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Weight-bearing radiographs and cone-beam computed tomography examinations in adult acquired flatfoot deformity

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ABSTRACT

Background: Optimal characterization of Adult acquired flatfoot deformity (AAFD) on two-dimensional radiograph can be challenging. Weightbearing Cone Beam CT (CBCT) may improve characterization of the three-dimensional (3D) structural details of such dynamic deformity. We compared and validated AAFD measurements between weightbearing radiograph and weightbearing CBCT images.
Methods: 20 patients (20 feet, right/left: 15/5, male/female: 12/8, mean age: 52.2) with clinical diagnosis of flexible AAFD were prospectively recruited and underwent weightbearing dorsoplantar (DP) and lateral radiograph as well as weightbearing CBCT. Two foot and ankle surgeons performed AAFD measurements at parasagittal and axial planes (lateral and DP radiographs, respectively). Intra- and Inter-observer reliabilities were calculated by Intraclass correlation (ICC) and Cohen's kappa. Mean values of weightbearing radiograph and weightbearing CBCT measurements were also compared.
Results: Except for medial-cuneiform-first-metatarsal-angle, adequate intra-observer reliability (range:0.61–0.96) was observed for weightbearing radiographic measurements. Moderate to very good interobserver reliability between weightbearing radiograph and weightbearing CBCT measurements were observed for the following measurements: Naviculocuneiform-angle (ICC:0.47), Medial-cuneiform-first-metatarsal-gapping (ICC:0.58), cuboid-to-floor-distance (ICC:0.68), calcaneal-inclination-angle (ICC:0.7), axial Talonavicular-coverage-angle(ICC:0.56), axial Talus-first-metatarsal-angle(ICC:0.62). Comparing weightbearing radiograph and weightbearing CBCT images, statistically significant differences in the mean values of parasagittal talus-first-metatarsal-angle, medial-cuneiform-first-metatarsal-angle, medial-cuneiform-to-floor-distance and navicular-to-floor-distance was observed ($P < 0.05$).
Conclusion: Moderate to very good correlation was observed between certain weightbearing radiograph and weightbearing CBCT measurements, however, significant difference was observed between a number of AAFD measurements, which suggest that 2D radiographic evaluation could potentially underestimate the severity of AAFD, when compared to 3D weightbearing CT assessment.

1. Introduction

Adult acquired flatfoot deformity (AAFD) is a complex and progressive deformity involving the three-dimensional (3D) architecture of forefoot, midfoot and hindfoot structures [1–5]. This debilitating deformity can differ in severity and location and is characterized by loss of the medial longitudinal arch, forefoot abduction and valgus alignment of the hindfoot [6]. Based on the clinical and radiographic assessment, four stages of severity have been described to thoroughly define this deformity and optimize its treatment options [5,7,8]. While nonoperative management is advised for early stage, surgical procedures are recommended for patients with major functional impairment, which is often observed in advanced stages [5]. Thus, due to the progressive nature of this deformity, early and correct staging of AAFD is of paramount importance [5,6]. Currently, weightbearing radiograph represents the main imaging tool for initial staging of AAFD [6].

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Several radiographic measurements using dorsoplantar (DP) and lateral views have been described to characterize the extent and stage of AAFD [6,9,10]. However, radiographic evaluation of AAFD may be limited, owing to concerns over its accuracy and reliability of such 2D imaging in defining this complex deformity [1,6]. Using the limited 2D data offered by weightbearing radiograph, it is quite difficult to determine the relative spatial positions of each structure, due to superimposition of lines and shades overlapping joints, bones and soft tissue [11]. In addition, weightbearing radiographs are inherently flawed, due to the spatial geometry of x-ray beams responsible for fan effect and rotation distortion, which could result in discrepancies between the angles and the distances measured on the weightbearing radiograph and their corresponding measurements in the real object [11]. Therefore, correct staging of AAFD using only weightbearing radiograph can be quite challenging and cumbersome which justifies the evaluation of advanced imaging modalities such as MRI and CT, which lacks the assessment under physiologic weightbearing condition [6]. Prior studies have also implemented multiplanar weightbearing imaging technique to produce CT-like images for the assessment of patients with AFFD under physiologic weight-bearing condition [12,13]. However, multiplanar imaging technique obtains a 180 rotational isometric scan which may provide limited data comparing to CT.

With recent development and image quality validation of Cone Beam Computed Tomography (CBCT) which provides enhanced image quality, we can now obtain high resolution 3D imaging of lower extremity structures, under normal physiologic weightbearing condition [14–16]. Given its excellent image quality, adequate contrast resolution for soft tissue and bony structures and markedly lower radiation dose, comparing to multi-detector CT (MDCT), it has been increasingly utilized for assessment of several foot and ankle disorders such as AAFD and syndesmotic injuries [14,15]. Previous reports have shown that validated AAFD measurements used in evaluation and staging of this deformity can be obtained with high reproducibility and reliability using weightbearing CBCT images [2,4]. Furthermore, it is reported that weightbearing CBCT assessment of hindfoot alignment, is significantly different from clinical evaluation of hindfoot valgus alignment [3]. However, limited information is currently available on comparison between AAFD measurements performed on weightbearing radiograph and weightbearing CBCT images. Thus, in this study, we intend to obtain and compare the reliability of AAFD measurements between weightbearing radiograph and weightbearing CBCT images. Our hypothesis is that weightbearing CBCT based measurements could be different from those obtained using weightbearing radiograph.

2. Material and methods

2.1. Study design

This prospective two-center study was approved by the institutional board review (IRB) and complied with the Health Insurance Portability and Accountability Act (HIPAA) and the declaration of Helsinki. Informed consents were obtained from all study participants.

2.2. Study subjects

Between October 2014 and June 2016, consecutive patients with clinical diagnosis of flexible AAFD were recruited in our tertiary hospital clinics. Patients younger than 18 years old, those who were unable to communicate effectively with the study personnel, unable to stand still for at least 40 s without additional aid, with rigid AFFD deformity, serious medical or psychiatric issues or contra-indications for standard CT scans such as pregnancy were excluded from this study. All study participants underwent weightbearing dorsoplantar and lateral radiograph, as well as weightbearing CBCT scan which was performed using an extremity dedicated CBCT scanner (Generation II, Carestream Health Inc, Rochester, NY) [17,18]. The weightbearing CBCT scan was performed while participants were standing in a physiological upright position, with their feet at shoulder width and distributing their weight evenly between their legs. The affected foot was placed in the gantry in a neutral position, while the contralateral leg was outside of gantry. A previously described protocol was applied for the weightbearing CBCT scan [4]. The raw isotropic 3D CT data were utilized to reconstruct images in axial, parasagittal and coronal planes and were transferred digitally into a software (Vue PACS, Carestream Health, Inc, Rochester, NY) for obtaining computer-based measurements [4]. Image annotations were removed and a random, unique number was assigned to each imaging study.

2.3. Measurements

Following a training protocols involving five AAFD feet, all weightbearing radiographic measurements were performed by two independent American board-certified foot and ankle orthopaedic surgeons. Consequently, following weightbearing CBCT training protocol, the same investigators performed AAFD measurements on weightbearing CBCT images, as well. Each reader was blinded to patient identification and other radiographic or CBCT measurements and the order of patient's images were randomized.

2.4. Lateral measurements on radiograph and parasagittal measurements on CBCT images

On weightbearing CBCT images, parasagittal plane was defined as the plane perpendicular to the horizontal platform and the plane parallel aligned to the longitudinal axis of the first metatarsal for medial column measurements [4]. For calcaneal inclination angle measurement, parasagittal plane was defined as the plane perpendicular to the horizontal platform and the plane parallel to the longitudinal axis of the second metatarsal angle instead of first metatarsal angle. was The talus-first-metatarsal-angle was defined as the angle created by the longitudinal axis of the first metatarsal and the longitudinal axis of the talus [9], which was defined as the line connecting the midpoints of the articular surfaces of talar head and talar neck in its narrowest width (Fig. 1A). Medial-cuneiform-first -metatarsal-angle was defined by the line between the longitudinal axis of medial cuneiform and the longitudinal axis of the first-metatarsal bone [19] (Fig. 1B). The axis of medial cuneiform was determined as the line connecting the midpoint of their distal and proximal articular surfaces. The navicular-medial-cuneiform- angle was also defined by the intersection of the longitudinal axes of medial cuneiform and navicular bones [2] (Fig. 1C). Plantar gapping of the first tarsometatarsal joint (medial cuneiform-first metatarsal gapping) was also assessed and was considered positive when the angulation between the opposing articular surfaces was higher than 10 degrees (Fig. 1D). The medial cuneiform to floor distance was defined as the distance in millimeters from the most inferior aspect of the medial cuneiform to the floor (Fig. 1E). The navicular to floor distance was determined as the distance in millimeters from the most inferior aspect of navicular bone to the floor (Fig. 1F). The cuboid to floor distance was also defined as the distance in millimeters from the most inferior aspect of the cuboid to the floor line, (Fig. 1G) [4,20,21]. The calcaneal inclination angle was defined as the angle created by a line connecting two most inferior points

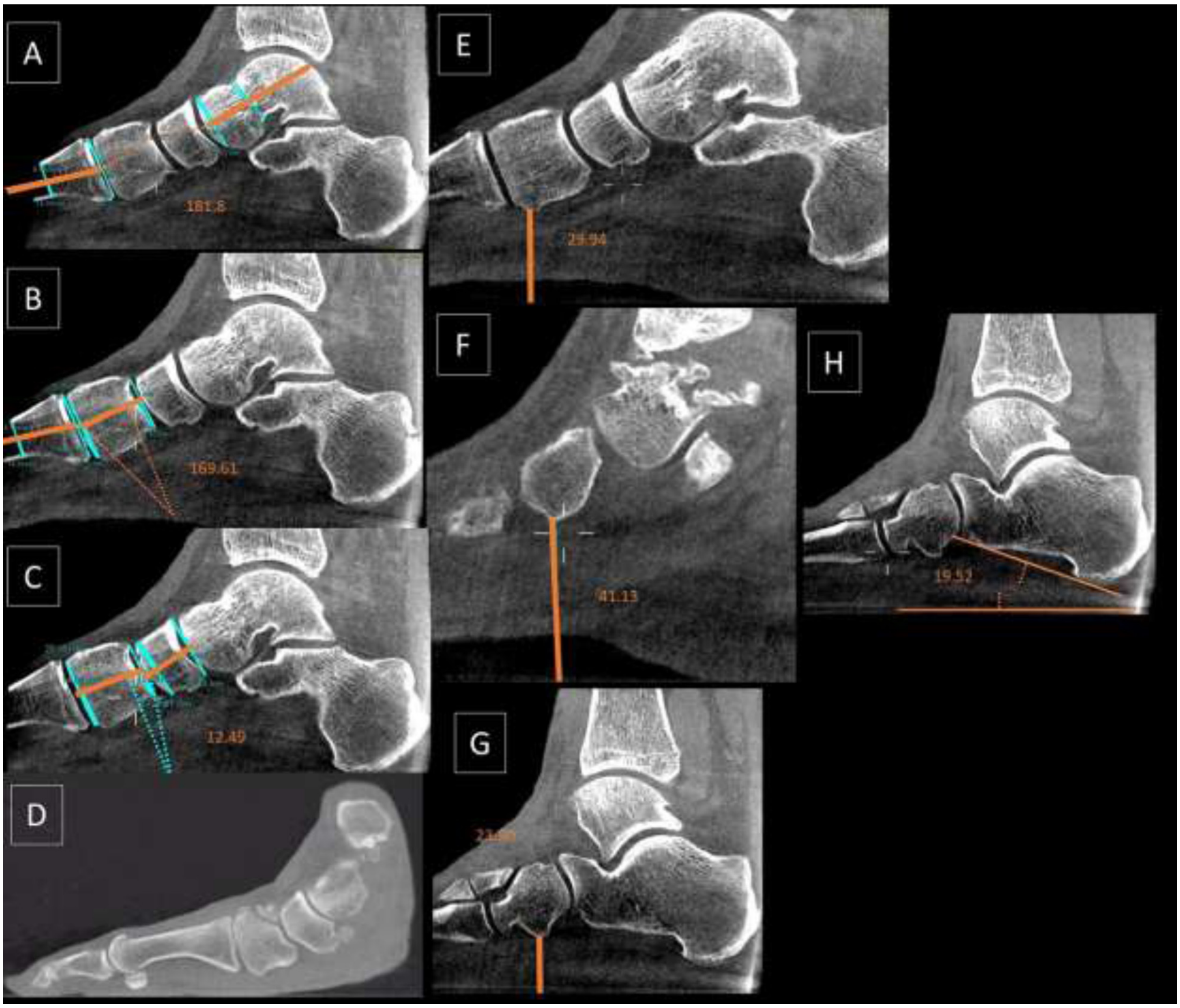

Fig. 1. Depiction of adult acquired flatfoot measurements in sagittal view: A) Talar-1 st metatarsal angle, B) Medial Cuneiform-1 st metatarsal angle, C)Naviculocuneiform angle, D) Medial Cuneiform- First metatarsal Gapping, E)Medial cuneiform to floor distance, F)Navicular to floor distance, G)Cuboid to floor distance, H)Calcaneal inclination angle.

of the calcaneus (Calcaneal tuberosity and the most distal and inferior point of the calcaneal articulating surface at the calcaneocuboid joint) and the supporting horizontal surface (Fig. 1H) [22].

2.5. Dorsoplantar measurements on radiograph and axial measurements on CBCT images

On weightbearing CBCT images, the axial plane was determined as parallel to the horizontal plane, displayed by the platform where patients were standing [4]. Talus-first-metatarsal-angle was defined by the intersection of first metatarsal longitudinal axis and talar axis, which was defined as the line connecting the midpoints of the articular surfaces of talar head and talar neck in its narrowest width (Fig. 2A) [9]. Talonavicular coverage angle was obtained, following the method which was previously described (Fig. 2B) [23].

2.6. Statistical analysis

The interobserver reliability of each measurement on weightbearing radiograph were calculated using Intra-class correlation (ICC) and Cohen Kappa, depending on the type of measurement (Numerical vs categorical). Correlations of 0.81–0.99 were considered as excellent; 0.61–0.8 as very good; 0.41–0.60 as moderate; 0.21–0.40 as fair, and lower than 0.20 as slight. The reliability of CT measurements was previously reported [2,4]. The mean values of weightbearing radiograph and weightbearing CBCT measurements were calculated, and the reliability of average measurements was calculated using the mentioned method [2,3]. Shapiro-Wilk W test was used to assess the distribution of average values. Student *t*-test and Wilcoxon rank test were employed to compare each measurement between weightbearing radiograph and weightbearing CBCT studies. Chi-square test was used to compare the presence of Medial Cuneiform- first metatarsal Gapping. P-value less than 0.05 was considered statistically significant.

3. Results

Thirteen patients with unilateral AAFD feet, consisting of six (46.1%) male and seven (53.8%) female participants, with mean age of 60 ± 6 years old and BMI of 28 ± 2 kg/m [2] were included in the present study. Thus, 13 feet were included in the analysis.

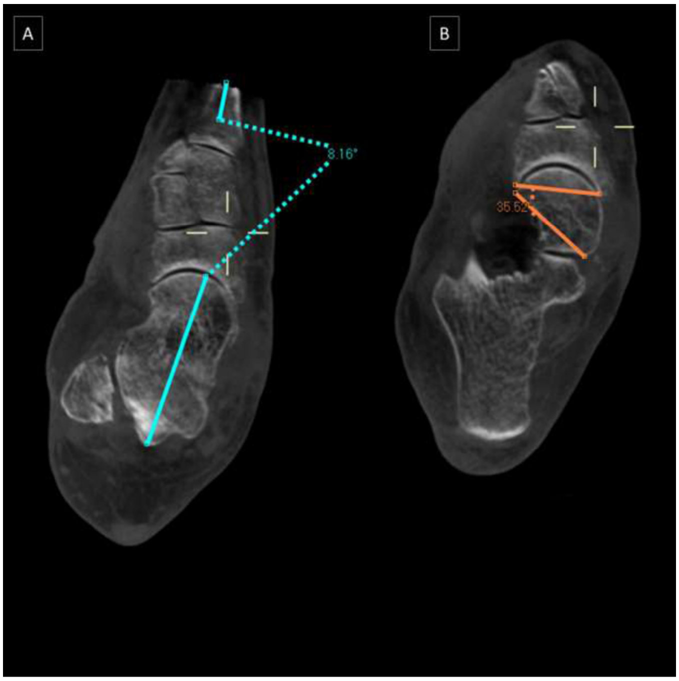

Fig. 2. Depiction of measurements in axial view: A) Talar-1 st metatarsal angle, B) Talonavicular angle.

3.1. Radiographic measurements

Regarding the weightbearing radiographic measurements, except for medial-cuneiform-first-metatarsal-angle, very good to excellent inter-observer agreement was observed between two investigators (Table 1). There was no statistically significant reliability for medial-cuneiform-first- metatarsal-angle between two readers.

3.2. Correlation between weightbearing radiograph and weightbearing CBCT measurements

When the reliability between average values of weightbearing radiograph and weightbearing CBCT measurements were obtained, there was statistically significant reliability between radiograph and CT measurements for naviculocuneiform-angle, medial-cuneiform-first-metatarsal-gapping, cuboid-to-floor-distance, calcaneal-inclination-angle,talonavicular-coverage-angle, axial/DP talus-first-metatarsal-angle. Regarding parasagittal/lateral talus-first-metatarsal-angle, medial-cuneiform-first-metatarsal-angle, medial-cuneiform-to-floor-distance, navicular-to-floor-distance, no statistically significant reliability was observed between radiograph and CT measuremnets. (Table 1).

3.3. Comparison between weightbearing radiograph and weightbearing CBCT measurements

When the average measurements of weightbearing radiograph and weightbearing CBCT were compared, the mean values of parasagittal/lateral talus-first-metatarsal-angle, medial-cuneiform-first -metatarsal-angle, medial-cuneiform-to-floor-distance and navicular-to-floor-distance were statistically significantly different between radiograph and CBCT studies (Table 2). Regarding medial-cuneiform-first -metatarsal-gapping, no difference was observed (P-value = 0.5) (Fig. 3).

4. Discussion

The findings of our study revealed significant correlation between weightbearing radiograph and weightbearing CBCT measurements in patients with AAFD, with moderate to very good inter-observer reliability for a number of measurements including naviculocuneiform angle, medial-cuneiform first-metatarsal plantar gapping, cuboid to floor distance, calcaneal inclination angle, talonavicular coverage angle and axial/DP talus first-metatarsal angle which indicate that, both modalities could be used for assessment of osseous alignment in patients with AAFD. This is in accordance with a prior study, which reported good to excellent reliability between radiographic measurements and those obtained from multi-planar weightbearing imaging [13]. Nevertheless, when the measurements obtained from two modalities were compared, our data displayed significantly decreased values for certain measurements such as medical cuneiform to floor distance and navicular to floor distance in weightbearing CBCT images. Although the difference is statistically significant, we were unable to determine which method is more accurate. However, it could be hypothesized that weightbearing radiographic evaluation might underestimate the osseous deformity, given the technical issues associated with radiograph measurements. Besides, angular alignment values such as

Table 1
The inter-observer reliability between two readers for adult acquired flatfoot measurements obtained from plain radiography and the reliabilities between average values of plain radiography and CBCT.

	Plain Radiography (Reader 1 vs 2)			Plain Radiography vs CBCT		
Adult Acquired flatfoot Measurement	ICC/ Cohen's kappa	95% CI/SE	P-value	ICC/ Cohen's kappa	95% CI/SE	P-value
Lateral View						
Talar-first metatarsal Angle (º)[a]	0.78	0.44–0.92	<0.001	−0.020	−0.55–0.51	0.5
Medial Cuneiform- First metatarsal Angle(º)[a]	0.30	−0.12–0.69	0.058	0.32	−0.25–0.72	0.1
Medial Cuneiform- First metatarsal Gapping[b]	0.80	0.18	0.003	0.58	0.24	0.02
Naviculocuneiform Angle(º)[a]	0.72	0.31–0.90	0.001	0.47	0.07–0.80	0.04
Medial Cuneiform to Floor Distance(mm)[a]	0.85	0.59–0.95	<0.001	0.42	−0.13–0.78	0.06
Navicular to Floor Distance(mm)[a]	0.96	0.89–0.98	<0.001	0.41	−0.14–0.77	0.06
Cuboid to Floor Distance(mm)[a]	0.89	0.69–0.96	<0.001	0.68	0.22–0.88	0.004
Calcaneal Inclination Angle(º)[a]	0.90	0.69–0.97	<0.001	0.70	0.28–0.90	0.002
Dorsoplantar View						
Talonavicular Coverage Angle(º)[a]	0.61	−0.07–0.88	<0.001	0.56	0.04–0.84	0.01
Talar- First metatarsal Angle(º)[a]	0.74	0.17–0.92	<0.001	0.62	0.12–0.86	0.009

ICC: Intraclass correlation; CI: Confidence interval; SE: Standard error.
[a] ICC values were reported.
[b] Cohen's kappa were reported.

Table 2
Comparison of average values of X-ray and CT Adult Acquired flatfoot measurements.

Adult Acquired flatfoot Measurements	X-ray Study		CT Study		P-value
	Mean/ Median	95%CI/ IQR	Mean/ Median	95%CI/ IQR	
Parasagittal/Lateral View					
Talus- First metatarsal Angle (º)[a]	11.8	6.2,17.5	27.3	22.1,32.5	0.003
Medial Cuneiform- First metatarsal Angle (º)[a]	3.0	1.9,4.0	6.04	3.9,8.1	0.02
Naviculocuneiform Angle (º)[a]	12.8	9.1,16.4	14.2	9.1,19.2	0.5
Medial Cuneiform to Floor Distance(mm)[a]	22.5	18.4,26.8	17.8	14.3,21.3	0.03
Navicular to Floor Distance(mm)[a]	31.2	26.2,36.1	22.7	17.9,27.5	0.009
Cuboid to Floor Distance(mm)[a]	17.1	14.4,19.8	15.7	13.3,18.1	0.3
Calcaneal Inclination Angle(º)[a]	12.1	9.5,14.8	13.6	11.8,15.4	0.07
Axial/Dorsoplantar View					
Talonavicular Coverage Angle(º)[b]	31.0	23.2	35.1	19.2	0.2
Talus- First metatarsal Angle(º)[b]	13.0	16.7	17.6	12.5	0.6

[a] Data distribution was normal and paired T-test was used.
[b] Data distribution was not normal and Wilcoxon rank test was used.

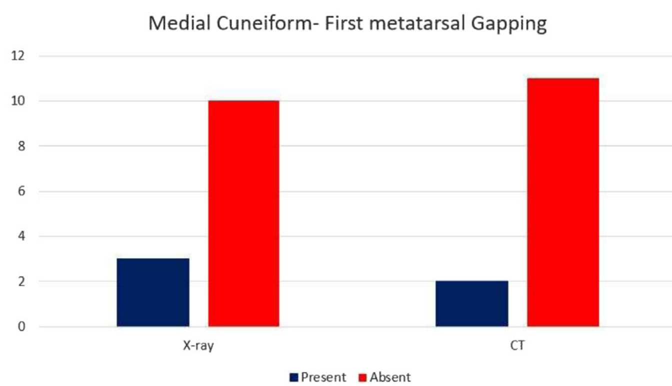

Fig. 3. Comparison of presence of Medial Cuneiform- First metatarsal Gapping between WBCR and WBCT studies.

parasagittal/lateral talus first-metatarsal angle and medial-cuneiform first-metatarsal angle were greater in weightbearing CBCT images. Our data are consistent with the findings of a prior study which compared several angle measurements between weightbearing radiograph, CT and bilateral weightbearing CT images in 30 consecutive patients with an indication for radiograph and 3D-imaging due to unilateral flatfoot deformity [24]. Their results also displayed higher values for parasagittal/lateral talus first-metatarsal angle in weightbearing CT images, comparing with weightbearing radiograph. The authors concluded that a slight foot supination due to malposition of lower extremity during radiographic examination could decrease the value of this measurement and explain the significant difference. In addition, they reported that values of axial/DP talus first-metatarsal angle were not significantly different between weightbearing radiograph and weightbearing CT, while its values were significantly higher for non-weight bearing CT, which suggests the impact of weightbearing on this measurement. In our study, no difference was also observed for this measurement between weightbearing CBCT and weightbearing radiograph. Therefore, it could be assumed that talus first-metatarsal angle at lateral/parasagittal view is influenced by the foot position, while this measurement at DP/axial view is only affected by the physiologic loading. A similar non-significant observation was noted for calcaneal inclination angle, which could suggest that this measurement might be impacted by the loading as well.

In this study, we intended to evaluate correlation between weightbearing radiograph and weightbearing CBCT measurements in patients with AAFD and compare their values between these two modalities. Several studies have assessed the reliability of weightbearing radiographic AAFD measurements, yet there is still conflicting data regarding the most reliable measurement [9,25–27]. A previous study reported that parasagittal/lateral talus first-metatarsal angle was associated with excellent inter-observer reliability and was the most accurate measurement to distinguish AAFD patients from control group [9]. However, other studies reported the highest reliability for calcaneal inclination angle, which confirms our results as well [26,27]. These variations in the current literature could be explained by several factors including observer experience as well as the difficulty to correctly address the bony landmarks. Consequently, there has been a growing interest in employing weightbearing CBCT for evaluation of AAFD patients, since this modality provides detailed visualization of this complex, 3D deformity [4,28–30]. A recent study reported that AAFD measurements could be obtained with high inter-observer reliability among readers of different clinical experience, which suggests that weightbearing CBCT could help to reduce the variation of AAFD measurements, due to different level of reader experience [2]. We were also able to show that weightbearing CBCT measurements displayed significantly more pronounced AAFD deformity than weightbearing radiographic evaluation. Although it is impossible to determine which modality is more accurate, given the shortcomings of radiographic evaluation, it could be hypothesized that weightbearing radiograph could underestimate the extent of bony deformity present in AAFD patients. This hypothesis is also supported by the findings of a previous study which compared talus related measurements obtained from multi-planar weightbearing imaging technique between AAFD patients and control group [13]. The authors reported significant differences in several measurements including talus-1st-metatarsal angle which were not evident on their radiographic measurements. Their study was the first to correlate and compare measurements from weightbearing multi-planar imaging technique and weightbearing radiograph, however, the authors focused on the site of deformity in relation with talus, emphasizing on talus-first metatarsal angle. While the present study confirmed their findings, our data provide additional information regarding other deformities involved in AAFD. Since weightbearing CBCT has the advantage of multi-planar reformation which provides considerable benefit for the assessment of complex, 3D deformities such as AAFD.

We acknowledge that our study has several important limitations. First, a small number of subjects were recruited in the study and no sample size analysis was performed to determine the power of study for detecting the difference in measurements between two modalities, which could negatively impact the findings of our study. Second, we did not compare the weightbearing radiograph and weightbearing CBCT measurements in asymptomatic control subjects. These measurements could be significantly different between two modalities even in normal ankles. Third, due to a limitation of image acquisition of weightbearing CBCT scanner, the whole length of first metatarsal could not be visualized which could lead to less accuracy for those measurements involving first-metatarsal. Fourth, we observed statistically significant difference between mean values of radiographic and CBCT based measurements, however we were not able to assess the clinical relevance of these differences in patients with AAFD, further studies are warranted to assess the clinical relevance of these differences on patient outcome and management. Fifth, we attempted to obtain CT images under the same condition of radiograph, however this could not be achieved, since the unilateral leg standing might not be the same in these two imaging modalities and this difference should be taken into account. Finally, the radiographic measurements were not corrected for radiographic magnification, however this would not impact the results of reliability, since correlation evaluation looks for pattern rather than exact similar values of measurement.

In conclusion, we observed moderate to very good correlation between certain weightbearing radiograph and weightbearing CBCT measurements. However, weightbearing CBCT measurements demonstrated significantly more pronounced osseous malalignment than weightbearing radiograph. The results of our study suggest that radiographic evaluation of patients with AAFD could potentially underestimate the bony deformity, compared with CBCT. In the treatment algorithm of AAFD patients, these findings should be considered when using weightbearing radiographic evaluation.

Conflict of interest statement

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 surgeons.

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