Weight-Bearing Computed Tomography Evaluation of First Metatarsal Frontal Plane Rotation in Hallux Abducto Valgus Deformity

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INTRODUCTION

There are a variety of 2-dimensional radiographic measurements that are evaluated prior to surgical treatment of hallux abducto valgus (HAV). Commonly measured radiographic angles include the intermetatarsal angle (IMA), hallux abductus angle (HAA), proximal articular set angle (PASA), and tibial sesamoid position. Recent literature has questioned whether these radiographic parameters can accurately describe the HAV deformity since they can only assess it in 2 dimensions, and therefore, can only really evaluate changes in the transverse and sagittal planes (1,2). It has been suggested that not only is HAV a triplane deformity, but also that the frontal plane rotational changes are a significant component of the deformity, which must be addressed for complete deformity correction. In 2013, Dayton et al (1) performed a study to evaluate the postoperative radiographic changes as well as the relationship between the frontal plane rotation and PASA in patients with HAV deformity who underwent a Lapidus procedure for correction. They have found a consistent valgus rotation of the first metatarsal in association with HAV deformity and observed a varus rotation of the metatarsal to have occurred when the joint was corrected into congruous alignment using the Lapidus procedure. Thus, they concluded that true correction of the HAV deformity must include frontal plane derotation of the metatarsal. They further concluded that the correction of PASA seen on postoperative radiographs was actually due to the frontal plane rotational changes affecting the appearance of the articular surface of the metatarsal head suggesting that PASA is merely a radiographic artifact.

Mortier et al (3) in 2012, performed a cadaveric study showing a statistically significant valgus position of the metatarsal head in feet with bunion deformities compared to those without the deformity. In 2014, Dayton et al (2) observed changes in radiographic angular relationships of the first ray after frontal plane rotation of the first metatarsal in cadaveric foot models and concluded this frontal plane rotation is an integral component of the HAV deformity. The concept of the frontal plane rotation in HAV deformity and its effect on other angular relationships seen on 2-dimensional radiographs brings in to question the true validity and adequacy of plain radiographs in accurately assessing this triplane deformity. With the advent of newer imaging technology, such as weight-bearing computed tomography (CT), the triplane changes, including the frontal plane rotation, which occur in the HAV deformity, can perhaps be more accurately assessed. The weight-bearing CT is more accurate because it can obtain a 3-dimensional dataset of angles that is independent of foot position/orientation and projection and is taken with the patient in full weight-bearing stance (4). The planes of the CT reformations can be rotated to ensure exact angle measurement if any malposition of the foot occurs (4).

The purpose of this study is to use weight-bearing CT images to evaluate the frontal plane rotation, IMA, HAA, PASA, and TSP in patients with and without HAV deformity. We hypothesize that because the weight-bearing CT allows 3-dimensional visualization, the frontal plane rotation will be more accurately assessed and compared to the other angular changes seen in HAV deformity. By comparing patients with and without HAV deformity, we can confirm the presence of a frontal plane component as well as its relationship to the other commonly measured angles. We also evaluated the relationship of these angles with those at the first metatarsal-cuneiform joint, hypothesizing that the greater the angular deformity at the joint, the more valgus frontal plane rotation is imparted on the first metatarsal.

MATERIALS AND METHODS

We reviewed preoperative weight-bearing CT images (Figure 1) of 60 adult feet using the PedCAT device (Curvebeam) taken between March 2015 and April 2016 by a single podiatrist (KF). There were 30 subjects with HAV deformity and 30 controls without HAV deformity. All of the control subjects had a pure hallux limitus or

Figure 1. Weight-bearing computed tomography image.

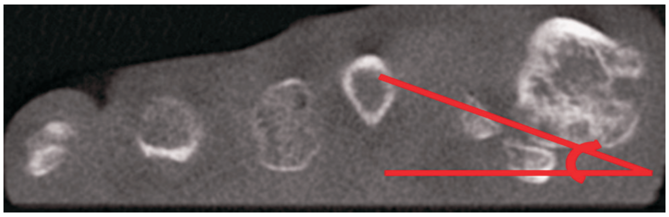

Figure 2. Frontal plane rotation (FPR): angle (°) created between a line parallel to the ground surface and a line drawn tangential to the medial and lateral borders of the crista at the metatarsal head. This depicts a valgus frontal plane rotation.

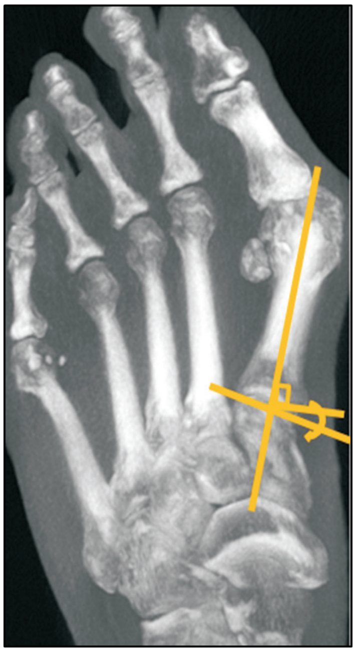

Figure 3. Proximal metatarsal obliquity angle (PMOA): the relationship between the first metatarsal-cuneiform articulation and the longitudinal axis of the first metatarsal, represented by subtracting 90° from the angle formed between a line tangential to the articular surface and a longitudinal line bisecting the first metatarsal proximal and distal metaphyseal-diaphyseal junction (PMOA = angle –90°).

rigidus deformity to ensure there was no component of HAV involved. Within the control group, there were 15 males and 15 females. Within the HAV group, there were 7 males and 23 females. All CT images reviewed were at 0.3-mm slab thickness. In all subjects, we measured the standard HAV angles, including the IMA, HAA, PASA, and TSP on the anterior-posterior view.

The technique used was consistent with that described previously by Gerbert as well as Green (5,6). The frontal plane rotation (FPR) was measured using the angle created between a line parallel to the ground surface and a line drawn tangential to the medial and lateral borders of the crista at the metatarsal head (Figure 2). A positive FPR value equates to a valgus rotation. Two additional previously undescribed angles at the first metatarsal cuneiform joint were also measured. The proximal metatarsal obliquity angle (PMOA) depicts the relationship between the first metatarsal-cuneiform articulation and the longitudinal axis of the first metatarsal. It is represented by subtracting 90° from the angle formed between a line tangential to the articular surface and a longitudinal line bisecting the first metatarsal proximal and distal metaphyseal-diaphyseal junction (PMOA; angle – 90°) (Figure 3).

The second angle is the cuneiform obliquity angle (COA), which represents the amount of obliquity of the medial cuneiform. It is measured by subtracting 90° from the angle formed between a line tangential to the first metatarsal-cuneiform articular surface and a line bisecting the longitudinal axis of the medial cuneiform (COA = angle – 90°) (Figure 4). We also noted whether the crista was eroded, eroded and flattened, or normal in each subject. Correlations were made among all measurements and compared between the 2 groups.

STATISTICAL ANALYSIS

Statistical software SAS version 9.2 was used to calculate the correlation coefficients (r) and associated *P* values. Graphs were created using Prism 5.0 (Graphpad). The Pearson correlation coefficient for determining association between variables was used for data analysis. *P* values less than or equal to 0.05 (5%) were considered statistically significant. All data included had an adequate sample population.

RESULTS

All of the measures were higher in the HAV group compared to the control group and were statistically significant (*P* < 0.001), except the PMOA, for which there was no statistically significant difference between the groups (*P* = 0.09). The mean IMA was 15.3° (range 9.7-23.0°) in the HAV group, and 8.5° (range 4.3-15.3°) in the control group. The mean HAA was 30.0° (range 10.6-58.4°) in the HAV group, and 5.8° (range 0.4-15°) in the control group. The mean PASA was 23.5° (range 6.0-55.7°) in the HAV group, and 3.7° (0.3-9.2°) in the control group. The mean TSP was 4.7 in the HAV group, and 1.5 in the control group. The mean COA was 27.3° (range 2.6-47.8°) in the HAV group, and 14.5° (2.5-31.3°) in the control group. All of the control subjects had a normal crista, whereas the HAV group had a mean of eroded and flattened crista. The mean FPR was 18.9° of valgus rotation (range 4.2-47.1°) in the HAV group and only 0.8° (range 1.0-3.0°) in the control group (Table 1).

Figure 4. Cuneiform obliquity angle (COA): represents the amount of obliquity of the medial cuneiform, measured by subtracting 90° from the angle formed between a line tangential to the first metatarsal-cuneiform articular surface and a line bisecting the longitudinal axis of the medial cuneiform (COA = angle –90°).

Overall, the frontal plane rotation (FPR) in the valgus direction had a high positive correlation with the IMA (r = 0.76), HAA (r = 0.80), PASA (r = 0.75), and TSP (r = 0.87), which were all statistically significant (*P* < 0.001) (Figure 5). FPR also had a moderate positive correlation with COA (r = 0.58 (*P* < 0.001)). There was no correlation between FPR and PMOA (r = -0.15 (*P* = 0.44). There was also a moderate correlation between FPR and the crista (r = -0.59; *P*<0.001)), meaning that a higher valgus FPR was associated with a more eroded crista (Tables 2-4).

The cuneiform obliquity angle (COA) had a high positive correlation with HAA (r = 0.73) and moderate positive correlation with IMA (r = 0.63), PASA (r = 0.66), and TSP (r = 0.64). The proximal metatarsal obliquity angle (PMOA) had no correlation with any of the other measurements.

Table 1. All measures in hallux abducto valgus (HAV) group versus control group*

	HAV		Control (HL)		
Measure	**Mean ± SD**	**Range**	**Mean ± SD**	**Range**	***P*†**
HAA	30.0 ± 11.2	10.6-58.4	5.8 ± 3.9	0.4-15	<0.001
IMA	15.3 ± 3.2	9.7-23.0	8.5 ± 2.6	4.3-15.3	<0.001
PASA	23.5 ± 12.5	6.0-55.7	3.7 ± 2.5	0.3-9.2	<0.001
TSP	4.7 ± 1.3	3.0-7.0	1.5 ± 0.6	1.0-3.0	<0.001
FSP	6.2 ± 2.2	2.0-11.7	0.8 ± 1.3	-1.8-5.0	<0.001
Crista‡	5.3 ± 0.9	4, 5, or 6	6 ± 0	All=6	<0.001
FPR	18.9 ± 9.3	4.2-47.1	2.9 ± 2.1	0.2-9.0	<0.001
PMOA	5.8 ± 4.7	0.7-21.7	4.0 ± 3.2	0.1-13.1	0.09
COA	27.3 ± 10.2	2.6-47.8	14.5 ± 7.2	2.5-31.3	<0.001

*HAA = hallux abductus angle; IMA = intermetatarsal angle; PASA = proximal articular set angle; FPR = frontal plane rotation; PMOA = proximal metatarsal obliquity angle; COA = cuneiform obliquity angle.
† By two-sample *t*-test for comparing means.
‡ + = valgus, - = varus. Crista 4= eroded crista; 5 = eroded and flattened crista; 6 = normal crista.

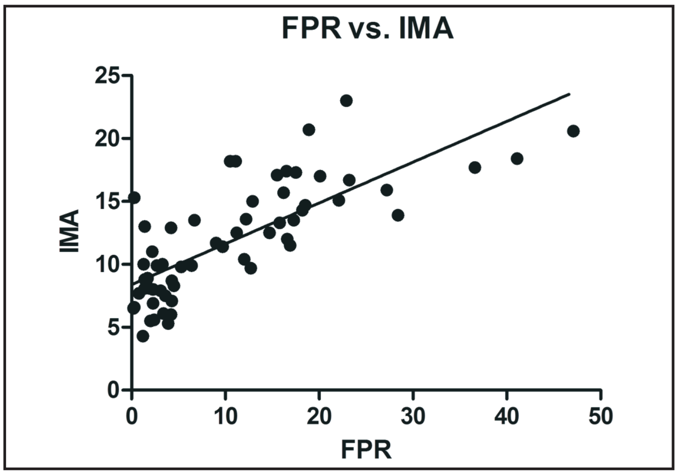

Figure 5A. Correlation graphs r = 0.76 ($P < 0.001$).

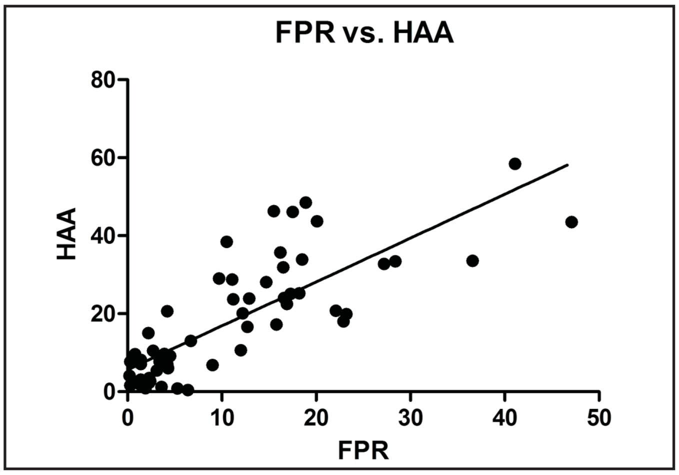

Figure 5B. Correlation graph r = 0.80 ($P < 0.001$).

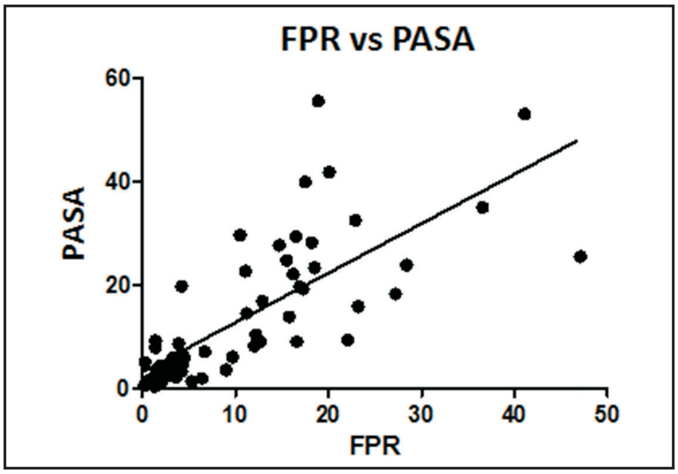

Figure 5C. Correlation graph r = -0.75 ($P < 0.001$).

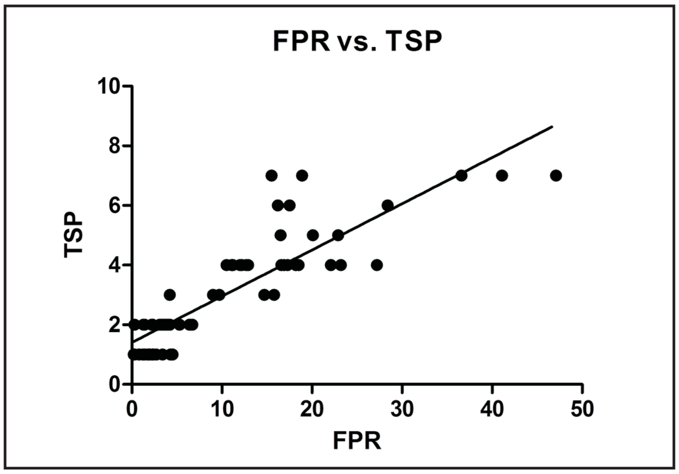

Figure 5D. Correlation graph r = 0.87 ($P < 0.001$).

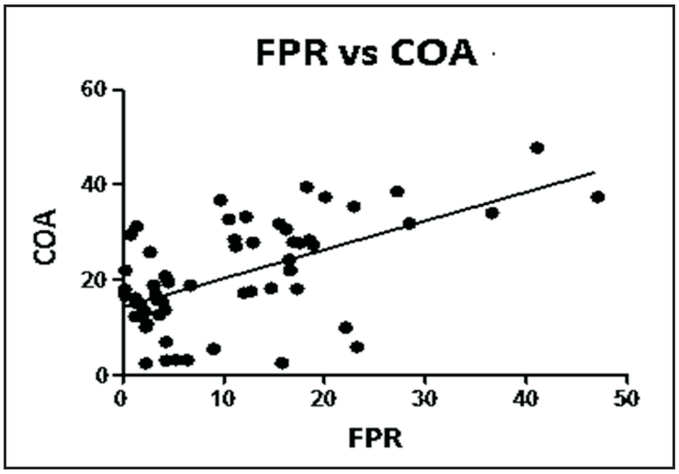

Figure 5E. Correlation graph r = 0.58 ($P < 0.001$); COA= Angle -90°.

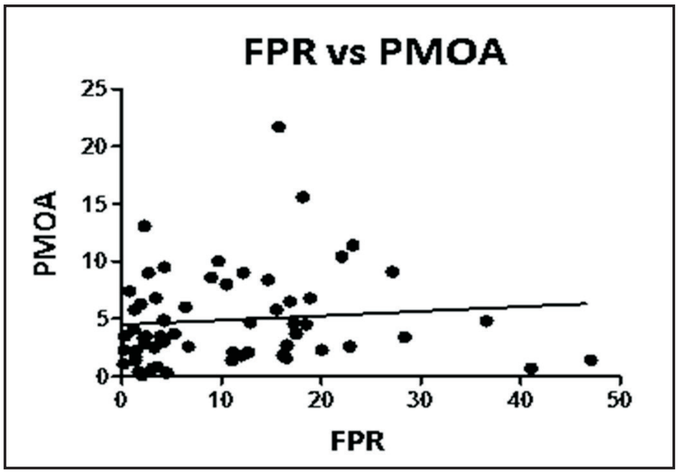

Figure 5F. Correlation graph r = -0.15 ($P = 0.44$); PMOA = Angle -90°.

DISCUSSION

Recent literature has suggested that the frontal plane rotational changes in hallux abducto valgus (HAV) deformity must be addressed in order to obtain complete correction. Furthermore, changes in multiple radiographic measurements have been observed to correspond with rotation of the first metatarsal in the frontal plane (2). There are several studies that assess the components of HAV deformity using 2-dimensional radiographs. These may not be adequate in assessing all 3 planes involved in the deformity, especially the frontal plane rotation. The weight-bearing CT is relatively newer technology that provides a safe, efficient

Table 2. All correlations

	HAA	IMA	PASA	TSP	Crista	FPR	PMOA	COA
HAA	1	0.80	0.90	0.90	-0.63	0.80	0.07	0.73
IMA		1	0.80	0.85	-0.68	0.76	0.08	0.63
PASA			1	0.85	-0.67	0.75	0.03	0.66
TSP				1	-0.62	0.87	0.02	0.64
Crista					1	-0.59	0.11	-0.43
FPR						1	0.10	0.58
PMOA							1	-0.15
COA								1

*Interpreted as >0.7 = good correlation; 0.4- 0.7 = moderate correlation; <0.4 = poor correlation.
Crista 4 = eroded crista, 5 = eroded and flattened crista, 6 = normal crista. See Table 1 for additional abbreviations.

Table 3. Specified correlations (HAV group vs control group)

Measures	All Subjects	*P*	Control	*P*	HAV	*P*
IMA vs PMOA	0.08	0.52	-0.03	0.87	-0.19	0.32
IMA vs COA	0.63	<0.001	0.22	0.25	0.40	0.03
FPR vs PMOA	0.10	0.44	0.22	0.24	-0.16	0.39
FPR vs COA	0.58	<0.001	-0.47	0.008	0.38	0.04
FPR vs IMA	0.76	<0.001	0.21	0.26	0.51	0.004
FPR vs PASA	0.75	<0.001	0.22	0.24	0.42	0.02
Crista vs FPR	-0.59	<0.001	---	---	-0.39	0.04

*Interpreted as >0.7 = good correlation; 0.4- 0.7 = moderate correlation; <0.4 = poor correlation.
Crista 4 = eroded crista, 5 = eroded and flattened crista, 6 = normal crista. See Table 1 for additional abbreviations.

way to obtain 3-dimensional measurements and to assess rotational changes. We used the PedCAT weight-bearing CT images to assess the frontal plane rotational changes as well as other commonly analyzed angles including the IMA, HAA, PASA, and TSP in addition to 2 new angular measurements, the cuneiform obliquity angle (COA) and proximal metatarsal obliquity angle (PMOA).

The PedCAT CT is more accurate because it can obtain a 3-dimensional dataset of angles, which is independent of foot position/orientation and projection and is taken with the patient in weight-bearing stance. It also adjusts for any malposition of the foot that may occur during image acquisition since the planes of the reformations can be rotated to ensure exact angle measurement. Overall, the PedCAT weight-bearing CT is more efficient compared to standard CT or radiographs. The image acquisition time is 70% faster than with standard radiographs and 35% faster than with conventional CT since patient positioning is easy and there is no adjustment of the scanner needed (4). It is also safe for the patient since the radiation dose is relatively low. The dose of one foot is 1.4 uSv, which is only 5.6% the dose of 1 unilateral conventional CT of foot/ankle and comparable to 6 unilateral plain radiographs (4).

Collan et al (7) used a portable weight-bearing CT to evaluate the rotational changes of the first ray using both nonweight-bearing and weight-bearing images in 10 patients with hallux abducto valgus compared with 5 asymptomatic controls. The measured angles were also compared to angles measure on plain 2-dimensional radiographs. They found that the 3-dimensional angles correlated very well with the angles measured on plain radiographs. Although they found a slight rotation/pronation of the first metatarsal in the HAV group, it was not statistically significant. However, the first proximal phalanx was noted to have a statistically significant rotation/pronation in the HAV group compared to the controls and increased when going from nonweight-bearing to weight-bearing. Their study showed that the rotational changes of bones of the forefoot can be reliably

Table 4. Correlations between frontal plane rotation and other measures*

Measures	All Subjects	*P*
FPR vs. HAA	0.80	< 0.001
FPR vs. IMA	0.76	< 0.001
FPR vs. TSP	0.87	< 0.001
FPR vs. FSP	0.78	< 0.001
Crista vs FPR	-0.59	< 0.001

*Interpreted as >0.7 = good correlation; 0.4- 0.7 = moderate correlation; <0.4 = poor correlation.
Crista 4 = eroded crista, 5 = eroded and flattened crista, 6 = normal crista
See Table 1 for additional abbreviations.

measured using a weight-bearing CT.

Kim et al (8) retrospectively evaluated the tibial sesamoid and first metatarsal position in the conventional CT axial view, the weight-bearing anterior-posterior radiographic view, and the tangential view. The frontal plane rotation of the first metatarsal at the head was measured using a line that bisects the medial and lateral sulci compared to a line perpendicular to the horizontal ground axis. Their results showed a relatively high value for the average first metatarsal pronation angle of 21.9° in those with HAV compared to 13.8° in those without HAV but found it to be independent of HAA and IMA. They also defined subgroups of hallux valgus deformity where there is "true sesamoid subluxation" with or without first metatarsal pronation.

Conventional CT images were obtained with participants in a semi-weight-bearing position produced by pushing their foot downward, and similar to our study, there was no dorsiflexion at the first metatarsophalangeal joint. Other studies (3,9,10) have assessed both the frontal plane rotation of the first metatarsal and sesamoid position using the sesamoid axial view, which demonstrates the dynamic position that occurs during push off when the fibular sesamoid moves forward and becomes parallel to the tibial sesamoid. The effect of the dynamic stabilizers, such as the flexor hallucis brevis, changes the position of the sesamoids and perhaps, the rotation of the metatarsal head as well. It remains unclear as to which position, dynamic or static, of the first ray provides a better view for assessing the first metatarsal frontal plane rotation and sesamoid position.

Our study used weight-bearing CT images to more precisely assess the angular changes and relationships that occur in those with HAV compared to those without the deformity. The results demonstrate the existence of a statistically significant pathologic valgus rotation, or pronation, involved in the HAV deformity, which supports previous clinical and cadaveric studies. The mean valgus rotation was 18.9° in HAV group compared to 0.8° in the non-HAV control group. The valgus rotation was highly correlated with both IMA and PASA, which further supports the idea that the frontal plane rotation could be contributing to PASA. The obliquity of the medial cuneiform was significantly higher in the HAV group compared to the control and the amount of obliquity was positively correlated with the valgus FPR of first metatarsal as well as the IMA. This suggests that the valgus frontal plane rotation may be derived from the first metatarsal cuneiform joint. Our results, in conjunction with those of previous research, demonstrate the presence of a significant valgus rotation of the first metatarsal contributing to the hallux abducto valgus deformity.

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