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# Foot arch height and rigidity index associated with balance and postural sway in elderly women using a 3D foot scanner

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**Background:** The maintenance of balance is a complex phenomenon that is influenced by a range of sensorimotor factors. Foot arch height index (AHI) and arch rigidity index (ARI) may also influence balance and postural sway. According to the literature, measurement of foot posture is widely considered to be an important component of musculoskeletal examination in clinical practice and research. On the other hand, the recent use of 3D foot scanners allows a large number of subjects to be scanned quickly and easily and helps to reduce the patient's radiation exposure from x-rays.

**Purpose:** The purpose of this study was to determine whether AHI and ARI are associated with balance and postural sway by examining a large community sample of elderly women using recent 3D foot scanner technology.

**Methods:** This cross-sectional study included 140 community-dwelling elderly women (73.9 ± 5.1 years) recruited in Kasama City, Japan. We assessed static and dynamic balance using one leg stance (OLS) and timed up & go (TUG). Postural sway variables, total path length (TPL) (cm), and area ($cm^2$) were measured by force plate. We measured AHI and ARI with DreamGP Incorporated's 3D foot scanner (Osaka, Japan). In this study, AHI was defined as the linear distance (mm) from the instep, defined by the foot scanning machine, to the supporting surface while sitting and while standing with 50% weight bearing on each foot, divided by truncated foot length. ARI was the ratio of AHIstand/AHIsit.

**Results:** After adjusting for potential confounders, univariate analyses revealed that AHI is significantly associated with OLS (P = 0.010), TPL (P= 0.031), and area (P = 0.024) in the sitting position. However, there was no association between standing AHI and balance or postural sway tests. Area (P= 0.024) was also associated with ARI.

**Conclusion:** Our findings suggest that sitting AHI is associated with balance and postural sway, while ARI is associated with area in elderly women. Therefore, AHI and ARI might play important part in defining balance control in elderly women.

**Key words:** older adults, 3D foot shape, arch height, postural stability



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Maintaining balance when performing functional tasks is a complex phenomenon that is influenced by a range of sensorimotor factors including lower-extremity muscle strength [1], peripheral sensation [2], reaction time, and visual acuity [3]. Foot arch height index

(AHI) and arch rigidity index (ARI) may also influence balance and postural sway [4].

Foot and leg problems are common conditions reported by older adults, particularly in women, and as such, they have a significant impact on the daily lives of many older people [5]. Since foot posture influences lower limb gait kinematics [6], muscle activity [7], functional ability, and balance [3], measuring foot posture is widely considered an important component of musculoskeletal examination in clinical practice and research [8]. However, many measurement approaches are not suitable for routine use as they are time-consuming or require specialized equipment and/or clinical expertise [8]. The recent use of 3D foot scanners allows a large number of subjects to be scanned quickly and easily and helps to reduce patients' exposure to x-rays [9].

There is anatomical variability in the navicular tuberosity, and when palpating this measuring point clinical experience of the practitioner can affect the consistency of the navicular height measurement. Therefore, Williams and McClay proposed measuring the height of the dorsum of the foot at 50% of foot length and dividing by either total foot length or truncated foot length [10]. They reported that the dorsum foot height divided by either total or truncated foot length had the highest values of the seven measurements they evaluated [10]. Several other researchers have also used the dorsal height at 50% foot length divided by the truncated foot length as a way to characterize arch height and have called the measurement AHI [11, 12, 13, 14, 15]. Williams and McClay also measured dorsal height at both 10% and 90% weight bearing and used radiographs to substantiate the validity of these two positions [10]. Several investigators measured dorsal foot height with the subject in a relaxed standing position, assuming 50% body weight on each foot [13, 14, 15]. Franettovich et al and Vinicombe et al have suggested that performing foot measurements at 50% weight bearing improves measurement reliability by decreasing balance-related issues that can occur as subjects intermittently change their foot position while attempting to stand with a partial amount of their body weight on the foot being assessed [15, 16]. On the whole, determining AHI measured at 50% of foot length with 50% weight bearing would appear to provide the clinician with a more reliable measurement than navicular height since we eliminate the need for palpating a bony landmark.

The available evidence in the literature indicates that foot and leg problems may be associated with functional impairment, but this information should be interpreted in light of certain study limitations, in particular, the way functional impairment and foot problems have been measured [5]. Foot problems have been clustered together with other pathologies and labeled 'lower extremity problems' [17], and participants' self-reported abilities and problems are often relied upon to determine functional impairment [5]. Few studies have incorporated objective evaluations of functional performance and foot posture [5]. Although self-reporting of many instruments of functional ability and foot problems can be valid [18], objective evaluations may be more sensitive to change and may provide better predictive validity [19].

Furthermore, most studies have not explored the influence of other health-related factors on the relationship between foot posture and functional performance. It is important to consider the relative contribution of foot posture to balance and postural sway after accounting for these potential confounders [5]. Moreover, previous studies have largely focused on radiographic or other less accessible measures of foot structure as potential predictors rather than tests that can be performed in a clinical setting [20].

We could find no published studies on the association between either AHI/ARI and balance or AHI/ARI and postural sway in an elderly population using a 3D foot scanner. Our objective was to provide additional insight into AHI and ARI in older women using a 3D foot scanner. The main objective of this study was to determine whether AHI and ARI are independently associated with balance and postural sway in a large community sample of older women after adjusting for the effects of medical factors using objective measures of balance status and the technology of 3D foot scanning.

## Methods

***Participants and data collection***

We conducted this cross-sectional study in August 2012 in Kasama City (population 79,266, proportion of older adults 24.0%), a rural region in Ibaraki prefecture, Japan. We mailed invitation letters to 831 older women aged 65–85 years randomly drawn from the Basic Resident Register.

A total of 170 older women participated in this study conducted in the Kasama City health center. Of these participants, we excluded 30 due to their reliance on walking sticks during the measurement or because they refused to remove their pantyhose preventing us from collecting foot and postural sway data. There were 140 participants for final data analysis. Medical histories, demographics, AHI, ARI, balance and postural sway variables are shown in Table 1. All participants provided a signed, informed consent. This study was approved by the Ethical Committee of University of Tsukuba.

***Measurement variables***

During the first two weeks of August 2012, we measured AHI, balance, postural sway and body mass index (BMI) of participants, and we gathered medical histories via face-to-face interviews.

*AHI*

We measured AHI and ARI using the 3D foot scanner by Dream GP Company, Japan (Figure 1). Modern 3D surface scanning systems can obtain accurate and reproducible digital representations of the foot shape and have been used successfully in medical, ergonomic footwear development applications [9].

Subjects individually sat with bare feet on the end of a table so their lower legs were non-weight bearing and their ankles were slightly plantar-flexed [21]. They placed their right feet onto the factory-delineated center of the scanner as the measurer assured proper positioning. To prevent ankle dorsiflexion, the subjects were instructed not to forcibly push the platform of the 3D machine [21]. Prior to starting the machine, light-blocking material attached to the rim of the scanner was secured to subjects' lower legs (Figure 1).

**Figure 1** 3D foot scanner by Dream GP Company, Japan.

When the scanner is started, a laser rotates on the rail around the foot measuring approximately 30,000 positions, including instep, heel, sole and toe, allowing the software to reproduce the exact shape of the foot. Each measurement is completed in about 13 seconds.

After completing measurements in a sitting position, participants stood up without changing their foot position inside the machine, set their left foot on an adjacent wooden platform next to and level with the platform inside the scanner and placed equal weight on each foot. This placed 50% of their body weight on the foot being assessed. The measurer checked the foot positioning in the scanner prior to starting the machine. Participants were also encouraged to use the handrail placed in front of them for balance, to relax their feet, and to ensure equal loading on each extremity. The handrail was placed at a level which they could easily reach without needing to raise or lower their arms too much. The participants looked straight ahead and stood as still as possible.

Once we obtained readings for the right foot in both sitting and standing positions, we repeated the measurements for the left foot. We collected 4 measurements on each person, right and left foot in both sitting and standing positions, and then sanitized the instruments with 70% alcohol prior to measuring the next person.

| Variables | Mean or % | SD or Number |
|---|---|---|
| Age (years) | 73.89 | 5.14 |
| BMI (kg/m$^2$) | 23.14 | 2.98 |
| Sitting AH (mm) | 59.65 | 3.87 |
| Standing AH (mm) | 55.02 | 3.88 |
| Sitting truncated foot length (mm) | 165.25 | 6.92 |
| Standing truncated foot length (mm) | 168.45 | 7.01 |
| Sitting AHI † | 0.36 | 0.03 |
| Standing AHI † | 0.33 | 0.03 |
| ARI | 0.91 | 0.03 |
| OLS (sec) | 30.30 | 21.64 |
| TUG (sec) | 6.86 | 1.93 |
| TPL (cm) | 31.48 | 12.03 |
| Area (cm$^2$) | 2.13 | 1.60 |
| Diabetes | 12.1% | N = 17 |
| Stroke | 4.3% | N = 6 |
| Low back pain | 21.4% | N = 30 |
| Knee pain | 15.0% | N = 21 |
| Hip pain | 2.1% | N = 3 |

*† Normalized to sitting or standing truncated foot length.*

**Table 1** Medical histories, demographic, static foot posture and postural sway variables.

| | Sitting AHI ①Low arch (n = 22) Mean ± SD | Sitting AHI ②Medium arch (n = 96) Mean ± SD | Sitting AHI ③High arch (n = 22) Mean ± SD | Linear trend *P* value | Bonferroni post-hoc test |
|---|---|---|---|---|---|
| *Balance tests:* | | | | | |
| One-leg balance with eyes open, sec | 22.47 ± 19.46 | 30.80 ± 21.44 | 35.21 ± 23.44 | .010 | ① < ③ |
| Timed up and go, sec† | 7.20 ± 1.58 | 6.86 ± 2.09 | 6.56 ± 1.46 | .372 | |
| *Postural sway items:* | | | | | |
| Total Path Length, cm† | 36.83 ± 16.44 | 31.23 ± 11.34 | 28.01 ± 9.02 | .031 | n.s. |
| Area, cm² † | 2.76 ± 2.48 | 2.16 ± 1.50 | 1.52 ± 0.61 | .024 | n.s. |

P values were adjusted for age, BMI and clinical histories: stroke, diabetes, low back pain, knee pain and hip pain.

Low arch: mean -1SD, medium arch: between -1SD to +1SD, High arch: mean +1SD

n.s.: not significant

†A low score on this scale indicates good physical performance.

**Table 2** Associations between Sitting AHI and Physical performance in older women.

In this study, AHI was defined as the linear distance (mm) from the instep as defined by the foot scanning machine, to the supporting surface while sitting and while standing with 50% weight bearing on each foot, divided by the truncated foot length [22]. ARI was the ratio of AHIstand/AHIsit [23].

*Balance*

We assessed static and dynamic balance tests as follows:

*1) One leg stance with eyes open (OLS).* This is a static balance test. Participants put both hands on their waist and gradually raised their preferred foot in front of them to approximately 20 cm above the floor. They maintained this position as long as possible (up to 60 seconds).

*2) Timed up and go (TUG).* This is a dynamic balance test. Participants rose from a chair, walked 3 m as quickly as possible, turned around, walked back, and sat down [24].

| | Standing AHI | | | | |
|---|---|---|---|---|---|
| | ①Low arch (n = 22) | ②Medium arch (n = 96) | ③High arch (n = 22) | Linear trend *P* value | Bonferroni post-hoc test |
| | Mean ± SD | Mean ± SD | Mean ± SD | | |
| *Balance tests:* | | | | | |
| One-leg balance with eyes open, sec | 30.57 ± 22.05 | 29.02 ± 21.32 | 34.76 ± 22.77 | .157 | |
| Timed up and go, sec† | 7.63 ± 2.54 | 6.66 ± 1.72 | 6.78 ± 1.84 | .061 | |
| *Postural sway items:* | | | | | |
| Total Path Length, cm† | 32.97 ± 15.14 | 31.80 ± 11.66 | 28.87 ± 9.73 | .362 | |
| Area,cm² † | 2.32 ± 1.53 | 2.21 ± 1.77 | 1.69 ± 0.86 | .265 | |

*P values were adjusted for age, BMI and clinical histories: stroke, diabetes, low back pain, knee pain and hip pain.*

Low arch: mean -1SD, medium arch: between -1SD to +1SD, High arch: mean +1SD

n.s.: not significant

†A low score on this scale indicates good physical performance.

**Table 3** Associations between Standing AHI and Physical performance in older women.

| | ARI | | | | |
|---|---|---|---|---|---|
| | ①Low rigidity (n = 22) | ②Medium rigidity (n = 96) | ③High rigidity (n = 22) | Linear trend *P* value | Bonferroni post-hoc test |
| | Mean ± SD | Mean ± SD | Mean ± SD | | |
| *Balance tests:* | | | | | |
| One-leg balance with eyes open, sec | 29.50 ± 21.40 | 30.97 ± 21.27 | 28.46 ± 24.26 | .677 | |
| Timed up and go, sec† | 6.95 ± 1.79 | 6.92 ± 1.98 | 6.47 ± 1.94 | .494 | |
| *Postural sway items:* | | | | | |
| Total Path Length, cm† | 31.09 ± 9.67 | 31.04 ± 12.19 | 34.01 ± 14.18 | .372 | |
| Area, cm² † | 1.97 ± 1.15 | 1.99 ± 1.47 | 3.00 ± 2.33 | .024 | ② < ③ |

P values were adjusted for age, BMI and clinical histories: stroke, diabetes, low back pain, knee pain and hip pain.

Low regidity: mean -1SD, medium regidity: between -1SD to +1SD, High regidity: mean +1SD

n.s.: not significant

†A low score on this scale indicates good physical performance.

**Table 4** Associations between ARI and Physical performance in older women.

*Postural sway*

Participants stood barefoot on a force plate (BM-101, TANITA Corporation, Japan) separating their heels 10.6 cm from the sagittal-horizontal axis of the force plate. Toes were adjusted in a symmetric and comfortable position. Participants' arms hung naturally at their sides as they looked at a fixed mark placed on a wall 1.5 m in front of them [25]. They were requested to stand as still as possible. Body sway was measured one time for 30 seconds [25]. The force plate measures selected for this study were the total path length (TPL) in cm traveled by the center of pressure (COP) in the allotted time and the 95% circular area ($cm^2$) for the COP.

***Statistical analysis***

Since t-test results indicated no significant differences between the left and right feet data, we used mean data from both feet in our analyses. For analyses, we divided participants into three groups based on standard scores of AHI & ARI: low arch height & low rigidity (mean-1 SD), medium arch height & medium rigidity (mean-1 SD to +1 SD), and high arch height & high rigidity (mean+1 SD).

To examine the associations between AHI/ARI and balance or postural sway, we used a one-way analysis of covariance (ANCOVA), which can adjust for potential confounders, because conditions such as age, BMI, cardiovascular disease and stroke, low back pain, knee pain, and hip pain are also likely to affect functional ability in older people [5]. Diabetes can also affect foot posture. Therefore, covariates included age, BMI and clinical histories: stroke, diabetes, low back pain, knee pain, and hip pain. We applied the Bonferroni post hoc test when the difference was significant ($p<0.05$) according to the ANCOVA results. Statistical analyses were performed using SPSS version 18.0.

## Results

After adjusting for potential confounders, univariate analyses revealed that AHI is significantly associated with OLS (P = 0.010), TPL (P= 0.031) and area (P = 0.024) in the sitting position. However, there was no association between standing AHI and balance or postural sway tests. Area (P= 0.024) was also associated with ARI (Tables 2-4).

## Discussion

This study revealed that sitting AHI was associated with balance and postural sway, and ARI was associated with area. However, we did not find standing AHI to be associated with balance or postural sway. The lack of standardization of data-collection methods and approaches for measurements are limitations of this study. Overall, the current study provided evidence that AHI is associated with balance and postural sway in elderly women. Women with a low arch or flatter foot had more postural sway and poor balance. ARI was only associated with area which high rigidity resulted in more sway. The results of our study are consistent with previous studies that have reported a flatter foot resulted in increased anteroposterior sway [3,26]. Cobb et al [26], believed that decreased joint congruity and, consequently, an increased reliance on soft tissue structures for stability, was the reason for decreased stability associated with increased forefoot varus. Spink et al [3] revealed that foot posture was an independent predictor of postural sway on foam, with a more pronated foot corresponding to a poorer performance. OLS is also a static balance test, more postural sway and shaking would result in a poor performance.

However, Menz et al [27] found that foot posture was not an independent predictor of performance in balance and functional tests. This inconsistency with our study may be due to how we defined foot posture. In our study, we used arch height to define foot posture, whereas, Menz et al used the Foot Posture Index (FPI) which is a multidimensional, visual observation tool consisting of 6 criteria scored on a 5-point scale (range -2 to +2). In the FPI, the summed score indicates the degree of pronation or supination in the posture of the foot, with higher scores representing a more pronated foot. This is completely different from AHI and categorizing the foot type based on that.

As for the ARI, a highly rigid foot resulted in more postural sway. According to the literature, there is a significant, but weak, relationship between arch height index and arch stiffness ($p = 0.00$, $R^2 = 0.09$) with a higher AHI corresponding to a stiffer arch [13]. However, when the foot in a sitting position has been categorized as low arched or flat foot, that would also result in less movement of arch height or high ARI. In this study, the mean ARI for low arch foot in a sitting position was 0.914 which is close to 1. Therefore, the association between ARI and area is inconsistent with our sitting AHI results that showed that a low arch foot results in poor performance in the postural sway.

In our study, while in a standing position, subjects with low arches were also likely to have more postural sway than the subjects with higher arches, but there was no significant association between standing AHI and postural sway or balance. This might be because the navicular bone and instep point move not only in a vertical direction during the stance phase of gait, but in the medial-lateral direction as well, especially during the later portion of the stance phase [28]. We considered only the vertical direction of movement for arch height in this study. If we could measure both lateral and vertical changes, the difference in postural sway may be statistically significant, however further research is required to investigate this.

Additionally, even though subjects were instructed to distribute their body weight equally when standing so that the assessed foot supported 50% weight bearing, we could not control this with accuracy. Therefore, there may be variations in percentage of weight bearing, and as a result, different standing AHI in a standing position. Tessem et al previously reported that the amount of asymmetry in weight distribution between extremities during relaxed standing is 4% or less in healthy subjects [29]. There are two other limitations of our study. Because of our study's cross-sectional design, we cannot prove a causal association, and we had only women as our subjects.

Despite these limitations, our study provides intriguing findings on the associations between sitting AHI and balance and postural sway and between ARI and postural sway in elderly women. Women with a low arch and highly rigid foot had more postural sway and poorer balance. These findings suggest that sitting AHI and ARI might be important for defining balance control in older women. Further research investigating the effect of foot arch height on falling is needed before making any generalizations on the potential risk of fall. Other areas of research should include the effect of shoes or other forms of support on balance and postural sway in older adults with lower arch height and highly rigid feet.

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