MANUSCRIPT

Title: Association between forefoot pain and sesamoid rotation angle determined using a weight-bearing plantar ultrasound imaging device

1. Introduction

Foot problems involving foot pain are common and can negatively affect daily living [1-3] by limiting mobility [4, 5], reducing the sense of well-being and health-related quality of life [2, 4, 6]. Foot pain has a higher prevalence in women, and it increases with age [7, 8]. It is most commonly located in the forefoot [2, 4, 7, 9] and toes [7], and is a symptom of various foot problems such as hallux valgus [2, 10], inefficient shock absorption [9], sesamoiditis [11], and metatarsalgia [12], to cite a few.

The forefoot contains the metatarsal heads that form the transverse arch of the foot, between the medial sesamoid (MS) bone and the fifth metatarsal head (5MTH) [13]. The transverse arch of the foot plays an important role as a shock absorber and force propulsor during gait [9, 13-15] to protect from metatarsalgia [9]. The forefoot is the only part of the foot that comes in contact with the ground in the terminal stance phase [13]. The first metatarsophalangeal joint (1MTPJ) transmits approximately 50% of the body weight during gait [16] and the sesamoids transmit loads greater than 300% of body weight during the push-off phase of gait [11, 17]. These functions and the complicated anatomy of the sesamoids make this region more susceptible to injuries leading to forefoot pain [9, 18-20].

We assume that the structure and the function of the transverse arch as a shock absorber can be a key factor in forefoot pain. Therefore, we thought to investigate the structure of the transverse arch and test if it related to forefoot pain. We measured the hallux valgus angle (HVA), as it is the most common deformity in female feet [21-23] and it is linked to foot pain

[23-25]; the transverse arch height (TAH), as it could indicate the flexibility of the transverse arch and its shock absorption function [13, 14]; and the sesamoid rotation angle (SRA), as the sesamoids rotate in hallux valgus deformity [26] that may affect forefoot pain instead of the deformity itself. We then associated these parameters with forefoot pain. For these measurements, we used a finger goniometer and a weight-bearing plantar ultrasound imaging device (WPUID). In addition, the ultrasound images were examined by inter-rater reliability and intra-rater reliability tests.

2. Methods

2.1. Subjects

During a health care event, a total of 277 adult women (37.5 ± 11.3 years old) joined our study. Our inclusion criteria were: Women above 20 years old, independent, and not pregnant. Written consent was obtained before participation in the study. Demographic data (age, height, weight, medical history, history of foot surgery, injury and forefoot pain) were obtained through a self-reporting questionnaire. The presence of pain in the forefoot was self-reported by answering the question: "Do you have any forefoot pain during daily activities?'' The choice of answers was: "No," "Yes, right foot only," "Yes, left foot only," or "Yes, both feet".

We excluded the participants with a history of injury or surgery in the lower limbs, those with neurological diseases, and those who supplied incomplete data in the questionnaire. Finally, 547 feet were included in this study and were categorised into two groups (a group with pain and a group without pain) according to the self-reported answers about forefoot pain. Each foot was considered as an individual sample.

This study was in accordance with the current local guidelines and the Declaration of Helsinki and was approved by the Ethical Committee for Human Experiments of K University (R0297).

2.2. Imaging device

The weight-bearing plantar ultrasound imaging device (WPUID) was developed to allow evaluation of the plantar coronal structure during weight-bearing (Fig. 1a). A solid 1 cm × 10 cm gel block (SONAGEL; Takiron Co. Ltd., Osaka, Japan) for ultrasound scanning and a digital weight scale (HD-660; Tanita, Tokyo, Japan) was integrated into the surface of the WPUID platform (Fig. 1a). A 92 mm-wide linear 5 to 10 MHz probe (EUP-L53L; Hitachi. Ltd., Tokyo, Japan) was affixed directly beneath the solid gel block perpendicular to the platform surface (Fig. 1b). A Noblus ultrasound machine (Hitachi. Ltd., Tokyo, Japan) was also connected to the WPUID. According to the design of the device, one forefoot has to be placed on the solid gel block for ultrasound evaluation and the other foot has to be situated on the digital weight scale to adjust the load on each foot. This device was previously used in other studies [13-15, 27].

2.3. Measurement protocol

The HVA (the angle between the first metatarsal axis and the proximal phalangeal axis) was measured according to a published protocol [28] using a goniometer, in a standing position with bare feet. One arm of the goniometer was placed against the medial surface of the hallux, and the other arm was placed against the medial surface of the first metatarsal. This method proved to be reliable in a previous study (with an intra-class correlation coefficient equal to 0.965 [28]).

The TAH and SRA measurements were obtained using the WPUID. First, the participants were asked to sit in a chair with one forefoot placed on the solid gel area of the WPUID. The examiner then adjusted the position of the foot so that the sesamoid bones and the 5MTH were on the solid gel area visible on the ultrasound screen. Second, the participants were asked to stand up while keeping one foot steady on the gel area of the WPUID and the other foot placed on the digital weight scale (Fig. 1a). Finally, when the digital weight scale indicated the value of half the body weight, a B-mode ultrasound image was obtained at a frequency of 9.0 MHz. The ultrasound image of the other foot was then obtained in the same manner. The ultrasound images were transferred to a computer and analysed using the ImageJ software (National Institutes for Health, Bethesda, MD, USA). Four points (the lowest points of the epiphysis of the MS, the lateral sesamoid (LS), the second metatarsal head (2MTH), and the 5MTH were used for TAH and SRA measurements. The TAH measurement was defined as the length of the line bordered by 2MTH and perpendicular to the line between the MS and 5MTH (Fig. 1c). The SRA measurement was defined as the angle between the horizontal plane and the line through the MS and the LS (Fig. 1c). These measurements were also previously used in other studies [13-15, 27].

The inter-rater reliability and intra-rater reliability of the TAH and SRA measurements were determined using 20 feet. The methods for taking and analysing the ultrasound images and parameters were the same as described above. The inter-rater class coefficient (ICC1,1) for the inter-rater reliability and the intra-rater class coefficient (ICC2,1) for the intra-rater reliability were obtained based on two measurements of TAH and SRA conducted within a 1-week interval by the same examiner and by independent examiners. We used the ICC interpretation scale of Landis and Koch: <0.4, poor to fair; 0.41–0.60, moderate; 0.61–0.80, excellent; and 0.81–1, almost perfect [29].

2.4. Statistical analyses

Differences between the two groups were analysed using the Mann-Whitney U test. To detect an association between each factor (HVA, TAH and SRA) and forefoot pain, we conducted univariate and multivariate logistic regression analyses with generalised estimating equations to account for potentially correlated outcomes for feet from the same individual. Multivariate logistic regression analyses were adjusted for moderator variables (age and body mass index (BMI)). The dependent variable was the presence of forefoot pain, whereas the factors (HVA, TAH and SRA) served as independent variables. The level of statistical significance was set at $p < 0.05$. Statistical analyses were conducted using the Statistical Package for Social Sciences (SPSS) version 20.0 (IBM Corp, Armonk, NY, USA).

3. Results

There were 472 feet (86.3%) in the group without pain and 75 feet (13.7%) in the group with pain. The demographic data (age, height, body weight and BMI) were not significantly different between the two groups (Table 1).

Concerning the HVA, TAH and SRA; only the SRA was significantly greater in the group with pain compared to the group without pain (Without pain: 5.3 ± 8.9, With pain: 7.9 ± 8.3, p = 0.031) (Table 1). HVA (Without pain: 13.2 ± 6.0, With pain: 14.5 ± 6.2, p = 0.057) and TAH (Without pain: 9.4 ± 4.1, With pain: 10.1 ± 3.9, p = 0.117) showed no significant differences between the groups (Fig. 2). HVA and SRA were measured in degrees and TAH in millimetres. The results are summarised in Table 1.

As for the relationship between forefoot pain and HVA, TAH and SRA; only SRA was significantly associated with forefoot pain, with an odds ratio (OR) of 1.034 (95% confidence interval (CI), 1.007–1.062; p = 0.015) for the univariate analysis and an adjusted odds ratio (AOR) of 1.034 (95% CI, 1.007–1.063; p = 0.015) for the multivariate analysis (Table 2).

Neither HVA nor TAH was significantly associated with forefoot pain during the univariate or multivariate logistic regression analyses (Table 2).

Furthermore, the ICC1,1 of SRA and the ICC1,1 of TAH measurements were 0.94 and 0.88, respectively, whereas the corresponding ICC2,1 values were 0.91 and 0.81 (Table 3). According to the scale of Landis and Koch [20], this corresponds to an almost perfect inter-rater and intra-rater reliability when using the WPUID and when analysing the images.

4. Discussion

Our main finding is the significantly higher SRA in the group with pain compared with the group without pain, and the significant relationship between SRA and pain. In contrast, there were no significant differences in HVA and TAH in both groups, and no significant relationship between HVA and pain or between TAH and pain.

The sesamoids are part of the biconcave plantar plate under the 1MTPJ (formed by the sesamoids and the tendons of the flexor hallucis longus and the flexor hallucis brevis muscles), which has the same characteristics on the medial and lateral longitudinal arches [16] by supporting compressive loads [30]. The shape of the plantar plate under the 1MTPJ may be lost as SRA increases and propulsion and shock absorption properties decrease which may be the cause of the pain. The location of the sesamoids under the 1MTH helps to elevate the 1MTH, provides it with a moment arm [20, 31], helps in distributing the force to it [31] and supports its articular surface [30]. An abnormal SRA may lead to changes in the soft structure around it, which can lead to other deformations [30], resulting in forefoot pain [31]. Increased SRA may agitate the compression function of the sesamoids as the anatomical length of the connecting ligament may also be agitated. Alternatively, forefoot pain could be caused by pressure exerted by the rotation of the sesamoid bones on the plantar nerve or by the pulling on tendons and ligaments and stressing of the soft tissues that make up the capsule. Furthermore, an abnormal SRA may also lead to variations in the plantar pressure pattern [32]. Koller et al. reported that the maximal force under the 1MTH increased with the grade of sesamoid subluxation, which is considered to correspond with an increase of SRA [32]. In addition, Cavanagh et al. revealed that the height of the sesamoid bones correlates with peak plantar pressure under the 1MTH [33]. Another study states that the severity of the forefoot pain under the metatarsals increases as forces increase [12], while MS is reported to take more pressure than LS [31] as LS is generally protected by its ability to slip between 1MTH and 2MTH [20]. Therefore, the rotation of the sesamoid bones may increase the load on MS or 1MTH or on both MS and 1MTH, which may result in forefoot pain (Fig. 3a). This higher load on either MS or 1MTH or on both MS and 1MTH could induce inflammation, leading to forefoot pain. Past studies suggested the investigation of the elasticity of the gastrocnemius muscle, degenerative joint disease, and the instability of the metatarsophalangeal joints in the case of forefoot pain without hallux valgus deformity [12]. However, our results emphasise the importance of SRA evaluation in patients with forefoot pain, and we suggest that the SRA be assessed when there are no other evident causes (such as hallux valgus, injuries, and calluses) of forefoot pain.

In this study, we used a WPUID, because coronal views of the transverse arch in a weight-bearing position are difficult to assess using imaging techniques such as computed tomography and magnetic resonance imaging. As for X-rays, a standing image would require the placement of the toes in static dorsiflexion [34, 35] to allow a clear view of the metatarsal heads and the sesamoids, which, depending on the dorsiflexion degrees, could trigger a Windlass mechanism [35] and change the biomechanics of the transverse arch. However, when using an ultrasound, the transverse arch is directly localised, allowing the view of the metatarsal heads and sesamoids during neutral positioning of the toes. Ultrasound was previously used in studies about TAH and length and thickness under the metatarsal heads in standing and in gait [9, 13-15, 19, 27, 36]. This study is different in that it assesses the structure of the transverse arch in feet with and without pain, relating these parameters to forefoot pain. To the best of our knowledge, it is the first study to do so. In addition, given the portability, the ease of use, the relatively lower cost and no exposure to harmful agents, a weight-bearing ultrasound can be used in various situations such as in clinical settings, sport fields and research trips, thereby permitting simple evaluation of the forefoot.

Besides the findings of this study, it does have a few limitations. First, we did not determine the exact location of pain in the forefoot, nor did we assess its degree and type. For example, pain in the medial part of the forefoot could be associated with SRA, whilst there may be another factor for pain in the lateral part of the forefoot. Second, we used a finger goniometer to measure the HVA; however, this measurement would have been more accurate had we taken standing X-rays. Third, we assessed only the repeatability of the imaging analyses. However, we could have better conducted a repeatability study using the WPUID by asking the subjects to take their foot off the device and reposition it. Fourth, we discuss that the association between forefoot pain and SRA based on increased loading and tension of the soft tissues connecting the sesamoids; however, we did not measure these possibilities in this study. Finally, TAH was evaluated only in the weight-bearing state, not enabling us to compare the TAH drop degree between non-weight-bearing and weight-bearing within the groups. Considering these limitations in future study plans may give clearer results on the mechanism of forefoot pain.

5. Conclusion

In summary, we investigated the relationship between the structure of the transverse arch (HVA, TAH and SRA) and forefoot pain and found that a higher SRA was significantly associated with forefoot pain.

Conflict of interest

The authors declare no conflict of interest.

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Tables

Table 1

Characteristics of the entire study group.

	All feet (n = 547)	Without pain (n = 472)	With pain (n = 75)	*p*
Age (years)	37.5 ± 11.3	37.4 ± 11.2	37.6 ± 12.3	0.914
Height (cm)	157.4 ± 5.6	157.5 ± 5.7	157.0 ± 5.1	0.660
Weight (kg)	51.4 ± 7.5	51.5 ± 7.5	51.2 ± 7.9	0.720
BMI (kg/m^2)	20.7 ± 2.8	20.7 ± 2.8	20.7 ± 2.9	0.890
HVA (degrees)	13.4 ± 6.1	13.2 ± 6.0	14.5 ± 6.2	0.057
TAH (mm)	9.5 ± 4.0	9.4 ± 4.1	10.1 ± 3.9	0.117
SRA (degrees)	5.7 ± 8.8	5.3 ± 8.9	7.9 ± 8.3	0.031*

Note. Data are presented as mean ± standard deviation. *$p < 0.05$, significant between group without pain and group with pain. BMI: body mass index; HVA: hallux valgus angle; TAH: transverse arch height, SRA: sesamoid rotation angle.

Table 2

Relationship between forefoot pain and HVA, TAH and SRA in univariate and multivariate logistic regression analyses.

	Univariate analysis			Multivariate analysis†		
	OR	95% CI	*p*	AOR	95% CI	*p*
HVA	1.033	0.997–1.071	0.073	1.033	0.997–1.071	0.073
TAH	1.044	0.979–1.113	0.192	1.043	0.914–1.095	0.197
SRA	1.034	1.007–1.062	0.015*	1.034	1.007–1.063	0.015*

Note. *$p < 0.05$. †Adjusted for age and body mass index. AOR: adjusted odds ratio; CI: confidence interval; OR: odds ratio; HVA: hallux valgus angle; SRA: sesamoid rotation angle; TAH: transverse arch height.

Table 3

Intra-rater and inter-rater reliability of measurements using the WPUID.

	Intra-rater reliability $ICC_{1,1}$ (95% CI)	Inter-rater reliability $ICC_{2,1}$ (95% CI)
SRA	0.94 (0.87–0.98)	0.91 (0.79–0.96)
TAH	0.88 (0.72–0.95)	0.81 (0.58–0.92)

Note. ICC: intra-class correlation coefficient; CI: confidence interval; SRA: sesamoid rotation angle; TAH: transverse arch height; WPUID: weight bearing plantar ultrasound imaging device

Figure Captions

Figure 1 — WPUID. (a) A digital weight-scale and a solid gel block were integrated into the sides of the platform. Participants stood with one foot on the digital weight scale and the other foot on the solid gel block. (b) A 92 mm wide linear ultrasound probe was affixed perpendicularly under the solid gel block. (c) Measurements of SRA and TAH were taken using an ultrasound image of the forefoot. The lowest points of the epiphysis of the MS, LS, second metatarsal bone (2MT), and 5MTH are marked. SRA was defined as the angle between a line passing through the MS and LS and the horizontal plane. TAH was defined as the length of the line perpendicular to the 2MT from the line through the MS and the 5MTH.

Figure 2 — SRA, TAH, and HVA in the groups without and with pain. *Significant difference between two groups at $p < 0.05$.

Figure 3 — The presumed mechanism of forefoot pain due to over-pronation of the sesamoid bones. (a) Forefoot pain might be caused by higher pressure on either the 1MTH or both MTHs or (b) the MS bone. The size of the bold arrows indicates the degree of pressure.