Gender differences of foot characteristics in older Japanese adults using a 3D foot scanner

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Abstract

Background: Knowledge of gender differences in foot shape assists shoe manufactures with designing appropriate shoes for men and women. Although gender differences in foot shapes are relatively known among young men and women, less is known about how the older men and women’s feet differ in shape. A recent development in foot shape assessment is the use of 3D foot scanners. To our knowledge this technology has yet to be used to examine gender differences in foot shape of Japanese older adults.

Methods: This cross-sectional study included 151 older men (74.5 ± 5.6 years) and 140 older women (73.9 ± 5.1 years) recruited in Kasama City, Japan. Foot variables were measured in sitting and standing positions using Dream GP Incorporated’s 3D foot scanner, Footstep PRO (Osaka, Japan). Scores were analyzed as both raw and normalized to truncated foot length using independent samples t-test and analysis of covariance, respectively.

Results: In men, the measurement values for navicular height, first and fifth toe and instep heights, ball and heel width, ball girth, arch height index (just standing), arch rigidity index and instep girth were significantly greater than the women’s, whereas the first toe angle, in both sitting and standing positions was significantly smaller. However, after normalizing, the differences in ball width, heel width, height of first and fifth toes in both sitting and standing and ball girth in sitting position were nonsignificant. According to Cohen’s d, among all the foot variables, the following had large effect sizes in both sitting and standing positions: truncated foot length, instep, navicular height, foot length, ball girth, ball width, heel width and instep girth.

Conclusion: This study provides evidence of anthropometric foot variations between older men and women. These differences need to be considered when manufacturing shoes for older adults.

Keywords: Anthropometry, Elderly, Footwear, Shoe design, Three-dimensional shape
studies, in Brazil and Australia, relating to such gender-related differences in older adults [4, 8]. However, in the Brazil study, all the foot measurements were obtained by caliper and goniometer [4]. In that study, women had significantly greater ball width and toe perimeters, while the heel width was significantly smaller relative to the height of the dorsal foot after normalizing the data to foot length. In addition, the first and fifth metatarsophalangeal angles were smaller in the men [4].

In the study conducted in Australia, the researchers measured foot anthropometrics using a calibrated 3D foot scanner. In that study, men had significantly larger measurements than the women for all dimensions with the exception of first toe angle. Men had significantly higher normalized first and fifth toe heights and a larger fifth toe angle, whereas women had a significantly longer normalized medial ball length and larger first toe angle [8]. In addition to gender differences, ethnic origin can also influence foot shape [9]. Therefore, studying older adults’ foot characteristic in each nation is indispensable [10].

The opportunity for podiatric research has improved in recent years with the new laser scanner technologies available for various applications [11]. This new technology with adequate speed of data capture provides the opportunity to quickly measure the three-dimensional shape of the foot in large populations. This can improve our ability to analyze gender differences more accurately. To the best of our knowledge, this technology has yet to be used for examining gender differences in foot shape of Japanese older adults.

Unfortunately, although inappropriate footwear is a known risk factor for falls of the elderly [12], little is known about what actually constitutes safe footwear for this age group [13]. Knowing the characteristics of older adults’ feet, including gender and ethnic differences, could improve footwear design and may reduce the risk of falls in the elderly. The main objective of this study was to determine gender differences in foot characteristics in a large community sample of older Japanese adults using the recently launched technology of 3D foot scanning. We could find no previous studies on this topic in Japan; this is the first such study.

Methods
Participants
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.

A total of 349 older adults participated in this study conducted in the Kasama City health center. Of these participants, we excluded 58 due to incomplete data, their reliance on walking sticks during the measurement or among women because of refusing to remove their pantyhose preventing us from collecting foot characteristic.

Table 1 Participant characteristics

| Variables      | Men = 151 | Women = 140 |
|----------------|-----------|-------------|
| Age (years)    | 74.5 ± 5.6| 73.9 ± 5.1  |
| Height (cm)    | 162.6 ± 5.7| 148.9 ± 5.7|
| Weight (kg)    | 61.28 ± 8.25| 51.38 ± 7.4|
| BMI (kg/m²)    | 23.13 ± 2.15| 23.14 ± 2.97|
| Diabetes       | 14.6 % N = 22 | 12.1 % N = 17 |
| Osteoporosis   | 0.7 % N = 1 | 16.4 % N = 23 |

There were 151 men (74.5 ± 5.6 years) and 140 women (73.9 ± 5.1 years) participants for final data analysis. Medical histories and demographics 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.

Measurements
Foot characteristics
We measured foot characteristics using the recently launched 3D foot scanner, Footstep PRO by Dream GP Company, Osaka, Japan (Fig. 1). Modern 3D surface scanning systems can obtain accurate and repeatable digital representations of the foot shape and have been used successfully in medical, ergonomic and footwear development applications [14]. An example of 3D image by Footstep PRO is shown in Fig. 2.

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 planar-flexed [15]. 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 [15]. Prior to starting the machine, light blocking material attached to the rim of the scanner was secured to subjects’ lower legs.

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

After completing measurement 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 leg in both sitting and standing positions and then sanitized the instruments with 70% alcohol prior to measuring the next person. Foot characteristics are shown in Fig. 3.

In this study, we used the following two methods for calculating arch height:

Navicular height (NH) and navicular drop (ND)
We measured navicular heights as described in the literature [16]. The subject sat on a chair with bare feet. The most prominent portion of the navicular tuberosities on both feet were palpated and marked with a small, round, black sticky point while the participants maintained a relaxed sitting position. The 3D scanner software located these black points as the point of the navicular.

One investigator (MS) performed all markings of the navicular tuberosity. This investigator was a licensed athletic trainer with 2 years’ experience in foot and posture assessment at the time of testing. In this study, navicular height
was defined as the linear distance (mm) from the most medial prominence of the navicular tuberosity to the supporting surface while sitting and while standing with 50 % body weight on each foot [17].

We defined navicular drop or foot mobility as the amount of vertical navicular excursion (mm) between the positions of the subtalar joint while neutral in sitting position and relaxed in bilateral standing (navicular drop) [18].

Arch height index (AHI) and arch rigidity index (ARI) Since skin markers over the navicular tuberosity have been shown to not track the actual position of the bone with complete accuracy [19], AHI was also used.

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 [20].

Arch rigidity index (ARI) is defined as the ratio of standing AHI divided by seated AHI (AHI stand/AHI sit). Values nearer to 1 indicate a stiffer (less flexible) foot [21].

All the foot data were collected automatically by the Footstep PRO. However, some of the data such as foot length, navicular height, ball width and angle of first and fifth toes were adjustable by defining their points in the software. For instance, we defined foot length in this study as a linear distance from the most prominent point of the calcaneal tuberosity to the tip of the longest toe. The first or second toe was chosen as the longest after viewing the 3D foot shape with the software.

**Statistical analysis**

Scores were analyzed as both raw and normalized to truncated foot length using independent samples $t$-test and analysis of covariance, respectively. Williams and McClay [22] indicated that using the truncated foot length, the perpendicular distance from the first metatarsophalangeal joint to the most posterior aspect of the heel, reduces the impact that toe deformities, such as claw toes and hallux valgus, may have on heel to longest toe foot length. Therefore, truncated foot length was used to normalize the data.

A $P$ value of less than 0.001 was considered statistically significant. For each subject, we averaged the right and left foot measurements for the analyses. Cohen’s $d$ is interpreted as a very small effect at less than 0.2, as a small effect between 0.2 to 0.5, as a moderate effect between 0.5 to 0.8, and as a large effect greater than 0.8. Statistical analyses were performed using SPSS version 18.0.
Results
In men, the measurement values for navicular height, first and fifth toe and instep heights, ball and heel width, ball girth, AHI (just standing), ARI and instep girth were significantly greater than the women’s, whereas the first toe angle, in both sitting and standing positions was significantly smaller. However, after normalizing, the differences in ball width, heel width, height of first and fifth toes in both sitting and standing and ball girth in sitting position were nonsignificant. According to Cohen’s d, among all the foot variables, the following had large effect sizes in both sitting and standing positions: truncated foot length, instep, navicular height, foot length, ball girth, ball width, heel width and instep girth (Table 2).

Discussion
This study demonstrates important anatomical differences of the foot between genders. Women have narrower feet in the heel and forefoot, and their instep, first and fifth toes and navicular height are also lower than men’s. Women also showed a greater first toe angle and lower ARI and AHI (just standing) compared to men. However, some of these differences were nonsignificant after normalizing to truncated foot length suggesting that the original findings were simply due to the fact that male feet tend to be larger than female feet. Furthermore, according to Cohen’s d, some differences were very small, and as a practical manner, the usefulness for shoe manufacturers to incorporate those differences is questionable.

Table 2 Independent sample t-test, ANCOVA (adjusted to truncated foot length) & Cohen’s d effect size

| Foot characteristics                      | Men (N = 151) Mean ± SD | Women (N = 148) Mean ± SD | t test P value | ANCOVA P value | Effect size (ES) | Guide of ES |
|-------------------------------------------|-------------------------|---------------------------|----------------|----------------|-----------------|-------------|
| Sitting truncated foot length (mm)         | 179.81 ± 7.46           | 165.25 ± 6.92             | P < 0.001      | –              | 2.03            | Large       |
| Sitting instep (mm)                        | 66.18 ± 4.30            | 59.65 ± 3.87              | P < 0.001      | P < 0.001      | 1.60            | Large       |
| Sitting NH (mm)                            | 48.23 ± 6.21            | 42.15 ± 5.14              | P < 0.001      | P < 0.001      | 1.07            | Large       |
| Sitting AHI                                | 0.37 ± 0.03             | 0.36 ± 0.03               | .021           | –              | 0.27            | Small       |
| Sitting foot length (mm)                   | 243.19 ± 9.07           | 224.69 ± 8.86             | P < 0.001      | –              | 2.07            | Large       |
| Sitting ball girth (mm)                    | 244.28 ± 11.65          | 227.95 ± 10.66            | P < 0.001      | .002           | 1.47            | Large       |
| Sitting ball width (mm)                    | 98.93 ± 5.08            | 92.55 ± 5.24              | P < 0.001      | .490           | 1.24            | Large       |
| Sitting heel width (mm)                    | 64.51 ± 4.22            | 59.93 ± 3.22              | P < 0.001      | .291           | 1.22            | Large       |
| Sitting first toe angle (degree)           | 10.42 ± 4.64            | 13.64 ± 6.92              | P < 0.001      | P < 0.001      | 0.55            | Moderate    |
| Sitting little toe angle (degree)          | 13.80 ± 4.00            | 13.35 ± 4.87              | .393           | .782           | 0.10            | Very small  |
| Sitting first toe height (mm)              | 18.03 ± 2.31            | 16.45 ± 2.16              | P < 0.001      | .057           | 0.71            | Moderate    |
| Sitting little toe height (mm)             | 12.88 ± 2.25            | 11.94 ± 1.85              | P < 0.001      | .564           | 0.46            | Small       |
| Sitting instep girth (mm)                  | 248.93 ± 11.54          | 227.70 ± 10.85            | P < 0.001      | P < 0.001      | 1.90            | Large       |
| Standing foot length (mm)                  | 246.20 ± 9.05           | 227.57 ± 9.13             | P < 0.001      | –              | 2.06            | Large       |
| Standing truncated foot length (mm)        | 182.16 ± 7.81           | 168.45 ± 7.01             | P < 0.001      | –              | 1.85            | Large       |
| Standing instep (mm)                       | 61.68 ± 4.51            | 55.02 ± 3.88              | P < 0.001      | P < 0.001      | 1.58            | Large       |
| Standing NH (mm)                           | 41.77 ± 6.32            | 35.76 ± 5.32              | P < 0.001      | P < 0.001      | 1.03            | Large       |
| Standing ball girth (mm)                   | 247.09 ± 11.23          | 230.55 ± 11.41            | P < 0.001      | P < 0.001      | 1.47            | Large       |
| Standing ball width (mm)                   | 101.53 ± 4.85           | 95.39 ± 5.74              | P < 0.001      | .251           | 1.16            | Large       |
| Standing heel width (mm)                   | 65.89 ± 4.05            | 60.64 ± 4.67              | P < 0.001      | .006           | 1.21            | Large       |
| Standing first toe angle (degree)          | 10.73 ± 4.95            | 14.90 ± 7.60              | P < 0.001      | P < 0.001      | 0.63            | Moderate    |
| Standing little toe angle (degree)         | 13.84 ± 4.11            | 13.62 ± 5.00              | .687           | .725           | 0.05            | Very Small  |
| Standing first toe height (mm)             | 17.39 ± 1.91            | 16.02 ± 2.29              | P < 0.001      | .465           | 0.65            | Moderate    |
| Standing little toe height (mm)            | 12.76 ± 2.05            | 11.74 ± 1.87              | P < 0.001      | .084           | 0.52            | Moderate    |
| Standing instep girth (mm)                 | 249.20 ± 11.05          | 228.30 ± 10.94            | P < 0.001      | P < 0.001      | 1.91            | Large       |
| Standing AHI                               | 0.34 ± 0.03             | 0.33 ± 0.03               | P < 0.001      | –              | 0.46            | Small       |
| Arch drop (instep difference) (mm)         | 4.51 ± 1.70             | 4.65 ± 1.62               | .464           | .008           | 0.09            | Very small  |
| ND (mm)                                    | 6.46 ± 2.53             | 6.39 ± 2.53               | .814           | .610           | 0.03            | Very small  |
| ARI                                        | 0.92 ± 0.03             | 0.91 ± 0.03               | P < 0.001      | –              | 0.43            | Small       |
According to Wunderlich et al., these small differences may not even be perceptible when incorporated into footwear [10]. In our study, the first toe angle was significantly greater in women. The presence of hallux valgus can explain the larger values found among the women, because it occurs more frequently in women [23–25].

Our results were different in some respects to the gender difference studies in Brazil and Australia. In Brazil, unlike the results of our study, the width and perimeter of the toes and the width of the heel in the women were significantly greater than the men's measurements. However, similar to our results, women had a significantly lower instep than men after normalizing the data to foot length, and the first and fifth metatarsophalangeal angles were smaller in the men [4]. Like our study, the Australian study used a 3D foot scanner and found men to have significantly larger values than the women for all dimensions with the exception of the first toe angle. However, men had significantly higher first and fifth toe heights and a greater fifth toe angle, and women had a significantly longer truncated foot length normalized within two common foot length categories, which is different than our results [8]. The inconsistencies between the Brazil and Australian studies and our study may be due to different measuring methods or foot categorization, or these may be true ethnic differences.

Our study results are consistent with previous studies on young or mixed-age populations. Krauss et al. showed that, for the same shoe size, young women had lower insteps than young men [1]. In addition, they found that women had smaller widths of the heel and the foot [1]. Aml et al. also compared foot measurements in the same foot-length category and observed that foot width and perimeter were greater in males than in females [26]. Furthermore, Wunderlich et al. normalized their data to the foot length and reported women's feet had smaller values for the height of the first toe and the perimeter of the instep [10].

When comparing arch height between men and women, results vary between studies. The results of our study are consistent with the study by Frey [5] who reported that women presented with flatter feet than men did. Hashimoto et al. [27] who used radiography, a more reliable measurement method, to verify arch height in young adults also noted that the women had lower arches than the men. Structural changes in the female body may lead to pronation of the foot. Compared to men, women have narrower shoulders, hips are in a more varus position, and knees are in a more valgus position, which induces a pronation of the rear feet [5].

On the other hand, our results are different from 2 other studies: a survey of 441 individuals 1–80 years of age by Staheli et al. [28] that used the arch index and indicated that males have flatter feet, and a study by Zitchock et al. [29] of 145 individuals 18–65 years of age that reported that standing AHI was not significantly different but ARI was significantly different between men and women. These inconsistencies may be related to ethnic, cultural, measurement tool and age differences.

It is acknowledged that, even though subjects were instructed to distribute their body weight equally when standing so that the assessed foot supported 50 %, we could not control this with accuracy. Therefore, there may be variations in percentage of weight bearing, and as a result, different standing NH and AHI in 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 [30]. Moreover, the sample used in this study was possibly more active or mobile due to excluding people reliant on walking sticks during the measurement.

Conclusion
Overall, the current study provided evidence of anthropometric foot variations of older men and women. The dissimilarities are primarily in instep height, instep girth, ball girth and navicular height. Shoe manufacturers should consider the gender differences in feet when designing shoes for older adults to accommodate the greater ball and instep girth and the instep and navicular height of men's feet and the greater first toe angle in women. Since the P value for standing heel width is also near 0.001, we recommend shoe designers also consider this difference. It remains to be seen, however, whether a shoe designed for the elderly based on gender differences suggested here would be perceived subjectively as being a better fit and, therefore, more comfortable. Further research should investigate how footwear designed according to gender differences affects fall risk.

Abbreviation
NH: Navicular height; ND: Navicular drop; AHI: Arch height index; ARI: Arch rigidity index.

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
MS carried out conception and design, data acquisition, analysis and interpretation, and drafting of the manuscript. NK participated in acquisition of the data, interpretation of the data, and manuscript development. TO participated in data interpretation, supervision and coordination of the study, and manuscript development. All authors read and approved the final manuscript.

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References
1. Krauss I, Grau S, Mauch M, Maiwald C, Horstmann T. Sex-related differences in foot shape. Ergonomics. 2008;51(11):1693–709.
2. Tomasoni D, Traini E, Amenta F. Gender and age related differences in foot morphology. Maturitas. 2014;79(4):421–7.
3. Chantelau E, Gede A. Foot dimensions of elderly people with and without diabetes mellitus—a data basis for shoe design. Gerontology. 2002;48(4):241–4.
4. de Castro AP, Rubens Rebelatto J, Rabiatti AT. The effect of gender on foot anthropometrics in older people. J Sport Rehabil. 2011;20(3):277.
5. Frey C. Foot health and shoe wear for women. Clin Orthop Relat Res. 2000;372:32–44.
6. Kouchi M. Foot Dimensions and Foot Shape: Differences Due to Growth. Anthropol Sci. 1998;106:161–88.
7. Scott G, Menz HB, Newcombe L. Age-related differences in foot structure and function. Gait Posture. 2007;26(1):69–75.
8. Mickle KJ, Munro BJ, Lord SR, Menz HB, Steele JR. Foot shape of older people: Implications for shoe design. Footwear Science. 2010;2(3):131–9.
9. Hawes MR, Sovak D, Miyashita M, Kang S-J, Yoshikoku Y, Tanaka S. Ethnic differences in foot geometry and the determination of shoe comfort. Ergonomics. 1994;37(1):187–96.
10. Wunderlich RE, Cavanagh PR. Gender differences in adult foot shape: implications for shoe design. Med Sci Sports Exerc. 2001;33(4):605–11.
11. Witana CP, Xiong S, Zhao J, Goonetilleke RS. Foot measurements from three-dimensional scans: A comparison and evaluation of different methods. INT J IND ERGONOM. 2006;36(9):789–807.
12. Lord SR, Menz HB, Sherrington C. Home environment risk factors for falls in older people and the efficacy of home modifications. Age Ageing. 2006;35 suppl 2:i55–9.
13. Guideline for the prevention of falls in older persons. J Am Geriatr Soc. 2001;49(5):664–72.
14. Telfer S, Woodburn J. The use of 3D surface scanning for the measurement and assessment of the human foot. J Foot Ankle Res. 2010;3:19.
15. Cornwell MW, McPail TG. Relationship between static foot posture and foot mobility. J Foot Ankle Res. 2011;4(4):1–9.
16. Brody DM. Techniques in the evaluation and treatment of the injured runner. Orthop Clin North Am. 1982;13(3):541–58.
17. Mueller MJ, Menz HB, Landorf KB. A protocol for classifying normal and flat-arched foot posture for research studies using clinical and radiographic measurements. J Foot Ankle Res. 2009;2:22.
18. Mueller MJ, Host JV, Norton BJ. Navicular drop as a composite measure of excessive pronation. J Am Podiatr Med Assoc. 1993;83(4):198–202.
19. Telfer S, Woodburn J, Turner DE. An ultrasound based non-invasive method for the measurement of intrinsic foot kinematics during gait. J Biomech. 2014;47(5):1225–8.
20. Teyhen DS, Stoltenberg BE, Collinsworth KM, Giesel CL, Williams DG, Kardouni CH, et al. Dynamic plantar pressure parameters associated with static arch height index during gait. CLIN BIOMECH. 2009;24(4):391–6.
21. Richards CJ, Card K, Song J, Hillstrom H, Butler R, Davis I. A novel arch height index measurement system (AHIMS): intra- and inter-rater reliability. Proceedings of American Society of Biomechanics Annual Meeting Toledo. 2003.
22. Williams DS, McClay IS. Measurements used to characterize the foot and the medial longitudinal arch: Reliability and validity. Phys Ther. 2000;80(9):864–71.
23. Kilmartin TE, Wallace WA. The aetiology of hallux valgus: a critical review of the literature. Foot. 1993;3(4):157–67.
24. Menz HB, Lord SR. Foot pain impairs balance and functional ability in community-dwelling older people. J Am Podiatr Med Assoc. 2001;91(5):222–9.
25. Dunn J, Link C, Felson D, Cincoli M, Keyser J, McKinlay J. Prevalence of foot and ankle conditions in a multicultural community sample of older adults. Am. J Epidemiol. 2004;159(5):491–8.
26. Aml A, Peker T, Turgut H, Uluken S. An examination of the relationship between foot length, foot breadth, ball girth, height and weight of Turkish university students aged between 17 and 25. Anthropol Anz. 1997;55(1):79–87.
27. Hashimoto M, Cheng H, Hirohashi K. Evaluation of the function of the human foot in two different conditions using radiography. J Phys Ther Sci. 2004;16(1):57–64.
28. Staheli L, Chew D, Corbett M. The longitudinal arch: a survey of eight hundred and eighty-two feet in normal children and adults. J Bone Joint Surg Am. 1987;69(3):426–8.
29. Zifchick RA, Davis I, Hillstrom H, Song J. The effect of gender, age, and lateral dominance on arch height and arch stiffness. Foot Ankle Int. 2006;27(5):367–72.
30. Tessem S, Hagström N, Fallang B. Weight distribution in standing and sitting positions, and weight transfer during reaching tasks, in seated stroke subjects and healthy subjects. Physiother Res Int. 2007;12(2):82–94.