Correlation of medial longitudinal arch morphology with body characteristics and locomotive function in community-dwelling older women: A cross-sectional study

Hidetoshi Nakao1, Masakazu Imaoka1, Mitsumasa Hida1, Ryota Imai1, Fumie Tazaki1, Takeshi Morifuji2, Masashi Hashimoto3 and Misa Nakamura1

Abstract

Purpose: This cross-sectional study aimed to investigate the effects of foot arch deformities on physical characteristics, muscular strength, and motor function in older women depending on the presence or absence of pain. Methods: Overall, 145 community-dwelling women aged 65 to 90 years were included in this study. We measured the foot arch height ratio (AHR, dorsal height/truncated foot length) and classified participants with AHR values above, below, or within 1.5 standard deviations into the high-arched group (HAG), Low-Arched Group (LAG), or normal-arched group (NAG), respectively. We also compared body characteristics (age, height, weight, body mass index (BMI), and skeletal mass index), muscle strength (handgrip strength and intrinsic foot strength (IFS)), and locomotive function (two-step value and gait speed) among the three groups. Results: Locomotive examination and muscle strength showed significant differences among the three groups only in the presence of pain; in the two-step test, HAG, NAG, and LAG values were 0.98 cm/cm, 1.19 cm/cm, and 1.18 cm/cm, respectively. The IFS measured 19.2 N, 24.2 N, 31.0 N, respectively, in the HAG, NAG, and LAG. Conclusion: This study suggests that decreased IFS affects the mobility function of high-arched feet in older women. Although there was no significant difference in the evaluation of pain, HAG showed the highest average value, which is considered to contribute to the decreased two-step value. It has been suggested that a high-arched foot in the presence of pain is associated with IFS weakness and may affect the decline of mobility function in older women.

Keywords
foot deformities, locomotive function, medial longitudinal arch, older women

Date received: 12 February 2021; Received revised 15 April 2021; accepted: 18 April 2021

Introduction

The foot has arch structures that play a functional role in stabilizing walking and posture. Older people have many foot problems, including deformity, neuropathy, and pain. Foot issues can cause walking difficulty and postural problems in all age groups and lead to more serious health problems in older people.1,2 Reportedly, 30% of the foot deformities in community-dwelling older people3,4 are associated with reduced walking speed,1 difficulty in daily living activities, and an increased risk of falls.5 Recent
studies have emphasized the link between increased health risks, such as frailty syndrome and falls in older people, and foot problems.6–8

The medial longitudinal arch (MLA) of the foot can serve as a shock absorber during upright walking, as well as aid in the attenuation of forces transmitted during standing.9 A very low MLA is considered a flatfoot deformity, while an excessive elevation is a high-arch deformity. An increased incidence of injuries has been noted in people with both low and high-arch deformities.10–12 Flatfoot and high-arch foot deformity have been reported to have a prevalence of 10 to 25%,13–15 and flatfoot16 or high-arch foot17 can impair the standing balance in healthy young people. In addition, previous studies have shown that the laceration stress associated with foot arch deformation is greater in the soft tissue of the female foot. Therefore, women are at higher risk of soft tissue damage, such as fasciitis, than men.18

In particular, foot pain is very common and has been reported to be associated with falls in older people.19,20 Awale et al. reported that higher odds of recurrent falls were observed in individuals with severe foot pain, as well as in individuals with planus foot posture.21

Therefore, it is important to investigate the relationship between abnormal foot arch morphology and motor function in older people depending on the presence or absence of pain. This cross-sectional study mainly aimed to investigate the effects of low-arch and high-arch deformities on physical characteristics, muscular strength, and motor function in older women.

Materials and methods

Participants

This cross-sectional study was conducted in the city of Kaizuka, Japan from August 17 to September 12, 2019. We published a brochure for a community health check-up program and placed it in the local newspapers and public offices, such as the city hall. This cross-sectional study was approved by the Osaka Kawasaki Rehabilitation University Research Ethics Review Board (approval number: OKRU-A019), and written informed consent was obtained from each participant prior to study inclusion. Community-dwelling elderly participants who underwent health examination in Kaizuka City, Osaka, and who provided informed consent were included in the study. The participants were 145 community-dwelling older women, aged 65 to 85 years. Participants who (1) required a cane or walker to perform the gait test, (2) had received certified support or nursing care, or (3) had developed dementia were excluded from the study.

Evaluation method and reliability of foot measurements

The dorsal height (DH), foot length (FL), truncated foot length (TFL), and DH/TFL ratio were assessed in this study. The methods of MLA measurement were based on the bony landmarks described by Williams and McClay.22 Herein, DH/TFL was defined as the AHR.

Williams and McClay reported that intra-class correlations showed a high reliability of >0.9 for all foot measurements. In the study by McPoil et al. using the arch height index, the intra-correlation coefficients were highly reliable, with a heel to toe length of 0.99 and a dorsal arch height of 0.98.23

During the measurement process, participants placed their leg on a 15-cm table, while in the standing position. They also gripped a side-cane to stabilize themselves while the measurements were being taken. Measurements were taken according to the load borne by participant, with the load up to 10% of their body weight.

FL was measured using a plastic device, and the DH was calculated as the height of the top from the floor at 50% of FL and was measured using a digital Vernier caliper (Shinwa, Niigata, Japan). While measuring DH, one examiner fixed a ruler at the dorsum of the foot, and another examiner measured the height of the ruler with a digital caliper (Figure 1).

The TFL value was measured using a digital photographic image and Adobe Photoshop (version 21.0). Two digital cameras (RX-0, SONY, Tokyo, Japan) were used to record the medial sagittal aspect and upper horizontal plane of the foot in the standing position. The digital image of the upper horizontal plane was used to confirm that the foot was in the neutral position, and the medial sagittal aspect was used to calculate the TFL (Figure 2). TFL was calculated by measuring the FL from the digital image of the medial sagittal aspect of the foot using the grading function of the image editing Adobe Photoshop software. The Hallux Length (HL) was then calculated using the measured FL value in the following formula “HL(Photoshop) × FL/FL(Photoshop).” The TFL was derived from the FL and HL with the following formula: FL-HL. Several investigators have previously measured the foot using similar digital photographic images.24–26
The participants were classified into three groups according to the foot AHR: normal-arched group (NAG), high-arched group (HAG), and low-arched group (LAG). Thus, the DH and FL were directly measured using the foot measurement method, and digital photography was used for the TFL.

Assessment of body characteristics

Physiological parameters measured using bioelectrical impedance analysis (Inbody270; Inbody, Tokyo, Japan) with 20 and 1000 kHz frequencies were obtained from the participants’ electronic medical records.27,28 Participants were instructed to grasp the handles of the analyzer and stand on electrodes in contact with the lower surface of their feet while they wore normal indoor clothing without socks or shoes. The surface of the hand electrode was placed in contact with all five fingers, while the participants’ heels and forefoot were placed on the circular foot electrode. They were asked to perform fast and avoid vigorous exercise for at least 1 hour before the assessment. The body mass index (BMI) was calculated by dividing the body weight (kg) by the height squared (m²). The appendicular skeletal muscle mass index (SMI) was derived from the appendicular muscle mass (kg) divided by the height squared (m²).

Muscle strength

Handgrip strength is a well-known measure of muscle strength and is significantly associated with whole body muscle strength.29 The maximum voluntary isometric strength of the handgrip of the dominant hand was measured while in a standing position, using a hand dynamometer Grip-D (Takei, Niigata, Japan). Other bodily movements were not permitted during measurement.

Intrinsic foot musculature plays an important role in stabilizing the foot.30–32 For the intrinsic muscle strength, a handheld dynamometer (Mobie MT-100, SAKAImed, Tokyo, Japan) was placed distal to the metatarsophalangeal (MTP) joint of the hallux toe while in the sitting position, and the pushing force against the floor surface was measured with the MTP joint extended (Figure 3). When measuring the intrinsic muscle strength, the midfoot was fixed with soft band so that the foot would not shift.

Locomotive examination (gait speed and two-step test)

The participants were instructed to walk 6.4 m (divided into two 2.0-m zones at each end and a 2.4 m middle zone) at a speed they found comfortable.33 The time required (in
seconds) to pass the 2.4-m middle zone was measured for the calculation of gait speed (m/s). The average of five gait tests was used for evaluation.

The two-step test is one of the evaluation techniques for Locomotive Syndrome and has a high correlation with various mobility tests.34 Here, the maximum length of two steps (cm) that could be performed without poor balance was adopted, and a standardized value of the stride length divided by the height (cm) ratio was defined as the two-step value (cm/cm).

**Pain measurement**

To assess the rate of pain, a questionnaire survey was conducted to determine the current presence or absence of pain. Pain was assessed by documenting each participant’s maximum pain intensity using a numerical rating scale (NRS) from 0 (“no pain”) to 10 (“the worst imaginable pain”).

**Statistical analysis**

The Shapiro-Wilk test was used to confirm the normality of the distribution of each evaluation item. As a result, normality was not recognized except among the variables of MLA morphology in the three groups.

The foot AHR was used to classify the foot deformities into the three groups (NAG, HAG, and LAG) in all participants. The $\chi^2$ test was used to compare presence or absence of pain in the three groups, and if presence of pain, the most painful location was tested.

Three groups of MLA morphology performed the Kruskal-Wallis test to compare body characteristics, muscle strength, and locomotive examination. The Kruskal-Wallis test was performed separately according to the presence or absence of pain. NRS variables were also analyzed only in the presence of pain. The Kruskal-Wallis test was applied and post hoc comparisons made using Mann-Whitney U-test.

The values of the survey data in this study have been summarized as the mean values ($\pm$ standard deviation).

IBM SPSS Statistics 26 (IBM Corp., Armonk, NY, US) was used for all statistical analyses, with the significance level set at <5%.

**Results**

**Comparison of foot measurements between the sexes and classification based on AHR**

There was a significant difference in the evaluation items FL, DH, and TFL. Based on AHR, three groups of foot arches were determined: NAG (<AHR $+1.5$ SD), HAG (>AHR $+1.5$ SD), and LAG ($\leq$AHR $-1.5$ SD). This grouping criterion was applied when both sides or one side was HAG or LAG.

Previously, several investigators set the standard by using one-sided foot measurements $\pm 1.5$ SD from the mean value.35,36 Utilizing the results of mean $\pm 1.5$ SD based on AHR, LAG was $<0.281$ on the right foot and $<0.279$ on the left foot, and HAG was $>0.376$ on the right foot and $>0.365$ on the left foot. Table 1 shows the comparison of foot measurements between the three groups by foot arches.

| Foot measurements | LAG (n = 14) | NAG (n = 112) | HAG (n = 19) | Kruskal-Wallis | Post hoc Mann-Whitney |
|-------------------|--------------|---------------|--------------|---------------|----------------------|
| FL (cm)           | Mean (SD)    | Mean (SD)     | Mean (SD)    | P < 0.05      | a–b(*) a–c(*)        |
| Rt                | 23.1 (0.9)   | 22.2 (0.9)    | 21.6 (1.0)   | P < 0.05      | a–b(*) a–c(*)        |
| Lt                | 23.1 (0.9)   | 22.3 (0.9)    | 21.8 (1.5)   | P < 0.05      | a–b(*) a–c(*)        |
| TFL (cm)          |              |               |             |               |                      |
| Rt                | 17.9 (0.9)   | 17.1 (0.8)    | 16.6 (0.8)   | P < 0.05      | a–b(*) a–c(*) b–c(*) |
| Lt                | 17.9 (0.7)   | 17.2 (0.7)    | 16.4 (1.0)   | P < 0.05      | a–b(*) a–c(*) b–c(*) |
| DH (cm)           |              |               |             |               |                      |
| Rt                | 5.2 (0.5)    | 5.5 (0.3)     | 6.2 (0.3)    | P < 0.05      | a–b(*) a–c(*) b–c(*) |
| Lt                | 5.0 (0.3)    | 5.5 (0.3)     | 6.0 (0.4)    | P < 0.05      | a–b(*) a–c(*) b–c(*) |
| AHR (DH/TFL)      |              |               |             |               |                      |
| Rt                | 0.28 (0.02)  | 0.32 (0.02)   | 0.37 (0.02)  | P < 0.05      | a–c(*) b–c(*)        |
| Lt                | 0.28 (0.01)  | 0.32 (0.01)   | 0.36 (0.01)  | P < 0.05      | a–c(*) b–c(*)        |

HAG: High-Arched Group; NAG: Normal-Arched Group; LAG: Low-Arched Group; FL: Foot Length; TFL: Truncated Foot Length; DH: Dorsal Height; AHR: Arch Height Ratio.

| Foot measurements | LAG (n = 14) | NAG (n = 112) | HAG (n = 19) | Kruskal-Wallis | Post hoc Mann-Whitney |
|-------------------|--------------|---------------|--------------|---------------|----------------------|
| FL (cm)           | Mean (SD)    | Mean (SD)     | Mean (SD)    | P < 0.05      | a–b(*) a–c(*)        |
| Rt                | 23.1 (0.9)   | 22.2 (0.9)    | 21.6 (1.0)   | P < 0.05      | a–b(*) a–c(*)        |
| Lt                | 23.1 (0.9)   | 22.3 (0.9)    | 21.8 (1.5)   | P < 0.05      | a–b(*) a–c(*)        |
| TFL (cm)          |              |               |             |               |                      |
| Rt                | 17.9 (0.9)   | 17.1 (0.8)    | 16.6 (0.8)   | P < 0.05      | a–b(*) a–c(*) b–c(*) |
| Lt                | 17.9 (0.7)   | 17.2 (0.7)    | 16.4 (1.0)   | P < 0.05      | a–b(*) a–c(*) b–c(*) |
| DH (cm)           |              |               |             |               |                      |
| Rt                | 5.2 (0.5)    | 5.5 (0.3)     | 6.2 (0.3)    | P < 0.05      | a–b(*) a–c(*) b–c(*) |
| Lt                | 5.0 (0.3)    | 5.5 (0.3)     | 6.0 (0.4)    | P < 0.05      | a–b(*) a–c(*) b–c(*) |
| AHR (DH/TFL)      |              |               |             |               |                      |
| Rt                | 0.28 (0.02)  | 0.32 (0.02)   | 0.37 (0.02)  | P < 0.05      | a–c(*) b–c(*)        |
| Lt                | 0.28 (0.01)  | 0.32 (0.01)   | 0.36 (0.01)  | P < 0.05      | a–c(*) b–c(*)        |

HAG: High-Arched Group; NAG: Normal-Arched Group; LAG: Low-Arched Group; FL: Foot Length; TFL: Truncated Foot Length; DH: Dorsal Height; AHR: Arch Height Ratio.
0.98 cm/cm, and NAG and LAG were 1.19 cm/cm and 1.18 cm/cm, respectively. Intrinsic foot muscle strength mean value was lost in the HAG at 19.2 N, while NAG and LAG were 24.2 N and 31.0 N, respectively.

### Table 2. Comparison of the three groups by presence or absence of pain based on the characteristics, muscle strength, and locomotive function.

| Presence of pain | LAG (N=8) a group Mean (SD) | NAG (N=55) b group Mean (SD) | HAG (N=10) c group Mean (SD) | Kruskal-Wallis | Post hoc Mann-Whitney |
|------------------|-----------------------------|-------------------------------|-------------------------------|---------------|----------------------|
| Characteristics  |                             |                               |                               |               |                      |
| Age (y)          | 73.1 (5.7)                  | 74.3 (4.7)                    | 75.0 (4.7)                    | n.s.          |                      |
| Height (cm)      | 151.8 (4.9)                 | 150.9 (5.7)                  | 151.5 (5.7)                  | n.s.          |                      |
| Weight (kg)      | 51.8 (5.5)                  | 51.7 (7.5)                   | 58.9 (12.4)                  | n.s.          |                      |
| BMI (kg/m²)      | 21.8 (2.3)                  | 22.5 (2.9)                   | 25.9 (4.9)                   | n.s.          |                      |
| SMI (kg/m²)      | 5.9 (0.5)                   | 5.6 (0.6)                    | 6.2 (1.0)                    | n.s.          |                      |
| Muscle Strength  |                             |                               |                               |               |                      |
| Handgrip Strength (kg) | 22.0 (2.8)               | 20.3 (3.6)                  | 22.2 (5.7)                   | n.s.          |                      |
| IFS (N)          | 31.0 (5.0)                  | 24.4 (11.0)                 | 19.2 (4.7)                   | p<0.05        | a-c(*)               |
| Pain             |                             |                               |                               |               |                      |
| NRS              | 2.75 (1.9)                  | 4.06 (2.9)                   | 4.20 (2.3)                   | n.s.          |                      |
| Locomotive Examination |                         |                               |                               |               |                      |
| Two-step-value (cm/cm) | 1.18 (0.09)               | 1.19 (0.14)                 | 0.98 (0.24)                  | p<0.05        | a-c(*) b-c(*)        |
| Gait speed (m/s) | 1.36 (0.13)                 | 1.27 (0.19)                 | 1.11 (0.26)                  | n.s.          |                      |

| Absence of pain | LAG (N=6) a group Mean (SD) | NAG (N=57) b group Mean (SD) | HAG (9) c group Mean (SD) | Kruskal-Wallis | Post hoc Mann-Whitney |
|------------------|-----------------------------|-------------------------------|----------------------------|---------------|----------------------|
| Characteristics  |                             |                               |                               |               |                      |
| Age (y)          | 73.1 (5.7)                  | 74.3 (4.7)                    | 75.0 (4.7)                    | n.s.          |                      |
| Height (cm)      | 151.8 (4.9)                 | 150.9 (5.7)                  | 151.5 (6.3)                  | n.s.          |                      |
| Weight (kg)      | 45.6 (5.7)                  | 49.7 (7.2)                   | 47.9 (6.0)                   | n.s.          |                      |
| BMI (kg/m²)      | 21.5 (4.3)                  | 21.8 (2.9)                   | 20.9 (2.9)                   | n.s.          |                      |
| SMI (kg/m²)      | 5.6 (0.6)                   | 5.6 (0.6)                    | 6.6 (0.3)                    | n.s.          |                      |
| Muscle Strength  |                             |                               |                               |               |                      |
| Handgrip Strength (kg) | 21.7 (3.1)               | 21.1 (4.1)                  | 19.9 (2.7)                   | n.s.          |                      |
| IFS (N)          | 17.5 (7.1)                  | 23.9 (10.7)                  | 23.8 (5.9)                   | n.s.          |                      |
| Locomotive Examination |                         |                               |                               |               |                      |
| Two-step-value (cm/cm) | 1.28 (0.12)               | 1.22 (0.13)                 | 1.18 (0.10)                  | n.s.          |                      |
| Gait speed (m/s) | 1.36 (0.14)                 | 1.30 (0.18)                 | 1.23 (0.17)                  | n.s.          |                      |

HAG: High-Arched Group; NAG: Normal-Arched Group; LAG: Low-Arched Group; BMI: Body Mass Index; SMI: Skeletal Muscle Mass Index; HS: Handgrip Strength; IFS: Intrinsic Foot Muscle Strength; n.s.: non-significant.

Discussion

This cross-sectional study mainly aimed to clarify the effect of foot arch morphology and the presence of pain on physical characteristics and muscle strength locomotive function in older women. On comparing the foot arches among the three groups in the community-dwelling older people, the bone structure of a high-arched foot may influence the decreased two-step value in the HAG. The average value 0.98 (cm/cm) of the two-step value of HAG with pain corresponds to less than the standard 1.1 (cm/cm), indicating Locomotive Syndrome and a state in which mobility function is deteriorated. As a result, the average value of the intrinsic foot muscle strength in the HAG with pain was 19.2 N, which was lower than the value of 31.0 N in the LAG with pain. In contrast, there was no difference in characteristics, muscle strength, or locomotive function by comparison of foot arch morphology in the absence of pain.

Regarding the association between the foot and balance function in older people, Menz et al. reported that foot flexibility, plantar sensation, and plantar flexor strength are important and independent predictors of stable performance. Tanaka et al. revealed that toe muscle function is particularly important for maintaining balance in older people and that older people place greater pressure on their toes than younger people to obtain sensory information to maintain their standing position.
In this study, it was suggested that the decrease in IFS affected mobility function in the HAG of the older women. One of the reasons HAG affected the decrease in two-step value, even though there was no difference in SMI and hand grip strength, may be due to the decrease in IFS. Mickel et al. reported that reduced toe flexor strength and the presence of hallux and toe deformities increase the risk of falling in older people. Furthermore, Menz et al. reported that fallers were more likely to fail the paper grip test using the lesser toe. In our study, because we did not investigate toe deformity, we do not know the detail of its association or incidence with foot arch morphology. Previous study stated that the presence of flatfoot and pes cavus is a potential risk factor for the lesser toe due to the formation of muscle imbalance in the foot. According to foot measurements, the shorter FL of the HAG compared to that of the LAG may be related to factors due to lesser toe.

There was no significant difference in the evaluation of pain, but HAG showed the highest mean value. This is considered to be one of the factors of the decrease in two-step value in older people. A high-arched deformity is a common finding in patients with foot pain, and the possibility that pain affects mobility function cannot be ruled out. Although this study did not show a difference in muscle mass among the three groups, Muchna et al. found that foot problems, especially foot pain and peripheral neuropathy, became more prominent as the frailty level worsened. In addition, Imai et al. reported that chronic pain was a risk factor for pre-frailty in older adults, and the presence of knee pain has a negative correlation with quadriceps strength. This finding suggests a link between the presence of pain and decreased IFS.

In the absence of pain, the difference in foot arch morphology did not show a significant difference in locomotive examination, and our results suggest that absence of pain in an abnormal foot arch morphology is not thought to affect the mobility function in older women. However, there are previous reports of the effects of abnormal foot arch morphology on motor function. A high-arched foot is more rigid than the normal foot, reducing the range of motion and lessening shock absorption. Several researchers have reported that the center of gravity shifts laterally during walking because of the effect of a high-arched foot. Additionally, Hösl et al. showed that there was no significant difference in gait propulsion between the normal foot and the asymptomatic flatfoot. These reports show the effect of abnormal foot arch morphology on movement, and especially in the presence of pain, attention should be paid to falls; furthermore, it is important to evaluate the strength of the intrinsic muscles of the foot.

There are some limitations to consider in the interpretation of these findings. The first limitation is that the interrater reliability of the measured values may be lower than in the previous report using a measurement device. The second limitation is that we did not locate the pain, which is a factor related to the decline of mobility function in older people. A high-arched deformity is a common finding in patients with foot pain, and the possibility that the location of the pain affected the two-step test cannot be ruled out. Research should be conducted to evaluate the relationship between pain in the lower back, hip, knee, and foot in older adults.

Conclusions
This cross-sectional study assessed the physical characteristics, muscle strength, pain, and locomotive function in community-dwelling older women with foot deformities by categorizing them into High-Arch, Low-Arch, and Normal-Arch groups. The findings of this study suggest that morphology, especially a high-arched foot, can have a significant negative effect on the two-step value and intrinsic foot muscle strength in older women, only in the presence of pain.

Acknowledgments
We would like to thank the individuals who participated in data collection and data entry, as well as the staff in the Kaizuka Municipal Office for their valuable support and participation.

Declaration of conflicting interests
The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding
The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the Osaka Gas Co., Ltd. The sponsors had no control over the interpretation, writing, or publication of this work.

ORCID iD
Hidetoshi Nakao https://orcid.org/0000-0002-0557-4404
Mitsumasa Hida https://orcid.org/0000-0002-2186-1171

References
1. Benvenuti F, Ferrucci L, Guralnik JM, et al. Foot pain and disability in older persons: an epidemiologic survey. J Am Geriatr Soc 1995; 43: 479–484.
2. Kohls-Gatzoulis J, Angel JC, Singh D, et al. Tibialis posterior dysfunction: a common and treatable cause of adult acquired flatfoot. BMJ (Clinical Research Ed) 2004; 329: 1328–1333.
3. Gorter KJ, Kuyvenhoven MM and de Melker 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.
4. Menz HB, Morris ME and Lord SR. Foot pain and disability in older persons: an epidemiologic survey. J Am Geriatr Soc 1995; 43: 479–484.
5. Benvenuti F, Ferrucci L, Guralnik JM, et al. Foot pain and disability in older persons: an epidemiologic survey. J Am Geriatr Soc 1995; 43: 479–484.
6. Menz HB, Auhl M and Spink MJ. Foot problems as a risk factor for falls in community-dwelling older people: a
systematic review and meta-analysis. Maturitas 2018; 118: 7–14.
6. Menz HB and Lord SR. The contribution of foot problems to mobility impairment and falls in community-dwelling older people. J Am Geriatr Soc 2001; 49: 1651–1656.
7. Mickle KJ, Munro BJ, Lord SR, et al. ISB Clinical Biomechanics Award 2009: toe weakness and deformity increase the risk of falls in older people. Clin Biomech 2009; 24: 787–791.
8. Muchna A, Najafi B, Wendel CS, et al. Foot problems in older adults associations with incident falls, frailty syndrome, and sensor-derived gait, balance, and physical activity measures. J Am Podiatr Med Assoc 2018; 108: 126–139.
9. Ker RF, Bennett MB, Bibby SR, et al. The spring in the arch of the human foot. Nature 1987; 325: 147–149.
10. Burns J, Crosbie J, Hunt A, et al. The effect of pes cavus on foot pain and plantar pressure. Clin Biomech 2005; 20: 877–882.
11. Kaufman KR, Brodine SK, Shaffer RA, et al. The effect of foot structure and range of motion on musculoskeletal over-use injuries. Am J Sports Med 1999; 27: 585–593.
12. Lakstein D, Fridman T, Ziv YB, et al. Prevalence of anterior knee pain and pes planus in Israel defense force recruits. Mil Med 2010; 175: 855–857.
13. Irwin TA, Anderson RB, Davis WH, et al. Effect of ankle arthritis on clinical outcome of lateral ankle ligament reconstruction in cavovarus feet. Foot Ankle Int 2010; 31: 941–948.
14. Manoli A, 2nd and Graham B. The subtle cavus foot, “the underpronator”. Foot Ankle Int 2005; 26: 256–263.
15. Sachithanandam V and Joseph B. The influence of footwear on the prevalence of flat foot. A survey of 1846 skeletally mature persons. J Bone Joint Surg Br 1995; 77: 254–257.
16. Cobb SC, Tis LL, Johnson BF, et al. The effect of forefoot varus on postural stability. J Orthop Sports Phys Ther 2004; 34: 79–85.
17. Hertel J, Gay MR and Denegar CR. Differences in postural control during single-leg stance among healthy individuals with different foot types. J Athl Train 2002; 37: 129–132.
18. Scher DL, Belmont PJ Jr., Bear R, et al. The incidence of planter fasciitis in the United States military. J Bone Joint Surg Am 2009; 91: 2867–2872.
19. Chaiwanichsiri D, Janchai S and Tantisiriwat N. Foot disorders and falls in older persons. Gerontology 2009; 55: 296–302.
20. Menz HB, Morris ME and Lord SR. Foot and ankle risk factors for falls in older people: a prospective study. J Gerontol A Biol Sci Med Sci 2006; 61: 866–870.
21. Awale A, Hagedorn TJ, Dufour AB, et al. Foot function, foot pain, and falls in older adults: the Framingham Foot Study. Gerontology 2017; 63: 318–324.
22. Williams DS and McClay IS. Measurements used to characterize the foot and the medial longitudinal arch: reliability and validity. Phys Ther 2000; 80: 864–871.
23. McPoil TG, Cornwall MW, Vicenzino B, et al. Effect of using truncated versus total foot length to calculate the arch height ratio. Foot (Edinb) 2008; 18: 220–227.
24. Cobb SC, James CR, Hjertsted M, et al. A digital photographic measurement method for quantifying foot posture: validity, reliability, and descriptive data. J Athl Train 2011; 46: 20–30.
25. Franetovich MM, McPoil TG, Russell T, et al. The ability to predict dynamic foot posture from static measurements. J Am Podiatr Med Assoc 2007; 97: 115–120.
26. Vicenzino B, Franetovich M, McPoil T, et al. Initial effects of anti-pronation tape on the medial longitudinal arch during walking and running. Br J Sports Med 2005; 39: 939–943.
27. Imaoka M, Nakao H, Nakamura M, et al. Effect of multi-component exercise and nutrition support on the cognitive function of older adults: a randomized controlled trial. Clin Interv Aging 2019; 14: 2145–2153.
28. Nakamura M, Tazaki F, Nomura K, et al. Cognitive impairment associated with locomotive syndrome in community-dwelling elderly women in Japan. Clin Interv Aging 2017; 12: 1451–1457.
29. Makizako H, Shimada H, Doi T, et al. Age-dependent changes in physical performance and body composition in community-dwelling Japanese older adults. J Cachexia Sarcopenia Muscle 2017; 8: 607–614.
30. Fiolkowski P, Brunt D, Bishop M, et al. Intrinsic pedal musculature support of the medial longitudinal arch: an electromyography study. J Foot Ankle Surg 2003; 42: 327–333.
31. Kokubo T, Hashimoto T, Nagura T, et al. Effect of the posterior tibial and peroneal longus on the mechanical properties of the foot arch. Foot Ankle Int 2012; 33: 320–325.
32. Okamura K, Fukuda K, Oki S, et al. Effects of plantar intrinsic foot muscle strengthening exercise on static and dynamic foot kinematics: a pilot randomized controlled single-blind trial in individuals with pes planus. Gait Posture 2020; 75: 40–45.
33. Shimada H, Suzuki T, Suzukawa M, et al. Performance-based assessments and demand for personal care in older Japanese people: a cross-sectional study. BMJ Open 2013; 3: e002424.
34. Yoshimura N, Muraki S, Oka H, et al. Association between new indices in the locomotive syndrome risk test and decline in mobility: third survey of the ROAD study. J Orthop Sci 2015; 20: 896–905.
35. Butler RJ, Davis IS and Hamill J. Interaction of arch type and footwear on running mechanics. Am J Sports Med 2006; 34: 1998–2005.
36. Xiong S, Goonetilleke RS, Wittana CP, et al. An indentation apparatus for evaluating discomfort and pain thresholds in conjunction with mechanical properties of foot tissue in vivo. J Rehabil Res Dev 2010; 47: 629–641.
37. Nakamura K and Ogata T. Locomotive syndrome: definition and management. Clin Rev Bone Miner Metab 2016; 14: 56–67.
38. Tanaka T, Noriyasu S, Ino S, et al. 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.
39. Mickle KJ, Munro BJ, Lord SR, et al. Foot pain, plantar pressures, and falls in older people: a prospective study. J Am Geriatr Soc 2010; 58: 1936–1940.
40. Ribeiro AP, Trombini-Souza F, Tessutti V, et al. Rearfoot alignment and medial longitudinal arch configurations of runners with symptoms and histories of plantar fasciitis. Clinics (Sao Paulo) 2011; 66: 1027–1033.
41. Statler TK and Tullis BL. Pes cavus. *J Am Podiatr Med Assoc* 2005; 95: 42–52.
42. Imai R, Imaoka M, Nakao H, et al. Association between chronic pain and pre-frailty in Japanese community-dwelling older adults: a cross-sectional study. *PloS One* 2020; 15: e0236111.
43. Hall MC, Mockett SP and Doherty M. Relative impact of radiographic osteoarthritis and pain on quadriceps strength, proprioception, static postural sway and lower limb function. *Ann Rheum Dis* 2006; 65: 865–870.
44. Teyhen DS, Stoltenberg BE, Eckard TG, et al. Static foot posture associated with dynamic plantar pressure parameters. *J Orthop Sports Phys Ther* 2011; 41: 100–107.
45. Wong L, Hunt A, Burns J, et al. Effect of foot morphology on center-of-pressure excursion during barefoot walking. *J Am Podiatr Med Assoc* 2008; 98: 112–117.
46. Hösl M, Böhm H, Multerer C, et al. Does excessive flatfoot deformity affect function? A comparison between symptomatic and asymptomatic flatfeet using the Oxford Foot Model. *Gait Posture* 2014; 39: 23–28.