery ability when the step length was increased (Hsiao-Wecksler and Robinovitch, 2007).

The EMG analysis in this study demonstrated a post-intervention increase in peak EMG activity of the RF and BF in both groups. However, pre- and post-intervention differences were not seen in EMG onset or peak timing. Cronin et al. (2013) compared the stepping leg EMG activity during balance recovery between multiple steppers with increased fall risk and single steppers with high stability, finding that peak EMG activity of the main stepping leg during the stepping movement was greater in the single steppers. Furthermore, step length positively correlated with the amount of hamstring EMG peak activity in the same study. BF activation generates a flexion torque about the knee at lift-off time, and RF activation flexes the hip and extends the knee during the swing phase in the stepping leg (Thelen et al., 2000). Therefore, increased post-intervention peak EMG activity of the RF and BF may be related to extended step length in the current study. However, the main effect of the balance exercise with or without WBV was increased motor unit recruitment in the stepping leg during balance recovery.

Compared with STE, WBV increased step velocity and peak EMG activity of the GC muscle during balance recovery. It has also been reported that squat movement on a WBV platform promoted muscle activity in the GC compared to the RF (Roelants M, et al., 2006). WBV also helped improve lower limb joint torque and power compared to standard strength training. Rees et al. (2008) provided evidence that WBV improves plantar flexor strength and power to a higher extent than knee flexor or extensor strength. The effects of vibration training may increase motor potentials (Kossev A, et al., 2001) as well as EMG signal frequency (Ritzmann R et al., 2010), suggesting an important excitability of the motor cortex along with muscle adaptations, producing greater neuromuscular efficiency (Bosco C et al., 1999; 2000). WBV adaptations at the neuromuscular level could improve the reflex response of the ankle muscles, which is thought to be indicated by the increased peak EMG activity of the plantar flexor during the stepping recovery in WBV after training. GC muscle activity provides a push-off during balance recovery from a forward fall (Thelen et al., 2000). Our earlier study showed that older women with a history of falls had significantly lower step length and velocity compared to those without a fall history (Ochi et al., 2014), suggesting the delay in peak EMG activity of the GC muscle was related with the reduced stability. There were gender differences in balance recovery from a forward fall as women also used greater plantar flexion torque than did men (Wojcik et al., 2001). The improvement in the plantar flexion response after WBV might contribute to an increased step velocity in older women. Because plantar flexion plays an important role in mobility and stability in older women (Suzuki et al., 2001; Kirkwood et al., 2011), the combination of WBV and balance training in the present study should help to improve functional performance and potential stability, i.e., the ability to recover balance from a simulated forward fall. These results show that adding WBV to balance training is promotes the ability to rapidly regain balance from a forward fall, though it did not affect walking speed or TUG as indices of fall risk.

A limitation of this study is that lower limb EMG activity was used as the main outcome for of the balance recovery step, and the changes of each joint moment were not used to address these issues. In addition, to assess the total index of lower limb muscle strength, only maximum isometric knee extension strength was measured, thus the hip and ankle joint torques are unknown. However, it was clarified that WBV and balance training increased step performance ability and lower limb muscle activity during balance recovery from a simulated fall in older women. Whether these effects correlate to the actual reduction of fall risk requires further investigation.

5. Conclusions

This study successfully reports that a home program including stability exercise improves mobility and balance recovery ability in older female nursing home residents. Enhanced function in balance recovery from a simulated fall was reflected in an increased amount of muscle activity rather than in changes in timing of EMG activity in the stepping leg. The addition of WBV further improved step velocity and promoted a greater peak EMG activity in the plantar flexors, which are responsible for push-off prior to foot-off during balance recovery.

Acknowledgements

This study received financial support from a Japan Society for the Promotion of Science Grant-in-Aid for Young Scientists (B) (23700674).

References

Aragão, F. A., Karamanidis, K., Vaz, M. A., & Arampatzis, A. (2011). Mini-trampoline exercise related to mechanisms of dynamic stability improves the ability to regain balance in elderly. *Journal of Electromyography & Kinesiology*, *21*, 512-518.

Arampatzis, A., Peper, A., & Bierbaum, S. (2011). Exercise of mechanisms for dynamic stability control increases stability performance in the elderly. *Journal of Biomechanics*, *44*, 52-58.

Bosco, C., Cardinale, M., & Tsarpela, O. (1999). Influence of vibration on mechanical power and electromyogram activity in human arm flexor muscles. *European Journal of Applied Physiology and Occupational Physiology*, *79*, 306-311.

Bosco, C., Iacovelli, M., Tsarpela, O., Cardinale, M., Bonifazi, M., Tihanyi, J., Viru, M., De Lorenzo, A., & Viru, A. (2000). Hormonal responses to whole-body vibration in men. *European Journal of Applied Physiology*, *81*, 449-454.

Bruyere, O., Wuidart, M. A., Di Palma, E., Gourlay, M., Ethgen, O., Richy, F., & Reginster, J. Y. (2005). Controlled whole body vibration to decrease fall risk and improve health-related quality of life of nursing home residents. *Archives of Physical Medicine and Rehabilitation, 86*, 303-307.

Carty, C. P., Cronin, N. J., Lichtwark, G. A., Mills, P. M., & Barrett, R. S. (2012). Lower limb muscle moments and power during recovery from forward loss of balance in male and female single and multiple steppers. *Clinical Biomechanics*, *27*, 1031-1037.

Carty, C. P., Cronin, N. J., Nicholson, D., Lichtwark, G. A., Mills, P. M., Kerr, G., Cresswell, A. G., & Barrett, R. S. (2014). Reactive stepping behaviour in response to forward loss of balance predicts future falls in community-dwelling older adults. *Age Ageing, 0,* 1-7. Epub ahead of print. doi: 10.1093/ageing/afu054.

Chapman, J. P., Chapman, L. J., & Allen, J. J. (1987). The measurement of foot preference.

Neuropsychologia, *25*, 579-584.

Clark, B. C., & Manini, T. M. (2008), Sarcopenia =/= dynapenia. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 63,* 829-834.

Cronin, N. J., Barrett, R. S., Lichtwark, G., Mills, P. M., & Carty, C. P. (2013). Decreased lower limb muscle recruitment contributes to the inability of older adults to recover with a single step following a forward loss of balance. *Journal of Electromyography & Kinesiology*, *23*, 1139-1144.

Grabiner, M. D., Bareither, M. L., Gatts, S., Marone, J., & Troy, K. L. (2012). Task-specific training reduces trip-related fall risk in women. *Medicine & Science in Sports & Exercise*, *44*, 2410-2414.

Hsiao-Wecksler, E. T., & Robinovitch, S. N. (2007). The effect of step length on young and elderly women's ability to recover balance. *Clinical Biomechanics* (Bristol, Avon), *22*, 574-580.

Hsiao-Wecksler, E. T. (2008). Biomechanical and age-related differences in balance recovery using the tether-release method. *Journal of Electromyography & Kinesiology*, *18*, 179-187.

Kirkwood, R. N., Trede, R. G., Moreira Bde, S., Kirkwood, S. & A., Pereira, L. S. (2011). Decreased gastrocnemius temporal muscle activation during gait in elderly women with history of recurrent falls. *Gait & Posture*, *34*, 60-64.

Kossev, A., Siggelkow, S., Kapels, H., Dengler, R., & Rollnik, J. D. (2001). Crossed effects of muscle vibration on motor-evoked potentials. *Clinical Neurophysiology*, *112*, 453-456.

Lam, F. M., Lau, R. W., Chung, R. C., & Pang, M. Y. (2012). The effect of whole body vibration on balance, mobility and falls in older adults: a systematic review and meta-analysis. *Maturitas*, *72*, 206-213.

Mansfield, A., Peters, A. L., Liu, B. A., & Maki, B. E. (2010). Effect of a perturbation-based balance training program on compensatory stepping and grasping reactions in older adults: a randomized controlled trial. *Physical Therapy*, *90*, 476-491.

Ochi, A., Yokoyama, S., Abe, T., Yamada, K., Tateuchi, H., & Ichihashi, N. (2014). Differences in muscle activation patterns during step recovery in elderly women with and without a history of falls. *Aging Clinical and Experimental Research*, *26*, 213-220.

Osawa, Y., Oguma, Y., & Ishii, N. (2013). The effects of whole-body vibration on muscle strength and power: a meta-analysis. *Journal of Musculoskeletal and Neuronal Interactions*, *13*, 342-352.

Raimundo, A. M., Gusi, N., Tomas-Carus, P. (2009). Fitness efficacy of vibratory exercise compared to walking in postmenopausal women. *European Journal of Applied Physiology*, *106*, 741-748.

Rees, S. S., Murphy, A. J., & Watsford, M. L. (2008). Effects of whole-body vibration exercise on lower-extremity muscle strength and power in an older population: a randomized clinical trial. *Physical Therapy*, *88*, 462-470.

Ritzmann, R., Kramer, A., Gruber, M., Gollhofer, A., & Taube, W. (2010). EMG activity during whole body vibration: motion artifacts or stretch reflexes? *European Journal of Applied Physiology*, *110*, 143-151.

Roelants, M., Verschueren, S. M., Delecluse, C., Levin, O., & Stijnen, V. (2006). Whole-body-vibration-induced increase in leg muscle activity during different squat exercises. *Journal of Strength and Conditioning Research*, *20*, 124-129.

Rogan, S., Hilfiker, R., Herren, K., Radlinger, L., & de Bruin, E. D. (2011). Effects of whole-body vibration on postural control in elderly: a systematic review and meta-analysis. *BMC Geriatrics*, *11*: 72. doi: 10.1186/1471-2318-11-72.

Rogan, S., Hilfiker, R., Schenk, A., Vogler, A., & Taeymans, J. (2014 a). Effects of whole-body vibration with stochastic resonance on balance in persons with balance disability and falls history - a systematic review. *Research in Sports Medicine: An International Journal, 22,* 294-313.

Rogan, S., Schmidtbleicher, D., & Radlinger, L. (2014 b). Immediate effects after stochastic resonance whole-body vibration on physical performance on frail elderly for skilling-up training: a blind cross-over randomised pilot study. *Aging Clinical and Experimental Research*, Epub ahead of print. doi: 10.1007/s40520-014-0212-4.

Rogers, M. W., Johnson, M. E., Martinez, K. M., Mille, M. L., & Hedman, L. D. (2003). Step training improves the speed of voluntary step initiation in aging. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *58*, 46-51.

Roudsari, B. S., Ebel, B. E., Corso, P. S., Molinari, N. A., & Koepsell, T. D. (2005). The acute medical care costs of fall-related injuries among the U.S. older adults. *Injury*, *36*, 1316-1322.

Russo, C. R., Lauretani, F., Bandinelli, S., Bartali, B., Cavazzini, C., Guralnik, J. M., & Ferrucci, L. (2003). High-frequency vibration training increases muscle power in postmenopausal women. *Archives of Physical Medicine and Rehabilitation*, *84*, 1854-1857.

Sitjà-Rabert, M., Rigau, D., Fort Vanmeerghaeghe, A., Romero-Rodríguez, D., Bonastre Subirana, M., & Bonfill, X. (2012). Efficacy of whole body vibration exercise in older people: a systematic review. *Disability and Rehabilitation*, *34*, 883-893.

Suzuki, T., Bean, J. F., & Fielding, R. A. (2001). Muscle power of the ankle flexors predicts functional performance in community-dwelling older women. *Journal of the American Geriatrics Society*, *49*, 1161-1167.

Thelen, D. G., Muriuki, M., James, J., Schultz, A. B., Ashton-Miller, J. A., & Alexander, N. B.

(2000). Muscle activities used by young and old adults when stepping to regain balance during a forward fall. *Journal of Electromyography & Kinesiology*, *10*, 93-101.

Wojcik, L. A., Thelen, D. G., Schultz, A. B., Ashton-Miller, J. A., & Alexander, N. B. (1999). Age and gender differences in single-step recovery from a forward fall. *Journals of Gerontology Series A: Biological Sciences and Medical Sciences*, *54*, M44-50.

Wojcik, L. A., Thelen, D. G., Schultz, A. B., Ashton-Miller, J. A., & Alexander, N. B. (2001). Age and gender differences in peak lower extremity joint torques and ranges of motion used during single-step balance recovery from a forward fall. *Journal of Biomechanics*, *34*, 67-73.

Zhang, L., Weng, C., Liu, M., Wang, Q., Liu, L., & He, Y. (2014). Effect of whole-body vibration exercise on mobility, balance ability and general health status in frail elderly patients: a pilot randomized controlled trial. *Clinical Rehabilitation, 28,* 59-68.

Table 1. Anthropometric data, physical function, and knee extension moments for the examined groups (mean ± SD).

Intervention	WBV group (n = 10)		STE group (n = 10)		Group effect (p)	Time effect (p)	Group × Time (p)
	Pre	Post	Pre	Post			
Age (yr)	80.9 ± 2.8	—	80.2 ± 3.3	—	—	—	—
Height (cm)	151.5 ± 3.8	—	150.2 ± 3.4	—	—	—	—
Body weight (kg)	53.7 ± 7.8	53.1 ± 6.8	55.6 ± 7.6	55.7 ± 7.8	0.51	0.50	0.35
Walking speed (m/s)	1.38 ± 0.18	1.50 ± 0.20	1.44 ± 0.24	1.45 ± 0.19	0.93	< 0.05	0.07
TUG (s)	9.06 ± 2.10	8.53 ± 1.85	8.52 ± 1.89	8.46 ± 1.59	0.72	< 0.05	0.09
Maximum KE strength (Nm/kg)	1.29 ± 0.29	1.47 ± 0.33	1.25 ± 0.25	1.40 ± 0.38	0.69	< 0.05	0.81
Number of absence/all training days	—	3/360	—	2/360	—	—	—
Total training volume (min)	—	1243 ± 97	—	1204 ± 56	—	—	—

Significance in each item except age, height, and total training volume were tested using a two-way analysis of variance.
Walking speed was calculated from 10-m walking time, TUG = timed up and go test time, Maximum KE strength = maximum isometric knee extension strength.

Table 2. Spatiotemporal parameters during step recovery from a forward fall for the examined groups (mean ± SD).

Intervention	WBV group (n = 10)		STE group (n = 10)				
	Pre	Post	Pre	Post	Group effect (p)	Time effect (p)	Group × Time (p)
Lift-off time (ms)	281 ± 29	276 ± 55	272 ± 46	268 ± 59	0.65	0.71	0.99
Step time (ms)	276 ± 46	263 ± 43	290 ± 39	299 ± 31	0.10	0.86	0.29
Step length (%height)	32.1 ± 5.2	33.8 ± 5.8	31.9 ± 5.0	34.2 ± 6.3	0.97	< 0.05	0.75
Step velocity (m/s)	1.79 ± 0.29	1.97 ± 0.31	1.67 ± 0.28	1.71 ± 0.24	0.15	< 0.01	< 0.05
Trunk angle at IL (deg)	13.1 ± 1.9	13.5 ± 2.3	12.9 ± 1.7	13.1 ± 2.0	0.72	0.34	0.75
Trunk angle at FC (deg)	23.5 ± 2.5	23.1 ± 2.6	22.0 ± 2.4	21.5 ± 2.3	0.15	0.24	0.89

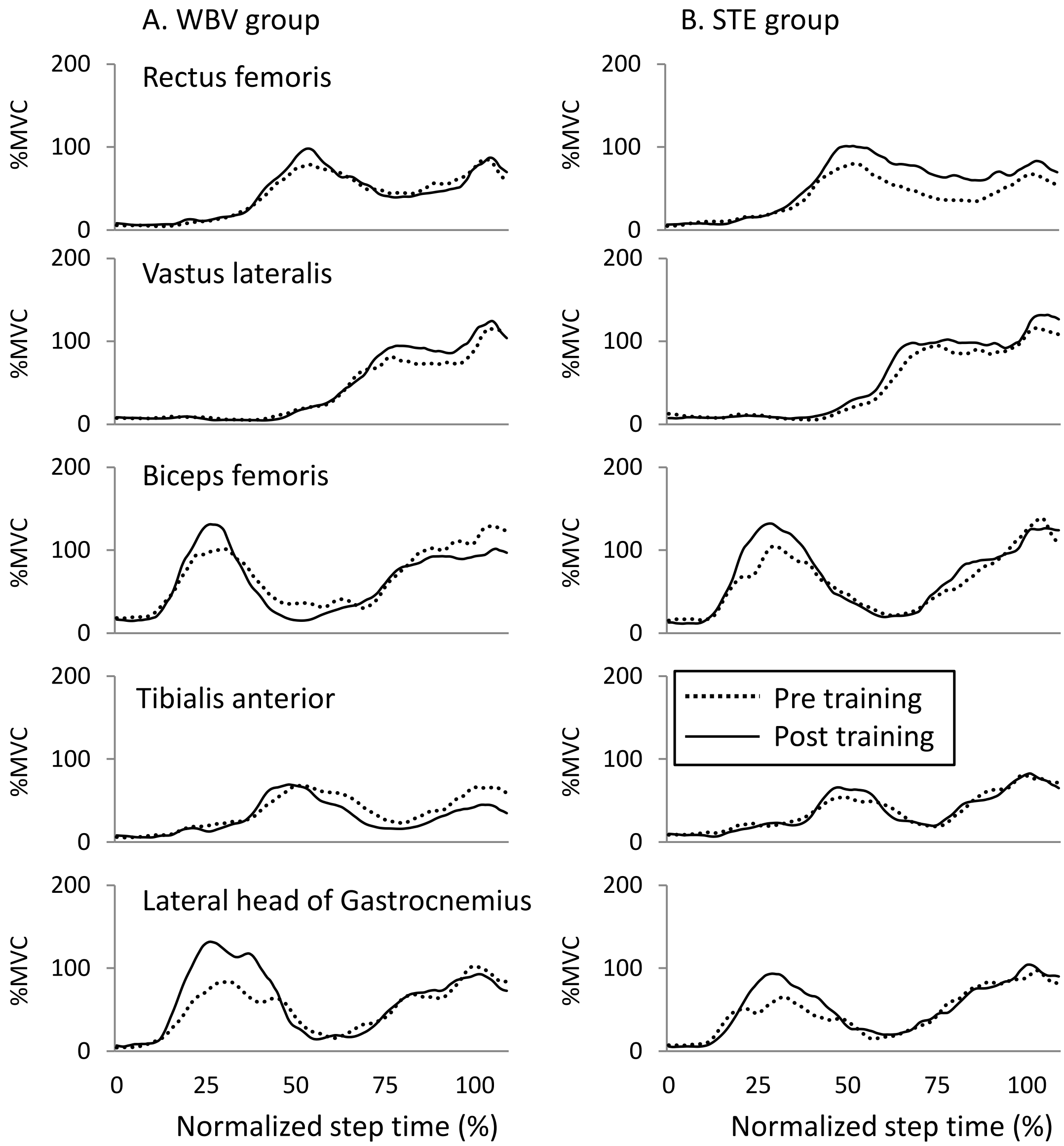
Significance was tested using two-way factorial analysis of variance.
IL= initial lean during pre-release, FC= foot contact after tether-release.

Table 3. EMG onset times (ms) and timing of first-peak EMG amplitude (ms) for all muscles from cable-release until foot contact (mean ± SD).

Intervention	WBV (n = 10)		STE (n = 10)				
	Pre	Post	Pre	Post	Group effect (*p*)	Time effect (*p*)	Group × Time (*p*)
EMG onset times							
RF	110 ± 22	107 ± 20	102 ± 28	103 ± 27	0.55	0.86	0.63
VAS	105 ± 23	103 ± 22	106 ± 19	101 ± 21	0.95	0.55	0.78
BF	96 ± 19	98 ± 19	93 ± 22	97 ± 17	0.75	0.62	0.85
TA	99 ± 19	97 ± 20	97 ± 19	101 ± 20	0.85	0.92	0.72
GC	93 ± 23	90 ± 14	97 ± 13	93 ± 22	0.62	0.40	0.92
Timing of first-peak EMG amplitude							
RF	310 ± 43	297 ± 43	300 ± 47	317 ± 41	0.70	0.87	0.33
VAS	446 ± 81	444 ± 77	431 ± 76	459 ± 82	0.99	0.48	0.44
BF	164 ± 36	163 ± 33	150 ± 32	159 ± 39	0.48	0.70	0.63
TA	288 ± 45	272 ± 47	280 ± 53	282 ± 60	0.93	0.65	0.58
GC	172 ± 31	160 ± 29	178 ± 49	169 ± 44	0.64	0.23	0.88

RF: rectus femoris, VAS: vastus lateralis, BF: biceps femoris, TA: tibialis anterior, GC: lateral head of gastrocnemius

Figure 1



A. WBV group
B. STE group
Rectus femoris
Vastus lateralis
Biceps femoris
Tibialis anterior
Lateral head of Gastrocnemius
%MVC
200
100
0
0
25
50
75
100
Normalized step time (%)
Pre training
Post training

Figure 1 Title

Fig.1. Ensemble-averaged myoelectric signals during the balance-recovery step.

Figure 1 Caption

Muscle activation levels were normalized by isometric maximum voluntary contraction for each muscle (% MVCs). The step time was normalized for the time from cable release to foot contact. The timing of foot-off in all participants appeared in about 47 - 51 %.

Figure 2

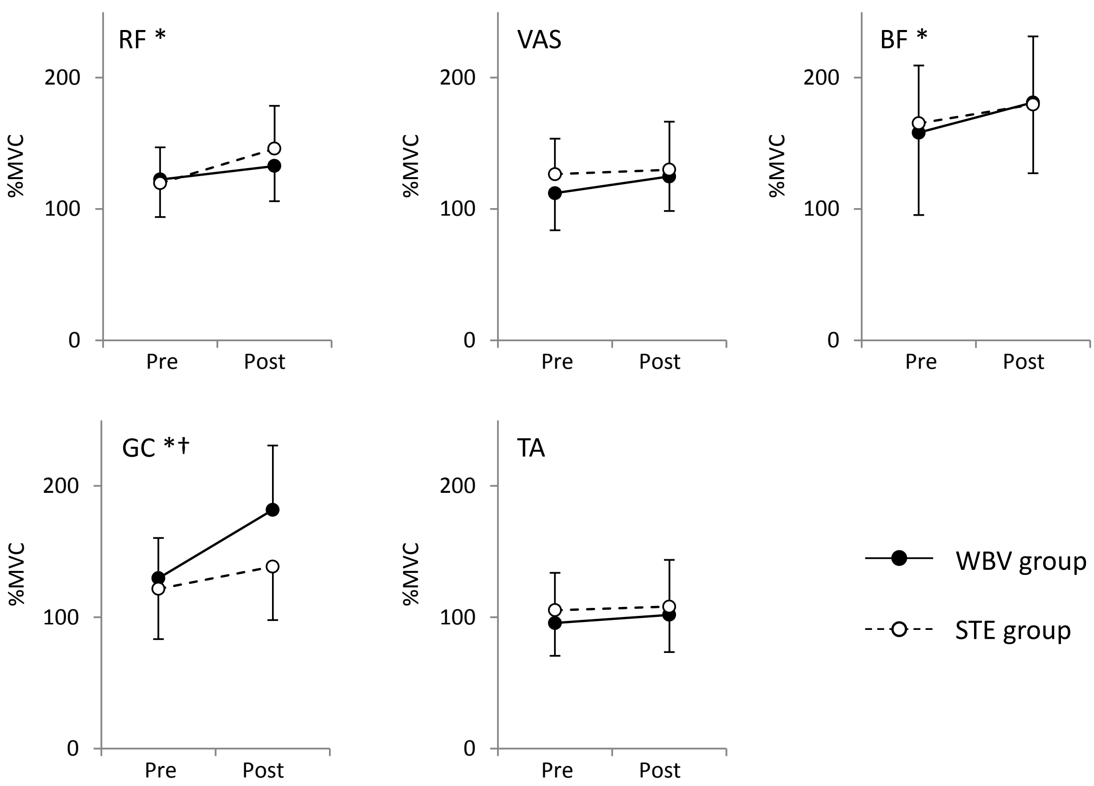


Figure 2 Title

Fig.2. Pre- and post-training comparisons of mean normalized peak EMG amplitude （% MVC） during balance recovery from a forward fall.

Figure 2 Caption

The EMG amplitude of each muscle was expressed as a percentage of the EMG value during the MVCs, which were calculated for both pre- and post-training. Significance was tested using a two-way ANOVA. The black circle and solid lines indicate WBV, and the white circle and broken lines indicate STE.

* $p < 0.05$ time effect

† $p < 0.05$ group × time interaction