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3D Biometrics for Hindfoot Alignment Using Weightbearing CT

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Abstract

Background: Hindfoot alignment on 2D radiographs can present anatomical and operator-related bias. In this study, software designed for weightbearing computed tomography (WBCT) was used to calculate a new 3D biometric tool: the Foot and Ankle Offset (FAO). We described the distribution of FAO in a series of data sets from clinically normal, varus, and valgus cases, hypothesizing that FAO values would be significantly different in the 3 groups.
Methods: In this retrospective cohort study, 135 data sets (57 normal, 38 varus, 40 valgus) from WBCT (PedCAT; CurveBeam LLC, Warrington, PA) were obtained from a specialized foot and ankle unit. 3D coordinates of specific anatomical landmarks (weightbearing points of the calcaneus, of the first and fifth metatarsal heads and the highest and centermost point on the talar dome) were collected. These data were processed with the TALAS system (CurveBeam), which resulted in an FAO value for each case. Intraobserver and interobserver reliability were also assessed.
Results: In normal cases, the mean value for FAO was 2.3% ± 2.9%, whereas in varus and valgus cases, the mean was −11.6% ± 6.9% and 11.4% ± 5.7%, respectively, with a statistically significant difference among groups ($P < .001$). The distribution of the normal population was Gaussian. The inter- and intraobserver reliability were 0.99 +/- 0.00 and 0.97 +/-0.02
Conclusions: This pilot study suggests that the FAO is an efficient tool for measuring hindfoot alignment using WBCT. Previously published research in this field has looked at WBCT by adapting 2D biometrics. The present study introduces the concept of 3D biometrics and describes an efficient, semiautomatic tool for measuring hindfoot alignment.
Level of Evidence: Level III, retrospective comparative study.

Keywords: weightbearing CT, PedCAT, TALAS, Foot Ankle Offset, hindfoot alignment

Introduction

The importance of hindfoot alignment (HFA) in the setting of hindfoot surgery has been described in the literature due to the relationship between alignment and operative outcome,[34,46,47] as in ankle arthrodesis and arthroplasty[4,5,11,17,21,30,32,48] or in knee arthroplasty.[7,27-29,41] HFA measures based on 2D radiographs are flawed by many anatomical and operator-related bias, which have been extensively investigated in the literature.[*] These include projection and rotational issues,[3,22] mostly with regards to the use of the tibia as a reference axis.[6] Previous studies on the HFA have focused on which technique to use and measurement methods.[†]

Furthermore, 2D measures traditionally do not account for the contribution of the forefoot in ankle biomechanics. Recently, 2 publications from different authors[1,22] have used HFA measures using the forefoot rather than the tibia as a reference, which seems to be one step forward in reducing the bias related to projection and rotation. However, these techniques were still based on 2D radiographs and were complicated to measure, and thus were not usable in daily practice. 3D weightbearing computed tomography (3D WBCT) provides an opportunity to solve the problems associated with 2D biometrics.[16,35] This could be done by creating a new generation of HFA measures or 3D biometrics based on 3D coordinates rather than trying to force-apply older HFA measurements based on 2D angles to this new 3D environment. The ideal criteria for this new kind of

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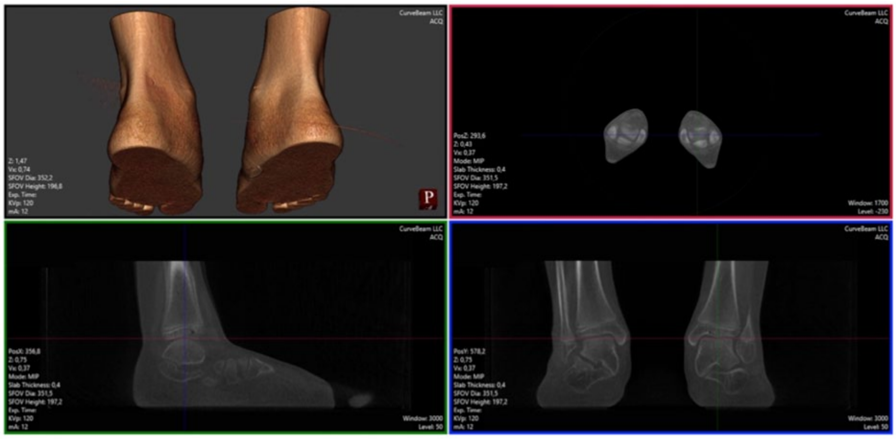

Figure 1. 3D views obtained by the weightbearing computed tomography built-in software.

tool would be as follows: physically meaningful, designed for 3D WBCT, computerized, and verifiable by data.

In this study, we investigated the efficacy of a new system: Torque Ankle Lever Arm System (TALAS; CurveBeam LLC, Warrington, PA) designed to satisfy those requirements and used to calculate a computerized, semiautomatic 3D biometric: the Foot and Ankle Offset (FAO). It represents the lever arm or the torque generated in the ankle from the combined actions of body weight and ground reaction force. This technique had been previously validated in a simulated 3D weightbearing (WB) environment on 2D radiographs, at a time when 3D WBCT was not readily available.[22] The objective of this study was to describe the distribution of FAO in a series of anonymized data sets from clinically normal, varus, and valgus cases. We hypothesized that normal, varus, and valgus cases would be significantly different and that the distribution should be Gaussian in the normal population. We also assessed the interobserver and intraobserver reliability of the FAO measurement.

Methods

This was a comparative study looking retrospectively at existing data captured as part of routine clinical care. The study was conducted with institutional review board approval.

We analyzed 135 anonymized consecutive data sets, of which 57 were from patients with normal hindfoot alignment (42%), 38 from patients with varus hindfoot alignment (28%), and 40 from patients with valgus hindfoot alignment (30%). All scans were obtained from WBCT scans using the PedCAT unit (CurveBeam) installed in the outpatients sector of an orthopaedic foot and ankle surgery referral center. The data sets were obtained using the following cone beam scanner settings: voxel size, 0.37 mm; field of view diameter, 350 mm; field of view height, 200 mm; exposure time, 9 seconds, total scan time, 54 seconds. The data sets were extracted from the existing database, containing the 3D image data (Figure 1) and patient demographics limited to side and clinical morphotype. Data sets were screened by 2 independent observers using the built-in software, CubeView (CurveBeam), and collected the 3D coordinates of specific anatomical landmarks required for the software to process and calculate FAO. Two independent observers collected the 3D coordinates (x, y, z), for the following landmarks: first metatarsal head WB point (A), fifth metatarsal head WB point (B), calcaneus WB point (C), and the talus centermost and highest point, respectively, in the coronal and sagittal planes (D1). The WB point was defined in the ground plane by its x and y coordinates as the lowest point (z coordinate nearest to 0) on the surface of the calcaneus and metatarsal WB surfaces. The center of the talus was defined as the highest point (z coordinate furthest to 0) on the talus in the centermost sagittal plane.

All these values were collected and stored anonymously in a spreadsheet, which a third investigator then ran the through a beta version of the Torque Ankle Lever Arm System, which calculated FAO values using an algorithm based on the inverted 3D pyramid model[22] (Figure 2):

1. A, B, C, and D1 were defined as, respectively, the WB points of the first metatarsal head, the fifth metatarsal head, the calcaneus and the talus;
2. the midpoint E between A and B;
3. the CE line was found, and the CE distance was called "foot length";

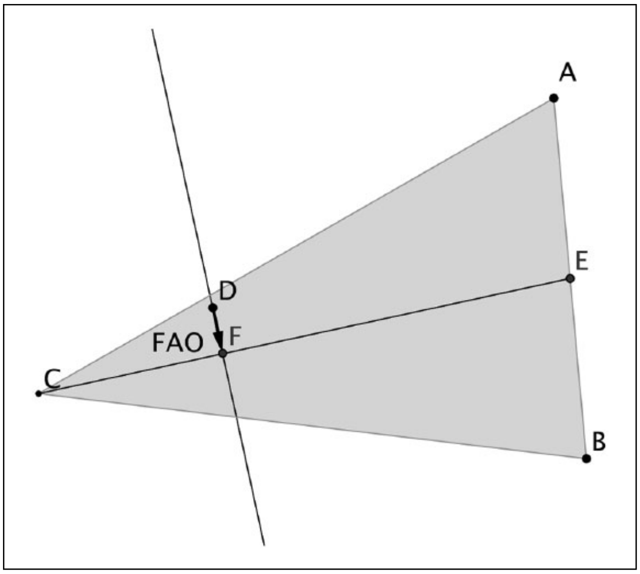

Figure 2. Schematic representation of Foot and Ankle Offset in the transverse plane (see the text for abbreviations).

4. D was the orthogonal projection of D1 on the ABC plane (i.e., the position of the center of the talus in the ground plane);
5. the perpendicular line to CE, which included D, was found (i.e., the line from the center of the talus to the midline of the foot on the ground plane);
6. F was the intersection of these 2 lines and thus DF was found, being positive when D was medial to F and negative when lateral;
7. FAO was DF/CE × 100 and was given as a percentage.

FAO therefore corresponds to the offset between the hindfoot-to-forefoot midline and the talus. It was therefore given as a percentage of foot-length and was theoretically representative of the torque, which would be produced in the ankle by this offset. This conversion to percentage of foot length was done to normalize the FAO value to foot size so that it was comparable between feet of different sizes, since the FAO was a metric, not an angle.

Statistical analysis

FAO values in 3 groups were compared using a 1-way analysis of variance. Normality test was performed using the Kolmogorov-Smirnov test method on the normal foot group. An intraclass correlation coefficient (ICC) 2-way mixed model was used to assess the intraobserver and interobserver reliability of FAO values. ICCs were calculated with the measurements performed twice by 2 independent observers on data sets in the 3 different groups: normal, varus, and valgus. ICC values range from 0 to 1, with a higher value indicating a better reliability. ICCs below 0.40 were considered poor, 0.40 to 0.59 fair, 0.60 to 0.74 good, and 0.75 to 1.00 excellent.

Data are presented as mean, standard deviation, range, and 95% confidence intervals (CIs). All analyses were carried out using Stata statistical software package (version 12.0, StataCorp, 2011). A P value <.05 was considered to indicate statistical significance.

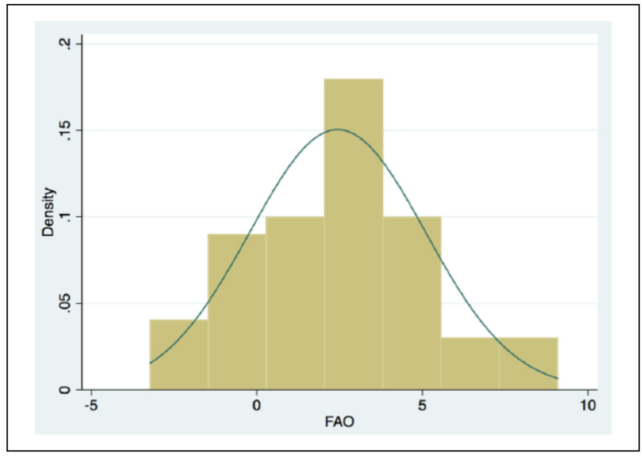

Figure 3. Gaussian distribution of Foot and Ankle Offset values in the normal population.

Results

In normal cases, mean value for FAO was 2.3% ± 2.9% (95% CI, 1.5%-3.1%; range, –3.2% to 9.0%), whereas in varus and valgus cases the mean was −11.6% ± 6.9% (95% CI, –13.9% to −9.4%; range, –26.4% to −1.0%) and 11.4% ± 5.7% (95% CI, 9.6%-13.3%; range, 2.0%-24.5%), respectively. The difference was statistically significant among the 3 groups ($P < .001$). FAO values distribution in the normal population was normal ($P > .81$) (Figure 3).

The inter- and intraobserver reliability of FAO measure were excellent, with small standard deviations; the global mean ICC was 0.99 ± 0.00 (95% CI, 0.99-1.00) and 0.97 ± 0.02 (95% CI, 0.92-1.02) for the inter- and intraobserver assessment, respectively. ICC values for the normal, varus, and valgus groups are shown in Table 1.

Discussion

This study confirmed our hypothesis that in a series of anonymized and independently reviewed 3D WBCT data sets, the FAO was successful in discriminating clinically normal from varus and valgus hindfoot alignment cases using a novel 3D biometric computerized, semi-automatic measurement. The distribution of FAO in the normal population

Table 1. Inter- and Intraobserver Reliability of Foot and Ankle Offset Measurement in Different Groups.

	ICC	SD	95% CI
Overall			
Interobserver	0.99	0.00	0.99-1.00
Intraobserver	0.97	0.02	0.92-1.02
Normal			
Interobserver	0.95	0.06	0.83-1.07
Intraobserver	0.96	0.04	0.88-1.05
Varus			
Interobserver	0.98	0.02	0.94-1.02
Intraobserver	0.93	0.09	0.75-1.11
Valgus			
Interobserver	0.99	0.00	0.99-1.00
Intraobserver	0.95	0.05	0.84-1.07

Abbreviations: FAO, Foot and Ankle Offset; ICC, intraclass correlation coefficient; SD, standard deviation.

was Gaussian. Additionally, intra- and interobserver reliability has proven excellent in all groups of normal, valgus, and varus cases.

In the authors' opinion, the originality of this study lies in the description of an entirely new concept (3D biometrics) for measuring HFA that avoided projection, rotation, and operator errors related to traditional 2D methods. This is concurrent with previous literature in which Richter et al[35] stated that WBCT imaging is a more accurate method of measuring angles because it is not subject to rotation and projection bias and because it is weightbearing.

Our technique's purpose was to limit the drawbacks of 2D measurement relating to rotational, projectional and operative issues. With respect to HFA, there is no Gold Standard or "true" measurement.[3,6,22] Rotation and other potential bias influence the value of HFA measurements.[3] However, in most studies, reliability is assessed using intra and interobserver reliability carried out on the same radiograph for each patient. So it is logical that the same observer (intra observer), or 2 observers (inter observer), given the same instructions, would find the same value. The real question is rather if 2 radiographs of the same patient taken at different times would result in the same value. To really assess reliability, the radiographs would therefore have to be repeated on each patient, which would be ethically difficult to explain. This was done in a previous study using a cadaveric setup[3] where a 30-degree difference in rotation of the foot could result in a 50% difference in HFA value. So repeatability truly lies in the radiographic setting. In setups where the position of the foot, the height of the x-ray source (angle between the horizontal and the direction of the X-Ray beam), the distance of the x-ray source, the individual practice of the radiographer, and the measurement technique all influence the end result, repeatability may be impaired. WBCT may permit better control over these variables through regular assessment, as is enforced by international regulation by scanning templates that incorporate markers of known length, angle, and spatial distribution so that it may be checked, without consequences for the patients, that measurements made by the machine are reliable. There are other advantages, including reduced spatial footprint, radiation dose (comparable to a series of 5 conventional radiographs), and time for acquisition (52 seconds). However, the clinical and economic efficiency of this technology still remains to be proven.

The clinical relevance for this study is therefore to report the possibility of developing dedicated 3D biometrics to provide more accurate measurement tools for planning foot and lower limb surgery in the future. This technology should also enable reliable and accurate data recording for the purposes of research and clinical audit. The software here described is a framework, in which 3D biometric tools such as FAO may be adapted suitably for WBCT.

The authors acknowledge some limitations in this study such as the absence of a post hoc sample size calculation, and the absence of a gold standard to compare to, which is always an issue when developing new measurements. We did not compare our measurements with a traditional HFA measurement, for example, as determined by the Saltzman view, which is generally accepted as the main method to assess HFA alignment. This would have required additional irradiation of patients, which could not be justified in this study setting. In addition, because there is no "true" or gold standard measure for HFA, it would not necessarily be an appropriate comparison.

We believe that establishment of the "true" HFA measurement that has relevance in clinical practice requires fully automatic measurement tools. A fully automated system may enable the gathering of data in great quantities in order to correlate varying pathologies. A "better" HFA measure will be one that improves the discrimination of a normal case from a pathologic one. In the meantime, an international collaborative effort has to be made to adapt traditional 2D measurements to WBCT and validate their use in a clinical setting. This would provide the basic tools and guidelines to evaluate and validate 3D biometrics. In the future, the involvement of reference centers will be required to conduct cost and clinical-effectiveness analyses for this technology. Such an evolution has been seen over the last 15 years in the dental area.[43,45]

Conclusion

In conclusion, a semiautomatic software was successfully used to assess HFA using a 3D biometric measurement, FAO. This new concept may represent the way forward to make the best of WBCT. Further research is warranted in order to properly validate such tools for clinical use. An international effort is required in order to adapt traditional

2D HFA measurements so that a set of guidelines for assessing new tools can be published. This is essential to make the research reproducible and comparable.

Declaration of Conflicting Interests

The author(s) declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: François Lintz, MD, FEBOT, reports personal fees from CurveBeam LLC, during the conduct of the study.

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