

Article

Comparison of the Changes in the Structure of the Transverse Arch of the Normal and Hallux Valgus Feet under Different Loading Positions

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Abstract: The transverse arch of the foot receives and transfers loads during gait. We aim to identify the difference in its structure between normal feet and hallux valgus (HV) feet and the effects of loading. Two groups, Without-HV and With-HV (HV $\geq 20^{\circ}$), were assessed using a weight-bearing plantar ultrasound imaging device to view the structure of the transverse arch. Measurements were recorded in sitting, quiet standing, and 90% weight-shift (90% W.S.) loading positions on the tested foot. Images were then processed using ImageJ software to analyze the transverse arch length (TAL), the length between the metatarsal heads (MTHs), transverse arch height (TAH), and the height of each MTH. TAL significantly increased in all positions in the With-HV group compared to that in the Without-HV group. It also increased in both groups under loading. TAH was not significantly higher in the With-HV group than in the Without-HV group in sitting and standing positions, except in the 90% W.S position, where both groups showed similar results. TAH decreased in both groups under loading. In summary, the structure of the transverse arch changes in HV feet and under loading conditions. This finding will help understand the structural differences between normal and HV feet and help resolve shoe fit problems in individuals with HV deformity.

Keywords: transverse arch height; hallux valgus; weight bearing ultrasound

1. Introduction

Hallux valgus (HV) is defined as the progressive deviation of the big toe by abduction of the hallux and adduction of the first metatarsal [1]. The development of HV is influenced by extrinsic (e.g., wearing high heels and tight shoes) and intrinsic (e.g., genetics, elasticity of the ligaments, age, and flat feet) factors [2–4]. This deformity has many effects. It alters foot function, gait, and weight-bearing patterns, causes pain, increases the risk of falling, results in difficulties in shoe fitting, and interferes with the alignment of the lesser toes [5,6], such as the dislocation of the second metatarsal [7].

The human foot is like a tripod, consisting of three flexible arches: the medial longitudinal arch (MLA), the lateral longitudinal arch, and the transverse arch. These arches work together and respond to the weight put on the foot while walking by providing shock absorption [8]. This study focuses on the transverse arch, which is in the forefoot [9], and is formed by the five metatarsal heads (MTHs) (Figure 1).





Figure 1. Representation of the three arches of the foot. The transverse arch is marked in red and it is contact with the ground during terminal stance.

As HV deformity causes the medial shifting of the first MTH, and because the first MTH itself is a part of the transverse arch, we hypothesized that feet with HV deformity would have a different transverse arch structure compared to feet without HV deformity. Furthermore, during the terminal stance of gait, 90% to 110% of the body weight is unilaterally transferred and supported by the forefoot and hallux, altering the alignments of the small joints [10]. In HV deformity, the alignment of the hallux is already altered. Therefore, we believed that the structure of the transverse arch would also be affected by loading in feet with HV compared to feet without HV.

Recently, ultrasound (US) usage has become more popular, as it provides high-resolution images at an affordable cost and enables easy manipulation [11], and it was previously used to assess forefoot structure [12,13]. Matsubara et al. [14] introduced an US machine, called the weight-bearing plantar ultrasound imaging device (WBPUID), which enables viewing of the transverse arch in weight-bearing conditions. In this study, we use the WBPUID to view the structure of the transverse arch in a simulated terminal stance, as there is a lack of devices that can measure the structure of the transverse arch in motion. To simulate the terminal stance, 90% of body weight was transferred on the tested foot, relying on the fact that 90% to 110% of body weight is being transferred on the foot in the terminal stance. We named this position as the 90% weight-shift (90% W.S.) position.

Substantial evidence concerning the structure of the transverse arch in feet with HV deformity is lacking. Therefore, this study focuses on the differences in the structure of the transverse arch between feet with and without HV deformity. We specifically took measurements from elderly women because they are more predisposed to this deformity, as they are reported to have more elasticity and to wear tight and high-heeled shoes, which affect the alignment of the first ray [2–4], and aging being an important risk factor for HV [2,15]. What's more, we use an affordable device and an easy method for a smoother analysis of the structure of the transverse arch in loading conditions. We hypothesized that with increasing loads, the transverse arch of feet with HV deformity would be wider in length and lower in height than feet without HV deformity. The loading positions were sitting, quiet standing, and 90% W.S. on the tested foot using a weight-bearing US as an assessment device. With this study, we aim to provide a perspective and an understanding of the differences in the transverse arch structure in feet with and without HV deformity, as well as of the effects of loading, along with the feasibility of our measurement methods.

2. Methods

2.1. Participants

Information about this study was sent through e-mails and mentioned in public information magazines in 2017. Japanese women (n = 220) were recruited upon their requests for participation. Exclusion criteria were: past surgeries in the lower limbs, injuries in the lower limbs during the last year, and dependence and inability to complete the test positions alone. Finally, 189 women were included in the study. Data from the right and left feet (n = 378) were obtained, and all feet were then divided into two groups: Without-HV (n = 260) and With-HV (n = 118, HV \geq 20°), regardless of the same person having HV on both feet. Demographic data (represented as mean \pm standard deviation [SD]) of the participants are presented in Table 1. The measures were taken during August and September 2017 in Kyoto and Ayabe cities (Japan). The study was conducted in accordance with the Declaration of Helsinki, and was approved by the Ethical Committee for Human Experiments of Kyoto University (Kyoto, Japan) (approval number R0450-1), and written informed consent was obtained from all participants.

	Without-HV (n = 260)	With-HV (n = 118)	<i>p</i> -Value
HV Angle (°)	9.4 ± 5.0	29.6 ± 9.4	< 0.0001 *
Age (years)	68.9 ± 9.3	69.6 ± 8.7	0.454
Height (cm)	153.7 ± 6.0	154.7 ± 6.0	0.146
Weight (kg)	52.8 ± 10.2	51.5 ± 7.7	0.161

Table 1. Demographic Data of 189 Participants. Results are shown as mean \pm SD; *p* = 0.05.

* significant result; (HV Hallux Valgus).

2.2. Experimental Design and Set-Up

HV angle was measured with a finger goniometer in a weight-bearing position with bare feet. To measure this angle, one arm of the goniometer was placed on the medial part of the proximal phalanx and the other arm on the first metatarsal bone of the big toe. This method has been evaluated and accepted previously [16,17]. Based on the study by Uritani et al. [18], feet with an HV angle lower than 20 degrees were assigned to the Without-HV group and those with an HV angle equal or higher than 20 degrees were assigned to the With-HV group. US images were taken by the customized machine WBPUID that allows taking images in a weight-bearing position [9,19] using an US diagnostic device (Noblus, Hitachi Aloka Medical, Tokyo, Japan) at B-mode US with a frequency of 9.0 MHz [9]. WBPUID was previously tested to evaluate the structure of the transverse arch in the coronal plane, and its images were in agreement with computed tomography ultrasonograms [14]. The device is rectangular in shape and has a built-in US probe on one side and a scale on the other side. The probe was installed from inside the box with an opening on the surface where patients can position their feet. A gel pad was cut to the same size of the probe opening and placed above it. US gel was also used on top of the gel pad before each test to ensure clearer visibility. On the other side, the scale allowed the control of weight distribution on both legs. Images were taken in three positions: (1) sitting, (2) quiet standing, and (3) 90% W.S. on the tested foot. The measurements were taken by two therapists. One therapist was in charge of positioning the feet on the US probe opening, monitoring, and taking the projected US images. The other therapist was in charge of giving the instructions in native language and monitoring the weight scale. First, body weight was measured, and calculations were done. Next, the therapist placed the tested foot on the US probe opening and confirmed the configuration of the lowest points of the epiphysis of the medial sesamoid bone (MS), the lateral sesamoid bone (LS), the second metatarsal head bone (2MTH), and the fifth metatarsal head bone (5MTH) [9]. For the 90% W.S. position (Figure 2), 90% of body weight was transferred onto the tested foot and shifted forward on its forefoot. This position is intended to simulate the terminal stance of gait in the static position, relying on the fact that 90% to 110% of body weight is being shifted unilaterally

in a terminal stance and that the heel is off the ground [10]. In order to prevent the participants from getting injured, we instructed them to shift their weight on the tested foot until the scale under the not-tested foot showed 10% of their body weight, and to sway their bodies forward. In other words, if the individual weighed 50 kg and the right foot was being tested, the instructions were given as: "Put your weight on your right foot until the scale under your left foot says 5 kg, then move your body forward." All participants were able to maintain this posture independently. A similar 90% weight-loading positioning and the WBPUID parameters were previously used and validated by our laboratory members [9,19].



Figure 2. The 90% Weight Shift Position. The participant stands on the box which contains an opening where an ultrasound probe is located and a scale and connected to the ultrasound device. The test-foot (left foot) is placed above the probe and the non-test-foot is placed on the scale, which permits to monitor the weight transfers.

2.3. US Data Analysis

After the measurements, the images were analyzed using ImageJ software (National Institutes of Health, Washington, DC, USA). All analysis was done by the same researcher. Figure 3 shows the US images and how the measurements were done. The distal epiphysis of the MTHs are marked in light-blue. The plantar surface is the plantar skin surface of the foot that touches the US gel (Figure 3A). Each MTH was marked by a yellow star at its lowest epiphysis. An adjacent mark of the same MTH was also marked on the plantar surface (Figure 3B). Transverse arch length (TAL) was measured as the line between the MS and 5MTH (Figure 3C). The length between each MTH was measured as the lines between each successive MTH separately (e.g., distance between the MS and LS, and distance between the LS and 2MTH) (Figure 3D). Transverse arch height (TAH) was measured as the line passing by the 2MTH marker and perpendicular to the TAL line (Figure 3E). The height of the MTHs was measured as the line between the MTH marker and its plantar marker (Figure 3F). TAH ratio was measured as TAH divided by TAL for adjustment. These measurements were calculated on Excel using the x and y landmarks resulting from ImageJ. TAL, TAH, and TAH ratio measurements have been previously validated [14,19].



Figure 3. US images. (**A**) The distal epiphysis of the MTHs is marked in light-blue color. (**B**) The distal epiphysis of the MTHs and their adjacent plantar ejection are marker in yellow stars for calculations. (**C**) TAL, line between MS, and 5MTH. (**D**) Length between MTHs. (**E**) TAH, line perpendicular to TAL. (F) Height of MTHs. TAL transverse arch length, TAH transverse arch height, MS medial sesamoid, LS lateral sesamoid, 2MTH second metatarsal head, 3MTH third metatarsal head, 4MTH fourth metatarsal head, 5MTH fifth metatarsal head, plMS plantar medial sesamoid marker, plLS plantar lateral sesamoid marker, pl2MTH plantar second metatarsal head marker, pl5MTH plantar third metatarsal head marker.

2.4. Statistical Analysis

Statistical analysis was done using JMP software (version 12.2.0, SAS Institute Inc., Cary, NC, USA). A *t*-test was used to compare the results between the two groups, one-way analysis of variance was used to compare the results between the three positions, and Tukey test was used as post-hoc analysis to compare the differences between the three positions within each group apart. The *p*-value was set at 0.05.

3. Results

US data results are summarized in Tables 2 and 3. Results are expressed as means \pm SD.

3.1. TAL

TAL (Table 2) had significantly increased in all positions in the With-HV group compared to that in the Without-HV group. We noticed a significant increase in length between the second and third MTH in all positions in the With-HV group compared to that in the Without-HV group. For both groups, TAL increased with an increase in loading. In the Without-HV group, TAL increased significantly in standing and 90% W.S. positions compared to that in the sitting position. We also noticed a significant increase in length between the second and third MTH and the third and fourth MTH in standing and 90% W.S. positions compared to that in the sitting position. In the With-HV group, TAL significantly increased in standing and 90% W.S. positions compared to that in the sitting position; an increase in length between the second and third MTH was noted in standing and 90% W.S. positions compared to that in the sitting and 90% W.S. position; an increase in length between the second and third MTH was noted in standing and 90% W.S. positions compared to that in the sitting and 90% W.S. position; an increase in length between the second and third MTH was noted in standing and 90% W.S. positions compared to that in the sitting position; an increase in length between the second and third MTH was noted in standing and 90% W.S. positions compared to that in the sitting position.

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	Without-HV (n = 260)		With-HV (n = 118)			
	Sitting	Standing	90% W.S.	Sitting	Standing	90% W.S.
TAL (mm)	67.8 ± 3.9	$69.2\pm4.4~^{\dagger}$	$69.8\pm4.4~^{\dagger}$	$69.5\pm4.0^{~\$}$	71.4 ± 4.2 §*	71.4 ± 4.2 §*
MS~LS Length (mm)	12.2 ± 1.8	12.6 ± 2.1	12.6 ± 2.1	12.1 ± 2.0	12.2 ± 1.8	12.3 ± 2.0
LS~2MTH Length (mm)	14.0 ± 2.4	14.0 ± 2.6	14.3 ± 2.5	14.4 ± 2.7	$14.9~^{\$}\pm2.8$	14.6 ± 2.5
2~3MTH Length (mm)	12.7 ± 1.7	13.2 \pm 1.9 ⁺	$13.2\pm1.9~^{+}$	$13.6\pm1.7~{}^{\S}$	14.3 ± 2.2 §*	14.4 ± 1.9 §*
3~4MTH Length (mm)	13.3 ± 1.8	$13.8\pm1.9~^{\dagger}$	13.8 \pm 2.1 ⁺	13.9 ± 1.6 §	14.1 ± 2.0	14.2 ± 2.2
4~5MTH Length (mm)	16.6 ± 2.1	16.8 ± 2.2	17.0 ± 2.0	16.6 ± 1.9	17.2 ± 2.2	$17.3\pm2.1~{*}$

Table 2. Transverse arch length and length between metatarsal heads between Without-HV group and With-HV group. Results are shown as mean \pm SD; *p* = 0.05.

Note: [§] between Without-HV and With-HV, compared to without-HV; [†] within Without-HV compared to Sitting; [‡] within Without-HV compared to Standing; ^{*} within With-HV compared to Sitting; ^{*} within With-HV compared to Standing; TAH transverse arch height, MS medial sesamoid, LS lateral sesamoid, 1MTH first metatarsal head, 2MTH second metatarsal head, 3MTH third metatarsal head, 4MTH fourth metatarsal head, 5MTH fifth metatarsal head.

3.2. TAH

TAH (Table 3) did not increase significantly in all positions in the With-HV group compared to that in the Without-HV group. We noticed that MS height decreased in all positions in the With-HV group compared to that in the Without-HV group, while LS height increased significantly in all positions in the With-HV group compared to that in the Without-HV group. For both groups, TAH generally decreased with the increase in loading. In the Without-HV group, TAH did not decrease significantly as the load increased, and LS height increased significantly in standing and 90% W.S. positions compared to that in the sitting position. Similarly, in the With-HV group, TAH decreased and LS height increased as the load increased.

	Without-HV (n = 260)		With-HV (n = 118)			
	Sitting	Standing	90% W.S.	Sitting	Standing	90% W.S.
TAH (mm)	4.0 ± 2.4	4.0 ± 2.4	3.9 ± 2.4	4.4 ± 2.5	4.3 ± 2.5	3.9 ± 2.3
TAH Ratio (%)	6.0 ± 3.5	5.8 ± 3.6	5.6 ± 3.4	6.4 ± 3.6	6.0 ± 3.5	5.5 ± 3.4
MS Height (mm)	6.3 ± 1.4	6.0 ± 1.2 ⁺	6.0 ± 1.2	5.9 ± 1.2 §	5.6 ± 1.2 §	5.9 ± 1.3
LS Height (mm)	8.1 ± 1.4	8.6 ± 1.4 ⁺	$8.6\pm1.5~^{\dagger}$	9.0 ± 1.5 §	9.3 ± 1.6 §	9.6 ± 1.7 §*
2MTH Height (mm)	10.1 ± 2.3	10.1 ± 2.3	10.0 ± 2.2	10.2 ± 2.3	10.1 ± 2.2	9.9 ± 2.2
3MTH Height (mm)	9.0 ± 1.8	9.1 ± 1.6	9.1 ± 1.6	9.0 ± 1.7	8.9 ± 1.6	8.9 ± 1.7
4MTH Height (mm)	8.4 ± 1.4	8.5 ± 1.4	8.7 ± 1.4 ⁺	8.4 ± 1.5	8.4 ± 1.5	8.5 ± 1.5
5MTH Height (mm)	6.7 ± 1.2	6.4 ± 1.1 ⁺	6.4 ± 1.2 ⁺	6.8 ± 1.2	$6.3 \pm 1.2^{*}$	6.3 ± 1.3 *

Table 3. Transverse arch height, TAH ratio and height of each metatarsal heads between Without-HV group and With-HV group. Results are shown as mean \pm SD; *p* = 0.05.

Note: [§] between Without-HV and With-HV, compared to without-HV; [†] within Without-HV compared to Sitting; [‡] within Without-HV compared to Standing; * within With-HV compared to Standing; TAH transverse arch height, MS medial sesamoid, LS lateral sesamoid, 1MTH first metatarsal head, 2MTH second metatarsal head, 3MTH third metatarsal head, 4MTH fourth metatarsal head, 5MTH fifth metatarsal head.

4. Discussion

The aim of this study was to investigate the difference in the structure of the transverse arch of the foot between women with and without HV deformity and to understand the effects of loading. Our results showed widening of TAL in the With-HV group compared to that in the Without-HV group, and a slight elevation in TAH in the With-HV group compared to that in the Without-HV group in sitting and standing positions; however, similar results were observed for TAH in the 90% W.S. position. As the load increased, both groups showed widening in TAL and compression in TAH.

The differences in TAL between individuals with and without HV may be due to the extensibility of the ligaments acting on the transverse arch. Abdalbary et al. [20] studied the tensile strength of the deep transverse metatarsal ligament (DTML), a ligament that runs and indirectly connects the metatarsal heads and acts as their stabilizer [21–23]. They compared the extensibility of the DTML

between women with HV and controls, and demonstrated that the tensile strength of the DTML was inferior in women with HV compared to that in controls, indicating that the DTML is indeed stretched in HV deformity [20], allowing the MTHs to separate from each other.

TAL also increased with an increase in load in both groups. The widening of the transverse arch in both groups is in accordance with the fact that the transverse arch splays and drops during gait, as it flattens when receiving loads [19]. Another study also reported that the metatarsal abducted at 50% body weight load, and these movements increased at 100% body weight load [24]. These previously proved findings explain the widening of TAL and the lengths between the metatarsal heads.

Our results showed higher TAH in the With-HV group than in the Without-HV group in sitting and standing positions. In the 90% W.S. position, however, TAH was similar between both groups. These results were unexpected as we had hypothesized that the transverse arch of the With-HV group would have a lower TAH. This result could be attributed to a protective mechanism that is activated in HV deformity to maintain the arch and enable propulsion. We suggest that the intrinsic muscles of the foot act on transverse arch, similar to the mechanism acting on the MLA. Previous studies have showed that under loading conditions during gait, the MLA compresses and absorbs the energy loads and then transmits it as propulsion forces [24–26]. To protect the MLA from collapsing completely, the intrinsic muscles of the foot activate a dynamic feedback-response system to assist in its stability, support, stiffness, and propulsion [24,27]. We think that the transverse arch of the With-HV group adopts a similar protective mechanism where muscular forces are acting on the transverse arch. HV feet have weaker intrinsic muscles than normal feet, and such individuals with HV feet are subjects for strengthening and rehabilitation exercises for HV prevention [28,29], particularly in the abductor hallucis muscle [11,27]. Intrinsic muscles of the foot are also regarded as accessory toe flexors that contribute to the stabilization of the foot when certain deformity occurs or excessive weight is being loaded by stiffening the arch and increasing its height [24,30]. In addition, a previous study about HV mentioned that intrinsic muscles are likely to activate earlier and have a higher activation than other muscles during gait [5]. Therefore, we could hypothesize that these muscles are a part of an active contractile mechanism that contributes to the stiffness of the arch [24,31,32] by attempting to protect its height; however, they are not strong enough to adduct the metatarsals and protect further widening of TAL.

Furthermore, HV deformity involves the pronation and adduction of the first metatarsal [19,21]. This change also affects the sesamoid bones. The positioning of the sesamoids in relation to the first metatarsal also differs between weight-bearing and non-weight-bearing conditions [33]. The information regarding this positioning is still controversial in the literature. While Schneider et al. [34] mentioned that the first metatarsal, not the sesamoid, shifts laterally, others [21,35] have mentioned the possibility of the pronation of the entire metatarso-sesamoid complex, depending on the degree of laxity of the ligaments. Considering the pronation of the entire metatarso-sesamoid complex in HV, we could explain the decrease in MS height and increase in LS height in the With-HV group compared with those in the Without-HV group; when the complex is pronated, the MS goes downward and its height is shortened, while the LS goes upward and its height is increased.

Lastly, the decrease in TAH during loading can be explained by the flexibility and dropping of the arch [19] and its propulsion ability. Under loading conditions, the transverse arch can be classified into two types: the hyper-flexible type, where the arch flattens at weight-bearing, and the hypo-flexible type, where the arch does not flatten during weight-bearing [19,36]. As TAH in the With-HV group decreased with increasing loads, we suggest that the transverse arch of the With-HV group is of the hyper-flexible type.

This study has many limitations. First, we considered the feet, regardless of whether HV was a bilateral deformity or not, and we did not consider the sesamoid classification grades, and considered the first metatarsal and sesamoid bones as one complex that pronates. Second, we have not measured the strength of the muscles acting on the foot. Third, the measurement positions were static and a simulation of the terminal stance of gait; in actual gait, muscle forces and center of pressure might

act differently on the structure of the transverse arch. However, our results on the effects of loading on the bony structure of the transverse arch in normal and HV feet suggest that in HV cases, passive elastic elements (such as the DTML) are hyper-mobile and act on the widening of the transverse arch, while active force-generating elements (such as the intrinsic muscles) act on the transverse to prevent its collapse and propel the necessary forces for gait. These findings can be used to improve and popularize muscular exercise regimens that are employed to prevent HV and allow better shoe fit for people with HV, such as the development of shoes allowing the widening of the transverse arch.

For further research, it would be important to evaluate the transverse arch structure in parallel with muscle activity in order to validate this muscular-action theory and have a clearer idea about the muscles participating in the transverse arch function.

5. Conclusions

In HV feet and under demanding loading positions, the bony structure of the forefoot changes compared to that in the normal feet and under unloaded positions. This study focuses on the bony alignment of the transverse arch of the foot, as well as the effects of different loads in HV and normal feet, by measuring the changes in arch length and height. This study shows that the arch structure was altered, in terms of changes in static and dynamic stabilizers acting on the feet, in response to deformity and loads. We suggest that the transverse arch of HV feet is a mobile structure absorbing and propelling energy by altering its length and height, and that a dynamic mechanism is activated that helps its stretched static stabilizers to prevent its collapse under loading. Future studies are needed to understand this mechanism and determine which muscles act directly upon the dynamics of the transverse arch. The present findings may be used as guidelines for transverse arch evaluation and for effective conservative and preventive treatments and for proper shoe fitting.

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