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Does Hallux Valgus Exhibit a Deformity Inherent to the First Metatarsal Bone?

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ABSTRACT

Hallux valgus is a common condition, and it still poses some challenges. The identification of factors associated with the development of the deformity is of paramount importance in obtaining a full correction of the disorder. Hallux pronation is one of the frequently found components, especially in larger deformities, but the cause and exact location of this condition are not fully understood. The aim of the present study was to investigate whether there is a rotational deformity inherent to the first metatarsal bone. A case-control study was conducted on patients with and without hallux valgus who were subjected to computed tomography with multiplanar reconstruction. Statistical analysis was performed by means of a mixed model adjusted for foot and gender to compare metatarsal rotation between cases and controls. Correlations between numerical quantitative measurements were investigated by means of Pearson's correlation coefficient obtained in a linear mixed model. A total of 82 feet (tests) were analyzed in the hallux valgus group and 64 feet (tests) in the control group (N = 146). The hallux valgus group was significantly different from the control group ($p < .001$). Mean metatarsal bone rotation was 15.36° (range 1.65° to 32.52°) in the hallux valgus group and 3.45° (range -7.40° to 15.56°) in the control group. The difference between the means was 11.9° (confidence interval 9.2° to 14.6°). In conclusion, patients with hallux valgus exhibited increased exclusive bone rotation of the first metatarsal toward pronation compared with the population without this condition.

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Hallux valgus is characterized by first ray deformity with various clinical manifestations (1–5). The identification of factors associated with the development of the deformity is of paramount importance in obtaining a full correction of the disorder. Hallux pronation is one of the frequently found components, especially in larger deformities, but the cause and exact location of this condition are not fully understood (2,3,6,7).

In 2 studies (8,9), metatarsal rotation in patients with and without hallux valgus was compared. The patients with hallux valgus exhibited greater first ray pronation compared with the healthy patients. The

authors suggested the following causes: fallen arches, ligament abnormalities, and disorders of muscle balance in gait. Yet, the method used for assessment was plain radiography, which is susceptible to variation and error, as shown in the literature (10–13).

The aim of the present study was to assess the intrinsic bone rotation along the full length of the first metatarsal bone. The instrument for analysis of patients with and without hallux valgus was computed tomography (CT) with multiplanar reconstruction.

Patients and Methods

The study began after approval by the institutional research ethics committee (Santa Casa de Misericórdia de Porto Alegre, CAAE 56605416.1.0000.5335), after a full review. Eligible participants consisted of a convenience sample of 131 patients identified at the orthopaedics and traumatology outpatient clinic between January 1, 2012, and December

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31, 2016, with multiple-detector CT with acquisition of isotropic scans of the feet having been performed. From these patients, only 91 met the inclusion criteria, corresponding to 46 cases of hallux valgus and 45 controls. Patients who met the inclusion criteria in both feet contributed with 2 examinations for analysis. The total number of examinations included was 146, of which 82 were in the hallux valgus group and 64 were in the control group.

Cases were identified and recruited by the principal author (E.P.C.) among symptomatic patients who were included in a previous data set where CT was performed before surgical treatment (14). Because CT is not routinely used for this pathology, we preferred to use this data set. The inclusion criterion in this group was the diagnosis of hallux valgus with indicated surgical treatment (3,15). The diagnosis of hallux valgus was defined as the presence of symptoms and pathological values for hallux valgus angle ($>15^\circ$) or intermetatarsal angle ($>9^\circ$). The exclusion criteria were neurological disease, advanced arthrosis of the metatarsophalangeal joint, congenital syndromes, previous metatarsal fractures, or foot surgery. Controls (patients without hallux valgus) were selected by the principal author (E.P.C.) among subjects who underwent a CT examination for investigation of other conditions, such as calcaneus fracture. In this group, all patients with concomitant hallux valgus diagnosis were excluded (3,15).

Individuals with associated hallux valgus were identified through clinical examination at outpatient clinics and analysis of imaging examinations (radiographs and CT scans). It should be noted that radiography was performed according to the patients' underlying pathology. Accordingly, some radiographs in the control group were performed without weightbearing. Other exclusion criteria were the presence of neurological disease, advanced arthrosis of the metatarsophalangeal joint, previous fracture or surgical procedures on the first metatarsal bone, and congenital syndromes.

CT scans were performed with a 64-detector Siemens Sensation Cardiac Scanner (Siemens Medical Solutions, Forchheim, Germany) (120 kV, 90 mAs, slice thickness 1.0 mm, pitch 0.9, radiation dose 6.89 mGy). Scans were acquired by means of isotropic acquisitions, stored in digital imaging and communications in medicine format, and analyzed by using image processing software (OsiriX MD, Pixmeo, Geneva, Switzerland) with 3-dimensional multiplanar reconstruction in a 2.0-mm-thick bone window. It was used to achieve the angle of rotation of the first metatarsus resulting from bone morphology only, without the interference of other associated components.

The intrinsic bone rotation angle of the first metatarsus was determined by using parameters already described in the literature (14,16–20). First, the central longitudinal axis of the first metatarsal bone was defined on the coronal, sagittal and axial planes, transversally aligned to the lateral cortex of the middle third of the diaphysis. The lateral cortex of the diaphysis was used as a parameter, following descriptions in previous studies conducted with cadavers, to compensate for the effect of metatarsal rotation in the selection of the central axis (Fig. 1) (11,21–24). On the basis of this reference, 2 sections transverse to the long axis of the first metatarsal bone were selected for measurement. The first coronal image was designated the metatarsal base (MB), and the second was designated the metatarsal head (MH). The first image was selected on the transverse plane, 1.0 cm distal to the first ray of the tarsometatarsal joint. The second image was selected on that same plane but located 0.5 to 1.2 cm proximal to the apex of the articular surface of the first MH, preferentially including the sesamoid bones and intersesamoid crest, closer to the vertex of the lines of force, based on criteria used in other studies (Fig. 2) (9,13,17,24). The intrinsic rotation of the first metatarsal bone was measured following reconstruction by merging the 2 images (MB and MH). The angle was formed by line A parallel to the lateral cortex of the MB (Fig. 2A) and by line B formed by the medial and lateral boundary of the plantar articular surface of the MH (Fig. 2B) -90° (9,13,16,17,19,20,24). Positive values indicate an anatomical rotation of the bone toward pronation, and negative values point to supination.

CT scans were evaluated by one of the authors (F.V.W.), a radiologist specializing in musculoskeletal diseases, at 2 different times with a 60-day interval. Considering that this method of measurement is not usual, intraobserver agreement analysis was performed by the principal author (E.P.C.) to verify the reliability of the measurement (16). The mean of the 2 measurements was used to increase the power of analysis, because it approached the true value. The radiographs were assessed by the principal author (E.P.C.), an orthopaedist specializing in foot and ankle surgery. The radiographs were taken under weightbearing conditions in accordance with Coughlin et al (15). Examiners were blinded to the participants' status.

It is important to highlight that CT scans were performed without weightbearing, although this condition is considered superior for pathologies of the foot and ankle. Therefore, it is appropriate to explain why its use is unnecessary for the study. First, it is noted that the bone anatomy is not modified by the position of the foot during the



Fig. 1. Central axis of the first metatarsal bone on the (A) sagittal, (B) axial, and (C) coronal planes.

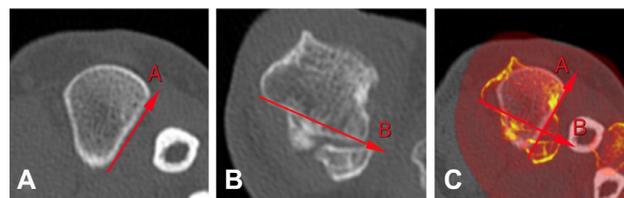


Fig. 2. Reference planes for measurements. Coronal sections selected (A) on the metatarsal base (MB) and (B) on the metatarsal head (MH). (C) Merging of the 2 images (MB and MH) measuring the angle between line A parallel to the lateral cortex of the base (MB) and line B formed by the medial and lateral boundary of the plantar articular surface of the (MH) -90° .

examination. Thus, regardless of whether the foot is in plantar or dorsal flexion, with or without weightbearing, the image of the bone anatomy captured is the same. Multiplanar reconstruction offers a bone anatomical image that can be virtually manipulated in all directions. Finally, the CT examination performed on the patients was sufficient to reach the objective of the study. In this context, ethical guidelines in research do not recommend subjecting the participants to a new intervention.

The study also examined whether increased metatarsal rotation toward pronation was associated with radiographic signs of severity in the hallux valgus group. The parameters assessed were hallux valgus angle, intermetatarsal angle, distal metatarsal articular angle, hallux valgus classification, sesamoid position according to the Hardy and Clapham classification (25) and according to the Smith classification (26), and presence of the round sign as modified relative to the original description (27,28). Negative round sign was defined as an angular shape, and positive round sign was defined as a round shape or an intermediate shape, because it was assumed that only 1 type would not exhibit either bone or ligament rotation (neutral rotation), according to previous reports in the literature (14,27,28).

To detect a difference in means with a magnitude of 0.6 SD unit (Cohen's $d = .6$) with a statistical power of 90% at a 2-tailed significance level ($\alpha/2$) of .05, we estimated a sample size of ≥ 120 observations (60 observations per group) allowing for clustered data (some patients contributed with >1 measurement).

Statistical analysis was performed by the principal author (E.P.C.) using a linear mixed model, which considers repeated measures within subjects adjusting for age and sex in the comparison of metatarsal rotation between cases and controls. Correlation between the various numerical measurements was evaluated with Pearson's correlation coefficient obtained from the linear mixed model, using centralized variables. Two-tailed significance level ($\alpha/2$) was set at 5% ($p \leq .05$). Data were processed and analyzed by using SPSS software (version 22.0) and R version 3.2.0.

Results

A total of 91 patients were included in the study: 46 in the hallux valgus group and 45 in the control group. The baseline characteristics of patients are shown in Table 1. A total of 82 feet (examinations) were analyzed in the hallux valgus group and 64 in the control group ($N = 146$ feet).

The measurement of bone rotation on CT with multiplanar reconstruction exhibited excellent intraobserver correlation, with a Pearson's coefficient of 0.96 ($p < .001$). Group comparison adjusted for age and sex demonstrated a significant difference; the patients with hallux valgus exhibited greater bone pronation (Fig. 3) ($p < .001$). The adjusted mean metatarsal rotation in the hallux valgus group was 15.36° (range 1.65° to 32.52°). In the control group, the mean rotation was 3.45° (range -7.40° to 15.56°). The difference between the means was 11.9° (confidence interval 9.2° to 14.6°).

In the hallux valgus group, increased metatarsal rotation exhibited a positive correlation with the distal metatarsal articular angle ($p < .001$; $r = 0.39$). However, there were no statistically significant correlations with the intermetatarsal angle ($p = .14$), hallux valgus angle ($p = 0.096$),

Table 1
Baseline characteristics of patients ($N = 146$ feet [tests] in 91 patients)

Characteristic	Hallux Valgus (n = 46)	Control (n = 45)	P Value
Age, yr, mean \pm SD	55.2 \pm 15.6	46.0 \pm 16.0	.006
Female sex, n (%)	44 (95.7)	25 (55.6)	<.001

Abbreviation: SD, standard deviation.

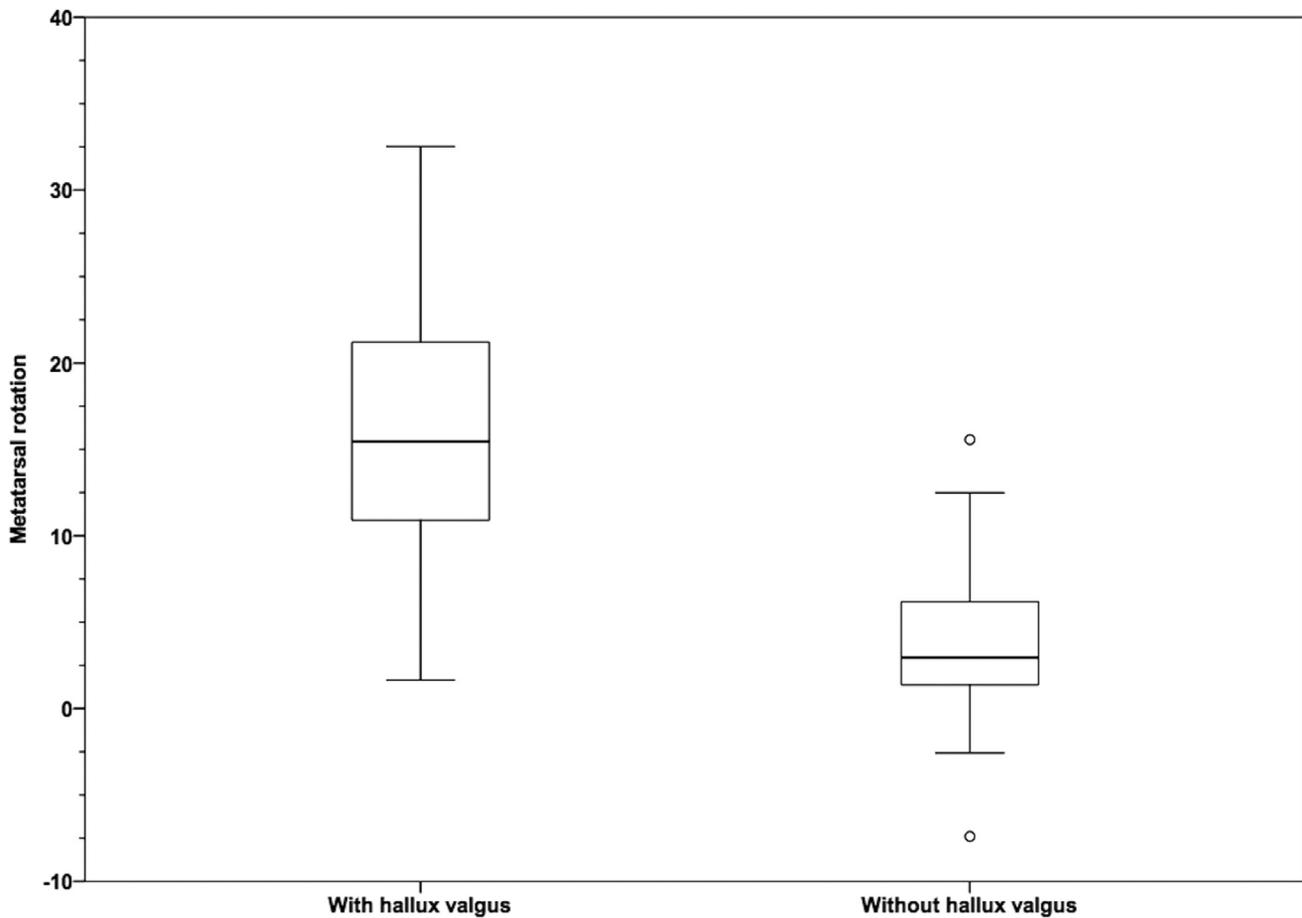


Fig. 3. Box plot graph comparing metatarsal rotation in degrees (axis X) (zero, neutral position; positive value, pronation; negative values, supination) in patients with hallux valgus (n = 46) and without hallux valgus (n = 45) (axis Y) (N = 146 feet [tests] in 91 patients).

or hallux valgus classification ($p = .38$) (Table 2). Increased metatarsal rotation was significantly associated with the presence of the round sign ($p = .019$), but no association was found with sesamoid position according to the Hardy and Clapham classification ($p = .12$) or the Smith classification ($p = .15$).

Discussion

Hallux valgus is a frequent disorder for which treatment poses some challenges (1–7,29). The literature describes countless treatments for the same degree of severity (1,3,29). In addition, the final outcomes are contradictory and conflicting, even for similar cases treated by the same surgeon and using the same surgical technique (1,3,6,7,29). The identification of factors associated with the development of deformity is of paramount importance in obtaining a full correction of the disorder. Hallux pronation is one of the frequently found components, especially in

larger deformities, but the cause and exact location of this condition are not fully understood (2,3,6,7).

The present study showed that patients with hallux valgus had an intrinsic anatomical variation of the first metatarsus characterized by an increase in bone rotation toward pronation compared with patients without this diagnosis. This finding might contribute in explaining the divergences in the clinical outcomes of similar cases subjected to surgical treatment performed by the same surgeon and with the same technique (6,7). One could hypothesize that intrinsic bone rotation (pronation) is the reason for the unsatisfactory outcomes exhibited by some cases, because clinical pronation is associated with poorer prognosis and relapse (1,3,6,7,27). In addition, countless frequently used surgical techniques, such as scarf and Ludloff osteotomy, which are not able to correct rotational bone deformity in the coronal plane, may lead to a poor outcome (6,7,27,29). In this situation, surgical techniques capable of coronal correction, such as some proximal first metatarsal osteotomy, or Lapidus, may be a better option (3,6,7,27,28).

A statistically significant correlation was found between increased first metatarsal bone rotation and increased distal metatarsal articular angle and with the presence of the round sign, but the association was weak. This fact may be because of cases in which metatarsal rotation was caused by ligamentous laxity or fallen arches rather than by intrinsic bone deformity. It is known that metatarsal rotation or sesamoid dislocation does not systematically occur in parallel with increase of the deformity (14,17,22). Thus, the progression of metatarsal deviation is not always accompanied by pronation (14,17,22). In addition, radiographic assessment includes imprecision (10,12–14). It is known that

Table 2
Linear correlation between metatarsal rotation and selected variables among patients with hallux valgus (n = 82 feet [tests] in 46 patients)

Variable	Metatarsal Bone Rotation Angle, ^a	P Value
Intermetatarsal angle	0.17	.14
Hallux valgus angle	0.19	.096
Hallux valgus classification	0.10	.38
Distal metatarsal articular angle	0.39	<.001

^a Correlation obtained in linear mixed model with adjustment for clustered observations.

first ray flexion or dorsiflexion alters the measurements performed with this method (10,12–14,22). In addition, the progression of hallux valgus is not symmetrical or proportional to the deformity, because there is variation in its clinical manifestations (14,17). The etiology of first ray pronation may be due to ligament instability, anatomical bone deformity, or both (14,17).

Statistically significant correlations were not found between increased metatarsal rotation, advanced age, increased hallux valgus angle, intermetatarsal angle, hallux valgus classification, and sesamoid dislocation according to the Hardy and Clapham classification or the Smith classification. These results indicate that the bone rotational deformity is not adaptive but, in some cases, might represent an intrinsic phenotypic characteristic. These results suggest that the deformity is not derived from Wolff's bone remodeling law (30). Some cases exhibited increased hallux valgus angle without bone rotation, whereas others exhibited a small deformity and increased bone rotation. More studies are needed for a better analysis of this phenomenon.

Two studies in the literature compared metatarsal rotation between patients with and patients without hallux valgus (8,9). These studies suggest that patients diagnosed with hallux valgus exhibit greater first ray pronation than do healthy individuals, the cause of which would be fallen arches associated or not associated with ligamentous abnormalities. However, the limitations of plain radiography do not allow distinguishing pronation of ligament origin from that of bone origin (10–12, 14,22). One of the aforementioned studies examined random anatomical specimens from cadavers without hallux valgus to analyze intrinsic bone rotation (9). Most cases exhibited bone torsion, with the MH in the neutral position or in supination with respect to the MB, whereas just a few cases exhibited pronation. The authors concluded that metatarsal pronation might be due to ligamentous and biomechanical factors at the cuneometatarsal level (9). However, they further observed that it was not possible to rule out intrinsic metatarsal bone rotation toward pronation as a factor contributing to the deformity in some cases. These findings are partially compatible with the control group results in our study. Nevertheless, there were more cases with pronation than with supination compared with the aforementioned study, which was conducted using cadavers (9).

The present study corroborated the findings of the 2 aforementioned studies, inasmuch as the patients with hallux valgus exhibited more pronation compared with patients without this condition (8,9). In contrast, we found greater rotational deformity of bone origin toward pronation among the patients with hallux valgus compared with those without this condition. Such bone pronation likely contributes to the severity of disease alone or in combination with other already known abnormalities. It is known that pronation is associated with poorer clinical outcomes (1,3,6,27,28).

This study has some limitations deserving mention, such as its retrospective design and convenience sample. It was not possible to confirm the findings through comparison to the gold standard, namely anatomical specimens. In addition, the cases were not followed to assess the correlation between increased metatarsal rotation and poorer clinical outcome. Lack of similar studies in the literature might hinder the interpretation of the results, since there are few parameters for comparisons. In addition, it is not possible to establish what values of metatarsal bone rotation are pathological or whether there is need for surgical correction of this deformity. There was a potential selection bias in the hallux valgus group, since all included patients had an indication for surgical treatment. This factor could have been associated with the selection of more severe cases; however, the percentage of cases at each stage of hallux valgus severity classification showed a normal distribution. Another possible bias could have been the inclusion of patients with radiographic criteria of hallux valgus in the control group; not all of them had a radiograph with standard weightbearing. Because this bias reduces the possibility of identifying a significant statistical difference

between the groups, it was considered unnecessary to subject the participants to a new intervention. Last, it is important to comment on why there was no matching of gender and age between groups. It is known that group pairing is performed to reduce possible biases of confusion. However, it is recommended to avoid pairing of variables that are not associated with outcome modification, because inefficient pairing reduces the variation of the factor studied in the target population. In this respect, there is evidence in the literature that the angle of the first metatarsal bone rotation shows no statistical difference between genders or age groups (31). Moreover, statistical analysis was performed using a linear mixed model, which considers repeated measures within subjects adjusting for age and gender in the comparison of metatarsal rotation between cases and controls.

In conclusion, patients with hallux valgus exhibited increased intrinsic rotation of the first metatarsal bone toward pronation when compared with the population without this condition. The findings of this study contribute to the understanding of the pathophysiology of hallux valgus, because they show a deformity of exclusive bone origin not previously reported in the literature. Further studies are needed to better understand the impact of this deformity on clinical outcomes and on the choice of treatment. Prospective studies with adequate follow-up length might be helpful in this regard. In addition, reference values for normal ranges also need to be investigated. Another important issue to be defined is the apex of the deformity and the anatomical region ideal for correction. Thus, the results do not support the use of routine CT in patients with hallux valgus.

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