Evaluation of First-Ray Mobility in Patients with Hallux Valgus Using Weight-Bearing CT and a 3-D Analysis System

A Comparison with Normal Feet

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Background: Some physicians report that patients with hallux valgus have hypermobility at the tarsometatarsal (TMT) joint of the first ray and 3-dimensional (3-D) deformity. With use of non-weight-bearing and weight-bearing computed tomography (CT), we evaluated the 3-D mobility of each joint of the first ray in feet with hallux valgus compared with normal feet.

Methods: Ten feet of 10 patients with hallux valgus and 10 feet of 10 healthy volunteers with no foot disorders were examined. All participants were women. Weight-bearing (a load equivalent to body weight) and non-weight-bearing CT scans were made with use of a device that we developed. Orthogonal coordinate axes were set and a 3-D model was reconstructed. Each joint of the first ray was aligned with the respective proximal bone, and 3-D displacement of the distal bone relative to the proximal bone under loading was quantified.

Results: At the talonavicular joint, significantly greater dorsiflexion of the navicular relative to the talus was observed in the hallux valgus group compared with the control group. At the medial cuneonavicular joint, the hallux valgus group showed significantly greater eversion and abduction of the medial cuneiform relative to the navicular. At the first TMT joint, the hallux valgus group showed significantly greater dorsiflexion, inversion, and adduction of the first metatarsal relative to the medial cuneiform. At the first metatarsophalangeal joint, the hallux valgus group showed significantly greater eversion and abduction of the first proximal phalanx relative to the first metatarsal (all $p < 0.05$).

Conclusions: The results of this study suggest that loading of the foot causes significant 3-D displacement not only at the TMT joint but also at the other joints of the first ray. There is increased mobility in the first ray in patients who have hallux valgus.

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Hallux valgus is one of the most prevalent foot disorders and affects more than 30% of adults aged ≥65 years[1]. The treatment of hallux valgus varies, and approximately 130 types of surgical treatment, including minor variations, have been described[2]. This is likely because many aspects of the etiology and pathology of hallux valgus remain unclear.

Most feet with hallux valgus exhibit hypermobility of the first ray. This hypermobility was first noted by Morton in 1928[3]. Lapidus later reported that increased mobility of the first metatarsocuneiform joint leads to hallux valgus[4]. Subsequently, Klaue et al.[5] studied hypermobility using an original device, while several others used methods such as radiography and fluoroscopy[6]. In most of those studies, the only parameters of mobility evaluated were plantar flexion and dorsiflexion in the sagittal plane. However, hallux valgus deformity consists of more than just 2-dimensional displacement; it also has 3-dimensional (3-D) components, including inversion-eversion[7]. To analyze 3-D deformity in detail, it is essential to obtain computed tomography (CT) images and use them to reconstruct 3-D

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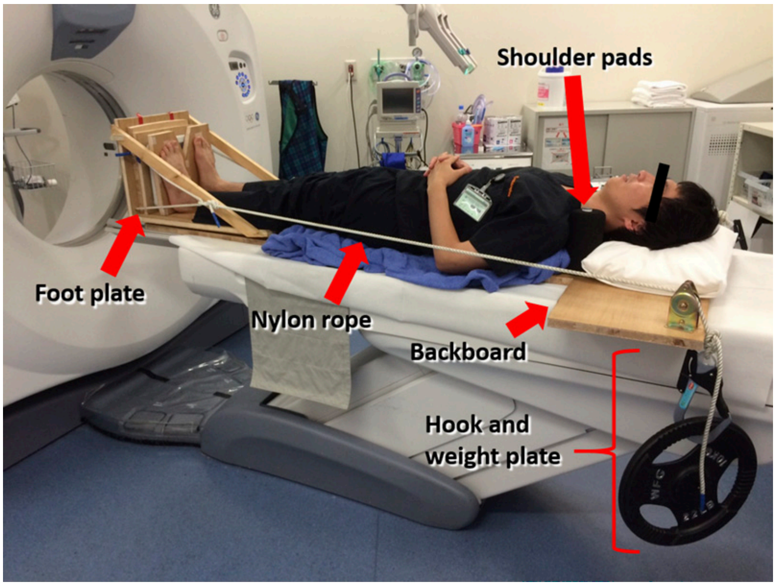

Fig. 1
The loading device and positioning for weight-bearing CT are demonstrated. To apply load, weight plates were hung from a hook suspended from a rope that was attached to a foot plate at the CT scanner. Load from the feet is supported by shoulder pads.

images. Moreover, standing on the foot exacerbates the deformity and symptoms in patients with hallux valgus. Tanaka et al. found that weight-bearing radiographs are important for structural evaluation of hallux valgus[8]. Standing radiographs are now commonly used to evaluate patients with hallux valgus. It would therefore follow that standing or weight-bearing CT images[9,10] would be preferable to supine (non-weight-bearing) CT images as well. Thus, we created a loading device that can be

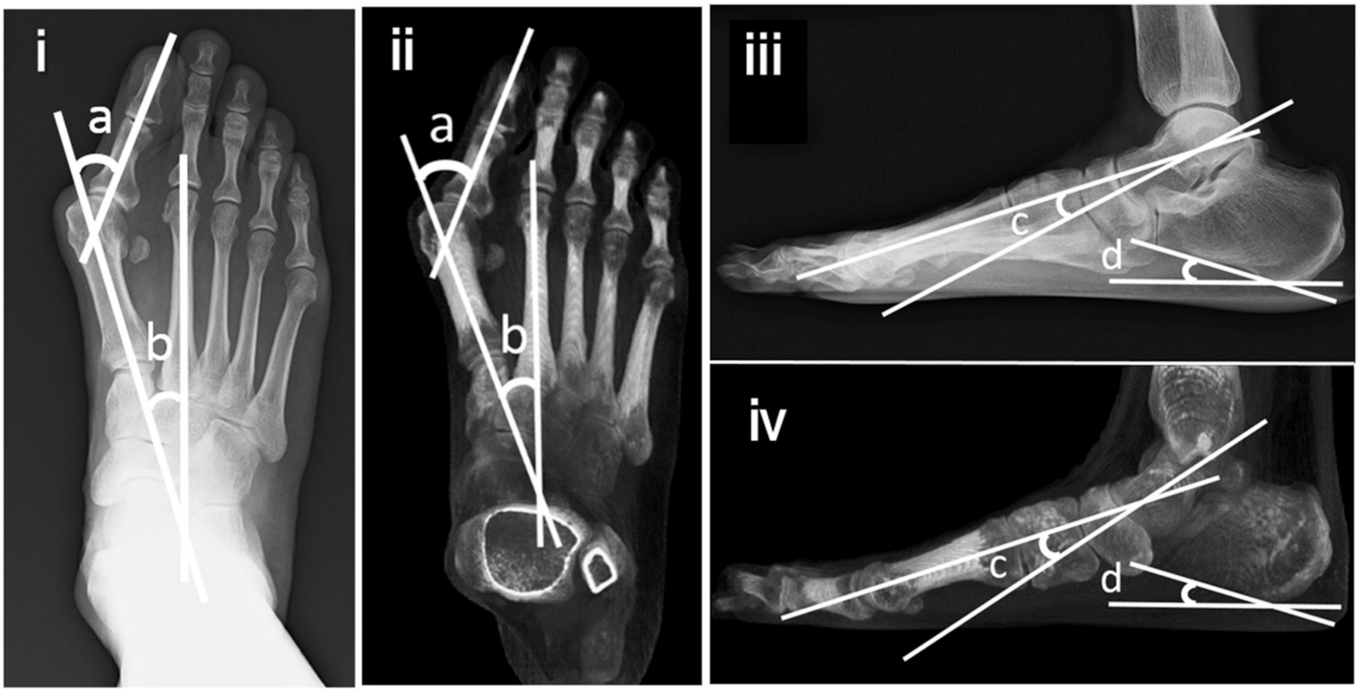

Fig. 2
Comparison of standing radiographs, including a frontal view (panel i) and lateral view (panel iii), and volume-rendered, weight-bearing CT images of the same patient, including a frontal view (panel ii) and lateral view (panel iv). a = the hallux valgus angle, b = the first-second intermetatarsal angle, c = the lateral talo-first metatarsal angle, and d = the calcaneal pitch angle.

TABLE I Characteristics of Subjects by Group

	Hallux Valgus Group, N = 10	Control Group, N = 10
Female *(no.)*	10	10
Age* *(yr)*	58 ± 14.2 (33-74)	56 ± 5.0 (50-66)
Body weight* *(kg)*	46.5 ± 3.0 (43-52)	48.5 ± 5.9 (41-57)
BMI* *(kg/m²)*	19.2 ± 2.6 (15.9-22.4)	20.4 ± 1.8 (18.1-23.5)

*The values are given as the mean and the standard deviation, with the range in parentheses.

used in conventional CT scanners to reproduce a standing state (Fig. 1)[11]. We hypothesized that joint mobility of the first ray, as represented by a change of the position of the bones with weight-bearing, is greater in feet demonstrating hallux valgus than in normal feet not only for the first tarsometatarsal (TMT) joint but also for the other joints constituting the first ray (the talonavicular joint, the medial cuneonavicular joint, and the first metatarsophalangeal [MTP] joint). The objective of the current study was to use our device to evaluate the 3-D mobility of each joint of the first ray in feet with hallux valgus compared with normal feet using non-weight-bearing and weight-bearing CT.

Materials and Methods

Subjects

In this case-control study, we examined 10 feet of 10 healthy volunteers with no history of foot disorders and no symptoms such as pain in the foot (the "control group") and 10 feet of 10 consecutive patients with severe idiopathic hallux valgus who were scheduled to undergo surgery because of increased symptom severity (the "hallux valgus group") between June 2014 and June 2015 in the Jikei University Katsushika Medical Center, Tokyo, Japan. The sample size was determined by a power analysis. Patients with hallux valgus and inflammatory arthritis or another foot condition were excluded from the study. All participants in both groups were women. The mean age (and standard deviation) was 56 ± 5.0 years in the control group and 58 ± 14.2 years in the hallux valgus group. This study was conducted in accordance with the Declaration of Helsinki and approved by the Research Ethics Committee of Jikei University. Written informed consent was obtained from all participants.

Imaging

CT images and standing radiographs were obtained for all of the patients with hallux valgus. The duration of time between radiographs and CT was within 1 month. An original loading device was used when obtaining the CT images. Subjects in both groups first underwent a non-weight-bearing CT scan of

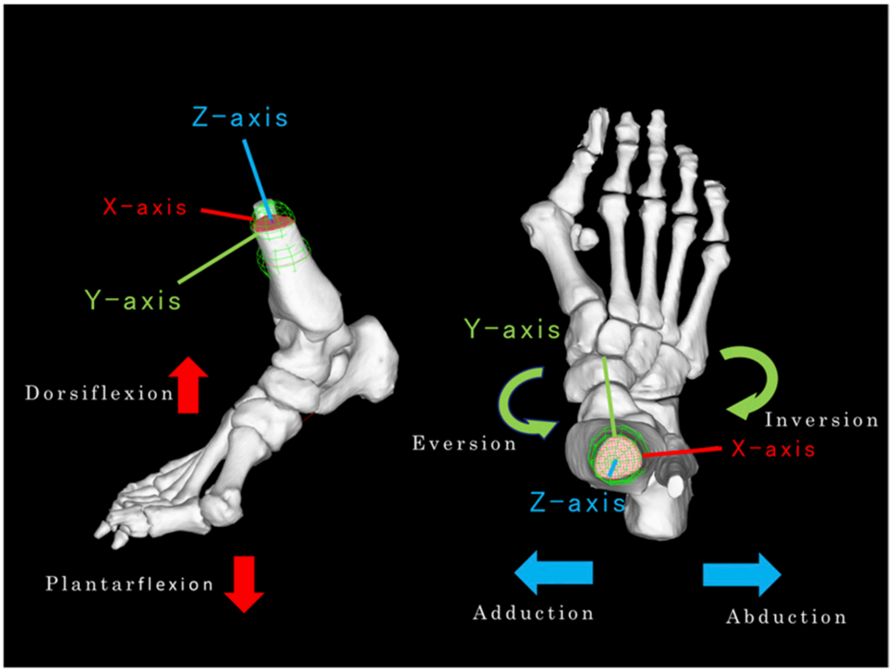

Fig. 3

A 3-D model of a foot with hallux valgus is shown. X axis = the vector product of the line connecting the center of the calcaneus with the head of the second metatarsal bone and the z axis, y axis = the cross-product of the z and x axes, and z axis = the axis of the tibia. Movement about the x axis = plantar flexion-dorsiflexion, movement about the y axis = eversion-inversion, and movement about the z axis = adduction-abduction.

TABLE II Spearman Rank Correlation Coefficients Between Demographic Characteristics and Radiographic Measurements in the Hallux Valgus Group*

	Coefficient	P Value
Age vs. HVA	0.479	0.162
Age vs. IMA	0.543	0.105
Age vs. T1MTA	0.239	0.507
Age vs. CPA	−0.163	0.654
Body weight vs. HVA	0.375	0.286
Body weight vs. IMA	0.594	0.070
Body weight vs. T1MTA	−0.087	0.811
Body weight vs. CPA	−0.249	0.487
BMI vs. HVA	0.320	0.367
BMI vs. IMA	0.601	0.066
BMI vs. T1MTA	0.119	0.743
BMI vs. CPA	0.236	0.511

*HVA = hallux valgus angle, IMA = first-second intermetatarsal angle, T1MTA = lateral talo-first metatarsal angle, and CPA = calcaneal pitch angle.

the foot while supine on the loading device with the lower limbs extended and the ankle joint in a neutral position. Next, they underwent a weight-bearing CT scan of the foot. With the feet in the same position, weight plates were added to the device, applying load to the feet until a scale (ATLAS) positioned between the foot plate and the soles of the feet showed that the weight was nearly equivalent to the subject's previously measured body weight. The slice thickness was 0.75 mm for all foot CT scans.

Image Analysis

The hallux valgus angle, the first-second intermetatarsal angle, the lateral talo-first metatarsal angle, and the calcaneal pitch angle were measured on standing radiographs of subjects in the hallux valgus group (Fig. 2, panels i and iii). CT image data were obtained using the DICOM (Digital Imaging and Communications in Medicine) standard. For both the control group and the hallux valgus group, the same parameters were measured on volume-rendered, weight-bearing CT images made using the same frontal and lateral views as on the radiographs (Fig. 2, panels ii and iv). These angles were measured 3 times by 2 surgeons who were members of the Japanese Board of Orthopaedic Surgery. Each observer was blinded to the results of the other observer.

Next, semi-automatic segmentation of each bone was performed and a 3-D model was created using the image analysis software Analyze (Mayo Foundation)[12-14]. The axis of the tibia was used as the z axis, the vector product of the line connecting the center of the calcaneus with the head of the second metatarsal bone and the z axis was used as the x axis, and the cross-product of the z and x axes was used as the y axis. Movement about the z axis was defined as adduction-abduction, movement about the x axis was defined

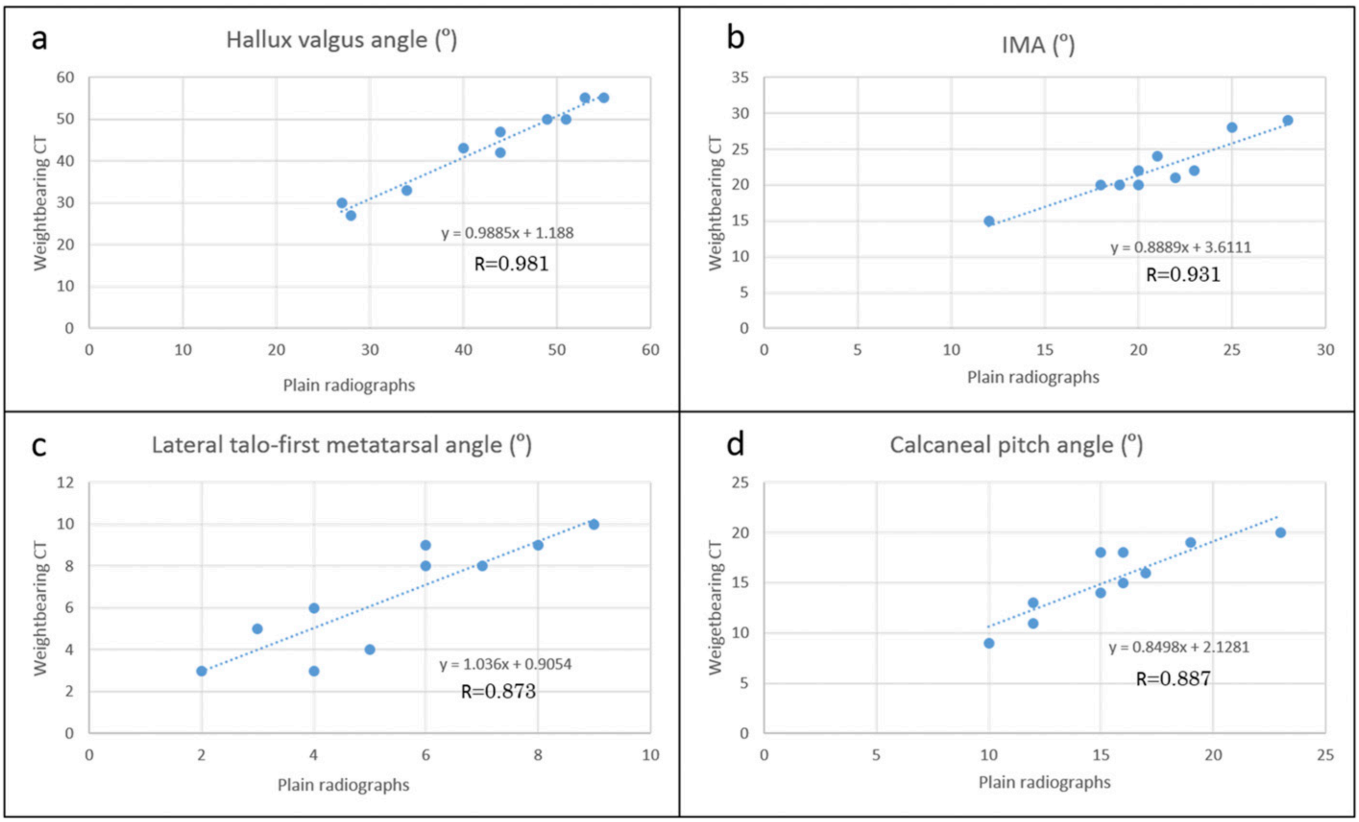

Fig. 4

Figs. 4-A through 4-D Correlations between alignment angles measured on radiographs and volume-rendered weight-bearing CT images of the hallux valgus group. Strong correlations were found for all of the measured parameters. **Fig. 4-A** Hallux valgus angle. **Fig. 4-B** First-second intermetatarsal angle (IMA). **Fig. 4-C** Lateral talo-first metatarsal angle. **Fig. 4-D** Calcaneal pitch angle.

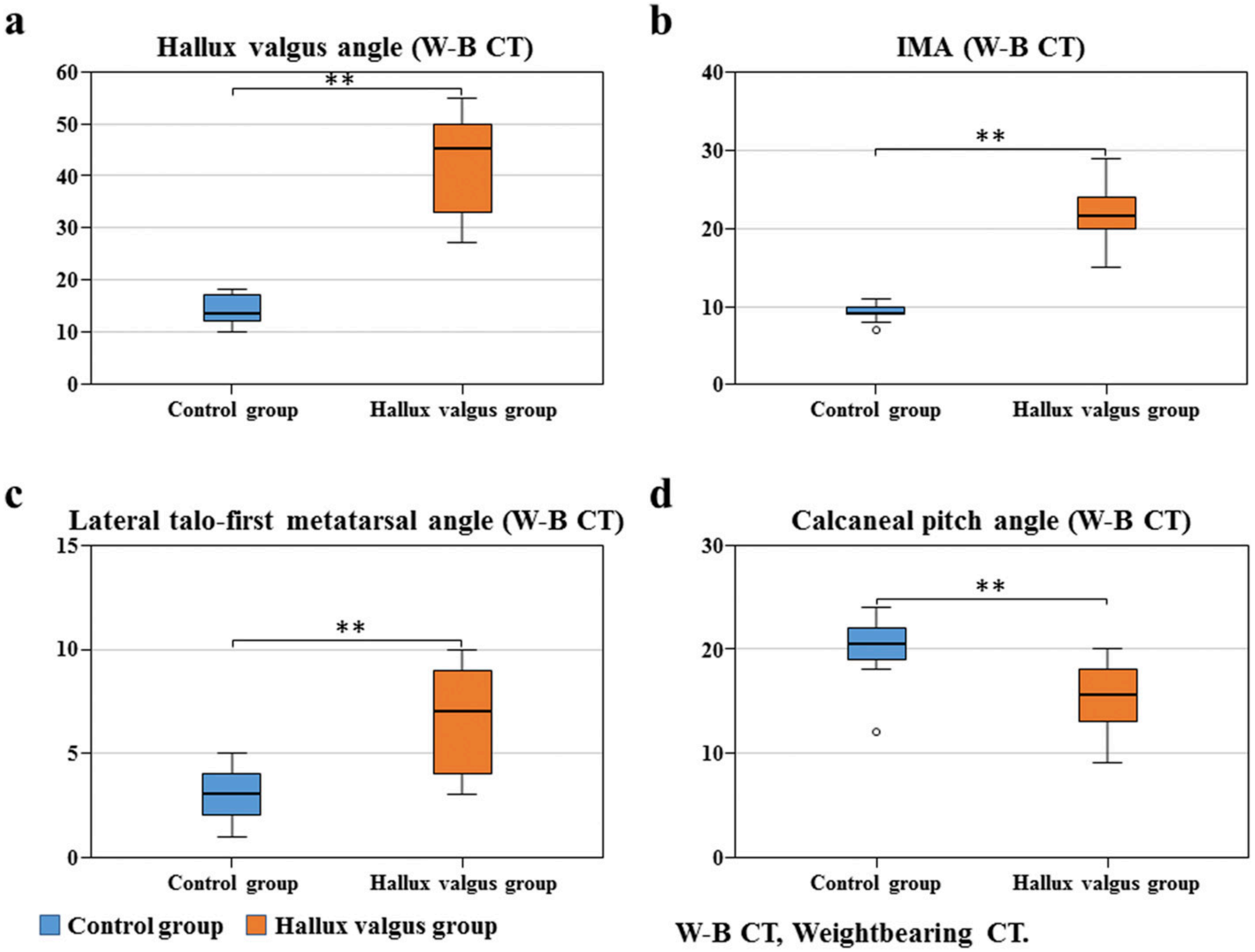

Fig. 5

Figs. 5-A through 5-D Comparison between the control group and the hallux valgus group for foot parameters measured on volume-rendered, weight-bearing (W-B) CT images. The boxes indicate the interquartile range (from 25% to 75%); the horizontal lines within the boxes indicate the median; the whiskers indicate the range (non-outliers); and the circles indicate data >1.5 times the interquartile range beyond the box, considered outliers. **P < 0.01. **Fig. 5-A** Hallux valgus angle. **Fig. 5-B** First-second intermetatarsal angle (IMA). **Fig. 5-C** Lateral talo-first metatarsal angle. **Fig. 5-D** Calcaneal pitch angle.

as plantar flexion-dorsiflexion, and movement about the y axis was defined as eversion-inversion (Fig. 3). With use of an iterative closest point (ICP) algorithm (which finds the closest point on a 3-D entity to a given point)[15], each joint that composes the first ray, namely, the talonavicular joint, the medial cuneonavicular joint, the first TMT joint, and the first MTP joint, was aligned using its respective proximal bone. Displacement of the distal bone relative to the proximal bone was quantified 3-dimensionally under non-weight-bearing and weight-bearing conditions.

Statistical Analysis

A power analysis was performed to determine the minimum number of patients needed for each group. The sample size was estimated for an independent-sample t test. King and Toolan[16] defined the first metatarsal-medial cuneiform angle (MMCA) for assessing hypermobility of the first ray at the first TMT joint on weight-bearing radiographs. The MMCA was a mean of 2° ± 1° in their hallux valgus group and 0.2° ± 0.6° in the control group. With these 2 averages (setting alpha = 0.05, and 1 – beta = 0.9), the power was calculated using a sample-size calculation tool (G*Power, version 3.0.10; Franz Faul, University of Kiel, Kiel, Germany), and a minimum of 6 cases were required for each group. We then set a sample size of 10 for each group.

Calculated measurements were compared between the groups using the 1-tailed Mann-Whitney U test (if necessary, Bonferroni correction was applied for multiple comparisons). Differences with a p value of <0.05 were considered significant.

Results

Comparisons Between the Groups

The characteristics of subjects by group are shown in Table I. In the hallux valgus group, the mean age was 58 ± 14.2 years (range, 33 to 74 years), the mean body weight was 46.5 ± 3.0 kg, and the mean body mass index (BMI) was 19.2 ± 2.6 kg/m². In the control group, the mean age was 56 ± 5.0 years (range, 50 to 66 years), the mean body weight was 48.5 ± 5.9 kg, and the mean BMI was 20.4 ± 1.8 kg/m².

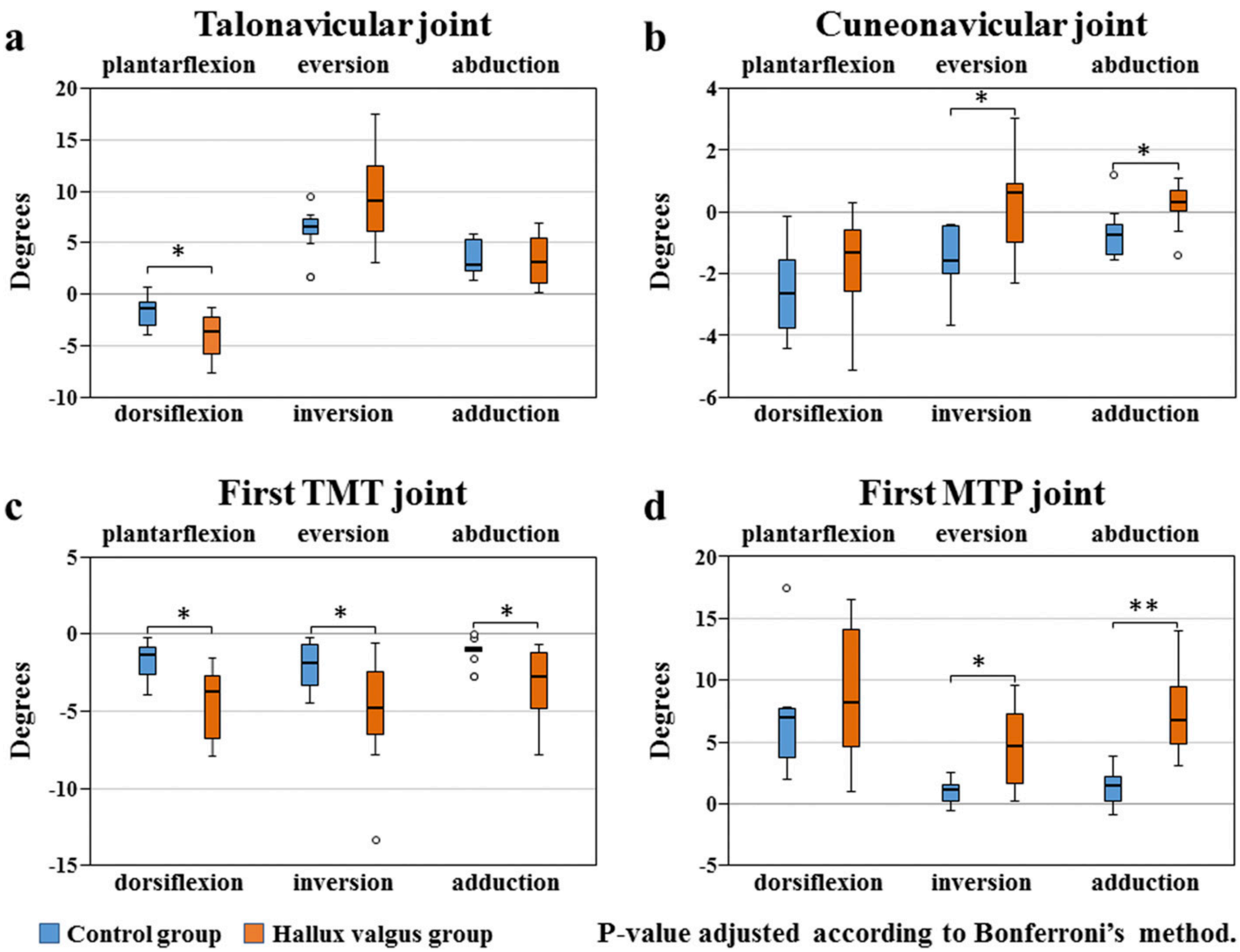

Fig. 6

Figs. 6-A through 6-D Comparison between the control group and the hallux valgus group for mobility at each joint of the first ray. Displacement of the proximal bone relative to the distal bone under loading was measured. The boxes indicate the interquartile range (from 25% to 75%); the horizontal lines within the boxes indicate the median; the whiskers indicate the range (non-outliers); and the circles indicate data >1.5 times the interquartile range beyond the box, considered outliers. *P < 0.05, and **p < 0.01. **Fig. 6-A** Talonavicular joint. **Fig. 6-B** Cuneonavicular joint. **Fig. 6-C** First tarsometatarsal (TMT) joint. **Fig. 6-D** First metatarsophalangeal (MTP) joint.

When assessed on radiographs, the mean measurements in the hallux valgus group were 42.5° ± 10.0° for the hallux valgus angle, 20.8° ± 4.3° for the first-second intermetatarsal angle, 5.4° ± 2.2° for the lateral talo-first metatarsal angle, and 15.5° ± 3.7° for the calcaneal pitch angle. There was no significant correlation between these parameters and age, body weight, and BMI (Table II). When these same parameters were assessed for the hallux valgus group on volume-rendered, weight-bearing CT images, the mean measurements were 43.2° ± 10.1° for the hallux valgus angle, 22.1° ± 4.1° for the first-second intermetatarsal angle, 6.5° ± 2.6° for the lateral talo-first metatarsal angle, and 15.3° ± 3.6° for the calcaneal pitch angle. There were very strong correlations between the measurements on radiographs and those on volume-rendered, weight-bearing CT images for all parameters (r = 0.873 to 0.981) (Fig. 4).

In the control group, the mean measurements on volume-rendered, weight-bearing CT images were 14.1° ± 2.8° for the hallux valgus angle, 9.3° ± 1.3° for the first-second intermetatarsal angle, 3.2° ± 1.3° for the lateral talo-first metatarsal angle, and 20.1° ± 3.4° for the calcaneal pitch angle. The measurements made using weight-bearing CT images differed significantly between the control group and the hallux valgus group for all parameters (p < 0.01) (Fig. 5).

Evaluation of Mobility of Each Joint of the First Ray

Talonavicular Joint

In the control group, the navicular exhibited a mean of 2.1° ± 1.6° of dorsiflexion, 6.3° ± 2.0° of eversion, and 3.4° ± 1.7° of abduction relative to the talus. In the hallux valgus group, the navicular exhibited a mean of 3.9° ± 2.2° of dorsiflexion, 9.6° ± 4.4° of eversion, and 3.4° ± 2.4° of abduction relative to the talus, with the hallux valgus group showing significantly greater dorsiflexion ($p = 0.043$) than measured for the control group (Fig. 6-A).

Medial Cuneonavicular Joint

In the control group, the medial cuneiform exhibited a mean of 2.5° ± 1.5° of dorsiflexion, 1.5° ± 1.0° of inversion, and 0.7° ± 0.8° of adduction relative to the navicular. In the hallux valgus group, the medial cuneiform exhibited a mean of 1.6° ± 1.6° of dorsiflexion, 0.2° ± 1.5° of eversion, and 0.2° ± 0.7° of abduction relative to the navicular, with the hallux valgus group showing significantly greater eversion ($p = 0.039$) and abduction ($p = 0.039$) than measured for the control group (Fig. 6-B).

First TMT Joint

In the control group, the first metatarsal exhibited a mean of 2.0° ± 1.3° of dorsiflexion, 2.6° ± 1.4° of inversion, and 1.1° ± 0.7° of adduction relative to the medial cuneiform. In the hallux valgus group, the first metatarsal exhibited a mean of 3.6° ± 2.3° of dorsiflexion, 4.9° ± 3.6° of inversion, and 3.2° ± 2.3° of adduction relative to the medial cuneiform, with the hallux valgus group showing significantly greater dorsiflexion ($p = 0.037$), inversion ($p = 0.047$), and adduction ($p = 0.035$) than measured for the control group (Fig. 6-C).

First MTP Joint

In the control group, the first proximal phalanx exhibited a mean of 6.7° ± 4.4° of plantar flexion, 0.9° ± 1.0° of eversion, and 1.2° ± 1.5° of abduction relative to the first metatarsal. In the hallux valgus group, the first proximal phalanx exhibited a mean of 9.1° ± 5.4° of plantar flexion, 4.6° ± 3.4° of eversion, and 7.1° ± 3.4° of abduction relative to the first metatarsal, with the hallux valgus group showing significantly greater eversion ($p = 0.015$) and abduction ($p < 0.01$) than measured for the control group (Fig. 6-D).

Discussion

In this study, we used a loading device that we developed to capture weight-bearing CT images of the foot. We previously evaluated the ability of our loading device to reproduce loading conditions in a standing position using a plantar pressure measurement system, but we did not evaluate its ability to reproduce foot alignment[11]. In the current study, we found very strong correlations between measurements of the hallux valgus angle, the first-second intermetatarsal angle, the lateral talo-first metatarsal angle, and the calcaneal pitch angle on standing radiographs with those measured on weight-bearing CT images (Fig. 4), which indicates that our device can reproduce foot alignment in a standing position and that weight-bearing CT images made with use of this device could serve as a useful substitute for standing radiographs when measuring joint angles.

There have been a few previous studies on first-ray mobility in hallux valgus using original devices[5,17,18]. As these studies used manipulation, only a limited amount of force could be applied and only dorsiflexion and plantar flexion could be observed. Moreover, it was impossible to measure the motion of each joint independently to determine which parts of the first-ray joints move the most. First-ray mobility has been evaluated in some cadaveric studies as well[19,20]. Joints of the first ray were evaluated independently in those studies, but the conditions of ligaments and other soft tissues in cadavers are different from those in the living body, and such differences likely affected joint mobility.

First-ray mobility has been evaluated using radiographs[16,21] or fluoroscopy[22] in other studies. All of the images in those studies were lateral views. Accordingly, the main type of mobility evaluated was sagittal mobility, the same as that evaluated with the device by Klaue et al[5]. However, Mortier et al. found that patients with hallux valgus exhibit an average of 12.7° of pronation[23], demonstrating that deformity in hallux valgus occurs 3-dimensionally. Therefore, we considered that deformity in feet with hallux valgus should also be evaluated 3-dimensionally.

Taking these findings into account, we designed an image analysis system for this study. First, we expected that weight-bearing CT images and 3-D models would be essential for detailed 3-D evaluation. We reconstructed the 3-D models of each bone by segmentation and used an ICP algorithm to align bones and quantify displacement under loading. ICP algorithms can match the shapes of 3-D objects without using any specified anatomical landmarks. They are very useful for evaluating 3-D bone mobility and comparing between the same subjects. Thus, we designed the device so that it could apply a load equivalent to each subject's body weight, which allowed us to capture CT images under the same conditions as standing radiographs. In this way, we were able to standardize imaging conditions between subjects.

We found that, under loading, the first metatarsal exhibited significantly more dorsiflexion relative to the medial cuneiform bone in feet with hallux valgus compared with normal feet. This reaffirms that patients with hallux valgus exhibit hypermobility in the sagittal plane, as has been described many times before[5,17,18]. However, we also found that feet with hallux valgus exhibited significantly more inversion and adduction when we evaluated the first TMT joint. This suggests that TMT joint hypermobility involves motion in all directions, not just the sagittal direction; in other words, that hypermobility is 3-D.

In addition to TMT joint hypermobility, we found significantly greater mobility compared with the normal feet for 1 or 2 of the 3 defined movement elements in the other joints that constitute the first ray. This suggests that first-ray hypermobility associated with hallux valgus occurs in all of these joints rather than in the TMT joint alone. Taken together, the results of this study affirm our hypothesis. We suggest that correction of the 3-D deformity should also be addressed 3-dimensionally in order to achieve anatomical restoration with proper function of the foot.

The relationship between first-ray hypermobility and progression of hallux valgus and associated deformity is still under debate. In a cadaveric study, Coughlin et al. compared the sagittal motion of the first ray before and after proximal osteotomy and soft-tissue reconstruction using a Klaue device and found that motion was significantly lower postoperatively, but they did not assess motion in comparison groups[24]. Other research has also shown that first-ray mobility decreases after surgery in patients with TMT joint hypermobility who undergo osteotomy[25-28]. Nevertheless, hypermobility of the first ray including that of the TMT joint remains an important aspect of the pathology of hallux valgus. Due to the shape of the TMT joint, simultaneous dorsiflexion and adduction of the first metatarsal occurs under loading, even in normal feet. We suggest that pes planus, metatarsus latus, and rotation of the hallux occur because of extensive spreading of the first and second metatarsals, namely, increased displacement in the medial column when these movements are amplified by hypermobility.

Our study had some limitations. First, we had a small sample size of only 10 subjects each in the hallux valgus group and the control group. Additionally, we mostly recruited middle-aged women as volunteers for the control group because most of our patients undergoing surgery for hallux valgus were middle-aged women, but further studies should include a larger number of subjects and compare results between age groups. Moreover, it is believed that the maximum degree of deformity and most severe symptoms are seen when standing on 1 leg, so it would be ideal if subjects were to undergo imaging with just 1 foot on the foot plate in order to capture a large degree of joint displacement. However, we decided to have subjects keep both feet on the foot plate for weight-bearing imaging because it would be easy for subjects to lose their balance when standing radiographs are made in such an unstable position, single-footed imaging would be more burdensome for them, and we wanted to capture CT images under the same conditions as radiographs in order to compare them. Moreover, as we found significant differences in every joint among the patients with hallux valgus, it appears that the load we applied was sufficient for comparison between the control group and the hallux valgus group. Finally, in this study we focused solely on the displacement of bones constituting joints, but surrounding soft tissues such as tendons, muscles, ligaments, and the plantar aponeurosis are deeply involved in actual joint dynamics. Detailed analysis of these components will also be necessary to elucidate the pathology of hallux valgus.

In summary, by using an original loading device, we were able to reproduce alignment in the standing position and perform detailed analysis of 3-D changes in the foot under loading. This indicates that the method we used is useful for analyzing the pathology of foot disorders in which changes in alignment occur under loading.

There is still debate about whether or not TMT joint hypermobility is a major cause of deformity in hallux valgus. The results of this study suggest that loading of the foot causes significant displacement not only at the TMT joint but also at the other joints that constitute the first ray. This suggests that hypermobility extends across the entire first ray. In future studies, our method and data should be useful for elucidating the pathology of hallux valgus and for selecting or developing methods to evaluate further details, such as the role of soft tissue and the mobility of the first ray after surgery. ■

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