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Foot and Ankle Characteristics Associated With Impaired Balance and Functional Ability in Older People

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Background. Ageing is associated with changes to the structure and function of the foot and ankle, and there is preliminary evidence that foot problems impair balance and increase the risk of falls. To explore this in more detail, we conducted a study to determine the relative contribution of several foot and ankle characteristics to performance on a range of balance and functional tests.

Methods. One hundred seventy-six people (56 men and 120 women, mean age 80.1 years, standard deviation 6.4 years) residing in a retirement village underwent tests of foot and ankle characteristics (including foot posture, range of motion, strength, and deformity), sensorimotor function (including vision, sensation, strength, and reaction time), and balance and functional ability (including tests of standing balance, leaning balance, stepping, sit-to-stand, and walking speed).

Results. Many foot and ankle characteristics and sensorimotor measures were associated with performance on the balance and functional tests in univariate analyses. Multiple regression analysis consistently revealed that ankle flexibility, plantar tactile sensitivity, and toe plantarflexor strength were significant and independent predictors of balance and functional test performance, explaining up to 59% of the variance in these test scores.

Conclusions. Foot and ankle characteristics, particularly ankle flexibility, plantar tactile sensation, and strength of toe plantarflexor muscles, are significant independent predictors of balance and functional ability in older people. Programs to improve the strength and flexibility of the foot and interventions to augment plantar sensation may be beneficial in improving mobility and reducing the risk of falls.

MAINTAINING balance and performing functional tasks depend on the interaction of multiple sensory, motor, and integrative systems. These systems include vision, vestibular function, peripheral sensation, strength, and reaction time (1). Functioning of each of these factors declines with age (2). By directly assessing an individual's physiological abilities, impairments in one or more physiological domains can be identified and their contribution to physical ability can be determined. In previous studies, this approach has been used to examine the relative contribution of sensorimotor factors to balance (3), functional ability (4,5), and risk of falling (1). However, there are a number of factors not included in this conceptual model. In particular, it is likely that foot problems have a detrimental effect on mobility that is independent of the influence of these factors.

Foot problems are reported by approximately 30% of community-dwelling older people (6–8), and are associated with reduced walking speed (7), difficulty in performing activities of daily living (7,9), and increased risk of falls (10–12). Despite the recognition of the detrimental effect of foot problems on mobility, the mechanism by which foot problems increase risk of falling has not been explored in detail. As the only source of direct contact with the ground during weight-bearing tasks, the foot contributes to the maintenance of stability in two main ways: (i) by providing mechanical support for the body via the osteoligamentous architecture of the arch and the coordinated function of lower limb muscles, and (ii) by the provision of sensory information regarding body position from plantar tactile mechanoreceptors. It is therefore likely that deficits in foot posture, flexibility, strength, or sensation impair this support function and predispose to loss of balance.

We have previously demonstrated that an overall measure of foot impairment based on the observation of foot lesions and structural deformities was significantly and independently associated with performance on clinical tests of balance and functional ability (13). However, very little is known about whether foot posture, range of motion (ROM), sensation, and strength may influence mobility. There is some evidence that excessively flat feet (14) or highly arched feet (15) may impair standing balance in healthy young persons, and a significant association between ankle ROM and balance has been reported in older women (16).

The aim of this study was to build on previous work to determine whether a broader range of tests of foot characteristics are significant determinants of balance and functional ability in a sample of older people. In particular, we were interested to ascertain whether these tests are capable of explaining additional variance in balance and functional performance after well established sensorimotor factors are considered.

Methods

Participants

The study sample comprised 176 people (56 men and 120 women) aged 62–96 years (mean 80.1 years, standard deviation = 6.4) who were residing in a retirement village. One hundred fifty-five resided in independent living units, and 21 resided in serviced apartments. Residents in serviced

Table 1. Prevalence of Major Medical Conditions, Medication Use, Participation in Physical Activity, and Mobility and ADL Limitations in Study Population

Condition	No. (%)
Medical conditions	
Heart condition	61 (34.7)
Poor vision	44 (25)
Stroke	9 (5.1)
Osteoarthritis	133 (75.6)
Diabetes	19 (10.8)
Incontinence	29 (16.5)
Medication use	
Cardiovascular medications	124 (70.5)
Psychoactive medications	45 (25.6)
Musculoskeletal medications	28 (15.9)
More than four medications	115 (65.3)
Physical activity	
Planned walks <1 day/wk	72 (40.9)
Incidental physical activity <1 h/day	34 (19)
Mobility and ADL limitations	
Occasionally use a walking aid	44 (25)
Difficulty with housework	89 (50.6)
Difficulty shopping	36 (20.5)
Difficulty cooking	30 (17)

apartments attended a communal dining room for all meals and had their rooms maintained by staff; however, all were independent in dressing, bathing, and toileting (Table 1). Residents were deemed ineligible for the study if they were unable to ambulate household distances without an assistive device or scored <7 on the Short Portable Mental Status Questionnaire (17). The participation rate was 54%. Age and sex data were available for nonresponders. Nonresponders were of similar age (80.1 years, standard deviation = 7.3) and gender (38% men) to participants. The Human Studies Ethics Committee at La Trobe University approved the study, and informed consent was obtained from all persons prior to their participation.

Foot and Ankle Characteristics

Foot and ankle characteristics were tested across five domains: foot posture, foot ROM, foot deformity and lesions, foot strength, and foot sensation. Foot posture was assessed using the foot posture index (18), arch index (19), and navicular height (20). Navicular height was corrected for differences in foot size by dividing it by the length of the foot (20). Ankle flexibility was measured in degrees using a modified version of the weightbearing lunge test (20). Participants rested their hand on a bench placed alongside them at waist height to reduce the demands for balance control when undertaking the test. First metatarsophalangeal joint (1st MPJ) ROM was measured in a nonweightbearing position with a goniometer while the examiner maximally extended the hallux (21). Foot deformity was evaluated by documenting the presence of hallux valgus, lesser toe deformities, corns, and calluses. The presence and severity of hallux valgus was determined using the Manchester scale (22). An overall measure of hallux valgus severity was determined by summing the scores for right and left feet. Presence of lesser digital deformity, corns, and calluses was determined according to previously published criteria (23), and a sum of the total number of each of these abnormalities for both feet was documented. The strength of the plantarflexor muscles of the hallux and lesser toes was determined using the paper grip test (24). Tactile sensitivity of the 1st MPJ was evaluated using an aesthesiometer using a two-alternative forced choice protocol (1). Reliability coefficients for each of these tests when performed by older people are reported elsewhere (20).

Sensorimotor Function Assessment

Sensorimotor function was assessed across four domains: vision (visual acuity and contrast sensitivity), sensation (tactile sensitivity of the lateral malleolus and proprioception), strength (knee extension and ankle dorsiflexion), and finger-press reaction time. Descriptions of the apparatus and procedures for these tests and their test–retest reliability are reported elsewhere (1).

Balance and Functional Assessment

The balance and functional tests are shown in Figure 1. Postural sway was measured using a sway meter that measured displacements of the body at the level of the waist (1). Testing was performed with participants, with eyes open, standing on the floor and on a medium-density foam rubber mat. Leaning balance was measured using the maximum balance range test and coordinated stability tests (25). Functional ability was evaluated using the alternate stepping test (the time taken to alternately place each foot on a 19 cm-high step eight times), sit-to-stand (time taken to rise from a 43-cm-high chair five times without using the arms), and walking speed over 6 meters. Reliability coefficients for each of these tests when performed by older people are reported elsewhere (1,5,25). All tests were performed barefoot to exclude the influence of footwear (26). Maximum balance range, coordinated stability, and walking speed were corrected for height prior to analysis.

Statistical Analysis

Variables with right-skewed distributions were log transformed. Pearson correlation coefficients were computed to examine the relationships between foot and ankle characteristics, sensorimotor measures, and balance and functional test performance scores. Independent samples t tests were performed to assess for differences in balance and functional test scores according to the paper grip test performance. All variables found to be significantly associated with the balance and functional tests were then entered into a series of stepwise multiple regression analyses to determine their relative importance in explaining variance in each of the tests. Age was then forced into the model to determine whether it could explain any more variance in the balance and functional test scores. To avoid the inclusion of misleading or unhelpful variables due to covariance among some independent variables, only the most highly correlated variable from each domain was included as a possible predictor at the entry of each block. Beta weights and signs for all variables entered into the regression model were also

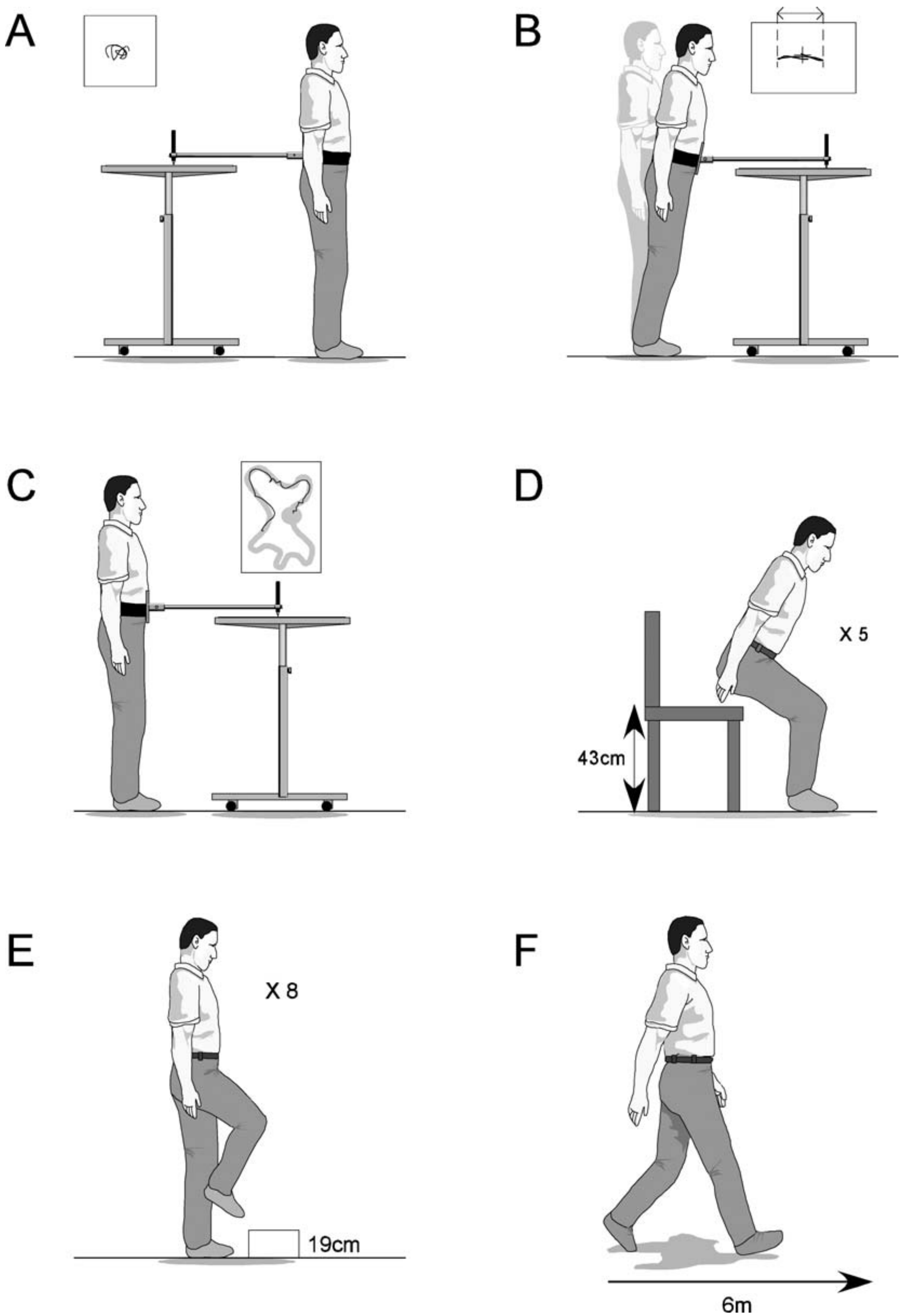

Figure 1. Balance and functional tests. **A,** postural sway; **B,** maximal balance range; **C,** coordinated stability; **D,** sit-to-stand; **E,** alternate step test; **F,** walking speed.

examined to ensure they made meaningful contributions to functional test performance. Change in the amount of variance (R^2) was assessed following the addition of age into the model. The standardized beta weights provided give an indication of the relative importance of the various measures entered into the model in explaining variance in balance and functional test scores. The data were analyzed using SPSS for Windows (SPSS, Inc., Chicago, IL).

Table 2. Descriptive Statistics for Each of the Variables Measured

Test	Mean (*SD*)	Range
Foot and ankle tests		
Foot posture index	5.01 (4.74)	−7 to 16
Arch index	0.24 (0.06)	0.02–0.36
Navicular height/foot length	0.105 (0.032)	0.003–0.176
Ankle flexibility, °	33.43 (10.77)	0–56
1st MPJ ROM, °	55.52 (16.85)	15–100
Hallux valgus severity	1.92 (1.89)	0–6
Corns	0.16 (0.57)	0–4
Calluses	1.57 (2.34)	0–13
Lesser toe deformities	2.74 (2.53)	0–8
1st MPJ tactile sensitivity, gm	4.49 (0.61)	3.27–5.86
Sensorimotor tests		
Visual acuity–high contrast (log MAR)	1.97 (2.16)	0.74–19.26
Visual acuity–low contrast (log MAR)	4.41 (3.71)	1.56–19.95
Contrast sensitivity, dB	20.31 (3.40)	5–24
Proprioception, ° error	1.65 (1.2)	0.1–5.8
Tactile sensitivity–ankle, gm	4.61 (0.59)	3.72–5.86
Knee extension strength, kg	21.68 (7.39)	6–46
Ankle dorsiflexion strength, kg	9.77 (5.19)	2–23
Reaction time, ms	273.90 (82.82)	169.6–703.5
Balance and functional tests		
Sway on floor, mm^2	61.47 (42.74)	32–329
Sway on foam, mm^2	165.75 (111.79)	54–1013
Maximum balance range, mm	138.03 (46.84)	35–246
Coordinated stability, errors	11.45 (10.38)	0–39
Alternate step test, s	16.58 (9.95)	5.75–35.27
Sit-to-stand, s	19.32 (10.72)	6.09–46.02
Walking speed, m/s	0.88 (0.24)	0.20–1.41

Results

Descriptive Statistics

Descriptive statistics for each of the foot and ankle, sensorimotor, and balance and functional test measurements are shown in Table 2.

Associations Between Foot and Ankle Characteristics and Balance and Functional Tests

Table 3 shows the associations between the foot and ankle tests and balance and functional test scores. The foot and ankle characteristics with the most consistent associations with balance and functional test scores were plantar tactile sensitivity, ankle flexibility, the presence of lesser toe deformities, and the severity of hallux valgus. Separating the sway values into anteroposterior and mediolateral components made little difference to these associations, with the exception of hallux valgus being associated with mediolateral sway on the floor ($r = 0.158$, $p = .037$). Table 4 shows the differences in functional test scores according to performances on the two paper grip tests. Independent sample *t* tests revealed that participants who failed the two paper grip tests performed worse on each of the balance and functional tests.

Associations Between Sensorimotor Tests and Balance and Functional Tests

Table 5 shows the associations between the sensorimotor tests and balance and functional tests. Most sensorimotor measures were associated with balance ability functional performance, with strength and reaction time tests exhibiting the strongest correlations.

Multiple Regression Analyses

Table 6 shows the results of the stepwise multiple regression analysis for each of the balance and functional tests. One or more of the foot and ankle test scores were found to be significant independent predictors of each of the tests. In particular, ankle flexibility was found to be an independent predictor of each test, exhibiting the highest ß weight for sway on the floor, coordinated stability, alternate step test, and sit-to-stand. One of the two paper grip tests and tactile sensitivity of the 1st MPJ were also found to be independent predictors of the balance and functional tests. With the exception of coordinated stability, the inclusion of age explained further variance in all tests.

Discussion

The findings of this study indicate that foot and ankle characteristics significantly contribute to balance and functional ability in older people. In particular, tactile sensitivity of the plantar surface of the foot and ankle flexibility were strongly correlated with postural sway, whereas ankle flexibility and the strength of toe plantarflexor muscles were consistently associated with the leaning tests and functional measures. The association between

Table 3. Associations Between Balance and Functional Tests and Foot and Ankle Characteristics (Pearson's *r*)

Test	FPI	AI	NH	AF	1st MPJ ROM	Corns	Calluses	Toe Deformities	Hallux Valgus	1st MPJ Tactile
Sway on floor‡	0.049	−0.050	−0.107	−0.226†	−0.129	−0.001	0.049	0.063	0.131	0.207†
Sway on foam‡	0.103	−0.013	−0.067	−0.301†	−0.160*	−0.029	0.041	0.154*	0.259†	0.292†
Maximum balance range	−0.151*	−0.106	0.154*	0.513†	0.219†	−0.125	−0.189*	−0.239†	−0.363†	−0.229†
Coordinated stability	0.024	0.030	−0.094	−0.540†	−0.152*	0.081	0.050	0.159*	0.274†	0.324†
Alternate step test‡	0.090	0.105	−0.194†	−0.545†	−0.116	0.019	0.075	0.179*	0.267†	0.228†
Sit-to-stand‡	0.054	0.019	−0.156*	−0.511†	−0.046	0.100	0.070	0.194†	0.276†	0.176*
Walking speed	−0.176*	−0.068	0.183*	0.550†	0.176*	−0.105	−0.153*	−0.237†	−0.339†	−0.176*

Note: *$p < .05$.

†$p < .01$.

‡Log transformed.

FPI = foot posture index; AI = arch index; NH = navicular height; AF = ankle flexibility; 1st MPJ ROM = first metatarsophalangeal joint range of motion; 1st MPJ tactile = first metatarsophalangeal joint tactile sensitivity.

Table 4. Balance and Functional Test Scores According to Performance on Paper Grip Tests

Test	Paper Grip Test–Hallux		Paper Grip Test–Lesser Toes	
	Passed ($N = 112$)	Failed ($N = 64$)	Passed ($N = 95$)	Failed ($N = 81$)
Sway on floor, mm^2	57.38 (40.63)	68.63 (45.66)*	57.09 (42.91)	66.60 (42.22)*
Sway on foam, mm^2	156.28 (120.27)	182.33 (93.75)*	149.33 (115.31)	185.01 (104.97)†
Maximum balance range, mm	150.96 (46.05)	115.39 (39.24)†	158.56 (43.01)	113.95 (39.22)†
Coordinated stability, errors	8.87 (9.43)	15.98 (10.48)†	6.33 (6.92)	17.45 (10.58)†
Alternate step test, s	14.05 (7.28)	21.00 (9.88)†	13.57 (6.91)	20.11 (9.77)†
Sit-to-stand, s	16.56 (8.88)	24.17 (11.97)†	16.27 (8.55)	22.90 (11.89)†
Walking speed, m/s	0.92 (0.22)	0.79 (0.25)†	0.96 (0.20)	0.78 (0.24)†

Notes: *Significant difference at $p < .05$.
†Significant difference at $p < .01$.

plantar sensation and standing balance is consistent with previous reports of increased postural sway in persons with peripheral neuropathy (27,28) and impaired postural responses when sensory input is blocked in healthy persons (29,30), and indicates that plantar mechanoreceptors provide functionally important information regarding body position (31). Similarly, the association between toe plantarflexor strength and maximal balance range is consistent with Endo and colleagues (32), who reported a strong correlation between force plate measures of toe plantarflexor strength and the anterior limit of the functional base of support. Toe muscle function may play a particularly important role in the maintenance of balance in older people. Tanaka and colleagues (33) have shown that when standing, older people exert greater pressure with their toes than do younger people, possibly in an attempt to intensify sensory information to maintain balance.

Contrary to previous findings in young persons (14,15), foot posture was not found to be a predictor of balance or functional ability. The presence of corns and calluses was also poorly correlated with the functional measures; however, this is most likely because these foot problems are almost ubiquitous in this age group (7). Consistent with our previous study (23), toe deformities (including hallux valgus) were significantly associated with balance and functional ability in univariate analyses; however, the inclusion of ankle flexibility and toe strength in this study precluded them from being included in the multivariate models due to their relatively weaker associations.

Despite the broad range of possible predictors included in the regression models, it is acknowledged that much of the variance in the balance and functional measures remains unaccounted for. The sway tests were relatively poorly predicted, explaining between 11% and 24% of the variance in test performance. The amount of explained variance in the leaning balance and functional tests was considerably greater (between 47% and 59%); however, other factors such as vestibular function and pain may have provided additional information. Nevertheless, the multiple R^2 values reported here compare favorably to other investigations of these functional measures (3–5), indicating that the foot and ankle measurements are useful additions to the sensorimotor test battery used previously.

The major foot and ankle predictors revealed by the study are potentially modifiable. Although peripheral sensory loss is generally irreversible, there is emerging evidence that augmenting tactile sensory information from the sole of the foot using insoles with raised projections (34) or vibrating pads (35) may improve balance in older people. Furthermore, interventions directed at increasing ankle and 1st MPJ ROM and increasing the strength of toe plantarflexor muscles may have some value in decreasing the risk of falls in older people. Previous studies indicate that ankle motion can be increased with stretching (36–38), Tai Chi (39), and water exercise (40) programs in older people; however, the effect of increasing ankle flexibility on balance and falls risk has yet to be explored. Similarly, preliminary evidence suggests that ''grasping'' exercises to strengthen toe muscles results in improved standing balance in older people (41); however, it is not known whether this translates to a decreased risk of falls.

Table 5. Associations Between Balance and Functional Tests and Sensorimotor Assessments

Test	Visual Acuity (High)	Visual Acuity (Low)‡	Contrast Sensitivity	Reaction Time‡	Proprioception‡	Tactile Sensitivity (Ankle)	Ankle Dorsiflexion Strength	Knee Extension Strength
Sway on floor‡	0.180*	0.189*	−0.127	0.082	−0.048	0.148*	−0.095	−0.040
Sway on foam‡	0.216†	0.212†	−0.176*	0.351†	0.227†	0.295†	−0.266†	−0.275†
Maximum balance range	−0.329†	−0.323†	0.328†	−0.454†	−0.259†	−0.263†	0.608†	0.600†
Coordinated stability	0.407†	0.408†	−0.421†	0.433†	0.310†	0.403†	−0.425†	−0.409†
Alternate step test‡	0.319†	0.306†	−0.349†	0.402†	0.279†	0.209†	−0.477†	−0.542†
Sit-to-stand‡	0.246†	0.233†	−0.318†	0.363†	0.274†	0.144	−0.491†	−0.505†
Walking speed	−0.289†	−0.298†	0.370†	−0.464†	−0.272†	−0.164*	0.535†	0.599†

Notes: $*p < .05$.
†$p < .01$.
‡Log transformed.

Table 6. Results of Multiple Regression Analyses

Test	Predictor Variable	β Weight	Multiple R^2
Sway on floor	Ankle flexibility	−0.226†	
	Tactile sensitivity 1st MPJ	0.165*	0.077
	Age	0.197*	0.110‡
Sway on foam	Reaction time	0.351†	
	Tactile sensitivity 1st MPJ	0.261†	
	Ankle flexibility	−0.172*	0.216
	Age	0.159*	0.238‡
Maximum balance range	Ankle dorsiflexion strength	0.608†	
	Ankle flexibility	0.337†	
	Paper grip test–lesser toes‖	0.252†	
	Knee extension strength	0.262†	
	Reaction time	−0.127*	
	1st MPJ ROM	0.114*	0.572
	Age	−0.162†	0.594§
Coordinated stability	Ankle flexibility	−0.540†	
	Paper grip test–lesser toes‖	−0.396†	
	Reaction time	0.253†	0.492
	Tactile sensitivity 1st MPJ	0.160†	0.515§
Alternate step test	Ankle flexibility	−0.545†	
	Knee extension strength	−0.417†	
	Visual acuity–high contrast	0.209†	
	Paper grip test–hallux‖	−0.157†	0.518
	Age	0.161†	0.537§
Sit-to-stand	Ankle flexibility	−0.511†	
	Knee extension strength	−0.387†	
	Paper grip test–hallux‖	−0.191†	
	Contrast sensitivity	−0.131*	0.445
	Age	0.193†	0.474§
Walking speed	Knee extension strength	0.599†	
	Ankle flexibility	0.407†	
	Contrast sensitivity	0.192†	
	Reaction time	−0.121*	0.554
	Age	−0.200†	0.585§

Note: *Significance of β weight $p < .05$.

†Significance of β weight $p < .01$.

‡Indicates change in R^2 when age entered into model ($p < .05$).

§Indicates change in R^2 when age entered into model ($p < .01$).

‖Indicates participant passed the test.

MPJ = metatarsophalangeal joint; ROM = range of motion.

Conclusion

Foot and ankle characteristics, particularly tactile sensitivity, ankle flexibility, and toe strength, are important determinants of balance and functional ability in older people. Intervention studies to reduce risk of falling may possibly benefit from augmenting sensory information from the foot and the inclusion of stretching and strengthening exercises for the foot and ankle.

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References

1. Lord SR, Menz HB, Tiedemann A. A physiological profile approach to falls risk assessment and prevention. *Phys Ther*. 2003;83:237–252.
2. Lord SR, Ward JA. Age-associated differences in sensori-motor function and balance in community-dwelling women. *Age Ageing*. 1994;23:452–460.
3. Lord SR, Clark RD, Webster IW. Postural stability and associated physiological factors in a population of aged persons. *J Gerontol Med Sci*. 1991;46:M69–M76.
4. Lord SR, Lloyd DG, Li SK. Sensori-motor function, gait patterns and falls in community-dwelling women. *Age Ageing*. 1996;25:292–299.
5. Lord SR, Murray SM, Chapman K, Munro B, Tiedemann A. Sit-to-stand performance depends on sensation, speed, balance, and psychological status in addition to strength in older people. *J Gerontol Med Sci*. 2002;57A:M539–M543.
6. White EG, Mulley GP. Footcare for very elderly people: a community survey. *Age Ageing*. 1989;18:275–278.
7. Benvenuti F, Ferrucci L, Guralnik JM, Gangemi S, Baroni A. Foot pain and disability in older persons: an epidemiologic survey. *J Am Geriatr Soc*. 1995;43:479–484.
8. Gorter KJ, Kuyvenhoven MM, deMelker RA. Nontraumatic foot complaints in older people. A population-based survey of risk factors, mobility, and well-being. *J Am Podiatr Med Assoc*. 2000;90:397–402.
9. Leveille SG, Guralnik JM, Ferrucci L, Hirsch R, Simonsick E, Hochberg MC. Foot pain and disability in older women. *Am J Epidemiol*. 1998;148:657–665.
10. Tinetti ME, Speechley M, Ginter SF. Risk factors for falls among elderly persons living in the community. *New Eng J Med*. 1988;319:1701–1707.
11. Koski K, Luukinen H, Laippala P, Kivela SL. Physiological factors and medications as predictors of injurious falls by elderly people: a prospective population-based study. *Age Ageing*. 1996;25:29–38.
12. Leveille S, Bean J, Bandeen-Roche K, Jones R, Hochberg M, Guralnik J. Musculoskeletal pain and risk of falls in older disabled women living in the community. *J Am Geriatr Soc*. 2002;50:671–678.
13. Menz HB, Lord SR. The contribution of foot problems to mobility impairment and falls in older people. *J Am Geriatr Soc*. 2001;49:1651–1656.
14. Cobb SC, Tis LL, Johnson BF, Higbie EJ. The effect of forefoot varus on postural stability. *J Orthop Sports Phys Ther*. 2004;34:79–85.
15. Hertel J, Gay MR, Denegar CR. Differences in postural control during single-leg stance among healthy individuals with different foot types. *J Athlet Train*. 2002;37:129–132.
16. Mecagni C, Smith JP, Roberts KE, O'Sullivan SB. Balance and ankle range of motion in community-dwelling women aged 64 to 87 years: a correlational study. *Phys Ther*. 2000;80:1001–1011.
17. Pfieffer E. A short portable mental status questionnaire for the assessment of organic brain deficit in elderly patients. *J Am Geriatr Soc*. 1975;23:433–441.
18. Redmond AC, Burns J, Crosbie J, Ouvrier R. An initial appraisal of the validity of a criterion based, observational clinical rating system for foot posture (abstract). *J Orthop Sports Phys Ther*. 2001;31:160.
19. Cavanagh PR, Rodgers MM. The arch index: a useful measure from footprints. *J Biomech*. 1987;20:547–551.
20. Menz HB, Tiedemann A, Kwan MMS, Latt MD, Lord SR. Reliability of clinical tests of foot and ankle characteristics in older people. *J Am Podiatr Med Assoc*. 2003;93:380–387.
21. Hopson MM, McPoil TG, Cornwall MW. Motion of the first metatarsophalangeal joint: reliability and validity of four measurement techniques. *J Am Podiatr Med Assoc*. 1995;85:198–204.
22. Garrow AP, Papageorgiou A, Silman AJ, Thomas E, Jayson MI, Macfarlane GJ. The grading of hallux valgus. The Manchester Scale. *J Am Podiatr Med Assoc*. 2001;91:74–78.
23. Menz HB, Lord SR. Foot pain impairs balance and functional ability in community-dwelling older people. *J Am Podiatr Med Assoc*. 2001;91:222–229.
24. de Win M, Theuvenet W, Roche P, de Bie R, van Mameren H. The paper grip test for screening on intrinsic muscle paralysis in the foot of leprosy patients. *Int J Lepr Other Mycobact Dis*. 2002;70:16–24.
25. Lord SR, Ward JA, Williams P. Exercise effect on dynamic stability in older women: a randomised controlled trial. *Arch Phys Med Rehabil*. 1996;77:232–236.

26. Arnadottir SA, Mercer VS. Effects of footwear on measurements of balance and gait in women between the ages of 65 and 93 years. *Phys Ther*. 2000;80:17–27.
27. Lord SR, Caplan GA, Colagiuri R, Ward JA. Sensori-motor function in older persons with diabetes. *Diabet Med*. 1993;10:614–618.
28. Richardson JK, Ashton-Miller JA, Lee SG, Jacobs K. Moderate peripheral neuropathy impairs weight transfer and unipedal balance in the elderly. *Arch Phys Med Rehabil*. 1996;77:1152–1156.
29. Magnusson M, Enbom H, Johansson R, Pyykko I. Significance of pressor input from the human feet in anterior-posterior postural control. The effect of hypothermia on vibration-induced body-sway. *Acta Otolaryngol*. 1990;110:182–188.
30. Perry SD, McIlroy WE, Maki BE. The role of plantar cutaneous mechanoreceptors in the control of compensatory stepping reactions evoked by unpredictable, multi-directional perturbation. *Brain Res*. 2000;877:401–406.
31. Kavounoudias A, Roll R, Roll JP. The plantar sole is a 'dynamometric map' for human balance control. *NeuroReport*. 1998;9:3247–3252.
32. Endo M, Ashton-Miller J, Alexander N. Effects of age and gender on toe flexor muscle strength. *J Gerontol Med Sci*. 2002;57A: M392–M397.
33. Tanaka T, Noriyasu S, Ino S, Ifukube T, Nakata M. Objective method to determine the contribution of the great toe to standing balance and preliminary observations of age-related effects. *IEEE Trans Rehabil Eng*. 1996;4:84–90.
34. Maki BE, Perry SD, Norrie RG, McIlroy WE. Effect of facilitation of sensation from plantar foot-surface boundaries on postural stabilization in young and older adults. *J Gerontol Med Sci*. 1999;54:M281–M287.
35. Priplata AA, Niemi JB, Harry JD, Lipsitz LA, Collins JJ. Vibrating insoles and balance control in elderly people. *Lancet*. 2003;362: 1123–1124.
36. Mills EM. The effect of low-intensity aerobic exercise on muscle strength, flexibility, and balance among sedentary elderly persons. *Nurs Res*. 1994;43:207–211.
37. Swank AM, Durham MP. Adding weights to stretching exercise increases passive range of motion for healthy elderly. *J Strength Cond Res*. 2003;17:374–378.
38. Sohng KY, Moon JS, Song HH, Lee KS, Kim YS. Fall prevention exercise program for fall risk factor reduction of the community-dwelling elderly in Korea. *Yonsei Med J*. 2003;44:883–891.
39. Wolf SL, Barnhardt HX, Kutner NG, McNeely E, Coogler C, Xu T. Reducing frailty and falls in older persons: an investigation of Tai Chi and computerized balance training. Atlanta FICSIT Group. Frailty and Injuries: Cooperative Studies of Intervention Techniques. *J Am Geriatr Soc*. 1996;44:489–497.
40. Alexander MJL, Butcher JE, MacDonald PB. Effect of a water exercise program on walking gait, flexibility, strength, self-reported disability and other psycho-social measures of older individuals with arthritis. *Physiother Can*. 2001;53:203–211.
41. Kobayashi R, Hosoda M, Minematsu A, et al. Effects of toe grasp training for the aged on spontaneous postural sway. *J Phys Ther Sci*. 1999;11:31–34.

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