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Reactive stepping behaviour in response to forward loss of balance predicts future falls in community-dwelling older adults

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Abstract

Background: a fall occurs when an individual experiences a loss of balance from which they are unable to recover. Assessment of balance recovery ability in older adults may therefore help to identify individuals at risk of falls. The purpose of this 12-month prospective study was to assess whether the ability to recover from a forward loss of balance with a single step across a range of lean magnitudes was predictive of falls.
Methods: two hundred and one community-dwelling older adults, aged 65–90 years, underwent baseline testing of sensori-motor function and balance recovery ability followed by 12-month prospective falls evaluation. Balance recovery ability was defined by whether participants required either single or multiple steps to recover from forward loss of balance from three lean magnitudes, as well as the maximum lean magnitude participants could recover from with a single step.
Results: forty-four (22%) participants experienced one or more falls during the follow-up period. Maximal recoverable lean magnitude and use of multiple steps to recover at the 15% body weight (BW) and 25%BW lean magnitudes significantly predicted a future fall (odds ratios 1.08–1.26). The Physiological Profile Assessment, an established tool that assesses variety of sensori-motor aspects of falls risk, was also predictive of falls (Odds ratios 1.22 and 1.27, respectively), whereas age, sex, postural sway and timed up and go were not predictive.
Conclusion: reactive stepping behaviour in response to forward loss of balance and physiological profile assessment are independent predictors of a future fall in community-dwelling older adults. Exercise interventions designed to improve reactive stepping behaviour may protect against future falls.

Keywords: *balance recovery, reactive stepping, ageing, falls prevention, older adults, forward loss of balance*

Background

Falls in older adults are a major global public health concern. Impaired sensori-motor function including vision, reaction time, balance, strength and gait function has been identified as key risk factors for falls in community-dwelling older adults, and is amenable to intervention [1]. Common tests of general sensori-motor function and balance in community-dwelling older adults include postural sway assessments, limit of stability tests, gait function (e.g. speed and variability), timed-up-and-go test (TUG), Berg Balance Scale, Tinetti Test and the physiological profile assessment (PPA). These tests generally evaluate the ability to maintain balance, because the whole body centre of mass typically remains within the base of support. However, for a fall to occur an individual must first experience loss of balance, and then subsequently be unable to recover their balance. It therefore follows that tests that evaluate the ability to rapidly recover

from loss of balance may also be effective in identifying older adults at risk of falling.

In the absence of opportunities to stabilise the body by grasping an external support, the main strategy used to recover balance from large postural perturbations is the rapid protective stepping response [2]. Older adults experience substantially greater difficulty in recovering from loss of balance by stepping than younger adults, across a broad range of experimental conditions [3–8]. The most common experimental method by which stepping responses have been examined to date involves participants being suddenly released from an initial static lean angle [2, 9]. Studies using this paradigm have mostly investigated forward loss of balance, and indicate that older adults have a lower maximum lean angle from which they can recover with a single step [9] and are more likely to require multiple steps to recover from a given lean angle than young adults [3]. The mechanisms underlying these age-related deficits are determined prior to touchdown of the stepping limb [10, 11] and include a shorter step length and poor control of upper body posture [3, 10, 12], weakness of the hip flexors and knee extensors [13], reduced lower limb muscle activation [14] and reduced power production in the stepping limb during the stepping phase [15]. Although balance recovery behaviour in response to a medio-lateral perturbation has been shown to be predictive of a future fall [16, 17], inability to recover with a single step following a forward loss of balance, which is the most common fall direction, is lacking. Furthermore, older fallers with a deterioration of anterior–posterior balance have been shown to be at higher risk of serious injury following fall events [18]. If specific measures of balance recovery ability in the anterior–posterior direction could be shown to be predictive of a future fall, then this would add to the mounting evidence concerning the clinical importance and functional relevance of stepping behaviour in falls prevention [19, 20].

The primary purpose of this 12-month prospective study was to assess whether the ability to recover from a forward loss of balance with a single step across a range of lean magnitudes was predictive of falls (all falls and forward falls). It was hypothesised that: (i) older adults who require multiple compared with single steps to recover from a forward loss of balance and older adults with a lesser maximal ability to recover with a single step following a forward loss of balance would be more likely to fall in the following year; and (ii) that reactive stepping responses would be stronger predictors of a future forward fall than measures of postural sway magnitude and the TUG test, because they more closely mimic the biomechanics of a real-world fall. A secondary purpose of this study was to assess whether women had more difficulty in recovering balance with a single step at each lean magnitude, and whether women have a greater odds of experiencing a fall in the 12-month period compared with men. We hypothesised that a greater proportion of women would require multiple steps at each lean magnitude and that sex (female) would be a predictor of a future fall.

Methods

Participants

Two hundred and fifty-nine community-dwelling older adults responded to an 'expression of interest' letter sent to 3,000 local residents. The list of 3,000 local residents was randomly selected from a pool of 56,709 local residents who were registered on the electoral roll and aged between 65 and 80 years. Individuals that reported neurological, metabolic, cardiopulmonary, musculoskeletal or uncorrected visual impairment were excluded. Ethics approval was obtained from the Institutional Human Research Ethics Committee and written informed consent was obtained prior to participation.

Balance recovery protocol

The balance recovery protocol was conducted as described previously [12]. Participants stood barefoot with their feet shoulder-width apart in an neutral posture and were tilted forward, keeping their feet flat on the ground, until 15, 20 or 25% of body weight (BW) was recorded on a load cell (S1W1kN, XTRAN, Australia) placed in series with an inextensible cable. Cable force on the load cell and centre of pressure recorded from a force platform were displayed in real-time to ensure anticipatory actions (e.g. antero-posterior and medio-lateral weight shifting) and were not evident in the period prior to cable release. The cable was released at a random time interval (2–10 s) following achievement of the prescribed posture and cable force (± 1%BW), and participants were instructed to relax while maintaining an upright posture and to regain balance with a single step using the stepping lower limb of their choice, once they perceived they were falling. Participants performed four trials at each lean magnitude, with block randomisation used to determine the lean magnitude sequence (i.e. 15, 20 or 25%BW) for the 12 trials. Whole body three-dimensional balance recovery kinematics were collected and calculated as described previously [21].

For each trial, participants were classified as adopting either a single or a multiple step balance recovery strategy [12]. The criteria used to distinguish a multiple step from a single step for each trial were: (i) a second step of any kind by the stepping leg or anterior progression of the non-stepping foot past the stepping foot following the initial step, or application of 20%BW or more to the ceiling restraint cable at any point during recovery [12]. The following groups were subsequently defined on the basis of the recovery strategy adopted by each participant across the four trials at each lean magnitude:

(1) Single steppers. Single step recovery strategy for all four trials.
(2) Mixed steppers. Mix of multiple and single step recovery strategies across four trials.
(3) Multiple steppers. Multiple step recovery strategy for all four trials or reliance on a multiple step recovery strategy at a lower lean magnitude.

Following the 12 trials, two to five additional trials were attempted by each participant to determine the maximal

recoverable lean magnitude (MRLM) that they could recover from with a single step. The cable was systematically increased in ∼1%BW increments until the participant could no longer recover with a single step.

PPA, postural sway and TUG

Falls risk was assessed using the PPA, which has been validated on over 2,000 adults predicting multiple faller and non-multiple faller individuals with 75% accuracy [1]. The PPA includes assessment of vision, sensation, leg strength, reaction time, postural sway and dynamic balance that provides an overall falls risk score between −2 (very low falls risk) and 4 (very marked falls risk) [1]. Individual postural sway components of the PPA were assessed separately and measured the amount of sway over a 30 s period [1]. Sway testing was performed with eyes open and closed, on a firm surface and on a medium-density foam rubber mat (15 cm thick). The TUG test was also performed as described previously [22].

Falls surveillance

A fall was defined as 'an unexpected event in which the participant came to rest on the ground, floor or lower level' [23]. Following baseline testing, participants were provided with a monthly falls diary containing questions relating to falls and injuries [23]. In the event of a fall, participants were instructed to complete the questions, as soon as possible in the month in which the fall occurred. A research assistant contacted each participant by phone once a month for 12 months to collect data relating to falls. Participants were subsequently classified as non-fallers, single- or multiple-fallers. Individuals were further classified as forward fallers if they experienced a loss of balance and came to rest in a location anterior to the initial perturbation on one or more occasions. Baseline data were collected for 209 participants and 201 participants were followed up over 12 months (Figure 1). The mean (±1 SD) age, height and mass of the remaining 201 participants (97 men and 104 women) were 72.9 ± 58 years, 1.66 ± 0.09 m and 74.8 ± 12.9 kg, respectively.

Statistical analysis

To assess whether dependent variables (age, sex, PPA, TUG, sway measures and balance recovery measures) could predict individuals who would experience one or more falls, compared with no falls, and one or more forward falls, compared with no falls, in the 12 months following baseline testing, Odds ratios (OR) representing the mean difference between groups were calculated. Significance of the OR was assessed using the Wald test. An additional forward stepwise binary logistic regression model was performed to assess the variable(s) that best predicted odds of a future forward fall. Statistical analyses were performed using IBM SPSS (Version 20, IBM SPSS, USA). Significance was accepted for $P < 0.05$.

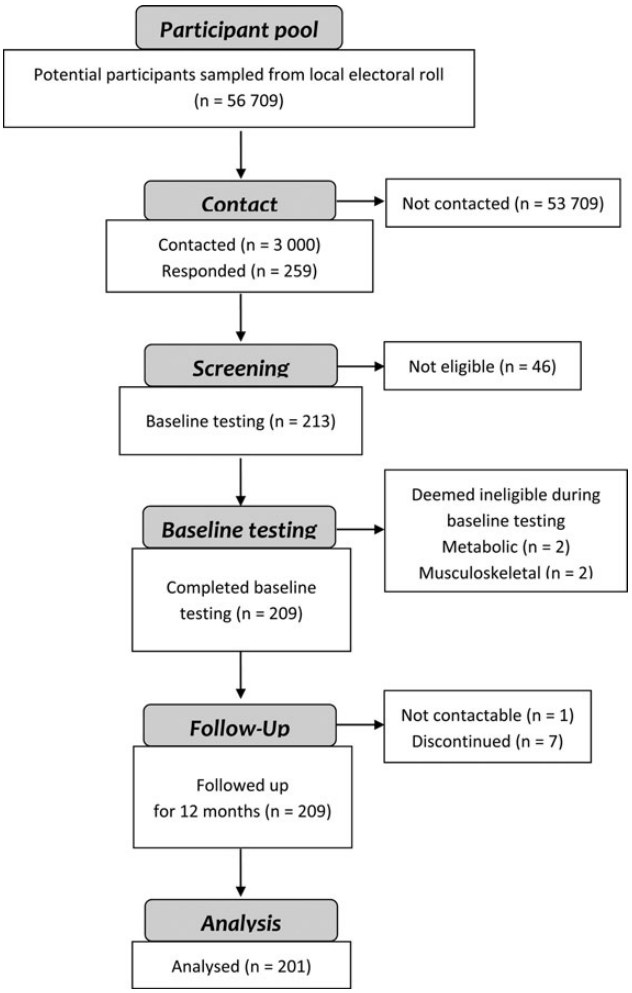

Figure 1. Flow chart of recruitment, screening and follow-up process.

Results

Participant passage

From the 259 people who volunteered for the project, 48 did not meet the eligibility criteria during screening or baseline testing and 8 did not complete the 12 month follow-up falls calendars.

A total of 201 people (97 men, 104 women, mean age 74.9 ± 5.8 years) completed baseline assessments and follow-up falls calendars (see Figure 1 for participant passage).

Falls surveillance

A total of 69 falls were recorded (range 1–7, mean = 1.6 per faller). Forty-eight falls (70%) resulted from a forward loss of balance, 9 (13%) from a backward loss of balance while in 12 cases (17%) the direction of balance loss was unknown. Of the 201 participants that completed follow-up, 157 (78%) did not experience a fall, 30 (15%) experienced 1 fall and 14 (7%) experienced 2 or more falls. Thirty-two participants (15.9%) were injured as a result of a fall with four participants sustaining fractures and five participants sustaining

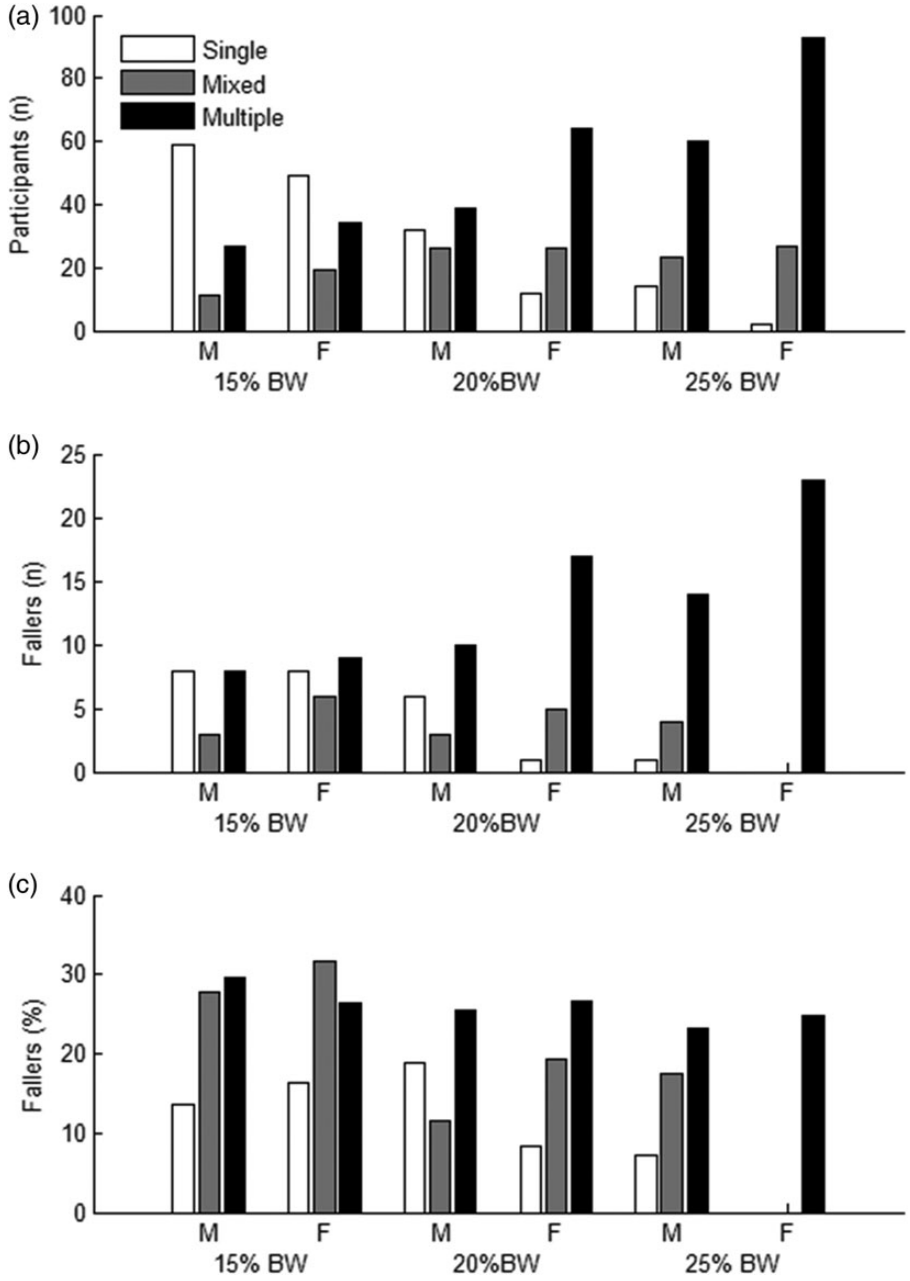

Figure 2. Number of older male and female participants who recovered using either single, mixed and multiple step recovery strategies at the 15%BW, 20%BW and 25%BW lean magnitudes (a), absolute number of fallers who recovered using either single, mixed and multiple step recovery strategies at each lean magnitude (b), and percentage of fallers who recovered using either single, mixed and multiple step recovery strategies at each lean magnitude (c). F, Female, M, Male.

significant soft tissue injuries; 22.4% of participants reported falling in the previous year.

Balance recovery measures

The number of older adults who recovered using a single step strategy decreased as lean magnitude increased (Figure 2a). At each lean magnitude, there were a greater number of female compared with male multiple steppers (Figure 2a). At each lean magnitude, there were a greater absolute (Figure 2b) and relative (Figure 2c) number of male and female multiple steppers who subsequently experienced a fall in the 12-month follow-up period compared with male and female single steppers.

Fall prediction

Demographic, traditional sensori-motor falls risk measures and balance recovery measures for non-fallers, fallers and the subgroup of forward fallers are presented in Table 1. Logistic regression analysis revealed that MRLM, use of multiple compared with single steps to recover from forward loss of balance at the 15%BW and 25%BW lean magnitudes and

Table 1. Demographic, sensori-motor and balance recovery measures (mean ± standard deviation) for non-fallers, single-fallers and multiple-fallers, and assessment of whether these risk factors predict occurrence of one or more falls in the 12-month follow-up period using odds ratio (OR)

Risk factors	Non-fallers ($n = 157$)	Fallers ($n = 44$)	Forward fallers ($n = 31$)	Odds ratio[a] (95% CI)	Odds ratio[b] (95% CI)
Demographic measures					
Age (years)	72.6 ± 5.5	74.2 ± 6.5	75.2 ± 6.8	1.05 (0.99–1.11)	1.12 (1.02–1.24)*
Sex (% female)	50%	57%	61%	1.20 (0.66–2.55)	1.56 (0.71–3.44)
Sensori-motor measures					
Timed Up and Go (s)	6.4 ± 1.8	6.7 ± 2.1	6.9 ± 2.4	1.03 (0.98–1.08)	1.04 (0.98–1.10)
PPA	0.6 ± 0.8	1.0 ± 1.2	1.2 ± 1.2	1.22 (1.06–1.40)*	1.31 (1.11–1.54)*
Sway floor eyes open (cm^2)	3.3 ± 3.1	3.8 ± 4.0	4.2 ± 4.5	1.08 (0.97–1.07)	1.03 (0.98–1.09)
Sway floor eyes closed (cm^2)	3.8 ± 3.7	5.1 ± 8.7	5.6 ± 10.1	1.05 (0.97–1.1)	1.06 (0.98–1.15)
Sway foam eyes open (cm^2)	10.3 ± 7.7	13.7 ± 14.2	14.4 ± 12.0	1.1 (1.00–1.24)	1.16 (1.02–1.33)*
Sway foam eyes closed (cm^2)	19.8 ± 18.8	21.9 ± 26.6	22.0 ± 26.3	1.1 (1.00–1.22)	1.01 (0.97–1.05)
Balance recovery measures					
Stepping strategy 15%BW	1.7 ± 0.9	2.0 ± 0.9	2.1 ± 0.9	1.13 (1.01–1.26)*	1.15 (1.01–1.30)*
Stepping strategy 20%BW	2.3 ± 0.8	2.5 ± 0.8	2.6 ± 0.8	1.08 (0.98–1.18)	1.14 (1.01–1.28)*
Stepping strategy 25%BW	2.6 ± 0.7	2.9 ± 0.4	3.0 ± 0.2	1.26 (1.00–1.58)*	1.83 (1.04–3.24)*
MRLM (%BW)	18.5 ± 7.0	15.8 ± 7.1	15.8 ± 7.1	1.15 (1.01–1.31)*	1.22 (1.05–1.42)*

Odds ratios refer to a unit change represented at the mean difference between non-fallers and fallers.
MRLM, maximal recoverable lean magnitude; BW, body weight; BH, body height.
[a]Odds ratios for predicting one or more falls.
[b]Odds ratios for predicting one or more forward fall.
*$P < 0.05$.

PPA score significantly increased the odds of experiencing a future fall. Use of multiple steps compared with single steps to recover from forward loss of balance at all lean magnitudes, PPA score, sway on foam with eyes open and age also significantly increased the odds of experiencing a future forward fall. Forward stepwise logistic regression analysis revealed that PPA and use of multiple steps compared with single steps to recover from forward loss of balance at the highest lean magnitude were independent predictors of a future fall (overall model: chi-square = 13.59, $P < 0.01$).

Discussion

In support of our hypothesis, measures of recovery from forward loss of balance by stepping were found to be predictive of real-world falls and forward falls in particular, over the subsequent 12 months in community-dwelling older adults. Consistent with these findings was the observation that a greater proportion of fallers were multiple steppers compared with single steppers at each lean magnitude. In fact only 1 of 44 participants who experienced a fall was able to recover with a single step at the 25%BW lean magnitude. These results build on the findings of Hilliard *et al.* [16] and Mille *et al.* [17] who showed that stepping reactions to medio-lateral and anterior perturbations were predictive of future falls. Furthermore, in a study of responses to multi-directional force-controlled waist-pull perturbations, Sturnieks *et al.* [24] found future fallers had a lower force threshold to stepping in the lateral and posterior directions, and that these reactive responses were predictive of falls. Furthermore, in a study of 477 retirement village residents, Lord *et al.* [25] found that poor performance in a choice stepping reaction time test was a significant and independent predictor for falls. Taken together, these findings suggest that improving the ability of older adults to respond to loss of balance through training of reactive stepping responses may be an efficacious fall prevention strategy. Indeed, there is already evidence that balance training which targets specific deficits in stepping behaviour leads to improvements in balance recovery [26]. There is also increasing evidence that repeated exposure to loss of balance can result in rapid improvements in balance recovery by stepping [19, 21]. These findings are consistent with the principles of training specificity and suggest that safely exposing older adults to loss of balance in a manner consistent with the dynamics of real-world fall scenarios may be a worthwhile adjunct to exercise-based fall prevention programmes. The effects of such interventions on actual falls remain unknown at this time.

Measures of postural sway and TUG performance are commonly used as measures of falls risk. However, in support of our hypothesis, only one of these measures (postural sway on foam with eyes open), predicted a future forward fall in the present study. Mackey and Robinovitch [27] reported a lack of association between postural steadiness during quiet stance and balance recovery by stepping. Our findings therefore extend those of Mackey and Robinovitch [27] and suggest that dynamic measures of balance recovery by stepping, which evaluate the ability to rapidly generate muscle force and to co-ordinate the recovery patterns in response to an unexpected perturbation, are more closely related to the mechanism of real-world falls than measures of postural sway and TUG.

Consistent with previous research, the PPA falls risk score was a significant predictor of a forward fall during the 12-month follow-up period [1, 28, 29]. The PPA addresses a variety of sensori-motor aspects including vision, sensation, leg strength, reaction time, postural sway and dynamic

balance. The finding that stepping strategy at the 25%BW lean magnitude and PPA were both independent predictors of a future forward fall suggests that reactive stepping ability is not adequately accounted for in the PPA and that additional measures of reactive steeping ability are required when evaluating falls risk in older adults.

Age and sex are also established and important risk factors for falls [30], but were not found to be significant predictors of general falls in the present study, although age was found to be a significant predictor of a future forward fall. The modest association between age and real-world falls in the current study most likely reflects the characteristics of the included participants, who were all living independently in the community and with no co-morbidities that would affect their motor function. Older participants with substantial balance deficits were therefore excluded from the study. The finding that multiple steppers at the two higher lean magnitudes consisted a greater proportion of females compared with males and the tendency for female participants to have a greater odds of experiencing a future fall is consistent with our previous finding of generalised muscle weakness in this subgroup [13]. The absence of association between sex and falls in the presence of sex differences in balance recovery measures may therefore reflect sex differences in other factors such as risk exposure to falls by sex (e. g. activity limitation).

The main practical application of the findings from this study is that they provide support for the use of reactive stepping tasks in balance training programmes and falls risk assessments, although the specific nature of these tasks may need to be modified for the clinical environment, especially in terms of equipment required. The mini-BESTest [31] is a recently compiled assessment tool that focuses on dynamic balance, specifically anticipatory transitions, postural responses, sensory orientation and dynamic gait for falls risk. The results of the current study provide support for using tools such as the mini-BESTest for assessing falls risk, as it includes a specific component on compensatory stepping correction.

Conclusion

Reactive stepping behaviour in response to forward loss of balance significantly predicted a future fall, whereas measures associated with postural sway did not. These findings point to the possibility that exercise interventions designed to improve reactive stepping behaviour together with other known sensori-motor deficits such as lower extremity strength and power may protect against future falls.

Key points

- Reactive stepping ability predicted a future fall.
- Sex, postural sway and timed-up-and-go tests did not predict a future fall.
- Reactive stepping training may reduce falls risk in older adults.

Conflicts of interest

None declared.

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Effects of vertical and side-alternating vibration training on fall risk factors and bone turnover in older people at risk of falls

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Abstract

Background: whole-body vibration training may improve neuromuscular function, falls risk and bone density, but previous studies have had conflicting findings.
Objective: this study aimed to evaluate the influence of vertical vibration (VV) and side-alternating vibration (SV) on musculoskeletal health in older people at risk of falls.