Sensorimotor and neuropsychological correlates of force perturbations that induce stepping in older adults

Author:
Sturnieks, Daina; Menant, Jasmine; Vanrenterghem, Jos; Delbaere, Kim; Fitzpatrick, Richard; Lord, Stephen

Publication details:
Gait & Posture
v. 36
Chapter No. 3
pp. 356-360
0966-6362 (ISSN)

Publication Date:
2012

Publisher DOI:
http://dx.doi.org/doi:10.1016/j.gaitpost.2012.03.007

Sensorimotor and neuropsychological correlates of force perturbations that induce stepping in older adults

Abstract

Inappropriate stepping in response to unexpected balance perturbations is more prevalent in older people, and in those at risk of falling. This study examined responses to force-controlled waist pulls and sought to identify physiological and cognitive explanatory variables for the force threshold for stepping. 242 older (79.7±4.2 years) and 15 young (29.5±5.3 years) adults underwent waist pull perturbations and assessments of physiological and neuropsychological functioning, general health and falls efficacy. Perturbation force that induced stepping, stepping strategy and number of steps were measured. The older group withstood less forceful perturbations with a feet-in-place strategy, compared to young. Likewise, older adults with high falls risk withstood less force than those with low risk. After controlling for body weight and gender, sway and lower limb strength were independent predictors of anterior stepping thresholds, reaction time was an independent predictor of posterior thresholds, and executive functioning and lower limb strength were independent predictors of the lateral thresholds. These results suggest that balance, strength and agility training, in addition to cognitive exercises may enhance the ability to withstand unexpected balance perturbations and reduce the risk of falls in older people.

Introduction

The ability to move the base of support (BOS) by stepping in response to large balance perturbations is crucial to control balance and prevent falling. Appropriate stepping should be based on a sensory assessment of the state of the body and a 'decision' made with consideration of the individual's neuromuscular capacity. Numerous studies have found that inappropriate step responses are significantly more prevalent in older people, and in those at risk of falling[1,2].

Previous studies have identified biomechanical parameters leading to protective stepping, including time and distance boundaries, and factors associated with successful balance recovery such as joint torques and step timing. However, little is known of the physiological or psychological contributors to the stepping response. For example, a study employing displacement-controlled waist-pull perturbations to examine triggers of protective stepping[3], found that the stepping threshold was best described by the displacement of the centre of pressure of the body relative to the BOS (i.e. the physical properties of the body). While older subjects showed lower stepping thresholds than young, these thresholds did not correspond with participant's performance in tests of sensorimotor function. This may be due to the non-compliant perturbation delivered to achieve a specified velocity or displacement, i.e. a displacement-controlled perturbation will displace the body to the target endpoint irrespective of any effort made to resist it. In most real life situations, the level of force of the perturbation, as well as an individual's ability to produce an opposing force, should also influence the trigger to step.

Good vision, sensation, muscular strength and speed may facilitate stability in response to unexpected balance perturbations via accurate perception of perturbation direction and magnitude, and fast and coordinated motor responses to maximise recovery. Rogers and colleagues[4] have shown that older adults often step before they need to, so it is likely that cognitive factors also influence the stepping response. Increased levels of fear and poor executive function might also lead to earlier steps that truncate the necessary information regarding perturbation characteristics and result in premature and therefore inappropriate stepping responses.

This study aimed to identify whether stepping thresholds to force-controlled waist pulls, and stepping strategies in response to the threshold pull, differed between young and older people, and between older people at low and high risk of falls. This force-controlled perturbation differs from previous studies as it

enables an individual to mount an opposing force that can control the position of the body relative to the BOS. Additional aims were to examine whether larger stepping force thresholds were associated with better performances in tests of balance, muscle strength, reaction time, vision, sensation, executive functioning and falls efficacy.

Methods

Participants

Two hundred and forty-two community-dwelling older participants (132 men, 110 women, mean age 79.7 years, SD=4.2) were recruited from a larger longitudinal study of cognitive function and ageing (Sydney Memory & Ageing study)[5]. Fifteen young adults (8 men, 7 women with mean age 29.5 years, SD=5.3) were recruited as a comparison group for anterior and lateral perturbations from institute staff and students. Exclusion criteria were: insufficient English language skills; neurological, musculoskeletal or cardiovascular impairment affecting the assessments, and a Mini-Mental State Examination score of <24[6]. The study was approved by the University Human Research Ethics Committee and participants provided informed consent prior to participation.

Protocol

Participants underwent assessments of waist-pull balance perturbations and physiological performance. On a separate visit, older participants completed neuropsychological assessments. Older participants also completed a questionnaire regarding demographics, general health (12-item World Health Organization Disability Assessment Schedule - WHODAS II[7]), medication use, concern about falling and falls in the 12 months preceding the assessment.

Waist-pull balance perturbations

Participants wore comfortable footwear and stood relaxed with a hip-width stance, connected to a motor via cables extending from a belt fixed firmly around their pelvis, at the level of the anterior and posterior illiac spine (Figure 1). After a random interval, the motor applied a controlled force (verified with a force transducer connected in series with the cables) for 0.5 s in different directions (anterior, posterior, left, right). The profile of the perturbation force was 300 ms ramp up to target force, 200 ms hold and 100 ms ramp down. Subjects were told to try to maintain their balance and only step if necessary to prevent falling. Perturbation directions were block randomised by anterior/posterior and left/right (lateral) directions. An estimated perturbation threshold (E) was calculated with an equation derived from a pilot study of 30 people (aged 19-81 years),

which predicted stepping threshold from the participant's body weight (BW). For antero-posterior perturbations, E=(0.422*BW)+35.0. For lateral perturbations, E(N)=(0.1448*BW)-23.1. Perturbation forces were randomly presented at E-10N, E-5N, E, E+5N, E+10N. If a step was not induced during this first block, a block including increased forces (+15N, +20N) was presented randomly. This method was repeated until a step was induced. To ensure safety, participants wore a harness that did not restrict stepping movements. The lowest perturbation force at which a participant took a step was recorded as the force threshold for stepping and determined for anterior, posterior and lateral pulls. Since our pilot work found no significant difference between left and rightward pulls, lateral thresholds were defined as the lowest force to induce a step, regardless of side. The number of steps taken at the threshold pull for each direction was recorded, as well as the strategy used in response to lateral pulls: either cross- or side-step[8]. Posterior data were unavailable for the young group due to equipment problems.

Physiological performance

Physiological performance was assessed according to the short-form Physiological Profile Assessment (PPA), involving five measures of sensorimotor function, with validity and reliability established in previously[9]. 1) Vision was assessed using the Melbourne Edge Test of contrast sensitivity. 2) Proprioception was measured using a seated lower limb-matching task. With eyes closed, participants align their great toe either side of a vertical protractor (60x60x1cm). The average alignment error (degrees) from 5 trials was recorded. 3) Lower limb muscular strength was measured as the maximal (from two trials) isometric knee extension force (kg) with participants seated, knee flexed to 90deg and a custom-built strain gauge attached to the lower leg. 4) Reaction time involved a random-delay light stimulus and finger-press response. The average of 10 trials was recorded. 5) Postural sway was measured using a swaymeter that recorded displacements of the body at the level of the waist. Participants stood on a foam rubber mat (40x40x7.5cm) with eyes open. The number of millimetre squares traversed by the pen attached to the swaymeter in 30 s was recorded. In previous studies, weighted contributions from these five variables provide a falls risk score that can predict future multiple fallers with 75% accuracy in community-living populations[10,11]. In this study, participants were categorized as having low (PPA</=0.6) or high falls risk (PPA>0.6), based on a cut-point derived from a large prospective cohort study[12].

Psychological Assessments

Cognitive processing performance (executive function and processing speed) was recorded as time taken to complete the Trail Making Test Part B[13]. Participants draw lines connecting a number of circles alternating

between letters and numbers (1-A-2-B). Concern about falling was evaluated using the Falls Efficacy Scale International (FES-I)[14].

Statistical analysis

Statistical analyses were performed using SPSS PASW Statistics 18, with significance set at $p<0.05$. For variables with skewed distributions, data were log-normalised. Analyses of covariance (ANCOVA) were used to compare stepping thresholds between young and older adults, while controlling for body weight and height. In the older adult sample, 2x2 ANCOVAs were used to assess main effects of gender and falls risk group on the force thresholds for stepping, MMSE, PPA, FES-I and WHODAS measures, controlling for age, body weight and height. Between-group (gender and falls risk) differences in single and multiple step responses to the threshold pull were examined using Chi-square tests. Multivariate linear regression analyses (stepwise method after controlling for height, body weight and gender) were performed to identify independent and significant explanatory variables for force thresholds for stepping. Standardized (z) scores for lower limb strength, postural sway, proprioception, vision, speed, executive functioning and FES-I were entered into the model.

Results

Demographic and health characteristics, falls history, PPA and FES-I scores for the older adult group are presented in Table 1. The older participants averaged low to moderate risk of falls as indicated by PPA scores and reported a moderate concern about falling as indicated by FES-I. Of the 242 older adults, 132 (55%) were classified as being at higher risk of falls (PPA score>0.6), of whom were older ($F_{1,241}=35.434$, $p<0.001$), had lower body weight ($F_{1,241}=20.813$, $p<0.001$) and a greater proportion were female ($\chi^2_{1,242}=4.302$, $p=0.038$).

Force thresholds for stepping

Thresholds for stepping in the anterior, posterior and lateral directions are presented in Table 2. Significantly lower force thresholds for stepping were found in the older adults compared to young while controlling for body weight and height (anterior $F_{(1,254)}=22.1$, $p<0.001$; lateral $F_{(1,248)}=20.4$, $p<0.001$).

In the older population, the high falls risk group had significantly lower thresholds for stepping than the low falls risk group in anterior ($F_{1,240}=14.087$, $p<0.001$), posterior ($F_{1,237}=13.277$, $p<0.001$) and lateral ($F_{1,233}=8.478$, $p=0.004$) directions (Table 2). Females stepped with less forceful perturbation than males in

anterior ($F_{1,240}$=12.111, p=0.001), posterior ($F_{1,237}$=33.948, p<0.001) and lateral directions ($F_{1,233}$=37.000, p<0.001), with no significant gender by falls risk group interaction for anterior and lateral directions (p>0.073). In the posterior direction, there was a significant gender by falls risk group interaction ($F_{1,237}$=4.175, p=0.042) with all comparisons being significantly different in Bonferroni post-hoc tests (p<0.001).

Stepping strategy

In response to the lateral pull, the cross-step strategy was used in 68% of older adults and 61% of young adults ($\chi^2_{1,221}$=0.355, p=0.551). In response to their threshold anterior pull, 77% of older adults took one step, 19% took two steps and 4% took three or more steps (23% took multiple steps). In the posterior direction, 62% of older adults took one step, 33% took two steps and 5% took three or more steps (38% took multiple steps). In the lateral direction, 42% of older adults took one step, 42% took two steps and 15% took three or more steps (57% took multiple steps).

There were no significant differences in the proportions of participants who took multiple steps between the low and high falls risk groups for anterior ($\chi^2_{1,241}$=0.265,p=0.607), posterior ($\chi^2_{1,241}$=0.318,p=0.573) and lateral directions ($\chi^2_{1,241}$=1.076,p=0.300).

Sensorimotor and neuropsychological correlates

Results of the stepwise multivariate models predicting anterior, posterior and lateral force thresholds to stepping are presented in Table 3. After increased body weight and male gender, reduced sway and increased lower limb strength were independent predictors of larger anterior stepping thresholds. Faster reaction time was an independent predictor of larger posterior stepping thresholds. Improved executive function and increased lower limb strength were independent predictors of the larger lateral stepping thresholds. These models explained 39-54% of the variance in the stepping thresholds.

Discussion

This study examined responses to force-controlled waist pulls and sought to identify physiological and cognitive explanatory variables for the force threshold for stepping. The novel force perturbation method provided participants with an opportunity to utilize their sensorimotor and cognitive capabilities to mount an opposing force during the perturbation and maintain balance. Results showed that community-living older

adults can generate an opposing force of 6-10% of their body weight to withstand unexpected waist-pull perturbations, with larger forces inducing a step.

Older adults had lower force thresholds for stepping than young, after controlling for height and weight. Age-related sarcopenia, reduced sensory acuity, slowed central processing and motor reaction times may contribute to older adult's reduced ability to withstand perturbation forces. In response to balance perturbations, older adults have been shown to have slower muscle onset latencies[15,16], reduced early muscle activity[17,18] and slower step times[19], compared to younger adults. In addition, reduced absorption of perturbation energy by muscle[20] and increased stiffness in older adults may contribute to reduced stepping thresholds, by transferring more of the perturbation energy to moving the COM[21,22,17], an interesting area for further study.

As expected, body weight was closely related to the threshold for stepping, providing the largest amount of explanatory information in the regression analyses. Without an active response, lighter participants with less inertial resistance would experience greater accelerations (or larger displacements). Indeed, the initial range of perturbation forces were delivered around an estimated threshold, based on body mass, and few participants required a second series of forces to induce a step. In addition to body weight, this study found specific sensorimotor and neuropsychological variables to provide explanatory detail in predicting stepping thresholds. While these variables contributed independent information, their contributions were relatively small. Other factors that may have added additional information to stepping thresholds might include pain, attention and motivation.

After body weight and gender, balance and muscle strength contributed independent information to the anterior threshold for stepping. Balance involves the integration of sensory information to establish a necessary motor response for maintaining postural equilibrium, such that those with better balance performance are probably better able to respond to an unanticipated perturbation. Regarding muscle strength and presuming an inverted pendulum-like behaviour, the ankle plantar flexors are likely to be the main contributor to the reactive response, being the main muscle group to facilitate shear force development to withstand an anterior perturbation. Shear forces might also be generated by more proximal intersegmental moments. It is likely that many older adults are capable of producing large enough forces in response to anterior perturbations, but not in the time available before a step is mechanically required, or perceived to be required. This idea agrees with previous studies, notably Mackey and Robinovitch[23] who found strength

and speed deficits were associated with a poorer ability to recover balance from a leaning position. Another study found lower limb strength and volitional step reaction time was associated with the recovery from a trip [24]. Successful trip recovery has previously been attributed to faster development of mechanical responses[25,26,27] and together with the current findings, suggest that in addition to balance training, interventions to increase strength as well as the speed at which force is produced may improve resistance to anterior perturbations.

Reaction time provided independent information, after body weight and gender, in predicting the posterior stepping threshold. A fast response to a posterior perturbation is necessary to maintain balance with feet-in-place, before the COM travels the relatively short distance to the posterior border of the BOS at the heel, where a step is necessary to prevent falling. Although the perturbation response would involve different pathways than the non-postural simple reaction time task, these results suggest that older adults with faster simple reaction time are more likely to maintain feet-in-place for a given level of perturbation force in the posterior direction.

Muscle strength and executive functioning were independent predictors of lateral stepping thresholds. The relationship between stepping thresholds and muscular strength is probably associated with the ability to control the COM position following the perturbation. The significant relationship between cognitive performance and lateral stepping likely reflects the need to plan an appropriate response, as higher level processing is required for stepping strategy selection. Lateral perturbations load the limb that 'ideally' would step to increase or move the BOS. In responding to a lateral perturbation, the brain must assess the level and rate of loading, as well as the available strength and reaction speed. If balance cannot be maintained with feet-in-place, an appropriate strategy must be selected – that is, whether a postural adjustment can be made to unload the limb allowing for a step sideways, if not, move the opposite (unloaded) limb either in a small sidestep or crossover step. Cross-stepping with the unloaded limb often necessitates multiple subsequent steps to regain balance and increases the risk of limb collisions[8]. Sidestepping with the loaded limb is, therefore, the safer option, but requires a faster and more powerful response. The cognitive processes involved are reflected by the significant and independent association between executive functioning and lateral stepping thresholds. Previous studies have shown deteriorating balance performance with concurrent tasks that challenge executive functioning, particularly in older adults[28,29]. By asking young and older adults to do an additional task, while small postural perturbations were delivered, Maki and

colleagues[30] found an age-related delay in generating a response, which they suggested was contributed to by the deterioration in cognitive ability (switching attention) in older people.

A multiple step strategy is necessary when the first step is inadequate to arrest body momentum and restore balance[31]. Our proportion of older adults who required multiple steps was similar to previous studies[32,8], which have shown that the first step must be adequate in speed, length and power to maintain the COM within stable limits. Mille and colleagues[8] found a 6-fold increase in future falls in people who took multiple steps in all perturbation trials. We did not find any differences in multiple steps between the high and low falls risk groups, suggesting that physiological falls risk was not associated with the number of steps required to regain balance at the threshold force. This might be due to frailer participants choosing to step with a smaller magnitude of perturbation force.

Females stepped with smaller perturbation force than males, with gender being a significant predictor of anterior and lateral stepping thresholds, independent of body height, weight and muscular strength. This suggests that something other than gender-related height, weight and strength differences contributed to the increased perturbation force thresholds in males. It is possible that gender-differences in height-normalised COM position might contribute to force thresholds. Not measuring COM position was a limitation of the study.

Approximately 55% of the older adults in this study were categorised into a high falls risk group based on a PPA cutpoint of 0.6 established in previous research[12]. This high risk group withstood less force with feet-in-place, in response to unexpected anterior, posterior and lateral balance perturbations – factors that might partially account for their increased risk of falling. Future work, involving a prospective study of falls will identify whether force thresholds for stepping in response to unexpected balance perturbations can accurately predict fallers and provide an opportunity for intervention to prevent falls in older people.

References

1. McIlroy WE and Maki BE. Age-related changes in compensatory stepping in response to unpredictable perturbations. J Gerontol A Biol Sci Med Sci 1996;51(6):M289-296.

2. Rogers M, Hedman L, Johnson M, Cain T and Hanke T. Lateral stability during forward-induced stepping for dynamic balance recovery in young and older adults. J Gerontol A Biol Sci Med Sci 2001;56(9):M589-594.

3. Mille ML, Rogers MW, Martinez K, Hedman LD, Johnson ME, Lord SR and Fitzpatrick RC. Thresholds for inducing protective stepping responses to external perturbations of human standing. J Neurophysiol 2003;90(2):666-674.

4. Rogers MW, Hedman LD, Johnson ME, Martinez KM and Mille ML. Triggering of protective stepping for the control of human balance: age and contextual dependence. Brain Res Cogn Brain Res 2003;16(2):192-198.

5. Sachdev PS, Brodaty H, Reppermund S, Kochan NA, Trollor JN, Draper B, Slavin MJ, Crawford J, Kang K, Broe GA, Mather KA and Lux O. The Sydney Memory and Ageing Study (MAS): methodology and baseline medical and neuropsychiatric characteristics of an elderly epidemiological non-demented cohort of Australians aged 70-90 years. Int Psychogeriatr 2010;22(8):1248-1264.

6. Tombaugh TN and McIntyre NJ. The mini-mental state examination: a comprehensive review. J Am Geriatr Soc 1992;40(9):922-935.

7. Home page for the World Health Organization Disability Assessment Schedule II (WHODAS II). http://www.who.int/icidh/whodas/index.html aJ.

8. Mille ML, Johnson ME, Martinez KM and Rogers MW. Age-dependent differences in lateral balance recovery through protective stepping. Clin Biomech 2005;20(6):607-616.

9. Lord SR, Menz HB and Tiedemann A. A physiological profile approach to falls risk assessment and prevention. Phys Ther 2003;83(3):237-252.

10. Lord SR, Clark RD and Webster IW. Physiological factors associated with falls in an elderly population. J Am Geriatr Soc 1991;39(12):1194-1200.

11. Lord SR, Ward JA, Williams P and Anstey K. Physiological factors associated with falls in older community-dwelling women. J Am Geriatr Soc 1994;42(10):1110-1117.

12. Delbaere K, Close JC, Heim J, Sachdev PS, Brodaty H, Slavin MJ, Kochan NA and Lord SR. A multifactorial approach to understanding fall risk in older people. J Am Geriatr Soc 2010;58(9):1679-1685.

13. Strauss E, Sherman E and Spreen O (2006). A compendium of neuropsychological tests: Administration, norms, and commentary. New York, Oxford University Press.

14. Yardley L, Beyer N, Hauer K, Kempen G, Piot-Ziegler C and Todd C. Development and initial validation of the Falls Efficacy Scale-International (FES-I). Age Ageing 2005;34(6):614-619.

15. Woollacott MH, Shumway-Cook A and Nashner LM. Aging and posture control: changes in sensory organization and muscular coordination. Int J Aging Hum Dev 1986;23(2):97-114.

16. Hasson CJ, Caldwell GE and Van Emmerik RE. Scaling of plantarflexor muscle activity and postural time-to-contact in response to upper-body perturbations in young and older adults. Exp Brain Res 2009;196(3):413-427.

17. Allum JH, Carpenter MG, Honegger F, Adkin AL and Bloem BR. Age-dependent variations in the directional sensitivity of balance corrections and compensatory arm movements in man. J Physiol 2002;542(Pt 2):643-663.

18. Lin SI and Woollacott MH. Postural muscle responses following changing balance threats in young, stable older, and unstable older adults. J Mot Behav 2002;34(1):37-44.

19. Hsiao-Wecksler ET and Robinovitch SN. The effect of step length on young and elderly women's ability to recover balance. Clin Biomech 2007;22(5):574-580.

20. Hall CD and Jensen JL. Age-related differences in lower extremity power after support surface perturbations. J Am Geriatr Soc 2002;50(11):1782-1788.

21. Maki BE, Holliday PJ and Fernie GR. Aging and postural control. A comparison of spontaneous- and induced-sway balance tests. J Am Geriatr Soc 1990;38(1):1-9.

22. Gu MJ, Schultz AB, Shepard NT and Alexander NB. Postural control in young and elderly adults when stance is perturbed: dynamics. J Biomech 1996;29(3):319-329.

23. Mackey DC and Robinovitch SN. Mechanisms underlying age-related differences in ability to recover balance with the ankle strategy. Gait Posture 2006;23(1):59-68.

24. Smeesters C, Hayes WC and McMahon TA. The threshold trip duration for which recovery is no longer possible is associated with strength and reaction time. J Biomech 2001;34(5):589-595.

25. Thelen DG, Wojcik LA, Schultz AB, Ashton-Miller JA and Alexander NB. Age differences in using a rapid step to regain balance during a forward fall. J Gerontol A Biol Sci Med Sci 1997;52(1):M8-13.

26. Pavol MJ, Owings TM, Foley KT and Grabiner MD. Mechanisms leading to a fall from an induced trip in healthy older adults. J Gerontol A Biol Sci Med Sci 2001;56(7):M428-437.

27. Pijnappels M, Bobbert MF and van Dieen JH. How early reactions in the support limb contribute to balance recovery after tripping. J Biomech 2005;38(3):627-634.

28. Brauer SG, Woollacott M and Shumway-Cook A. The influence of a concurrent cognitive task on the compensatory stepping response to a perturbation in balance-impaired and healthy elders. Gait Posture 2002;15(1):83-93.

29. Woollacott M and Shumway-Cook A. Attention and the control of posture and gait: a review of an emerging area of research. Gait Posture 2002;16(1):1-14.

30. Maki BE, Zecevic A, Bateni H, Kirshenbaum N and McIlroy WE. Cognitive demands of executing postural reactions: does aging impede attention switching? Neuroreport 2001;12(16):3583-3587.

31. Pai YC, Rogers MW, Patton J, Cain TD and Hanke TA. Static versus dynamic predictions of protective stepping following waist-pull perturbations in young and older adults. J Biomech 1998;31(12):1111-1118.

32. Hsiao ET and Robinovitch SN. Elderly subjects' ability to recover balance with a single backward step associates with body configuration at step contact. J Gerontol A Biol Sci Med Sci 2001;56(1):M42-47.

Table 1: Demographic, health and falls characteristics of the older adult group

	Total n=242	Male n=132	Female n=110	Low Falls Risk n=110	High Falls Risk n=132
Mean (SD)					
Age (years)	79.7 (4.2)	80.1 (4.2)	79.3 (4.1)	78.3 (3.9)	81.4 (4.3)^
Height (m)	1.64 (0.09)	1.70 (0.07)	1.58 (0.07)*	1.66 (0.09)	1.63 (0.09)^
Weight (kg)	71.7 (13.4)	77.1 (11.4)	65.3 (12.7)*	75.4 (13.7)	68.0 (11.6)^
MMSE score [a]	28.4 (1.6)	28.3 (1.7)	28.6 (1.5)	28.9 (1.2)	28.1 (1.8)
PPA Falls risk score [b]	0.77 (0.93)	0.70 (0.95)	0.85 (0.90)	0.00 (0.49)	1.41 (0.68)^
Melbourne Edge Test	21.4 (1.7)	21.3 (1.7)	21.5 (1.7)	22.0 (1.4)	20.9 (1.7)^
Proprioception (deg)	2.48 (1.63)	2.46 (1.766)	2.49 (1.60)	1.95 (1.11)	2.92 (1.85)^
Muscle strength (kg)	30.4 (11.5)	36.0 (11.0)	23.6 (7.8)*	34.2 (11.3)	27.2 (10.6)^
Reaction time (ms)	230 (37)	226 (36)	235 (39)	210 (23)	247 (39)^
Postural sway (mm)	196 (96)	193 (101)	199 (90)	137 (42)	246 (100)^
FES-I score [c]	21.74 (5.3)	20.9 (5.0)	22.8 (5.5)*	21.2 (5.2)	22.2 (5.4)
WHODAS [d]	18.4 (6.2)	18.3 (7.1)	18.4 (5.1)	17.4 (5.7)	19.2 (6.6)
Number (%)					
Reported fear of falling	80 (33.1)	36 (27.3)	44 (40.0)	27 (24.5)	53 (40.2)
Previous faller	80 (33.1)	43 (32.6)	37 (28.0)	35 (31.8)	45 (34.1)
> 4 medications	137 (56.6)	76 (57.6)	61 (55.5)	58 (52.7)	79 (59.8)

a - Mini Mental State Examination score [6], score range 0-30.

b – Physiological Profile Assessment score (scores < 1 indicate a low or mild risk of suffering falls in the year following assessment) [9].

c – Falls Efficacy Scale – International [14], score range 16 (low concern) - 64 (high concern).

d - 12-item World Health Organization Disability Assessment Schedule - WHODAS II [7], score range 12-60.

* significantly different to Males ($p<0.05$)

^ significantly different to Low Falls Risk ($p<0.05$)

Table 2. Stepping thresholds (N) for the young and old, and old subgroups of males, females, low and high falls risk groups. Data presented as Mean (SD).

	Young n=15	Old n=242	Old Male n=132	Old Female n=110	Low Falls Risk n=110	High Falls Risk n=132
anterior	81.1 (17.6)	50.3 (14.0)$^{+}$	55.0 (13.2)	44.7 (11.4)*	55.8 (13.2)	45.9 (12.0)^
posterior	-	45.6 (12.2)	51.3 (12.4)	38.8 (10.2)*	50.9 (13.2)	41.4 (11.2)^
lateral	94.0 (21.5)	71.7 (21.4)$^{+}$	81.8 (18.9)	59.0 (17.1)*	79.5 (19.4)	65.0 (20.7)^

$^{+}$significantly different to Young while controlling for body weight and height ($p<0.05$)

*significantly different to Old Males while controlling for body weight and height ($p<0.05$)

^significantly different to Low Falls Risk while controlling for body weight and height ($p<0.05$)

Table 3. Results of stepwise multivariate regression models, predicting anterior, posterior and lateral force thresholds for stepping

Threshold	Model result	Significant predictors		Explained variance
Anterior	$F_{5,223}$=32.562, p<0.001	body weight	β=0.383, p<0.001	
		gender	β=-0.161, p=0.034	
		sway	β=-0.221, p<0.001	
		muscle strength	β=0.201, p=0.002	41%
Posterior	$F_{4,221}$=35.756, p<0.001	body weight	β=0.366, p<0.001	
		gender	β=-0.243, p=0.001	
		reaction time	β=-0.206, p<0.001	39%
Lateral	$F_{4,217}$=51.994, p<0.001	body weight	β=0.512, p<0.001	
		gender	β=-0.228, p=0.001	
		executive functioning	β=-0.126, p=0.010	
		muscle strength	β=0.137, p=0.015	54%

Figure 1. Waist-pull balance perturbation setup for lateral direction pull trials. Subjects were turned 90deg for anterior/posterior pull trials.