J. Phys. Ther. Sci.
27: 705–710, 2015

Original Article

Relationship between foot posture measurements and force platform parameters during two balance tasks in older and younger subjects

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Abstract. [Purpose] The aim of this study was to compare age-related differences in balance and anthropometric posture measurements of the foot and to determine any relationship between them. [Subjects and Methods] Sixty-eight older and 42 younger adults participated in this study. Foot posture was tested for four domains: 1) hallux flexion and extension range of motion using a goniometer, 2) navicular height and 3) length of the foot using a pachymeter, and 4) footprint (width of forefoot, arch index and hallux valgus). Balance was tested under two conditions on a force platform: bipodal in 60-s trials and unipodal in 30-s trials. The sway area of the center of pressure and velocity in the anteroposterior and mediolateral directions were computed. [Results] Older individuals showed significantly poorer balance compared with younger adults under in the unipodal condition (center of pressure area 9.97 vs. 7.72 cm^2). Older people presented a significantly lower hallux mobility and higher values for width of the forefoot and transverse arch index than younger adults. The correlations between all foot posture and center of pressure parameters varied across groups, from weak to moderate (r −0.01 to −0.46). Low hallux mobility was significantly related to higher center of pressure values in older people. [Conclusion] These results have clinical implications for balance and foot posture assessments.

Key words: Posture, Aging, Foot

(This article was submitted Aug. 21, 2014, and was accepted Oct. 21, 2014)

INTRODUCTION

The aging process is often associated with biomechanical changes in the foot with effects on lateral deviation of the legs, the plantar arch, and intrinsic muscular strength of the toes[1–5)]. The most prevalent toe disorder is the hallux valgus, which is characterized by a lateral deviation of the big toe away from the midline of the body[6, 7)]. The prevalence of this disorder is 36% in those over 65 years, while the rate in adults is 23%[7)]. This disorder is often associated with pain, mobility impairment, postural instability, and an increased risk of falls[8–10)].

Genetic history, abnormal hind foot kinematics, wearing high-heeled shoes, bony abnormalities, foot muscular dysfunction and imbalance could be associated with the etiology of hallux valgus[11–15)]. The foot provides a direct source of contact with the ground during standing and walking activitie and with pain and/or structural deformity, it is likely in turn to impair balance and consequently increase the risk of falls. As suggested by Menz et al.[16)], the foot contributes to maintenance of postural stability in two ways: 1) mechanical support for the body via the osteoligamentous arch and the coordinated function of lower limb muscles, and 2) sensory information with regard to body position and proprioception from plantar tactile mechanoreceptors.

Foot posture can be measured objectively by anthropometric approaches as well as by photographs or footprint analysis with digital imaging software (e.g., ImajeJ, SAPO)[16, 17)]. Other approaches include use of the Manchester Scale to assess the level of severity of hallux valgus[18, 19)], X-ray angular measurement[20, 21)], a force plate for balance and force reaction measurements[22)], and electromyography or an ultrasound system for measurement of muscular dysfunction of the foot[23–25)]. These last techniques provide both accurate and reliable information[21–25)], although they require high-tech equipment and are costly for clinical practice.

Some evidences has shown that excessively flat feet and highly arched feet impair standing balance in healthy young subjects[26, 27)]. Also, a significant association was observed in measurements of the ankle range of motion (ROM) and balance in older subjects[28)]. Based on differences between younger and older subjects in the neuromuscular and bony systems, it would be of interest to perform a comparison of foot posture measurements and balance in an experiment

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using the same design. The purposes of this study were to 1) compare age differences for a broader range of anthropometric posture measurements of the foot and for two main balance parameters on a force platform under two balance conditions (bipodal and unipodal), and 2) to determine the relationship between all these measurements in both younger and older subjects.

SUBJECTS AND METHODS

A total of 110 healthy female volunteers (n=68 older and n=42 younger subjects) participated in the present study. The mean characteristics of the older subjects were as follows: age 68±5 yrs, body mass 63±11 kg, height 1.52±0.1 m, and body mass index (BMI) 27±4 kg/m^2. Those of the younger subjects were as follows: age 21±2 yrs, body mass 60±8 kg, height 1.64±0.1, and BMI 22±3 kg/m^2. All subjects were recruited by convenience from the local community. The inclusion criteria were as follows for older subjects: (1) age more than 60 years old, physically independent, no falls in the previous year, and a score >18 on the Mini-Mental State Examination[29]. The inclusion criteria for the younger group were age between 18 and 30 years and being healthy. General exclusion criteria for both groups were as follows: participation in any physical activity program, neuromusculoskeletal disorders, labyrinthitis, and chronic cardiovascular system diseases. The subjects were informed about the study's experimental protocol, and potential risks and written consent was obtained before their participation. The consent forms were previously approved by the local ethics committee (CEP 276.702).

Prior to performing all measurements, the subjects were familiarized with the experimental protocol, especially with respect to assessment under two balance conditions on a force platform. Foot posture was tested across four domains[16, 17, 30–34]. For hallux flexion and extension ROM, an analog goniometer was used for angle measurements. The subjects were in an orthostatic position with the limb to be evaluated placed on a bench (approximately at 90° of knee flexion) allowing free movements of the hallux. The first metatarsophalangeal joint (hallux joint) was then measured in a non-weight-bearing position with a goniometer while the examiner maximally extended and flexed the hallux[32]. Three trials of the hallux ROM by side (right foot, R; left foot, L) were performed, and the mean was retained. For goniometry measurements, the navicular height was measured in centimeters (cm) using an analog pachymeter while the subject was bearing her full weight, and was then corrected for differences in foot size by dividing it by the length of the foot[34], which was measured with a pachymeter. For both measurements (navicular height and length of the foot), three trials were performed for both feet by the examiner, and the mean was computed.

The footprints were obtained using a carbon-paper imprint material with the subject standing in a relaxed position under the following standardized conditions: barefoot and arms parallel to their trunk. Afterwards, the foot imprint material was analyzed using a computer graphics tablet and the imaging software ImageJ v.145 (National Institutes of Health, Bethesda MD, USA), and the reference footprint parameters (area of the foot on paper) were then calculated, as previously detailed by Bega[31]: the width of the forefoot is the quotient of the total length of the foot (corrected by height) divided by three; the arch index in the transverse plane of the footprint is calculated as the quotient of the width of the forefoot divided by three (e.g., defined as high values for flatfeet and low values for arched feet)[17, 31], and finally, the physiological hallux valgus of the footprint was calculated by multiplying by 2% of the total length of the foot[31].

After the foot measurements, the participants stood on a force platform (BIOMEC400, São Paulo, Brazil) under the following two conditions: (1) the bipodal condition (BC: two legs placed on force platform) during 60-s trials[35]; and (2) the unipodal condition (UC: leg preferred on force platform) during 30-s trials. There was a rest period of approximately 30 s between each trial under both conditions, and the mean was retained for analysis. During all trials, the participants were instructed concerning the following standardized conditions: barefoot, eyes open and looking at a target (cross) placed on a wall at eye level 2 m away, and arms at the sides or parallel to the trunk[36].

Force reaction signals from the platform were collected with a sampling at 100 Hz and filtered with a Butterworth low-pass second-order filter at 35 Hz. Signals were then converted through a stabilographic analysis to extract all of the parameters associated with movements of the center of pressure (COP), such as the ellipse area (95%) of the COP (A-COP in cm^2) and mean velocity (VEL in cm/s) of the COP sway in the anteroposterior (A/P) and mediolateral (M/L) directions. The test-retest reliability of these main parameters of balance has been shown to be excellent for both groups[36].

All variables were normally distributed, as verified with the Shapiro-Wilk test. The Student's unpaired t-test was used to assess between-group differences in anthropometric variables, foot posture measurement, and balance parameters. Pearson's correlation coefficients were used to assess the relationship between all foot posture measurements and balance parameters under both conditions. The SPSS software (version 15 for Windows) was used to perform all statistical analyses, with significance taken at 5% ($p < 0.05$).

RESULTS

Significant differences between groups were found for age, height, and BMI variables, but not for body mass. From goniometry measurements, older subjects presented lower ROM values for the hallux than young adults, with significant differences ($p<0.01$) between groups for all variables (Table 1). A moderately high size effect was shown, which in itself is clinically interesting.

Significant differences between older and younger subjects were found for all variables in the pachymeter (navicular height and length of the foot) and footprint (width of forefoot, arch index, and hallux valgus) measurements (Table 2). For both sides (R and L), older individuals presented lower values than younger adults for navicular height and length of the foot (pachymeter), and for hallux valgus (footprint) variables, with a moderate size effect between them.

Table 1. Goniometry measurement of the hallux in flexion and extension

Variables	Older (n=68) Mean (SD)	Young (n=42) Mean (SD)	Size effect
ROM Flexion-R (°)	54 (7)	57 (7)*	0.41
ROM Flexion-L (°)	50 (6)	55 (5)*	0.81
ROM Extension-R (°)	48 (8)	53 (8)*	0.61
ROM Extension-L (°)	51 (9)	55 (7)*	0.45

ROM, range of motion of the hallux in flexion and extension. R: right side; L:, left side. *p<0.05: Significant differences between the groups (older < ROM of hallux than young). There was a moderately high size, which in itself is clinically interesting.

Table 3. Postural balance results under bipodal and unipodal conditions (BC and UC)

Variables	Older (n=68) Mean (SD)	Young (n=42) Mean (SD)	Size effect
Bipodal condition			
BC A-COP (cm^2)	1.2 (0.9)	1.1 (0.6)	0.09
BC VEL A/P (cm/s)	0.7 (0.1)	0.6 (0.1)	0.24
BC VEL M/L (cm/s)	0.5 (0.1)	0.5 (0.1)	0.26
Unipodal condition			
UC A-COP (cm^2)	9.9 (3.7)	7.7 (2.6)*	0.70
UC VEL A/P (cm/s)	2.9 (0.8)	2.2 (0.5)*	1.02
UC VEL M/L (cm/s)	3.3 (0.7)	2.4 (0.6)*	1.20

Mean values are shown with the standard deviation (SD) in parentheses. BC, bipodal balance condition; UC, unipodal balance condition. A-COP: the ellipse area (95%) of the center of pressure (COP). VEL: mean velocity of the COP sway in both directions of movement anteroposterior (A/P) and mediolateral (M/L).
*p<0.05: significant differences between groups only under the unipodal condition. Under the bipodal condition, a weak effect size was found. Under the unipodal condition, a very strong effect size was found.

Table 2. Foot posture measurements obtained with the pachymeter and footprint

Variables	Older (n=68) Mean (SD)	Young (n=42) Mean (SD)	Size effect
Pachymeter measurements			
Navicular height-R (cm)	7.5 (0.7)	7.7 (0.5)*	0.31
Navicular height-L (cm)	7.5 (0.7)	7.8 (0.5)*	0.47
Length feet-R (cm)	22.1 (1.1)	22.6 (1.0)*	0.47
Length feet-L (cm)	21.9 (1.14)	22.5 (1.1)*	0.53
Footprint measurements			
Width of fore feet-R (cm)	8.8 (0.8)	8.4 (0.4)*	0.58
Width of fore feet-L (cm)	8.8 (0.5)	8.4 (0.4)*	0.58
Arch index-R (cm)	3.7 (0.9)	3.3 (0.7)*	0.51
Arch index-L (cm)	3.7 (0.9)	3.2 (0.7)*	0.59
Hallux valgus-R (cm)	0.43 (0.1)	0.44 (0.5)*	0.07
Hallux valgus-L (cm)	0.43 (0.1)	0.45 (0.2)*	0.13

Mean values are shown with the standard Deviation (SD) in parentheses.
R: right side; L: left side. Pachymeter measurements: navicular height and length of the foot; Footprint measurements: width of forefoot, arch index and hallux valgus. *p<0.05: significant differences between groups. The size effects for the pachymeter are moderate. The footprint measurements are also generally moderate but for both hallux valgus measurements, the effect sizes are really weak, even though the values are significant. From a clinical perspective, the hallux measurements are not interesting.

In contrast, high values were found for width of the forefoot and transverse arch index variables in older compared with younger subjects (Table 2), thus characterizing the flatfeet of older people. From the footprint measurements, the size effect was moderate across measurements but for both the hallux valgus, the effect sizes were weak, even when the values were significant. From a clinical perspective, the hallux measurements are not interesting.

Poor balance in older people in comparison with younger people was seen only under the unipodal conditions (UC) for all COP parameters (Table 3). The COP values were significantly higher in older subjects than in younger subjects (e.g., A-COP of 9.97 vs. 7.72 cm^2). Interestingly, a very strong effect size was found only under the unipodal condition. The correlations between all foot posture measurements and COP parameters varied across groups, from weak to moderate (r −0.01 to −0.46; Tables 4 and 5). No systematic advantage of any one foot posture measurement in relation to COP parameters was found across the groups. The best and most significant correlations were found for the hallux ROM (r −0.046 for ROM in extension with A-COP under the unipodal condition) and navicular height (r −0.041 for navicular height under the bipodal condition for VEL-AP) with the COP parameters.

DISCUSSION

Older and younger people had differences in all foot posture measurements, the older having lower hallux mobility and higher values of forefoot width and transverse arch index than young adults, thus characterizing the flatness of their feet. However, no systematic advantage of any one foot posture measurement (goniometry, pachymeter, footprint) in relation to COP parameters was found across groups, although low mobility of the hallux was related to higher COP values (poor balance), especially in older people.

To the authors' knowledge and based on a literature search on this issue[10,15–17, 22, 26–28)], a comparison of older and younger adults in the same study for different foot posture measurements and COP parameters under two conditions, and an examination of the correlation between all these measurements have not been previously reported. With regard to foot posture measurements, age-related differences can be dependent on changes in orthopedic anatomy and/or foot architectural and anthropometric characteristics with the increase in age[1–3)]. Older healthy people (without apparent deformities) present a lower ROM of the hallux and flatfeet compared with young adults[16, 28, 37)], which support our findings. It is also known that aging is associated with neuro-musculoskeletal alterations and decreased physiological functions, which in turn can lead to problems

Table 4. *Pearson* coefficient correlation between goniometry measurements and balance COP parameters

Variables	Groups	Balance COP parameters					
		BC-ACOP	BC-VELAP	BC-VELML	UC-ACOP	UC-VELAP	UC-VELML
		r	*r*	*r*	*r*	*r*	*r*
ROM Flx-R	Older	0.13	0.12	0.04	–0.38*	–0.03	0.08
	Young	0.29	0.15	0.23	–0.01	–0.21	–0.24
ROM Flx-L	Older	–0.03	0.13	0.16	0.29	–0.20	–0.01
	Young	0.33*	0.20	0.34*	–0.21	–0.33*	–0.16
ROM Ext-R	Older	–0.06	0.30*	0.26	–0.08	0.15	0.10
	Young	–0.34*	–0.16	–0.06	–0.20	–0.02	0.01
ROM Ext-L	Older	–0.04	–0.06	–0.13	–0.46*	–0.17	0.01
	Young	–0.31*	–0.18	–0.10	0.03	0.03	0.12

r, Coefficient correlation values and p values in parentheses. BC: bipodal balance condition; UC: unipodal balance condition. A-COP: the ellipse area (95%) of the center of pressure (COP). VEL: mean velocity of the COP sway in both directions of movement anteroposterior (A/P) and mediolateral (M/L). ROM: range of motion of the hallux in flexion (Flx) and extension (Ext). R: right side; L: left side. *$p<0.01$: significant correlation between goniometry measurements and balance COP parameters.

Table 5. *Pearson* coefficient correlation between foot posture measurements (pachymeter and footprint measurements) and balance COP parameters

Variables	Groups	Balance COP parameters					
		BC-ACOP	BC-VELAP	BC-VELML	UC-ACOP	UC-VELAP	UC-VELML
		r	*r*	*r*	*r*	*r*	*r*
Nav. height-R	Older	0.04	–0.27	–0.18	–0.18	–0.23	–0.23
	Young	–0.36*	–0.09	–0.18	–0.25	0.13	0.12
Nav. height-L	Older	0.11	–0.41*	–0.28	–0.18	–0.32*	–0.39*
	Young	–0.06	0.03	–0.09	–0.14	0.05	0.08
Length feet-R	Older	0.06	–0.01	–0.16	0.01	–0.21	0.07
	Young	–0.03	0.08	–0.03	0.25	0.26	0.35*
Length feet-L	Older	–0.14	0.01	–0.21	0.04	–0.18	–0.12
	Young	–0.02	0.10	–0.02	0.28	0.25	0.29
Width feet-R	Older	0.23	0.26	–0.12	0.12	0.08	0.28
	Young	0.01	–0.05	–0.11	0.08	0.12	0.12
Width feet-L	Older	0.12	0.08	–0.07	0.13	0.02	0.03
	Young	0.02	–0.02	–0.02	0.26	0.17	0.23
Arch Index-R	Older	0.18	0.16	–0.01	0.11	0.33*	0.09
	Young	–0.14	0.06	–0.08	0.10	0.10	–0.10
Arch Index-L	Older	0.14	–0.04	–0.15	0.23	0.09	–0.05
	Young	–0.09	–0.07	–0.18	0.27	0.08	0.09
Hallux valgus-R	Older	0.07	–0.02	–0.20	0.02	–0.21	–0.09
	Young	0.07	0.12	–0.01	0.27	0.29	0.36*
Hallux valgus-L	Older	–0.01	–0.04	–0.29	0.01	–0.17	–0.05
	Young	–0.03	0.10	–0.02	0.26	0.25	0.29*

r, Coefficient correlation values and p values in parentheses. BC: bipodal balance condition; UC: unipodal balance condition. A-COP: the ellipse area (95%) of the center of pressure (COP). VEL: mean velocity of the COP sway in both directions of movement anteroposterior (A/P) and mediolateral (M/L). R: right side; L: left side. Pachymeter measurements: navicular (Nav.) height and length of the foot. Footprint measurements: width of forefoot, arch index and hallux valgus. *$p<0.01$: significant correlation between foot posture measurements (pachymeter and footprint) and balance COP parameters.

such as muscular weakness and lack of mobility, as well as other sensory-motor deficits and a consequent loss of balance[15–17, 25, 28, 29], which also support our results of poor balance in the elderly.

In the present study, older people presented worse performance for balance only under the unipodal condition. These results agree with previous studies for this condition[36, 38] but are contrary to those of another study[35], which assessed healthy community-dwelling older adults using a double-leg stance task. No difference was identified under the bipodal condition in our findings, which is also supported by the size effects. An explanation for this could be collection of the data at 30 s, while in previous work, the time series was stopped at 60 or 120 s. However, as suggested by Parreira et al.[38], differences between older and younger adults are observed with 10 s COP time series. At this time, motor control strategies as well as real balance deficits from muscular weakness or sensorymotor impairment become more evident between groups. In this case, we assumed then that a bipodal condition is not adequate to discriminate postural control, since both populations can perform similar short-term postural adjustments. Compared with the bipodal condition, the unipodal condition has often been more associated with the prediction of falls as well as fall-related injuries[39].

The clinical relevance of foot posture measurements in both older and younger adults is that foot structures have an influence on balance[26, 27]. It is suggested that the presence of non-weight-bearing frontal-plane foot postures such as forefoot varus, rearfoot varus, plantar-flexed fifth ray, or ankle joint equinus result in increased compensatory foot pronation during weight bearing, which in turn causes compensatory hypermobility of the subtalar joint and midtarsal joint and consequently can create an unstable base of support that may translate into impaired postural balance. Cobb et al.[26], evaluating 32 healthy young adults (mean age 29 yrs) in a one-leg stance platform task, showed decreased postural stability in individuals with increased forefoot varus (>7°). The authors explained their results as being due to a decrease in joint subtalar congruity and increased reliance on soft tissue structures for foot stability. Hertel et al.[27], also evaluating young adults (n=30, mean age 22 yrs), reported an increased COP sway area in individuals with pes cavus foot structures compared with those with pes rectus foot structures. The authors showed no differences in either COP sway area or COP sway velocity between subjects with pes planus foot structures compared with those with pes rectus foot structures. However, both the studies of Cobb[26] and Hertel[27] collected only limited COP time-series data computed at 5 and 10 s, respectively, during the one-leg stance task. As stated before, a short time series is not enough to accurately discriminate the balance mechanism of postural control in the two different groups[38]. In contrast, the present study showed significant differences between older and younger subjects for all variables in the pachymeter (navicular height and length of the foot) and footprint (width of fore foot, arch index and hallux valgus) measurements and COP measurements in a 30 s time series instead of 5 or 10 s time series, which were used by Cobb[26] and Hertel[27].

The relationship between hallux ROM and COP parameters is in agreement with previous studies[16, 28], although the experimental protocols were not exactly the same. Mecagni et al.[28], evaluating women between 64 and 87 yrs old, showed an association (in mean $r = -0.30$) of ankle ROM with functional balance. Menz et al.[16], evaluating 156 older women (mean age 80 yrs), reported a significant association (β weight = −0.226 from multiple regression analyses) between ankle flexibility and sway functional balance on the floor. The authors pointed out also that this mobility measure and others such as plantar flexor strength can explain 59% of the variance in the balance scores. Our results are in agreement with these, at least for the ROM of the hallux in relation to with COP parameters. In summary, our results suggest that some foot characteristics can influence in COP sway on force platform measurements. These results have clinical and research implications for balance rehabilitation programs for the elderly as well as for prevention programs linked to musculoskeletal foot postural disorders. Foot posture characteristics are of concern, since cutaneous plantar afferent activity is often important in the regulation of postural control[37]. If individuals with foot postural disorders receive less afferent input from the plantar cutaneous receptors, they may have less efficient mechanisms of control of their upright posture during a single-leg stance. However, further research is needed on this issue.

Finally, the results of this study cannot necessarily be generalized to all older individuals. Toe weakness and deformity, foot posture deformities, ankle mobility, and foot muscular strength were not investigated. A side comparison was not performed, although no significant differences in postural control measurements have been reported between the right and left limbs or dominant and nondominant limbs[40]. In conclusion, older people showed poor balance compared with young adults only under the unipodal condition. Older individuals have low hallux mobility and high values for the width of the forefoot and transverse arch index compared with young adults, thus characterizing their flatfeet. Low mobility of the hallux was significantly related to higher COP values (poor balance) under the bipodal condition, and this was especially the case for older subjects under the unipodal condition.

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