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Three-dimensional analysis of tarsal bone response to axial loading in patients with hallux valgus and normal feet

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ABSTRACT

Background: Patients with hallux valgus present a variety of symptoms that may be related to the type of deformity. Weightbearing affects the deformities, and the evaluation of the load response of tarsal bones has been mainly performed using two-dimensional plane radiography. The purpose of this study was to investigate and compare structural changes in the medial foot arch between patients with hallux valgus and normal controls using a computer image analysis technique and weightbearing computed tomography data.

Methods: Eleven patients with hallux valgus and eleven normal controls were included. Computed tomograms were obtained with and without simulated weightbearing using a compression device. Computed tomography data were transferred into a personal computer, and a three-dimensional bone model was created using image analysis software. The load responses of each tarsal bone in the medial foot arch were measured three-dimensionally and statistically compared between the two groups.

Findings: Displacement of each tarsal bone under two weightbearing conditions was visually observed by creating three-dimensional bone models. At the first metatarsophalangeal joint, the proximal phalanges of the hallux valgus group showed significantly different displacements in multiple directions. Moreover, opposite responses to axial loading were also observed in both translation and rotation between the two groups.

Interpretation: Weightbearing caused deterioration of the hallux valgus deformity three-dimensionally at the first metatarsophalangeal joint. Information from the computer image analysis was useful for understanding details of the pathology of foot disorders related to the deformities or instability and may contribute to the development of effective conservative and surgical treatments.

1. Introduction

Hallux valgus deformity, a major foot problem, is characterized by varus of the first metatarsal bone and valgus of the big toe. The typical symptom is pain in the medial prominence at the first metatarsal head (bunion). Symptoms induced by this disease vary and include painful plantar callosity, pain at the overlapped big toe and second toe, or midfoot pain (Easley and Trnka, 2007). Combined deformities are also observed, including pronation of the big toe, lateral shift of the sesamoid bones, spread foot, or flat foot (Perera et al., 2011). These deformities may be related to a variety of symptoms, and physicians often need to analyze these relationships before treatment.

The evaluation of foot structure in hallux valgus has mainly been performed using two-dimensional plane radiography. However, previous studies have reported that limitations exist in examinations in the coronal plane or examinations involving rotation (Saltzman et al., 1996; Suzuki et al., 2004). Recently developed computer image analysis techniques have enabled precise three-dimensional analysis using data from computed tomography (CT) or magnetic resonance imaging. We have developed a method for three-dimensional image analysis using weightbearing CT data (Suzuki et al., 2014; Watanabe et al., 2012). This method is capable of capturing detailed structural information on changes in the tarsal bones induced by weightbearing, which is useful for understanding the physiological phenomena and pathological status of normal or disordered feet. Flatfeet analyses using weightbearing CT images revealed that abnormal instability occurred in the joints constructing foot arch three-dimensionally (Ferri et al., 2008; Kido et al., 2011; Zhang et al., 2013). Medial foot arch is an important structure to support body weight and the arch changes with weightbearing. Previous investigators reported the relationship between hallux valgus and foot arch (Geng et al., 2015; Glasoe et al., 2010; Perera et al., 2011). However, insufficient information is still

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available to understand effects of weightbearing on feet with hallux valgus or its pathogenesis of deformity deterioration.

In this study, our purpose was to investigate and compare load responses of the tarsal bones composing the medial foot arch between patients with hallux valgus and patients with normal feet using computer image analysis and weightbearing CT data. Our hypothesis was that load response of the hallux valgus feet was different from that of the normal feet in terms of direction or amount of displacement.

2. Methods

2.1. Patients and controls

This study protocol was approved by the institutional review board of our facility. Eleven patients with hallux valgus were included. All of the patients underwent surgical treatment and preoperative CT. The mean age of the patients was 62.7 years (range, 51–74 years) and all patients were female. The inclusion criteria for the controls were patients >40 years old; no previous foot pain, injuries, or surgeries; and foot X-rays that were within normal anatomical limits. Eleven patients (11 ft) met the criteria and the mean age of the controls was 55.9 years (range, 40–72 years), with 6 females and 5 males. Control CT images were obtained from the opposite side (normal side) of the foot when a patient underwent CT of both feet simultaneously. Original disorders of the controls were post-traumatic arthrosis (4 patients), aseptic necrosis of the talus (3), sesamoid bone disorder (2), ectopic ossification (1), and bursitis (1). Hallux valgus was defined as a lateral deviation of the hallux on the first metatarsal with a hallux valgus angle (HVA) over 20° in a weightbearing anteroposterior X-ray of the foot. The HVA is the relationship of the long axis of the proximal phalanx to the long axis of the first metatarsal. All of the hallux valgus patients showed the HVA over 30°. A calcaneal pitch angle formed by the horizontal and a line from the base of the heel and inferior cortex of the calcaneus was also measured in a weightbearing lateral X-ray of the foot.

2.2. CT and image analysis

CT was performed in the supine position with neutral ankle position. The CT images were acquired from the distal tibia to the whole foot (Aquilion PRIME; Toshiba Medical Systems, Otawara, Japan) using 0.5-mm slice thicknesses, 120 kVp, 100 mAs, and a 0.5-s rotation time. A compression device (DynaWell L-spine, abbreviated as DynaWell; DynaWell Inc., Las Vegas, USA) was used for axial loading (Danielson and Willén, 2001). This nonmagnetic compression device consisted of a vest, two adjustable cords, and a footplate. The patients wore the vest over their shoulders and upper chest. Two adjustable cords on opposite sides of the vest were attached to the footplate. The feet were positioned against a footplate on the compression device with extended hips and knees. Axial load could be applied by tightening the cords. The applied load was measured using scales on the footplate. Under non-weightbearing conditions, 2 kg axial loading was applied to keep the ankle neutral. Under weightbearing conditions, one-third of the patient's weight was applied to 1 ft during CT examination. We confirmed that the center of the plantar pressure was not statistically different between standing condition and the simulated axial-loading condition in our preliminary study (Watanabe et al., 2012). Digital Imaging and Communication in Medicine (DICOM) data of CT were transferred to a personal computer (PC) and a three-dimensional bone model was created using image analysis software (Mimics ver. 16; Materialise Co., Ltd., Belgium). Each tarsal bone constructing the medial foot arch was isolated (talus, navicular, medial cuneiform, first metatarsal, proximal phalanges of the big toe). The three-dimensional rectangular coordinate system was set and the translational distance and rotational displacement were then calculated using three-dimensional computer-aided design software (3-Matics, ver. 8; Materialise Co., Ltd., Belgium) for each tarsal bone (Suzuki et al., 2014). The coordinate origin was set at the centroid of the talus under weightbearing condition. The z-axis was oriented in the proximal-distal, the y-axis was oriented in the anterior-posterior, and the x-axis was oriented in the medial-lateral direction. The z-axis was perpendicular to the foot plate, the y-axis was parallel to the projection of the axis of the second metatarsal, and the x-axis was the product of the x- and z-axes following the right-hand rule passing through the centroid of the talus. Motion (translation) in a direction was defined as medial/lateral translation for the x-axis, anterior/posterior translation for the y-axis, and proximal/distal translation for the z-axis. Rotation was defined as dorsiflexion/plantarflexion about the x-axis, inversion/eversion about the y-axis, and adduction/abduction about the z-axis. Three-dimensional displacement of each tarsal bone relative to its proximal bone was calculated from the non-weightbearing condition to the weightbearing condition. For example, for the talonavicular joint, the talus under non-weightbearing condition was superimposed over the talus under weightbearing condition (Fig. 1). Positional difference of the centroid of the navicular on the coordinate system between the conditions was calculated as the translational displacement. Afterwards, the navicular under the non-weightbearing condition was overlapped with the navicular under the weightbearing condition by matching both centroids. The rotational angle was calculated around the three axes using the centroid of the navicular as the center of the three axes. These processes were applied to the naviculocuneiform joint, the tarsometatarsal joint, and the first metatarsal proximal phalanges joint (MTP). Calculated displacement data were statistically analyzed and compared between the hallux valgus group and control group using the unpaired *t*-test. The displacement data were also compared between the males and the females in the control group. The HVA and the calcaneal pitch angle measured from weightbearing X-rays was compared between the hallux valgus group and control group using the unpaired *t*-test. The level of statistical significance was set at $P < 0.05$.

3. Results

Weightbearing X-rays of the hallux valgus group showed a mean HVA of 42.2° and a mean calcaneal pitch angle of 21.1°, and those of the control group were 16.2° and 24.4°, respectively. A statistical difference was observed in the HVA between the two groups ($P < 0.001$). The amount of the three-dimensional displacement of each tarsal bone from CT measurement did not show significant difference between the males and the females in the control group.

The three-dimensional displacements of each tarsal bone under the two weightbearing conditions were visualized on a PC by creating three-dimensional bone models. The displacement data are shown in Fig. 2. In the talonavicular joint, axial loading displaced the navicular in the same direction in both the hallux valgus and normal control groups, and no significant difference was observed in the amount of displacement. In the naviculocuneiform joint, the response to axial loading was small in both groups. In the tarsometatarsal joint, although the amount of displacement was small, a significant difference was observed in the anterior/posterior translation between the two groups ($P = 0.032$). In the first MTP, the proximal phalanges of the hallux valgus group showed significantly different displacements in multiple directions (*P* values; medial/lateral: 0.005, anterior/posterior: 0.019, adduction/abduction: 0.024, inversion/eversion: 0.002). Moreover, opposite responses to axial loading were also observed in the medial/lateral, anterior/posterior translation, adduction/abduction, and inversion/eversion directions between the two groups.

4. Discussion

This study compared alignment changes of the medial foot arch as a reaction to axial loading between patients with hallux valgus and normal controls using computer image analysis of CT data. The results demonstrated that displacement at the first MTP was significantly different