

## Hindfoot alignment of adult acquired flatfoot deformity: A comparison of clinical assessment and weightbearing cone beam CT examinations<sup>☆</sup>



Cesar de Cesar Netto<sup>a,b,c,\*</sup>, Delaram Shakoor<sup>a</sup>, Lauren Roberts<sup>c</sup>, Apisan Chinanuvathana<sup>a,b</sup>, Alireza Mousavian<sup>a,b</sup>, Francois Lintz<sup>d</sup>, Lew C. Schon<sup>b</sup>, Shadpour Demehri<sup>a</sup>, Weight Bearing CT International Study Group<sup>1</sup>

<sup>a</sup> Russell H. Morgan Department of Radiology and Radiological Science, Johns Hopkins University School of Medicine, 601 North Caroline Street, Baltimore, MD 21287, United States

<sup>b</sup> Department of Orthopaedic Surgery, Medstar Union Memorial Hospital, 201 E University Pkwy, Baltimore, MD 21218, United States

<sup>c</sup> Department of Foot and Ankle Surgery, Hospital for Special Surgery, 535 East 70th Street, New York, NY 10021, United States

<sup>d</sup> Foot and Ankle Surgery Department, Clinique de l'Union, Saint-Jean, Toulouse, France

### ARTICLE INFO

#### Article history:

Received 25 July 2018

Accepted 16 October 2018

#### Keywords:

Adult acquired flatfoot deformity

Flatfoot

Weightbearing

Weightbearing CT

Cone beam CT

Hindfoot alignment

### ABSTRACT

**Background:** Clinical assessment of hindfoot alignment (HA) in adult acquired flatfoot deformity (AAFD) can be challenging and weightbearing (WB) cone beam CT (CBCT) may potentially better demonstrate this three-dimensional (3D) deformity. Therefore, we compared clinical and WB CBCT assessment of HA in patients with AAFD.

**Methods:** In this prospective study, we included 12 men and 8 women (mean age: 52.2, range: 20–88) with flexible AAFD. All subjects also underwent WB CBCT and clinical assessment of hindfoot alignment. Three fellowship-trained foot and ankle surgeons performed six hindfoot alignment measurements on the CT images. Intra- and Inter-observer reliabilities were calculated using intra-class correlation (ICC). Measurements were compared by paired T-tests, and p-values of less than 0.05 were considered significant.

**Results:** The mean of clinically measured hindfoot valgus was 15.2 (95% confidence interval [CI]: 11.5–18.8) degrees. It was significantly different from the mean values of all WB CBCT measurements: Clinical Hindfoot Alignment Angle, 9.9 (CI: 8.9–11.1) degrees; Achilles tendon/Calcaneal Tuberosity Angle, 3.2 (CI: 1.3–5.0) degrees; Tibial axis/Calcaneal Tuberosity Angle, 6.1 (CI: 4.3–7.8) degrees; Tibial axis/Subtalar Joint Angle 7.0 (CI: 5.3–8.8) degrees, and Hindfoot Alignment Angle 22.8 (CI: 20.4–25.3) degrees. We found overall substantial to almost perfect intra- (ICC range: 0.87–0.97) and inter-observer agreements (ICC range: 0.51–0.88) for all WB CBCT measurements.

**Conclusions:** Using 3D WB CBCT can help characterize the valgus hindfoot alignment in patients with AAFD. We found the different CT measurements to be reliable and repeatable, and to significantly differ from the clinical evaluation of hindfoot valgus alignment.

Level of evidence: Level II—prospective comparative study.

© 2018 European Foot and Ankle Society. Published by Elsevier Ltd. All rights reserved.

## 1. Introduction

Adult-acquired flatfoot deformity (AFFD) represents a progressive and complex structural deformity of foot [1]. Although Posterior Tibial Tendon (PTT) dysfunction has historically been recognized as the principal culprit leading to collapse of the medial longitudinal arch (MLA) [2], further soft tissue insufficiency and underlying bony deformities have been implicated in the development of AFFD [3,4]. Equinus contracture, spring ligament, interosseous and deltoid ligament attenuation as well as an increased innate valgus angulation of the subtalar joint can

<sup>☆</sup> This work was based on an industrial grant from Carestream, Inc., which provided a monetary incentive to subjects who underwent Cone Beam CT examinations. The decision to recruit the subjects who met the criteria was based on clinical presentation and decided by the orthopaedic surgeon.

\* Corresponding author at: 535 E 70th street, Hospital for Special Surgery, New York, NY, 10021, United States.

E-mail address: [cesardecesarnetto@gmail.com](mailto:cesardecesarnetto@gmail.com) (C. de Cesar Netto).

<sup>1</sup> Weight Bearing CT International Study Group: Martinus Richter, Cesar de Cesar Netto, Francois Lintz, Arne Burssens, Alexej Barg, Kris Buedts, Mark Easley, Scott J Ellis, Bryan D Den Hartog, Alexandre L Godoy-Santos, Nicola Krähenbühl, John M Marzo, Lew C Schon, Matthew Welck.

predispose to and eventually lead to subtalar joint eversion and subsequent hindfoot valgus [3,5].

Currently, a set of measurements based on clinical and radiographic examinations are employed to evaluate hindfoot alignment [6]. Although these measurements have been extensively described, substantial disagreement remains in clinical judgment and radiographic measures to define an accurate method for the evaluation of hindfoot alignment [7,8]. Clinical assessment including visual evaluation, Harris mat footprint and quantitative measures such as valgus index have been defined, however they have shown to be highly unreliable due to significant inter-observer variation even among experienced orthopedic surgeons [6,7,9].

Furthermore, radiographic assessment of hindfoot alignment is quite cumbersome. The two dimensional nature of plain radiographs limits their accuracy and optimal evaluation of hindfoot alignment is hampered by complex anatomy of subtalar joint [4,10]. Besides, lack of standardized methods to evaluate the alignment is another source of disagreement [8]. Previous cohorts used distinct set of reference points as well as different hindfoot specific views including long axial view [11–13]. Some studies used angular measurements, while others employed linear measurements. Prior reports have also indicated that mal-positioning during image acquisition, inconsistent angulation or superimposition could generate considerable measurements errors [6,14]. Therefore, radiographic measures of hindfoot alignment are associated with major fundamental flaws due to several anatomical and observer-related bias.

Cross sectional imaging modalities including Computed Tomography (CT) provide enhanced, detailed visualization of hindfoot with simultaneous demonstration of different structures, however, they are only able to provide images obtained with the patient supine [15,16]. Additionally, in patients with AFFD, hindfoot instability has been observed when a weight bearing condition is applied [17]. Therefore, due to the major impact of loading on hindfoot alignment, it is crucial to assess suspected cases in the standing position [18]. Recent developments in CT scan design has contributed to the advent of cone-beam computed tomography (CBCT). This novel technique allows imaging of lower extremity in a normal upright weight bearing state. Initial studies reported excellent image quality with sufficient contrast resolution to visualize soft tissue and bone exceeding conventional radiography and multiple detector computed tomography (MDCT) [19,20].

Considering the ability of WB CBCT to demonstrate three-dimension deformities in a standing physiologic set up with an enhanced visualization of bony landmarks and soft tissue

structures, the application of this modality in patients with AFFD has recently been demonstrated to accurately reflect the effect of body weight in this dynamic deformity [21]. Measurements used in the staging and evaluation of the deformity were also reported to be repeatable and reliable when performed by experts [21], but also by in-training medical personnel [22]. Also recently, significant correlation between clinical and conventional radiographic hindfoot alignment was demonstrated in patients with flexible AFFD, but the radiographic measurements of hindfoot valgus were found to be significantly more pronounced valgus alignment than the standardized clinical evaluation [22]. Thus, in this study, we intended to compare clinical assessment of hindfoot valgus alignment with different possible hindfoot alignment measurements performed on WB CBCT images, in patients with AFFD. Our hypothesis was that measurements would correlate but different degrees of valgus alignment would be found, depending on the anatomical landmarks used.

## 2. Materials and methods

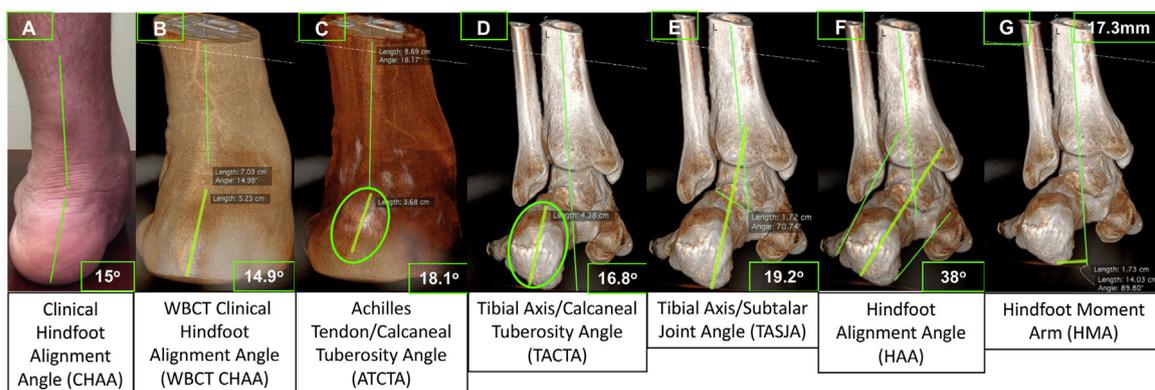
### 2.1. Study design

This dual-center IRB-approved prospective study complied with the Health Insurance Portability and Accountability Act (HIPAA) and the Declaration of Helsinki. Informed consent was signed by all study participants.

### 2.2. Subjects

In the two involved tertiary hospital clinics, consecutive patients with clinical diagnosis of symptomatic flexible AFFD from October 2014 till June 2016 were recruited. We excluded patients who were younger than 18 years old, were not able to communicate efficiently with clinical study personnel or were not able to stand still independently for at least 40 s. Individuals with the inability to bear weight, a rigid deformity or those who had standard contra-indications for standard CT scans including pregnancy or those with serious medical or psychiatric issues were also not enrolled in this prospective study.

Coronal plane clinical hindfoot alignment of all study participants was measured in the physiologic WB position by the most experienced of the senior authors (LCS). Patients were instructed to stand in a comfortable and natural stance position and the medial border of each foot was positioned over two parallel lines that were drawn into the floor, controlling for rotational misalignment. The measurement obtained here, named Clinical Hindfoot Alignment Angle (CHAA) (Fig. 1A), was similar to the standing tibio-calcaneal



**Fig. 1.** Example of measurements performed: (A) Clinical Hindfoot Alignment Angle (CHAA); (B) weightbearing computed tomography Clinical Hindfoot Alignment Angle (WBCT CHAA); (C) Achilles Tendon/Calcaneal Tuberosity Angle (ATCTA); (D) Tibial axis/Calcaneal Tuberosity Angle (TACTA); (E) Tibial axis/Subtalar Joint Angle (TASJA); (F) Hindfoot Alignment Angle (HAA); (G) Hindfoot Moment Arm (HMA).

angle (STCA) and was based on clinical expertise of the senior author and evaluation of anatomical surface landmarks [7,22].

Following clinical examination, all patients underwent WB CBCT examinations.

### 2.3. CBCT imaging technique

All CT studies were conducted using a CBCT extremity scanner (Generation II, Carestream Health Inc., Rochester, NY). All imaging studies were performed under physiological upright WB position with the patients standing with their feet almost at shoulder width, distributing body weight evenly between their both legs. We employed the same scan protocol that was described in prior studies [21,23,24].

### 2.4. WB CBCT measurements

To develop computer-based measurements, the raw 3D data were used to generate create axial, coronal and sagittal image slices and were digitally transferred into our dedicated software (Vue PACS, Carestream Health, Inc., Rochester, NY). Image annotations were deleted, and a unique random number was allocated to each imaging study.

Following a mentored training protocol entailing five AAFD cases, three fellowship trained foot and ankle surgeons applied different hindfoot alignment measurements independently using the dedicated software. All observers were blinded, and the order of images were randomized. One month following the first assessment, a second set of measurements for intra-observer reliability was performed by one of the observers. The measurements were performed on the clinical reconstructed 3D images. Rotational position control was assured with the use of images where the medial aspect of the heel and the most medial aspect of forefoot, medial eminence of the 1st metatarsal were in line with each other. The images used were also tangential to the floor.

The first measurement performed aimed to mimic the clinical hindfoot alignment evaluation and was named WBCT Clinical Hindfoot Alignment Angle (WBCT CHAA). It was obtained on 3D images where the windowing was set to maintain the surface anatomical landmarks, including the skin (Fig. 1B).

The second measurement was performed in an image with the same positioning, but the windowing was changed, removing the skin and subcutaneous, but keeping some of the overlying soft tissue structures including the Achilles tendon. That image also allowed a better evaluation of the calcaneal tuberosity, used as a bony anatomical landmark. The angle measured was formed by the longitudinal axis of the Achilles tendon and the longitudinal axis of the calcaneal tuberosity and was named Achilles Tendon/Calcaneal Tuberosity Angle (ATCTA) (Fig. 1C). To adequately assess the alignment of the calcaneal tuberosity, we used similar technique drawing ellipses as described by Johnson et al. [12].

The last four measurements were performed in images with the same positioning, however with different windowing that

removed all the soft tissue structures, maintaining only the bony anatomy. The third measurement obtained was the Tibial Axis/Calcaneal Tuberosity Angle (TACTA), which was formed by the intersection of axes of calcaneal tuberosity and the tibia (Fig. 1D). The fourth measurement was the Tibial Axis/Subtalar Joint Angle (TASJA) formed by the intersection of tibial axis and the line connecting midpoint of the posterior facet of the subtalar joint and most inferior point of the calcaneal tuberosity (Fig. 1E). The fifth measurement was the Hindfoot Alignment Angle (HAA), as described by Williamson et al. [25] (Fig. 1F) and the sixth measurement was the Hindfoot Moment Arm (HMA) (Fig. 1G), as described by Saltzman and el-Khoury [11].

Positive values were considered valgus alignment.

### 2.5. Statistical analysis

Data analysis was performed with JMP Pro version 12.2.0 (SAS Institute, Marlow-Buckinghamshire, UK). We used Shapiro–Wilk W test to evaluate the normal distribution of each set of measurements. The intraobserver and interobserver reliability were assessed by intraclass correlation coefficient (ICCs). Correlations between 0.81–1 were regarded almost perfect, 0.61–0.8 were considered as considered as substantial, while 0.41–0.6 were considered as moderate, 0.21–0.4 were regarded as fair and 0.1–0.2 were considered as slight agreement and less than 0.1 were regarded as poor agreement [21,26]. Measurements obtained from clinical examination and WB CBCT images were compared by one way ANOVA and paired Students t-tests or the Wilcoxon rank-sum tests and nonparametric comparison for each pair by the Wilcoxon method. We used a linear regression model to evaluate the relation between values of hindfoot moment arm and measurements obtained from clinical examinations as well as WB CBCT images. P-values of less than 0.05 were considered significant.

## 3. Results

Twenty patients (12 men and 8 women) with mean age of 52.2 (range, 20–88) years old and mean body mass index value of 30.35 (range, 19–46) kg/m<sup>2</sup> were included in this cohort.

We observed almost perfect intraobserver agreement for all WB CBCT 3D measurements, with ICC ranging from 0.87 to 0.97. Interobserver agreement, measured by ICC, ranged from 0.51 to 0.88. A summary of the agreements is presented in Table 1.

A summary with the mean values and 95% confidence interval (CI) for all hindfoot valgus measures performed on the 3D WB CBCT images are outline in Table 2, and a graphical plot demonstrating the means values of each measurement is shown in Fig. 2.

The hindfoot alignment measurements were found to significantly differ ( $p < 0.0001$ ) and the paired comparison is detailed in Table 3. The mean Clinical Hindfoot Alignment Angle was 15.2 (95% CI, 11.5–18.8) degrees. It was found to demonstrate significantly increased valgus alignment when compared to the WBCT CHAA (mean difference, 5.23°,  $p = 0.0047$ ), ATCTA (mean difference,

**Table 1**  
Intra- and interobserver reliability for three-dimensional (3D) weightbearing (WB) cone beam computed tomography (CBCT) hindfoot valgus measures.

		Intraobserver agreement		Interobserver agreement	
		ICC	Classification	ICC	Classification
Soft tissue windowing level	WBCT Clinical Hindfoot Alignment Angle (WBCT CHAA)	0.94	Almost perfect	0.51	Moderate
	Achilles Tendon/Calcaneal Tuberosity Angle (ATCTA)	0.93	Almost perfect	0.76	Substantial
Bone windowing level	Tibial Axis/Calcaneal Tuberosity Angle (TACTA)	0.87	Almost perfect	0.63	Substantial
	Tibial Axis/Subtalar Joint Angle (TASJA)	0.90	Almost perfect	0.80	Substantial
	Hindfoot Alignment Angle (HAA)	0.88	Almost perfect	0.73	Substantial
	Hindfoot Moment Arm (HMA)	0.97	Almost perfect	0.88	Almost perfect

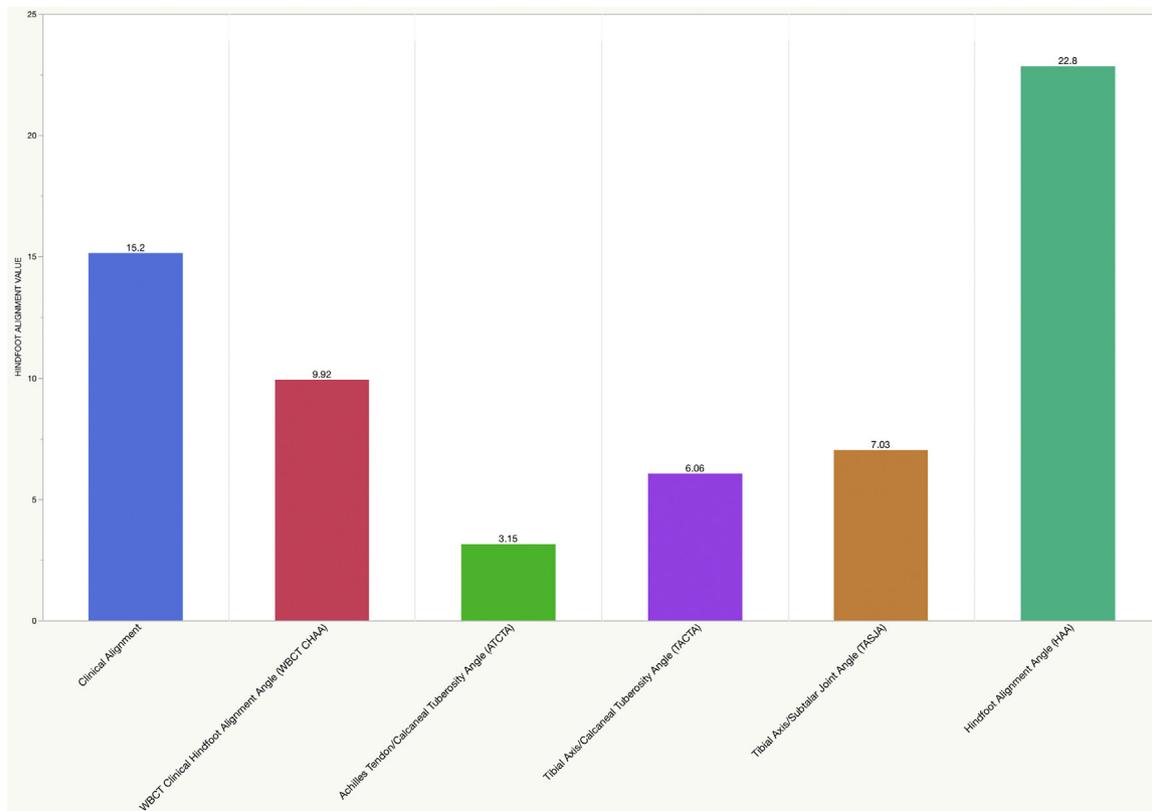
Abbreviations: ICC, intraclass correlation coefficient.

**Table 2**

Summary of three-dimensional (3D) weightbearing (WB) cone beam computed tomography (CBCT) hindfoot valgus measures.

		3D WB CBCT hindfoot alignment			
		Mean value	Standard error of the mean	Lower 95% CI	Upper 95% CI
Soft tissue windowing level	WBCT Clinical Hindfoot Alignment Angle (WBCT CHAA)	9.9°	0.53	8.9°	11.0°
	Achilles Tendon/Calcaneal Tuberosity Angle (ATCTA)	3.2°	0.95	1.3°	5.0°
Bone windowing level	Tibial Axis/Calcaneal Tuberosity Angle (TACTA)	6.1°	0.86	4.3°	7.8°
	Tibial Axis/Subtalar Joint Angle (TASJA)	7.0°	0.88	5.3°	8.8°
	Hindfoot Alignment Angle (HAA)	22.8°	1.22	20.4°	25.3°
	Hindfoot Moment Arm (HMA)	15.1 mm	0.88	13.4 mm	16.9 mm

Abbreviations: CI, confidence interval.

**Fig. 2.** Graphical plots representing mean values for the different measurements of hindfoot alignment.

12.00°,  $p < 0.0001$ ), TACTA (mean difference, 9.10°,  $p < 0.0001$ ), and TASJA (mean difference, 8.12°,  $p < 0.0001$ ). However, it was found to be significantly decreased when compared to the hindfoot valgus alignment measured by the HAA (mean difference,  $-7.70^\circ$ ,  $p < 0.0001$ ).

The mean of HMA was 15.1 (95% CI, 13.4–16.9) mm. The hindfoot moment arm was correlated significantly with the HAA ( $p < 0.0001$ ), increasing by 0.51 mm for every degree increase in the HAA (Adjusted  $R^2 = 0.48$ ) (Fig. 3). The HMA was also correlated significantly with the Clinical Hindfoot Alignment Angle ( $p = 0.0087$ ), increasing by 0.53 mm for every degree increase in the clinical alignment angle (Adjusted  $R^2 = 0.29$ ) (Fig. 4).

#### 4. Discussion

To the authors' knowledge, this is the first study to compare the evaluation of clinical and 3D WB CBCT hindfoot alignment in patients with AAFD. We found the different WB CBCT measurements modalities performed in this study to be repeatable and reliable, but to significantly differ from each other and from the

clinical evaluation of hindfoot valgus alignment. Our findings demonstrated that the valgus hindfoot alignment in patients with AAFD is significantly influenced by the anatomical landmarks used to define the angular measurement. We also found that the clinical assessment of hindfoot valgus by an experienced observer was significantly different from the HAA measured in WB CBCT images, demonstrating underestimation of the hindfoot valgus by the clinical evaluation, similar to reported data for conventional radiographs [22].

The proper assessment of hindfoot alignment and valgus deviation is paramount in the diagnosis and staging of AAFD [27–30]. Various studies have looked at defining an accurate way of clinically assessing hindfoot alignment [7,31–35], and the ability to correct the hindfoot valgus deformity intraoperatively, bringing the heel into a clinically neutral positioning has been shown to correlate with significant improvement in clinical outcomes [36]. Accurate radiographic definition of hindfoot valgus is also important and both hindfoot alignment and long axis views have been utilized as radiographic incidences in the assessment of WB hindfoot alignment [6,11,12,37]. These radiographic views and the

**Table 3**  
Paired T-test comparison of clinical and WB CBCT hindfoot alignment measurements.

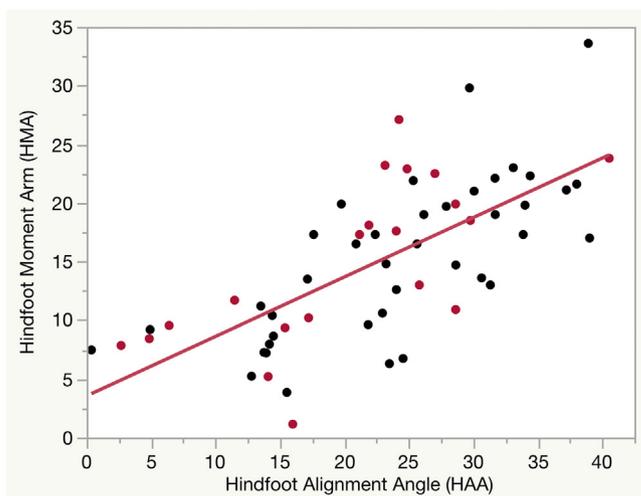
Measurement 1	Measurement 2	Mean difference	Standard error of the difference	Lower 95% confidence interval	Upper 95% confidence interval	P-value
Hindfoot Alignment Angle (HAA)	Achilles Tendon/Calcaneal Tuberosity Angle (ATCTA)	19.69817	1.299332	17.1417	22.25467	<0.0001*
Hindfoot Alignment Angle (HAA)	Tibial Axis/Calcaneal Tuberosity Angle (TACTA)	16.79217	1.299332	14.2357	19.34867	<0.0001*
Hindfoot Alignment Angle (HAA)	Tibial Axis/Subtalar Joint Angle (TASJA)	15.81867	1.299332	13.2622	18.37517	<0.0001*
Hindfoot Alignment Angle (HAA)	WBCT Clinical Hindfoot Alignment Angle (WBCT CHAA)	12.92817	1.299332	10.3717	15.48467	<0.0001*
Clinical alignment	Achilles Tendon/Calcaneal Tuberosity Angle (ATCTA)	11.99967	1.837534	8.3842	15.61510	<0.0001*
Clinical alignment	Tibial Axis/Calcaneal Tuberosity Angle (TACTA)	9.09367	1.837534	5.4782	12.70910	<0.0001*
Clinical alignment	Tibial Axis/Subtalar Joint Angle (TASJA)	8.12017	1.837534	4.5047	11.73560	<0.0001*
Hindfoot Alignment Angle (HAA)	Clinical alignment	7.69850	1.837534	4.0831	11.31393	<0.0001*
WBCT Clinical Hindfoot Alignment Angle (WBCT CHAA)	Achilles Tendon/Calcaneal Tuberosity Angle (ATCTA)	6.77000	1.299332	4.2135	9.32650	<0.0001*
Clinical alignment	WBCT Clinical Hindfoot Alignment Angle (WBCT CHAA)	5.22967	1.837534	1.6142	8.84510	0.0047*
Tibial Axis/Subtalar Joint Angle (TASJA)	Achilles Tendon/Calcaneal Tuberosity Angle (ATCTA)	3.87950	1.299332	1.3230	6.43600	0.0031*
WBCT Clinical Hindfoot Alignment Angle (WBCT CHAA)	Tibial Axis/Calcaneal Tuberosity Angle (TACTA)	3.86400	1.299332	1.3075	6.42050	0.0032*
Tibial Axis/Calcaneal Tuberosity Angle (TACTA)	Achilles Tendon/Calcaneal Tuberosity Angle (ATCTA)	2.90600	1.299332	0.3495	5.46250	0.0260*
WBCT Clinical Hindfoot Alignment Angle (WBCT CHAA)	Tibial Axis/Subtalar Joint Angle (TASJA)	2.89050	1.299332	0.3340	5.44700	0.0268*
Tibial Axis/Subtalar Joint Angle (TASJA)	Tibial Axis/Calcaneal Tuberosity Angle (TACTA)	0.97350	1.299332	-1.5830	3.53000	0.4543

\* P-value <0.05.

multiple anatomical landmarks and angles reported in the literature aim to accurately demonstrate the true bone alignment and the relationship in between the axis of the tibia and the axis of the calcaneus [6,11–13,37–41]. Superposition and enlargement of structures as well as inadequate alignment of the foot and ankle during image acquisition have been shown to significantly hinder the evaluation of bone alignment [41–43]. The ability of standardized clinical assessment in predicting radiographic bone

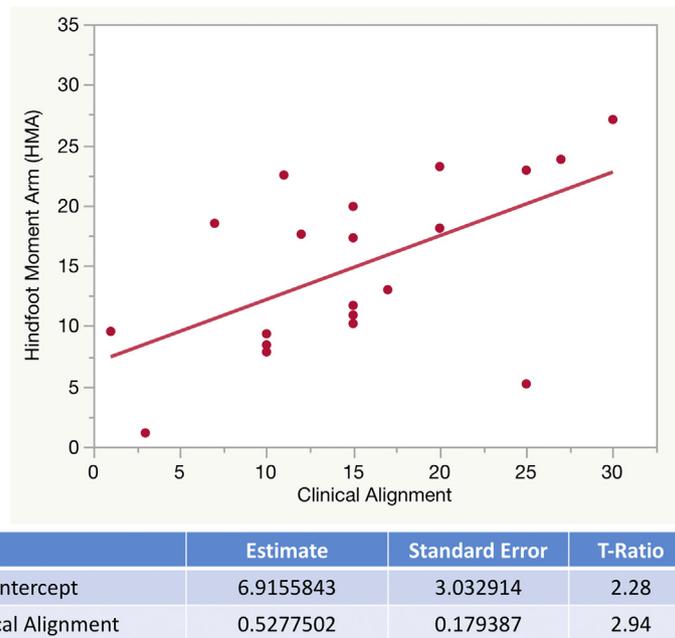
hindfoot alignment in patients with stage II AAFD was recently reported in the literature [22]. This study demonstrated that even though significant correlation was found between clinical and radiographic alignments, clinical assessment underestimated of the radiographic valgus alignment of about 10–15°, when measured by the HAA [22].

The use of WB CBCT scans in the assessment of foot and ankle pathologies has recently begun increasing [44]. Important benefits



	Estimate	Standard Error	T-Ratio	P-value
Intercept	3.5540918	1.676834	2.12	0.0383*
Hindfoot Alignment Angle (HAA)	0.5066449	0.067921	7.46	<.0001*

**Fig. 3.** Graphical plotting and detailed results for linear regression model comparing Hindfoot Moment Arm (HMA) and Hindfoot Alignment Angle (HAA) measurements. Estimate values for intercept and HAA, standard error, T-ratio and P-values.



**Fig. 4.** Graphical plotting and detailed results for linear regression model comparing Hindfoot Moment Arm (HMA) and clinical alignment measurements. Estimate values for intercept and HAA, standard error, T-ratio and P-values.

in the assessment of 3D bone relationship and bone alignment in patients with AAFD have been demonstrated in the literature [14,21,22,45–47], with low radiation dosage, extraordinary spatial resolution and fast imaging acquisition time [48,49].

Bursens et al. studied the use of WB CBCT in the assessment of hindfoot alignment [14]. They have shown that this imaging modality allows adequate assessment in patients with valgus and varus deformities, revealing significant differences in the measurements depending on the anatomical landmarks and angular measurements used. Even though different Hindfoot Alignment Angles were used in our study, we also found that the measurements change significantly depending on the anatomical landmarks used. One important difference to be noted is that Bursens et al discovered that the clinical alignment measured in WB CBCT, with the image windowing maintaining the skin and surface landmarks, demonstrated increased valgus alignment when compared to bone measurements. Similar to prior results reported in the literature using conventional radiographs [22], our study determined completely opposite results when using the HAA as described by Williamson et al. [25]. We found the HAA to demonstrate significantly increased valgus when compared to both real and WB CBCT clinical hindfoot alignment evaluation, with mean differences of approximately 13 and 8° respectively. It is our understanding that the HAA represents the best bone measurement of hindfoot alignment, using more reliable landmarks and considering the 3D format of the calcaneus including its lateral wall and the sustentaculum tali. It is the first-time the use of the HAA is reported in WB CBCT images, and we found it to be reliably performed.

Our study was also the first to evaluate the HMA, as described by Saltzman and el-Khoury [11], using 3D WB CBCT images, demonstrating almost perfect intra- and interobserver reliability. Similar to prior results in the literature [25], we found the HMA to significantly correlate with both HAA and clinical hindfoot alignment evaluation, increasing approximately 0.5 mm for every degree increase in both hindfoot alignment angulations. The amount of HMA increase found for every degree of HAA differs from the value described by Williamson et al. [25]. The authors reported in their study increases of approximately 0.8 mm for

every degree increase in the HAA measured in conventional radiographs. The difference in the values could be potentially explained by a more adequate evaluation of the real 3D hindfoot alignment using WB CBCT images, when compared to conventional radiographs. Unfortunately, no certain affirmation can be made regarding this. It is important to emphasize that an adequate evaluation and a positive and significantly correlation between hindfoot alignment and HMA is important so surgeons can predict the amount of medial slide that is needed intraoperatively when performing a calcaneal osteotomy in the treatment of patients with AAFD [36,50].

There are some limitations of the current study to be considered. Firstly, the sample population included was relatively small and no power analysis was performed. The statistically significant differences in the measurements found nevertheless demonstrate adequate sample size to achieve the objectives of our study. Also, the present study did not compare the differences in clinical and WB CBCT hindfoot alignment measures in control patients. It would be important to investigate in the near future if similar measurement differences would be present in patients with normal hindfoot alignment. Another important fact is that even when controlling for rotational misalignment during the clinical and WB CBCT assessment of patients, some inconsistency and error can still exist when performing the measurements.

In conclusion, our study provides evidence that the use of 3D WB CBCT imaging can potentially help us to more adequately understand AAFD. Further to this, it can help us determine which anatomical landmarks should be used to correctly assess the true valgus hindfoot alignment in patients with this disease. We found the different WB CBCT measurements observed to be reliable and repeatable, and to significantly differ from the clinical hindfoot alignment.

#### Conflicts of interest

This work was based on an industrial grant from Carestream, Inc., which provided a monetary incentive to subjects who underwent Cone Beam CT examinations. The decision to recruit

the subjects who met the criteria was based on clinical presentation and decided by the orthopaedic surgeon.

Dr. Cesar Netto reports: Paid consultancy for a company or supplier (CurveBeam, Ossio). Stock or stock options in a company or supplier (CurveBeam).

Dr. Francois Lintz reports: Dr. Lintz reports consultancy for Curvebeam, outside the conduct of the study.

Dr. Lew Schon reports: Grants, personal fees, non-financial support and other from Zimmer/Biomet, outside the submitted work; Royalties from a company or supplier (Arthrex, Darco, DJ Orthopaedics, Wright Medical Technology, Zimmer/Biomet). Speakers bureau/paid presentations for a company or supplier (Zimmer/Biomet, Tornier, Wright Medical). Paid consultant for a company or supplier (Zimmer/Biomet, Bonfix, Guidepoint Global, Gerson Lehrman Group, Spinesmith Celling Bioscience, Tornier, Wright Medical). Unpaid consultant for a company or supplier (Royer Biomedical, Carestream Health). Stock or stock options in a company or supplier (Royer Biomedical, Bioactive Surgical, Healthpoint Capital, Stem Cell Suture Company, Wright Medical). Research support from a company or supplier as a PI (Biocomposites, Zimmer/Biomet, Bioventus, Royer Biomedical, Spinesmith, Synthes). Other financial or material support from a company or supplier (Bioactive Surgical, Concepts in Medicine LLC, OMEGA, Smith & Nephew). Royalties, financial or material support from publishers (Elsevier-publishing textbook royalty).

Dr. Shadpour Demehri reports: Paid consultancy for Toshiba Medical Systems and Carestream Health.

## References

- Greisberg J, Hansen ST, Sangeorzan B. Deformity and degeneration in the hindfoot and midfoot joints of the adult acquired flatfoot. *Foot Ankle Int* 2003;24:530–4.
- Giza E, Cush G, Schon LC. The flexible flatfoot in the adult. *Foot Ankle Clin* 2007;12:251–71 vi.
- Vulcano E, Deland JT, Ellis SJ. Approach and treatment of the adult acquired flatfoot deformity. *Curr Rev Musculoskelet Med* 2013;6:294–303.
- Cody EA, Williamson ER, Burket JC, Deland JT, Ellis SJ. Correlation of talar anatomy and subtalar joint alignment on weightbearing computed tomography with radiographic flatfoot parameters. *Foot Ankle Int* 2016;37(8):874–81. doi:http://dx.doi.org/10.1177/1071100716646629 Epub 2016 May 2.
- Ozan F, Doğar F, Gençer K, Koyuncu Ş, Vatansever F, Duygulu F, et al. Symptomatic flexible flatfoot in adults: subtalar arthroereisis. *Ther Clin Risk Manag* 2015;11:1597.
- Buck FM, Hoffmann A, Mamisch-Saupe N, Espinosa N, Resnick D, Hodler J. Hindfoot alignment measurements: rotation-stability of measurement techniques on hindfoot alignment view and long axial view radiographs. *AJR Am J Roentgenol* 2011;197:578–82.
- Haight HJ, Dahm DL, Smith J, Krause DA. Measuring standing hindfoot alignment: reliability of goniometric and visual measurements. *Arch Phys Med Rehabil* 2005;86:571–5.
- Coughlin MJ, Kaz A. Correlation of Harris mats, physical exam, pictures, and radiographic measurements in adult flatfoot deformity. *Foot Ankle Int* 2009;30:604–12.
- Menz H. Clinical hindfoot measurement: a critical review of the literature. *Foot* 1995;5:57–64.
- Hirschmann A, Pfirrmann CW, Klammer G, Espinosa N, Buck FM. Upright cone CT of the hindfoot: comparison of the non-weight-bearing with the upright weight-bearing position. *Eur Radiol* 2014;24:553–8.
- Saltzman CL, el-Khoury GY. The hindfoot alignment view. *Foot Ankle Int* 1995;16:572–6.
- Johnson JE, Lamdan R, Granberry WF, Harris GF, Carrera GF. Hindfoot coronal alignment: a modified radiographic method. *Foot Ankle Int* 1999;20:818–25.
- Reilingh ML, Beimers L, Tuijthof GJ, Stufkens SA, Maas M, van Dijk CN. Measuring hindfoot alignment radiographically: the long axial view is more reliable than the hindfoot alignment view. *Skeletal Radiol* 2010;39:1103–8.
- BursSENS A, Peeters J, Buedts K, Victor J, Vandeputte G. Measuring hindfoot alignment in weight bearing CT: a novel clinical relevant measurement method. *Foot Ankle Surg* 2016;22:233–8.
- Seltzer SE, Weissman BN, Braunstein EM, Adams DF, Thomas WH. Computed tomography of the hindfoot. *J Comput Assisted Tomogr* 1984;8:488–97.
- Van Bergeyk AB, Younger A, Carson B. CT analysis of hindfoot alignment in chronic lateral ankle instability. *Foot Ankle Int* 2002;23:37–42.
- Kido M, Ikoma K, Imai K, Tokunaga D, Inoue N, Kubo T. Load response of the medial longitudinal arch in patients with flatfoot deformity: in vivo 3D study. *Clin Biomech* 2013;28:568–73.
- Haleem AM, Pavlov H, Bogner E, Sofka C, Deland JT, Ellis SJ. Comparison of deformity with respect to the talus in patients with posterior tibial tendon dysfunction and controls using multiplanar weight-bearing imaging or conventional radiography. *J Bone Joint Surg Am* 2014;96:e63.
- Tuominen EK, Kankare J, Koskinen SK, Mattila KT. Weight-bearing CT imaging of the lower extremity. *Am J Roentgenol* 2013;200:146–8.
- Thawait GK, Demehri S, AlMuhit A, Zbijewski W, Yorkston J, Del Grande F, et al. Extremity cone-beam CT for evaluation of medial tibiofemoral osteoarthritis: initial experience in imaging of the weight-bearing and non-weight-bearing knee. *Eur J Radiol* 2015;84:2564–70.
- de Cesar Netto C, Schon LC, Thawait GK, da Fonseca LF, Chinanuvathana A, Zbijewski WB, et al. Flexible adult acquired flatfoot deformity: comparison between weight-bearing and non-weight-bearing measurements using cone-beam computed tomography. *J Bone Joint Surg Am* 2017;99:e98.
- de Cesar Netto C, Kunas GC, Soukup D, Marinescu A, Ellis SJ. Correlation of clinical evaluation and radiographic hindfoot alignment in stage II adult-acquired flatfoot deformity. *Foot Ankle Int* 2018;39(7):771–9. doi:http://dx.doi.org/10.1177/1071100718762113 Epub 2018 Mar 28.
- Carrino JA, Al Muhit A, Zbijewski W, Thawait GK, Stayman JW, Packard N, et al. Dedicated cone-beam CT system for extremity imaging. *Radiology* 2013;270:816–24.
- Demehri S, Muhit A, Zbijewski W, Stayman J, Yorkston J, Packard N, et al. Assessment of image quality in soft tissue and bone visualization tasks for a dedicated extremity cone-beam CT system. *Eur Radiol* 2015;25:1742–51.
- Williamson ER, Chan JY, Burket JC, Deland JT, Ellis SJ. New radiographic parameter assessing hindfoot alignment in stage II adult-acquired flatfoot deformity. *Foot Ankle Int* 2015;36:417–23.
- Landis JR, Koch GG. The measurement of observer agreement for categorical data. *Biometrics* 1977;159–74.
- Bluman EM, Myerson MS. Stage IV posterior tibial tendon rupture. *Foot Ankle Clin* 2007;12:341–62 viii.
- Johnson KA. Tibialis posterior tendon rupture. *Clin Orthop Relat Res* 1983;140–7.
- Johnson KA, Strom DE. Tibialis posterior tendon dysfunction. *Clin Orthop Relat Res* 1989;196–206.
- Myerson MS. Adult acquired flatfoot deformity: treatment of dysfunction of the posterior tibial tendon. *Instr Course Lect* 1997;46:393–405.
- Grumbine NA, Santoro JP. The tendo Achillis as it relates to rearfoot position. A new classification for evaluation of calcaneal stance position. *Clin Podiatr Med Surg* 1990;7:203–16.
- Keenan AM, Bach TM. Clinicians' assessment of the hindfoot: a study of reliability. *Foot Ankle Int* 2006;27:451–60.
- Lamm BM, Mendicino RW, Catanzariti AR, Hillstrom HJ. Static rearfoot alignment: a comparison of clinical and radiographic measures. *J Am Podiatr Med Assoc* 2005;95:26–33.
- Smith-Oricchio K, Harris BA. Interrater reliability of subtalar neutral, calcaneal inversion and eversion. *J Orthop Sports Phys Ther* 1990;12:10–5.
- Slullitel G, Álvarez V, Lopez V, Calvi JP, Calvo AB. How accurate is clinical evaluation in hindfoot coronal alignment? *Foot Ankle Orthop* 2017;2(4). . Article first published online: October 17, 2017; Issue published: December 1, 2017 https://doi.org/10.1177/2473011417731563.
- Conti MS, Ellis SJ, Chan JY, Do HT, Deland JT. Optimal position of the heel following reconstruction of the stage II adult-acquired flatfoot deformity. *Foot Ankle Int* 2015;36:919–27.
- Mendicino RW, Catanzariti AR, John S, Child B, Lamm BM. Long leg calcaneal axial and hindfoot alignment radiographic views for frontal plane assessment. *J Am Podiatr Med Assoc* 2008;98:75–8.
- Arangio G, Rogman A, Reed 3rd JF. Hindfoot alignment valgus moment arm increases in adult flatfoot with Achilles tendon contracture. *Foot Ankle Int* 2009;30:1078–82.
- Sutter R, Pfirrmann CW, Espinosa N, Buck FM. Three-dimensional hindfoot alignment measurements based on biplanar radiographs: comparison with standard radiographic measurements. *Skeletal Radiol* 2013;42:493–8.
- Tuijthof GJ, Herder JL, Scholten PE, van Dijk CN, Pistecky PV. Measuring alignment of the hindfoot. *J Biomech Eng* 2004;126:357–62.
- Willauer P, Sangeorzan BJ, Whittaker EC, Shofer JB, Ledoux WR. The sensitivity of standard radiographic foot measures to misalignment. *Foot Ankle Int* 2014;35:1334–40.
- Baverel L, Brillhault J, Odri G, Boissard M, Lintz F. Influence of lower limb rotation on hindfoot alignment using a conventional two-dimensional radiographic technique. *Foot Ankle Surg* 2017;23:44–9.
- Saltzman CL, Brandser EA, Berbaum KS, DeGnore L, Holmes JR, Katcherian DA, et al. Reliability of standard foot radiographic measurements. *Foot Ankle Int* 1994;15:661–5.
- Barg A, Bailey T, Richter M, Netto C, Lintz F, BursSENS A, et al. Weightbearing computed tomography of the foot and ankle: emerging technology topical review. *Foot Ankle Int* 2018;39(3):376–86. doi:http://dx.doi.org/10.1177/1071100717740330 Epub 2017 Nov 24.
- Richter M, Lintz F, Zech S, Meissner SA. Combination of PedCAT weightbearing CT with pedography assessment of the relationship between anatomy-based foot center and force/pressure-based center of gravity. *Foot Ankle Int* 2018;39(3):361–8. doi:http://dx.doi.org/10.1177/1071100717744206 Epub 2017 Dec 18.
- Richter M, Seidl B, Zech S, Hahn S. PedCAT for 3D-imaging in standing position allows for more accurate bone position (angle) measurement than radiographs or CT. *Foot Ankle Surg* 2014;20:201–7.

- [47] Lintz F, Welck M, Bernasconi A, Thornton J, Cullen NP, Singh D, et al. 3D biometrics for hindfoot alignment using weightbearing CT. *Foot Ankle Int* 2017;38:684–9.
- [48] Carrino JA, Al Muhit A, Zbijewski W, Thawait GK, Stayman JW, Packard N, et al. Dedicated cone-beam CT system for extremity imaging. *Radiology* 2014;270:816–24.
- [49] Tuominen EK, Kankare J, Koskinen SK, Mattila KT. Weight-bearing CT imaging of the lower extremity. *AJR Am J Roentgenol* 2013;200:146–8.
- [50] Chan JY, Williams BR, Nair P, Young E, Sofka C, Deland JT, et al. The contribution of medializing calcaneal osteotomy on hindfoot alignment in the reconstruction of the stage II adult acquired flatfoot deformity. *Foot Ankle Int* 2013;34:159–66.