Age and Ageing 2003; **32:** 137–142 Age and Ageing Vol. 32 No. 2

Age-related differences in walking stability

HYLTON B. MENZ, STEPHEN R. LORD, RICHARD C. FITZPATRICK

Prince of Wales Medical Research Institute, High Street, Randwick, New South Wales 2031, Australia

Address correspondence to: H. B. Menz. Fax: (+61) 2 9382 2722. Email: h.menz@unsw.edu.au

Abstract

Background: a large proportion of falls in older people occur when walking; however the mechanisms underlying impaired balance during gait are poorly understood.
Objective: to evaluate acceleration patterns at the head and pelvis in young and older subjects when walking on a level and an irregular walking surface, in order to develop an understanding of how ageing affects postural responses to challenging walking conditions.
Methods: temporo-spatial gait parameters and variables derived from acceleration signals were recorded in 30 young people aged 22–39 years (mean 29.0, SD 4.3), and 30 older people with a low risk of falling aged 75–85 years (mean 79.0, SD 3.0) while walking on a level and an irregular walking surface. Subjects also underwent tests of vision, sensation, strength, reaction time and balance.
Results: older subjects exhibited a more conservative gait pattern, characterised by reduced velocity, shorter step length and increased step timing variability. These differences were particularly pronounced when walking on the irregular surface. The magnitude of accelerations at the head and pelvis were generally smaller in older subjects; however the smoothness of the acceleration signals did not differ between the two groups. Older subjects performed worse on tests of vision, peripheral sensation, strength, reaction time and balance.
Conclusion: the adoption of a more conservative basic gait pattern by older people with a low risk of falling reduces the magnitude of accelerations experienced by the head and pelvis when walking, which is likely to be a compensatory strategy to maintain balance in the presence of age-related deficits in physiological function, particularly reduced lower limb strength.

Keywords: *gait, balance, accelerometry, obstacle, accidental falls*

Introduction

It is now well established that a large proportion of falls in older people occur when walking [1, 2], and several cross-sectional studies have revealed significant changes in gait patterns associated with advancing age. The most consistent finding of these studies is that older people walk more slowly than young people [3–9]. This has been found to be a function of both a shorter step length [7, 8, 10] and increased time spent in double limb support [8, 11, 12]. These age-related changes in walking patterns have generally been interpreted as indicating the adoption of a more conservative, or less destabilising gait [13–15], suggesting that older people compensate for their reduced physical capabilities by being more cautious [16].

However, the gait changes that are thought to represent the adoption of a more stable walking pattern have also been shown to be risk factors for falls in prospective studies [3, 17–23]. This paradox arises because temporo-spatial gait parameters provide only indirect measures of stability, and therefore provide limited insights into the maintenance of balance when walking. Although it appears that reduced walking speed is a compensatory strategy to maintain balance, the fact that some older people who adopt this strategy are nevertheless still likely to suffer from falls suggests that there is another aspect of their gait that predisposes to an increased likelihood of a loss of balance when walking.

In a previous study, we reported that the measurement of acceleration patterns of the head and pelvis could be used as an indicator of whole body balance when walking on different surfaces, and that an individual's self-selected walking speed is optimal in relation to minimising the variability of head and pelvis movements [24]. The purpose of this study was to determine whether acceleration patterns when walking at a self-selected speed differ between young people and older people, thereby providing insights into the compensatory strategies adopted by older people to maintain balance in the presence of reduced physiological capabilities. We specifically selected older people with a low risk of falling, as although these subjects exhibit normal age-related declines in the major physiological systems that contribute to stability, their physiological abilities are sufficiently high to prevent recurrent falls. We hypothesised that older people with a low risk of falling have similar head and pelvis stability to younger adults, but that this is associated with significant reductions in walking speed.

Methods

Subjects

The young subject group comprised of 30 healthy volunteer subjects (11 men, 19 women) ranging in age from 22–39 years (mean 29.0, SD 4.3). None had any history of neurological or orthopaedic conditions likely to affect their balance or mobility. The older subject group comprised 30 people (8 men, 22 women) aged 75–85 years (mean 79.9, SD 3.0) who were recruited from the community as part of a larger randomised controlled trial of tailored falls prevention strategies. Subjects were excluded from the study if they had Parkinson's disease or a Short Portable Mental Status Questionnaire (SPMSQ) score <7 [25]. The 30 older subjects were selected based on their performances on a physiological profile assessment that includes tests of visual acuity, contrast sensitivity, depth perception, vibration sense, proprioception, knee extension and ankle dorsiflexion strength, reaction time and balance. Descriptions of the apparatus and procedures for these tests, and their test-retest reliability scores have been reported elsewhere [26–28]. This series of physiological tests have been found to predict those at risk of falling with 75% accuracy in both community and institutional settings [29, 30]. After performing each of the tests, an overall falls risk score was calculated. The score is a single index derived from a discriminant function analysis based on data from large population studies [31, 32]. The subjects with the lowest falls risk score were selected for inclusion in the study. The Human Studies Ethics Committee at the University of New South Wales gave approval for this study, and informed consent was obtained from all subjects prior to their participation.

Gait analysis

Linear accelerations of the body were measured along three orthogonal axes (vertical, antero-posterior and medio-lateral) using two tri-axial piezo-resistant accelerometers, one mounted on the top of a lightweight foam bicycle helmet and the other affixed to a belt at the level of the sacrum. The accelerometers were connected to a lightweight laptop computer via a data acquisition card interface and both were housed in a small backpack. The entire apparatus weighed 2.5 kg. All subjects were provided with appropriately sized Oxford-style lace-up shoes.

A 20-m long by 1.5-m wide walkway was constructed to provide a partially yielding, irregular walking surface. The walkway consisted of a 5-mm pile of artificial grass underlain with two layers of 20-mm thick soft foam rubber and 20-mm thick wooden blocks of varying sizes and shapes in an arbitrary manner. Two markings were made on the walkway 15 m apart to designate the trial distance. Participants were also tested on a level corridor. A diagrammatic representation of a subject undertaking the test is shown in Figure 1.

Subjects were instructed to walk at their normal comfortable walking speed. Two trials of each surface condition were performed in a randomised order. Full descriptions of the data processing protocol, the derivation of acceleration variables and test-retest reliability have been described previously [24]. The following variables were calculated from the acceleration signals:

i. Walking velocity (m/s)
ii. Cadence (steps/min)
iii. Average step length (cm)
iv. Step timing variability
v. Acceleration root mean square (RMS)
vi. Harmonic ratio of acceleration signals

The harmonic ratio provides an indicator of the 'smoothness' and rhythm of the acceleration signal, with higher ratios representing a more stable walking pattern [24].

Statistical analysis

All analyses were performed using SPSS Release 10 for Windows (SPSS Inc, Chicago, USA). All data were explored for normal distribution. Variables with positively skewed distributions were $\log_{10}$ transformed prior to inferential analysis. Differences in the physiological tests between the young and old groups were assessed using independent *t*-tests. For the gait variables, a series of two-way repeated measures ANOVAs was used to evaluate the effect of subject age group (young or old) and walking surface (level or irregular). Following the determination of a significant main effect for subject age-group, a series of pair-wise comparisons were performed to assess for differences between the two groups using a series of Bonferroni-adjusted *t*-tests on the level and irregular walking speed data. A *P*-value of <0.025 was required for differences to be considered statistically significant. Associations between each of the physiological tests and the basic gait parameters were evaluated using Pearson's *r* correlation coefficient.

Results

Subject characteristics

The young subjects were taller (171.3 ± 7.8 *vs* 161.8 ± 9.3 cm, $t_{58} = -4.3$, $P < 0.001$) than the old subjects. There was no significant difference between the groups

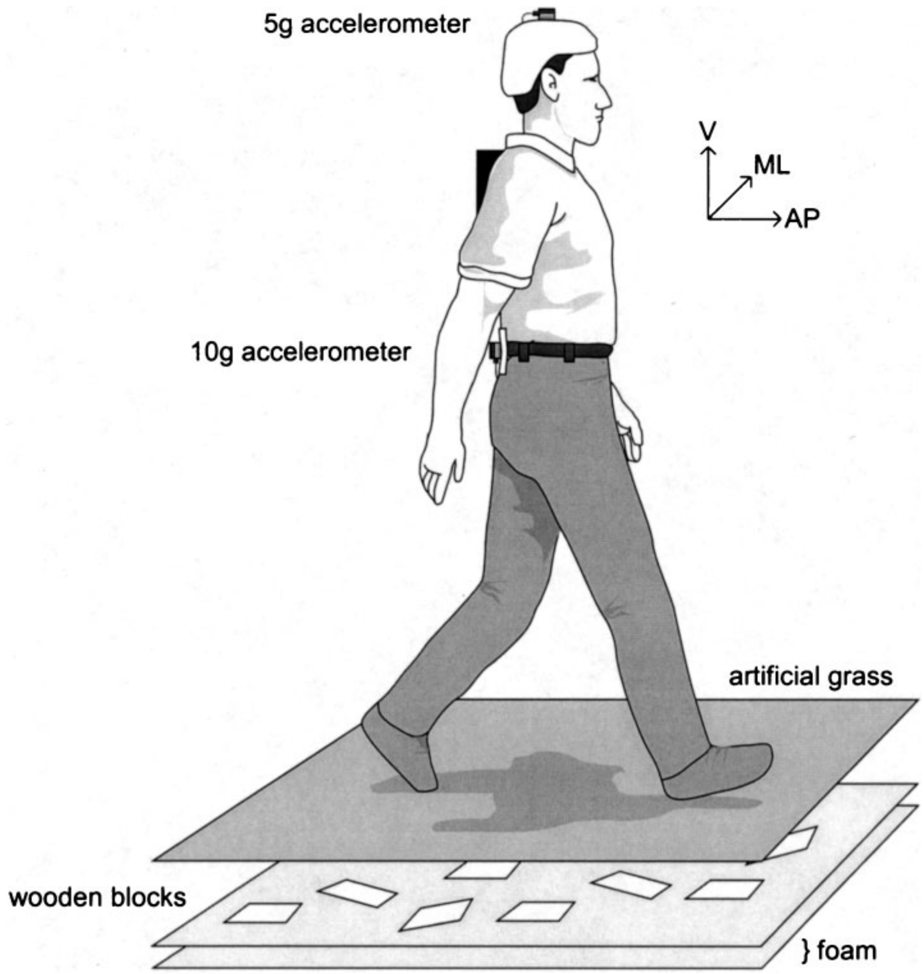

Figure 1. Testing procedure.

with respect to bodyweight (67.3 ± 11.6 *vs* 65.8 ± 12.7 kg, $t_{58} = -0.4$, $P = 0.635$), however the younger subjects had a lower body mass index (22.9 ± 3.4 *vs* 25.1 ± 3.9, $t_{58} = 2.3$, $P = 0.023$).

Differences in physiological assessment tests between young and old subjects

The old subjects had significantly poorer visual acuity (both high- and low-contrast), contrast sensitivity, depth perception, vibration sense, ankle dorsiflexion strength and quadriceps strength, exhibited greater sway on the foam with eyes closed and made more errors on the coordinated stability test. The overall falls risk score was significantly higher in the older subjects (see Table 1).

Differences in temporo-spatial gait parameters between young and old subjects

There were significant age-group effects for velocity ($F_{2,1} = 16.55$, $P < 0.001$), step length ($F_{2,1} = 24.30$, $P < 0.001$) and step timing variability ($F_{2,1} = 21.82$, $P < 0.001$). There were significant age-group-walking surface interaction effects for velocity ($F_{2,1} = 8.05$, $P = 0.006$) and step length ($F_{2,1} = 9.58$, $P = 0.003$). The old subjects exhibited slower velocity, shorter step length and greater step timing variability on both walking surfaces (see Table 2).

Differences in acceleration RMS between the young and old subjects

There were significant group effects for acceleration RMS at the pelvis in the vertical ($F_{2,1} = 16.05$, $P < 0.001$), antero-posterior ($F_{2,1} = 14.14$, $P < 0.001$) and medio-lateral ($F_{2,1} = 11.13$, $P = 0.001$) planes, and at the head in the vertical ($F_{2,1} = 11.44$, $P = 0.001$) and medio-lateral ($F_{2,1} = 4.35$, $P = 0.041$) plane. There were significant age-group-walking surface interaction effects for acceleration RMS at the pelvis in the antero-posterior ($F_{2,1} = 9.45$, $P = 0.003$) and medio-lateral ($F_{2,1} = 6.25$, $P = 0.015$) plane, and at the head in antero-posterior ($F_{2,1} = 7.56$, $P = 0.008$) planes. The paired *t*-tests revealed that older subjects exhibited significantly smaller acceleration RMS values at the pelvis in all three planes and at the head in the

Table 1. Physiological assessment comparisons between young and old subjects

	Young	Old
Visual acuity – high contrast[a]	0.66 (0.16)	1.13 (0.34)
Visual acuity – low contrast[a]	0.90 (0.23)	2.16 (0.64)**
Contrast sensitivity[b]	23.55 (0.74)	20.17 (2.17)**
Depth perception[c]	4.61 (3.80)	19.49 (34.24)**
Vibration sense[d]	3.04 (2.04)	38.99 (27.29)**
Proprioception[e]	1.03 (0.72)	1.37 (1.15)
Ankle dorsiflexion strength[f]	14.02 (3.47)	9.79 (3.65)**
Knee extension strength[f]	60.79 (21.44)	32.53 (13.57)**
Reaction time[g]	226.53 (23.87)	237.57 (23.38)
Sway on floor – eyes open[h]	46.20 (19.60)	56.60 (17.75)
Sway on floor – eyes closed[h]	56.20 (23.42)	87.73 (13.53)
Sway on foam – eyes open[h]	135.70 (49.23)	115.43 (39.69)
Sway on foam – eyes closed[h]	212.73 (71.87)	264.33 (127.67)**
Coordinated stability[i]	0.40 (0.86)	3.10 (3.79)**
Falls risk score[j]	−0.22 (0.70)	0.18 (0.35)**

Significant difference at $P<0.05$. **Significant difference at $P<0.01$.
[a]Smallest visual angle (minutes) correctly reported at 3 m.
[b]Decibel log contrast.
[c]Difference in matching rods (mm).
[d]Microns of motion perpendicular to body surface.
[e]Difference in matching position of lower limbs (degrees).
[f]Strength measured in kilograms.
[g]Simple finger press reaction time measured in milliseconds.
[h]Millimetre squares traversed by pen on swaymeter in 30 s.
[i]Number of errors.
[j]Single index score derived from discriminant function analyses.
NB: High scores on 1, 3, 4, 5, 7, 8, 9 and 10 and low scores on 2 and 6 indicate impaired performance.

Table 2. Temporo-spatial gait parameters for young and old subjects

	Young	Old
Velocity		
Level surface	1.33 (0.19)	1.17 (0.16)**
Irregular surface	1.34 (0.21)	1.11 (0.18)**
Cadence		
Level surface	103.31 (7.30)	107.97 (8.20)
Irregular surface	104.87 (8.17)	101.50 (8.93)
Step length		
Level surface	73.34 (7.85)	65.13 (7.12)**
Irregular surface	76.27 (8.30)	65.54 (7.06)**
Step timing variability		
Level surface	0.03 (0.02)	0.05 (0.02)
Irregular surface	0.04 (0.02)	0.05 (0.01)**

*Significant difference at $P<0.025$. **Significant difference at $P<0.010$.

vertical plane when walking on both surfaces (see Table 3).

Differences in harmonic ratios between the young and old subjects

There were no significant age-group effects for harmonic ratios at the pelvis or head on either walking surface (see Table 4).

Table 3. Acceleration RMS for young and old subjects

	Young	Old
Level surface		
Pelvis		
Vertical	0.26 (0.07)	0.20 (0.05)**
Antero-posterior	0.19 (0.04)	0.17 (0.03)**
Medio-lateral	0.19 (0.05)	0.16 (0.05)*
Head		
Vertical	0.21 (0.06)	0.17 (0.05)**
Antero-posterior	0.17 (0.05)	0.15 (0.04)
Medio-lateral	0.11 (0.04)	0.13 (0.03)**
Irregular surface		
Pelvis		
Vertical	0.29 (0.08)	0.22 (0.06)**
Antero-posterior	0.25 (0.05)	0.20 (0.04)**
Medio-lateral	0.26 (0.07)	0.12 (0.05)**
Head		
Vertical	0.23 (0.06)	0.17 (0.05)**
Antero-posterior	0.17 (0.05)	0.18 (0.04)
Medio-lateral	0.12 (0.06)	0.13 (0.03)

*Significant difference at $P<0.025$. **Significant difference at $P<0.010$.
NB. Higher values represent larger magnitude accelerations.

Table 4. Harmonic ratios for young and old subjects

	Young	Old
Level surface		
Pelvis		
Vertical	2.93 (1.16)	3.07 (0.08)
Antero-posterior	3.36 (1.32)	3.55 (1.08)
Medio-lateral	2.05 (0.75)	2.06 (0.71)
Head		
Vertical	3.57 (1.32)	3.62 (1.05)
Antero-posterior	2.35 (0.89)	2.16 (0.59)
Medio-lateral	2.48 (1.13)	2.73 (0.85)
Irregular surface		
Pelvis		
Vertical	2.24 (0.83)	2.22 (0.57)
Antero-posterior	2.49 (0.84)	2.50 (0.71)
Medio-lateral	1.52 (0.48)	1.43 (0.29)
Head		
Vertical	2.72 (0.99)	2.60 (0.77)
Antero-posterior	1.69 (0.62)	1.67 (0.53)
Medio-lateral	2.10 (0.79)	2.29 (0.68)

NB. Higher values represent smoother, more rhythmic acceleration patterns.

Associations between physiological tests and temporo-spatial gait parameters

Walking speed and step length were strongly associated with quadriceps strength and ankle dorsiflexion strength in the older subjects, however the associations between these variables were generally not as strong in the young group (see Table 5).

Discussion

The physiological test battery used in this study enables the identification of deficits in each of the major physiological systems that contribute to balance [26]

Table 5. Associations between velocity, step length and lower limb strength for young and old subjects

	Velocity		Step length	
	Level	Irregular	Level	Irregular
Young				
Quadriceps	0.19	0.34	0.32	0.42*
Ankle dorsiflexion	0.21	0.40*	0.32	0.41*
Old				
Quadriceps	0.41*	0.42*	0.56**	0.55**
Ankle dorsiflexion	0.39*	0.33	0.52**	0.51**

*$P<0.05$.

**$P<0.01$.

and gait [8]. The older subjects in this study exhibited significantly reduced vision, peripheral sensation, lower limb strength and reaction time compared to the younger subjects, which is consistent with previous applications of these tests in large community samples [32]. However, we specifically selected older people with the best test performances from our total sample. The falls risk score of our selected sample group was 0.18, representing a low risk of falling compared to age-matched controls from large community studies [29–31]. These subjects therefore represent a group with a relatively higher level of functioning compared to age-matched controls, and could therefore be considered to exhibit 'optimal' gait and mobility for their age.

Compared to the younger group, older subjects exhibited significantly reduced velocity, step length and increased step timing variability. These results are consistent with previous reports [3–10, 33] and represent the characteristically 'cautious' gait pattern commonly observed in older people. However, of particular interest is that these differences were more pronounced when walking on the irregular surface, indicating that the older subjects may have perceived this condition as a greater threat to their stability, and subsequently adopted an even more conservative gait pattern than when walking on level ground.

The acceleration data provides a more direct indication of stability when walking than the temporo-spatial gait parameters. Acceleration root mean square (RMS) was generally smaller in the older subjects. Previously, we have reported that when subjects are instructed to walk at a range of speeds from very slow to very fast, acceleration RMS increases in an exponential manner [24]. Therefore, the reduced magnitude of accelerations in the older subjects can be attributed to their reduced walking speed, and it is possible that older people adopt this slower speed to keep the magnitude of head and pelvis accelerations at a tolerable level. However, antero-posterior and medio-lateral accelerations at the head did not differ between the two groups when walking on the irregular surface, suggesting that the older subjects may have some difficulty in attenuating head accelerations when walking.

Despite their impaired physiological capabilities, the older subjects exhibited the same degree of 'smoothness' in their acceleration patterns, as evidenced by the lack of differences between the two groups with regard to the harmonic ratios. Previous studies have shown that older people with balance problems have smaller harmonic ratios than those without balance difficulties [34]. Given that this variable is a useful indicator of overall gait stability [24, 34], it can be concluded that the older people in this study had similar head and pelvis stability to the younger group, despite their relative deficits in physiological abilities.

Overall, these results indicate that the conservative basic gait pattern evident in older people may be a compensatory strategy to ensure adequate stabilisation of the head and pelvis. The significant associations between lower limb strength, velocity and step length are consistent with previous studies [8, 35], and indicate that the normal age-related decline in leg strength may be the primary limiting factor that prevents older people from walking at an equivalent speed to younger people. However, as walking speed and step length can be modified by cognitive influences, it is also likely that the gait patterns observed in older people are partly due to a reluctance rather than an inability to walk more quickly. This is supported by the observation of reduced speed when walking on the irregular surface – a more challenging condition that may induce a more hesitant gait pattern due to fear of tripping and falling.

In conclusion, this study has shown that older people with a low risk of falling modify their basic gait pattern to ensure that their head and pelvis remain stable. Thus, in older people with optimum physiological abilities, adopting a reduced velocity and shorter step length is unlikely to increase risk of falls when walking.

Key points

- Old people adopt a more conservative gait pattern than young people, characterised by reduced velocity and step length, and increased step timing variability.
- The magnitude of accelerations at the head and pelvis are smaller in older people, however the smoothness of acceleration patterns is very similar.
- Adopting a more conservative gait pattern may be a compensatory strategy to ensure that the head and pelvis remain stable, thereby reducing the likelihood of falls when walking.

Acknowledgements

This project was funded by the NHMRC Health Research Partnerships Grant: *Prevention of Injuries in Older People*. We acknowledge Susan Murray, Kirsten Chapman, Bridget Munro and Anne Tiedemann for conducting the physiological tests, and Dr Susan Ogle, Head of the Aged Care and Rehabilitation Department, for the use of the testing facilities at the Royal North Shore Hospital.

References

1. Cali CM, Kiel DP. An epidemiologic study of fall-related fractures among institutionalized older people. J Am Geriatr Soc 1995; 43: 1336–40.

2. Norton R, Campbell AJ, Lee-Joe T, Robinson E, Butler M. Circumstances of falls resulting in hip fractures among older people. J Am Geriatr Soc 1997; 45: 1108–12.

3. Imms FJ, Edholm OG. Studies of gait and mobility in the elderly. Age Ageing 1981; 10: 147–56.

4. Cunningham DA, Rechnitzer PA, Pearce ME, Donner AP. Determinants of self-selected walking pace across ages 19 to 66. J Gerontol 1982; 37: 560–4.

5. O'Brien M, Power K, Sanford S, Smith K, Wall J. Temporal gait patterns in healthy young and elderly females. Physiother Can 1983; 35: 323–6.

6. Hagemon PA, Blanke DJ. Comparison of gait of young women and elderly women. Phys Ther 1986; 66: 1382–7.

7. Oberg T, Karsznia A, Oberg K. Basic gait parameters: reference data for normal subjects, 10–79 years of age. J Rehabil Res Dev 1993; 30: 210–23.

8. Lord SR, Lloyd DG, Li SK. Sensori-motor function, gait patterns and falls in community-dwelling women. Age Ageing 1996; 25: 292–9.

9. Bohannon RW. Comfortable and maximum walking speed of adults aged 20–79 years: reference values and determinants. Age Ageing 1997; 26: 15–9.

10. Elble RJ, Thomas SS, Higgins C, Colliver J. Stride-dependent changes in gait of older people. J Neurol 1991; 238: 1–5.

11. Ferrandez A-M, Pailhous J, Durup M. Slowness in elderly gait. Exp Aging Res 1990; 16: 79–89.

12. Winter DA, Patla AE, Frank JS, Walt SE. Biomechanical walking pattern changes in the fit and healthy elderly. Phys Ther 1990; 70: 340–7.

13. Sudarsky L. Geriatrics: gait disorders in the elderly. New Eng J Med 1990; 322: 1441–6.

14. Winter DA, Patla AE, Frank JS, Walt SE. Biomechanical walking patterns in the fit and healthy elderly. Phys Ther 1990; 70: 340–7.

15. Woollacott MH, Tang P-F. Balance control during walking in the older adult: research and its implications. Phys Ther 1997; 77: 646–60.

16. Maki BE. Gait changes in older adults: predictors of falls or indicators of fear? J Am Geriatr Soc 1997; 45: 313–20.

17. Guimaraes RM, Isaacs B. Characteristics of the gait in old people who fall. Int J Rehabil Med 1980; 2: 177–80.

18. Luukinen H, Koski K, Laippala P, Kivela S-L. Risk factors for recurrent falls in the elderly in long-term institutional care. Public Health 1995; 109: 57–65.

19. Dargent-Molina P, Favier F, Grandjean H *et al.* Fall-related factors and risk of hip fracture: the EPIDOS prospective study. Lancet 1996; 348: 145–9.

20. Ho SC, Woo J, Chan SS, Yuen YK, Sham A. Risk factors for falls in the Chinese elderly population. J Gerontol 1996; 51: M195–8.

21. VanSwearingen JM, Paschal KA, Bonino P, Yang JF. The modified Gait Abnormality Rating Scale for recognizing the risk of recurrent falls in community-dwelling elderly adults. Phys Ther 1996; 76: 994–1002.

22. Woolley SM, Czaja SJ, Drury CG. An assessment of falls in elderly men and women. J Gerontol 1997; 52A: M80–87.

23. Gunter K, White K, WC WH, Snow C. Functional mobility discriminates nonfallers from one-time and frequent fallers. J Gerontol 2000; 55: M672–6.

24. Menz HB, Lord SR, Fitzpatrick RC. Acceleration patterns of the head and pelvis when walking on level and irregular surfaces. Gait Posture 2003 (in press).

25. Pfieffer E. A short portable mental status questionnaire for the assessment of organic brain deficit in elderly patients. J Am Geriatr Soc 1975; 23: 433–41.

26. Lord SR, Clark RD, Webster IW. Postural stability and associated physiological factors in a population of aged persons. J Gerontol 1991; 46: M69–76.

27. Lord SR, Dayhew J. Visual risk factors for falls in older people. J Am Geriatr Soc 2001; 49: 508–12.

28. Lord SR, Ward JA, Williams P. Exercise effect on dynamic stability in older women: a randomised controlled trial. Arch Phys Med Rehabil 1996; 77: 232–6.

29. Lord SR, Clark RD, Webster IW. Physiological factors associated with falls in an elderly population. J Am Geriatr Soc 1991; 39: 1194–200.

30. Lord SR, Ward JA, Williams P, Anstey K. Physiological factors associated with falls in older community-dwelling women. J Am Geriatr Soc 1994; 42: 1110–7.

31. Lord SR, Sambrook PN, Gilbert C *et al.* Postural stability, falls and fractures in the elderly: results from the Dubbo Osteoporosis Epidemiology Study. Med J Aust 1994; 160: 684–91.

32. Lord SR, Ward JA. Age-associated differences in sensori-motor function and balance in community dwelling women. Age Ageing 1994; 23: 452–60.

33. Hausdorff JM, Edelberg HK, Mitchell SL, Goldberger AL, Wei LY. Increased gait unsteadiness in community-dwelling elderly fallers. Arch Phys Med Rehabil 1997; 78: 278–83.

34. Yack HJ, Berger RC. Dynamic stability in the elderly: identifying a possible measure. J Gerontol 1993; 48: M225–30.

35. Buchner DM, Larson EB, Wagner EH, Koepsell TD, DeLateur BJ. Evidence for a non-linear relationship between leg strength and gait speed. Age Ageing 1996; 25: 386–91.

Received 24 May 2002; accepted in revised form 6 September 2002