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Evaluation of a Weightbearing CT Artificial Intelligence-Based Automatic Measurement for the M1-M2 Intermetatarsal Angle in Hallux Valgus

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Abstract

Background: Weightbearing cone beam computed tomography (WBCT) has been gaining traction as a useful imaging modality in the diagnosis and follow-up of foot and ankle musculoskeletal pathologies due to the ability to perform quick, low-dose, 3-dimensional (3D) scans. However, the resulting wealth of 3D data renders daily clinical use time-consuming. The aim of this study was to evaluate a new artificial intelligence (AI)–based automatic measurement for the M1-M2 intermetatarsal angle (IMA) in hallux valgus (HV). We hypothesized that automatic and manual measurements would have a strong correlation, and that the AI software would yield better reproducibility and would be faster compared with manual measurements.
Methods: This was a multicenter retrospective comparative case-control study in which a total of 128 feet were included from 93 patients who underwent WBCT scans as part of their routine follow-up: 59 feet with symptomatic HV and 69 controls. The IMA was measured automatically using the AI software and manually on digitally reconstructed radiographs (DRRs). The AI software produced both an automatic 2D (auto 2D) and 3D (auto 3D) measurement.
Results: There were strong intermethod correlations between the DRR IMA and the auto 2D (HV, $r = 0.61$; control, $r = 0.60$; all $P < .0001$) and auto 3D (HV, $r = 0.63$; control, $r = 0.52$; all $P < .0001$) measurements, respectively. The intrasoftware reproducibility was very close to 100%. Measurements took 23.6 $\pm$ 2.31 seconds and 14.5 $\pm$ 1.18 seconds, respectively, when taken manually on DRRs and automatically. Controls demonstrated a mean DRR IMA of 8.6 (95% CI, 8.1-9.1), mean auto 2D of 11.2 (95% CI, 10.7-11.7), and mean auto 3D IMA of 11.0 (95% CI, 10.5-11.5). The HV group demonstrated significantly increased IMA compared with controls ($P < .0001$), with a mean DRR IMA of 15.4 (95% CI, 14.8-16.1), mean auto 2D of 17.8 (95% CI, 17.2-18.4), and mean auto 3D IMA of 16.8 (95% CI, 16.8-17.4).
Conclusion: Measurements generated by the WBCT AI-based automatic measurement system for IMA demonstrated strong correlations with manual measurements, with near-perfect reproducibility. Further developments are warranted in order to make this tool more usable in daily practice, particularly with respect to its use in the presence of hardware in the foot.
Level of Evidence: Level III, retrospective comparative study.

Keywords: weightbearing CT, WBCT, artificial intelligence, intermetatarsal angle, IMA, hallux valgus, machine learning

Introduction

The recent advent of weightbearing cone beam computed tomography (WBCT) as a standard modality for foot and ankle musculoskeletal pathology has allowed for a more complete 3-dimensional (3D) understanding of deformities.[11,16,19,23] Visualizing multiplanar bony anatomy in physiologic stance has allowed for improvements to be made in both the diagnosis and treatment of such pathologies.[12] However, the wealth of information generated by this new generation of technology raises several challenges.

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First is the shift from conventional radiography, which relies on 2-dimensional (2D) projection images. Studies have highlighted the inherent limitations of 2D plain films, namely the superimposition of objects, rotational bias, and user dependency.[1,2,10] In contrast, WBCT by nature presents anatomy in 3D, and while this may be more accurate in that respect, it is also more complex to visualize, navigate, and interpret both manually and with software tools. Defining reliable anatomic landmarks in the 3 spatial planes is arguably more difficult than in 2D, and this can introduce a new kind of variability related to choosing a single reproducible plane in which to perform a given measurement.[3] Naturally, this creates a learning curve that is still currently time-consuming when performed manually. Still, a standardized manual measurement has been shown to be reliable.[19]

One solution to this problem is the development and validation of automatic measurement tools that would relieve clinicians and improve the poor reproducibility that may be associated with taking complex 3D measurements manually. Recent studies have demonstrated the utility of semiautomatic WBCT measurements to compute complex 3D measurements,[16,23] but even these require the initial manual selection of coordinates, which may introduce variability. The resulting intra- and interrater reliabilities for these semiautomatic measurements have been reported to be between 85% and 99%.[16]

Recently, a novel, fully automatic measurement system utilizing deep learning artificial intelligence (AI) software has been developed (CubeVue; CurveBeam LLC, Hatfield, PA). The system is based on a deep learning AI algorithm that performs automatic segmentation of the long bones of the forefoot, thereby generating 3D vectors that map the spatial orientation and allow for measurements to be generated in 3D space. Our aim was to test a beta version of this software in a frequent foot condition, namely the hallux valgus (HV) deformity. HV is one of the most common foot and ankle pathologies, for which a crucial element of diagnosis and surgical decision-making relies on the preoperative assessment of angular measurements such as the M1-M2 intermetatarsal angle (IMA).[7] Therefore, these measurements must be accurate, reliable, and reproducible in order to properly guide treatment.

The primary aim of this study was to investigate the validity of the WBCT AI software by assessing whether the automatic IMA measurements would correlate with those made manually by trained observers, with excellent test-retest reliability. A secondary objective was to determine whether the software could distinguish symptomatic HV cases from asymptomatic controls. Our third objective was to compare the time required to perform manual and automatic measurements. We hypothesized that the 2 modalities would have a strong correlation and that the automatic measurement would be faster and would demonstrate higher, near-perfect reliability.

Table 1. Diagnoses of Control Patients.

Diagnosis	No. of feet (n = 69)
Ankle instability	12
Ankle arthritis	3
Ankle fracture	3
Ankle osteochondral lesion	3
Calcaneus fracture	2
Talocalcaneal coalition	2
Lisfranc injury	1
Subtalar arthritis	1
Naviculocuneiform arthritis	1
Ganglion cyst	1
Mild cavus foot	1
Achilles tendinopathy	1
Uninjured contralateral foot	38

Methods

Study Design

This was a retrospective, multicenter case-control study of WBCT scans obtained as part of routine follow-up from January 2018 to February 2019. This study was approved by the respective institutions' research steering committees and was performed according to the ethical standards set forth by the 1964 Declaration of Helsinki. Ethical approval was obtained through submission of the study protocol to our Institutional Review Board (IRB). Upon approval, the following registration number was issued by the IRB: COS-RGDS-2019-09-003-LINTZ.

Patient Cohort

WBCT scans from a total of 126 adult patients were obtained for this study, which consisted of 68 patients with a primary diagnosis of symptomatic HV both clinically and radiographically (IMA, ≥10 degrees; HVA, ≥15 degrees)[17] by a senior fellowship-trained foot and ankle surgeon (F.L.) and 58 patients who served as controls. Control patients were defined as patients who underwent a WBCT as part of routine follow-up for a condition that was not associated with forefoot pathology, as detailed in Table 1.

Patients with previous forefoot surgery (n = 3), severe first metatarsophalangeal arthritis (n = 2), and/or progressive collapsing flatfoot deformity (n = 2) were not included in either the HV or control groups. Previous forefoot surgery with metal hardware is incompatible with the autosegmentation process, and irregularity of joint surfaces in the setting of severe arthritis can negatively affect the AI software from accurately identifying the joint. A potential relationship between progressive collapsing foot deformity (PCFD) and HV led to the exclusion of these patients to minimize confounding variables.

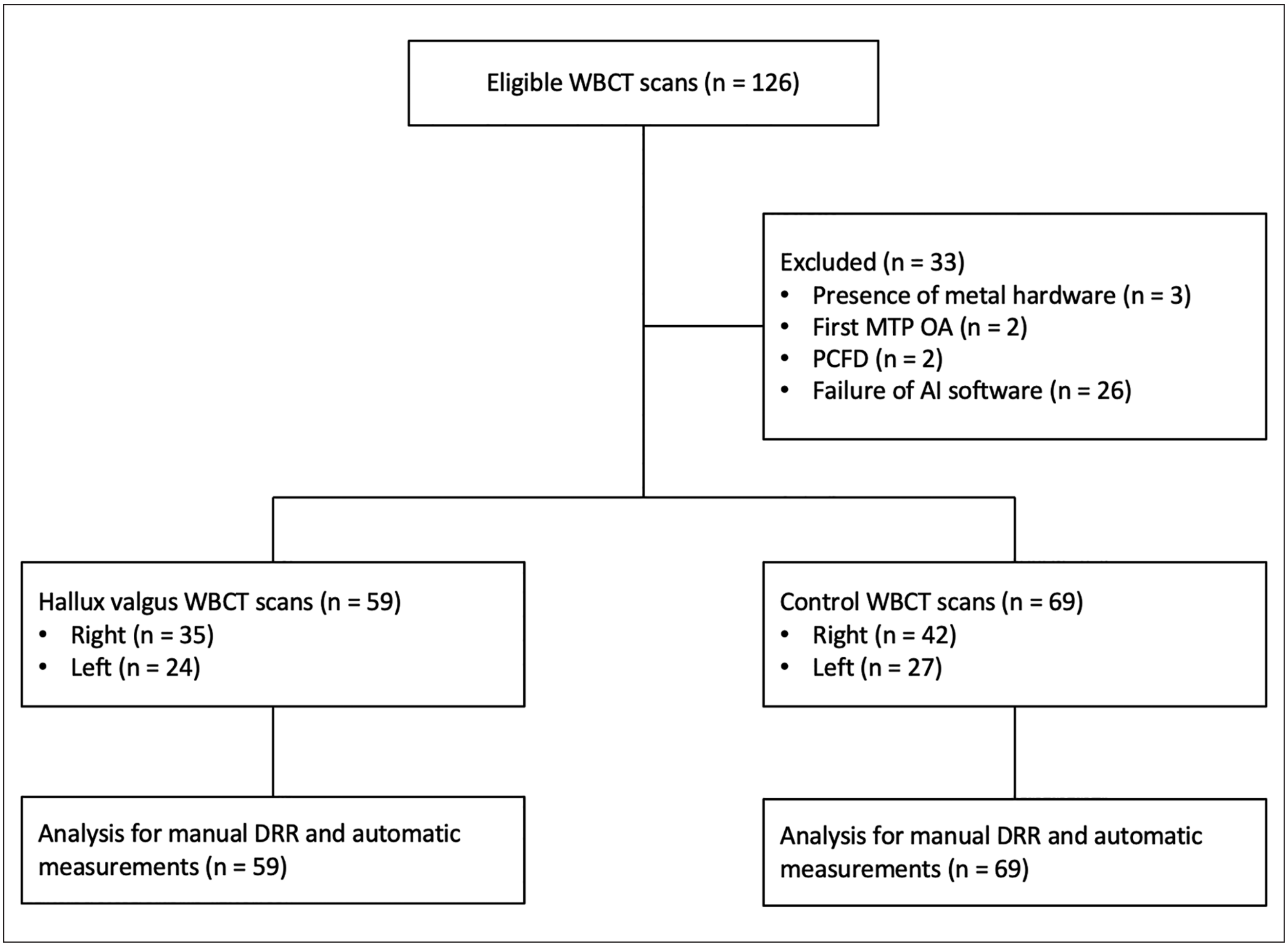

Figure 1. CONSORT (Consolidated Standards of Reporting Trials) flow diagram. DRR, digitally reconstructed radiograph; MTP OA, first metatarsophalangeal joint osteoarthritis; PCFD, progressive collapsing foot deformity; WBCT, weightbearing cone beam computed tomography.

Furthermore, scans in which the software failed to produce automatic measurements ($n = 26$) were excluded from analysis.

In total, WBCT scans from 93 adult patients were analyzed for this study, 44 patients (59 feet; 35 right and 24 left) in the HV group and 49 patients (69 feet; 42 right and 27 left) in the control group (Figure 1). The study cohort consisted of 66 (71%) female and 27 (29%) male patients, with a mean age of 49.6 ± 15.8 years (range, 18-79 years), and mean body mass index (BMI) of 26.7 ± 5.9 kg/m^2 (range, 17.6-42.3 kg/m^2). Patient demographics for each group are tabulated in Table 2.

All patients were assessed with a standing WBCT scan of the bilateral feet in full weightbearing stance as part of routine follow-up (PedCAT; CurveBeam LLC, Hatfield, PA).

The IMA measurement was first determined manually on the dorsoplantar view of digitally reconstructed radiographs (DRRs) produced by the standard WBCT software (CubeVue; CurveBeam LLC, Hatfield, PA) using the Cobb angle measurement tool (Figure 2).[19] Manual measurements (DRR IMA) for each data set were performed twice each, 1 week apart, and repeated by a second trained observer (J.D., C.F.) to calculate interobserver and intraobserver reliability coefficients (intraclass correlation coefficients, ICCs). Following manual measurements, the AI automatic system was utilized to generate automatic measurements (Autometrics; CurveBeam, Warrington, PA). The software algorithm analyzes voxel density in order to construct a 3D model based on an ellipsoid representation of the metatarsals where the longest inertial axis corresponds to the anatomical axis of the bone. This software performs automatic segmentation of the first and second metatarsals and produces a 3D and 2D (auto 3D and auto 2D) IMA. The latter is a ground projection of the former, mimicking the projected angle that is traditionally obtained on conventional plain radiographs (Figure 2). In order to assess intrasoftware or test-retest reliability, the AI software was trialed twice for each data set.

Table 2. Patient Demographics.

	Hallux valgus	Control	Total
No. of feet	59	69	128
Age, y, mean ± SD	57.5 ± 11.8	42.4 ± 15.7	49.6 ± 15.8
Sex, % female	88.6	55.1	71
BMI, kg/m^2, mean ± SD	26.4 ± 5.9	26.9 ± 6	26.7 ± 5.9

Abbreviations: BMI, body mass index.

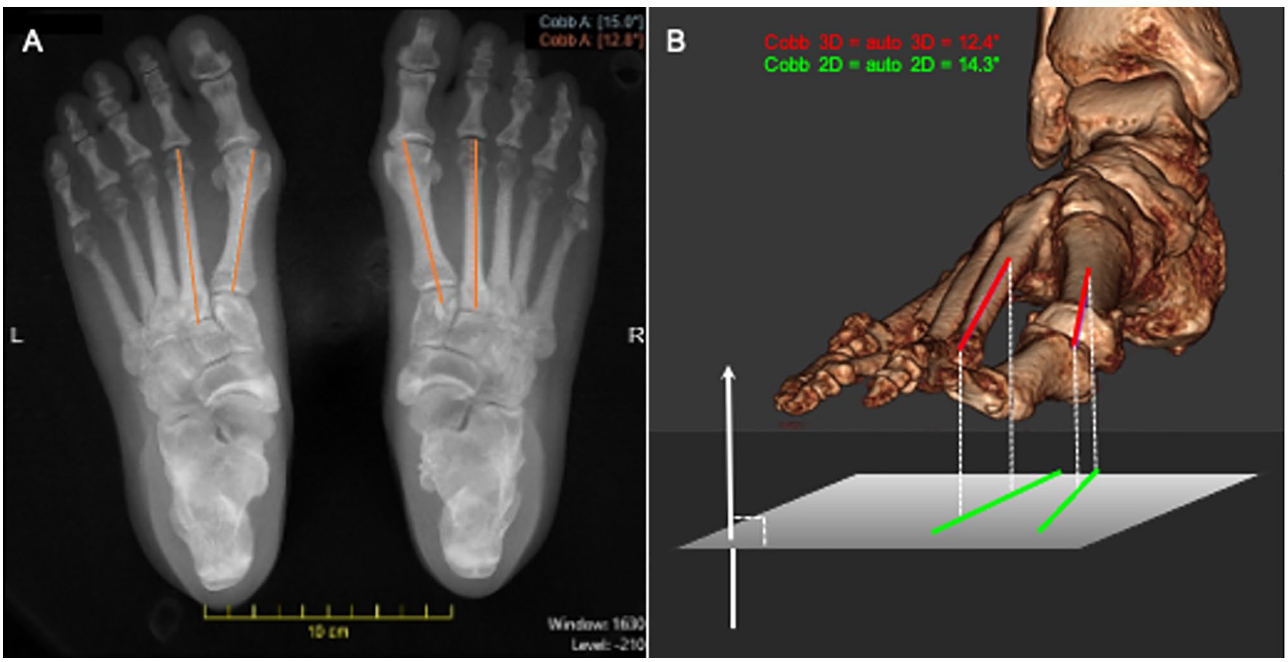

Figure 2. Intermetatarsal angle (IMA) measurements. (A) Manual IMA taken with the Cobb measurement tool digitally reconstructed radiographs. (B) Automatic 2- and 3-dimensional (auto 2D and auto 3D) IMA measurements taken with the automatic weightbearing computed tomography software.

Time measurements were performed to evaluate the required time to complete DRR IMA and automatic measurements (auto 2D and auto 3D) on a subset of 21 bilateral scans.

Statistical Analysis

The normality of continuous variables was assessed using a Shapiro-Wilk test. Comparisons between variables were performed using chi-square or Fisher exact tests for categorial variables and Student *t* tests or Wilcoxon tests for continuous variables. Comparisons between paired variables were assessed using chi-square Mantel-Haenszel tests for categorical variables and Student *t* tests or Wilcoxon signed-rank tests for quantitative variables.

The ICCs were also calculated to determine intraobserver, interobserver, and intrasoftware reliability. Measurement modalities were compared by bivariate linear regression analysis, and intermethod correlation was assessed by Pearson or Spearman correlation coefficients.

All calculations were made with JMP Pro 15.0.0 (SAS Institute, Cary, NC), with the level of statistical significance set at $P < .05$.

Results

Both manual and automatic measurements demonstrated significantly higher IMA measurements in the HV group compared with the control group. The mean manual DRR IMA was 15.4 (95% CI, 14.8-16.1) in the HV group versus 8.6 (95% CI, 8.1-9.1) in the control group ($P < .001$). The mean auto 2D and auto 3D IMAs in the HV group were 17.8 (95% CI, 17.2-18.4) and 16.8 (95% CI, 16.8-17.4), respectively, which were both significantly higher than the auto

Table 3. Comparison Between Manual and Automatic IMA Measurements in Patients Diagnosed With HV and in Controls.[a]

	HV group (n = 59)	Control group (n = 69)	P value
Manual IMA	15.44 (14.81-16.07)	8.58 (8.08-9.09)	**<.0001**
Auto 2D IMA	17.78 (17.15-18.40)	11.21 (10.70-11.71)	**<.0001**
Auto 3D IMA	16.80 (16.81-17.43)	11.03 (10.52-11.54)	**<.0001**

Abbreviations: HV, hallux valgus; IMA, intermetatarsal angle.
[a]Data are presented as mean (95% CI) unless otherwise noted. Bold face type indicates statistical signifance ($P < .05$).

2D (mean, 11.2; 95% CI, 10.7-11.7) and auto 3D (mean, 11.0; 95% CI, 10.5-11.5) IMA measurements of the control group ($P < .0001$ for both). Respective means are tabulated in Table 3.

Bivariate analysis revealed a positive linear correlation between manual DRR IMA and auto 2D ($R^2 = 0.39$, $P <$ 0001) and auto 3D ($R^2 = 0.40$, $P < .0001$) IMA in patients with HV (Figure 3). A similar positive linear correlation was observed when comparing manual DRR IMA with auto 2D ($R^2 = 0.40$, $P < .0001$) and auto 3D ($R^2 = 0.30$, $P < .0001$) IMA in the control group. Multivariate analysis demonstrated strong intermethod correlations between the DRR IMA and the auto 2D (HV, $r = 0.61$; control, $r = 0.60$; all $P < .0001$) and auto 3D (HV, $r = 0.63$; control, $r = 0.52$; all $P < .0001$) measurements, respectively.

There was excellent intraobserver and interobserver reliability for the manual DRR IMA, with ICCs of 0.95 and 0.84, respectively. In terms of the automatic system, the intrasoftware ICC for both HV and control groups was very close to 100%, for both the auto 2D (0.99) and auto 3D (0.99) IMA.

The average time taken to manually measure IMA was 23.6 ± 2.31 seconds, while the software took an average of 14.5 ± 1.18 seconds to produce both auto 2D and 3D measurements.

Discussion

The results of the current study confirmed our initial hypothesis that the AI software generated automatic measurements that moderately correlated with manual measurements and was capable of reliably discriminating patients with clinical HV from controls. In addition, the AI software demonstrated a significantly higher test-retest reliability approaching near-perfect reproducibility and a better speed compared with manual measurements.

These findings have several important implications. First is the validation that an automatic AI software may be applicable in the clinical setting to determine a frequently measured radiographic parameter. HV is one of the most common causes of forefoot pain, for which treatment options rely on the severity of angular deformity. The most pronounced aspect of HV is appreciated on the anteroposterior (or axial) plane, as the first metatarsal head shifts medially with the great toe moving laterally with progressive subluxation of the first metatarsophalangeal joint.[9] Hence, treatment algorithms have historically focused on restoring alignment utilizing angular measurements made on 2D radiographs.[8,9,13] However, HV itself is a 3D deformity in which there is pronation at the metatarsophalangeal joint.[6,18] Recent WBCT studies have demonstrated significant preoperative deformities present in the sagittal and axial planes, in addition to the coronal plane.[4-6,14,15] Therefore, it is clear that a 2D measurement may not be sufficient in describing an otherwise complex deformity with multiplanar involvement, and a 3D measurement may be more appropriate.

This has led to several studies aimed at interpreting conventional 2D measurements such as the IMA in a 3D environment. In all of these studies, 3D measurements were determined via manual selection of coordinates, which can prove to be spatially challenging and therefore prone to user variability. Furthermore, the manual selection of coordinates has been shown to differ based on different described methods, which further introduces variability.[22]

The results of the current study provide a potential solution to both of these challenges, bridging the gap between the wealth of data collected and our interpretation of these data to clinical practice. Because the program utilizes deep learning algorithms, the system is able to automatically calculate a 3D IMA measurement without human input. This spares the clinician from having to manually select spatial coordinates and reduces error associated with user bias. Of course, there may still be a small amount of variability relative to how the neural network is encoded, but despite that the test-retest reliability here was already very close to 100%. Traditionally, manual IMA measurements have been cited in the literature as having relatively poor reproducibility.[7,20,21] In one such study by Coughlin and Freund,[7] the authors found that only 83.8% of IMA measurements made by physicians were within 3 degrees of concordance. With near-perfect reproducibility observed in the current study, the AI software demonstrated superior reliability compared with manual 2D measurements, which in our current study demonstrated an intraobserver and interobserver reliability of 0.95 and 0.84, respectively. Furthermore, because this software utilizes automatic segmentation to generate measurements on WBCT, this technology can be adapted to

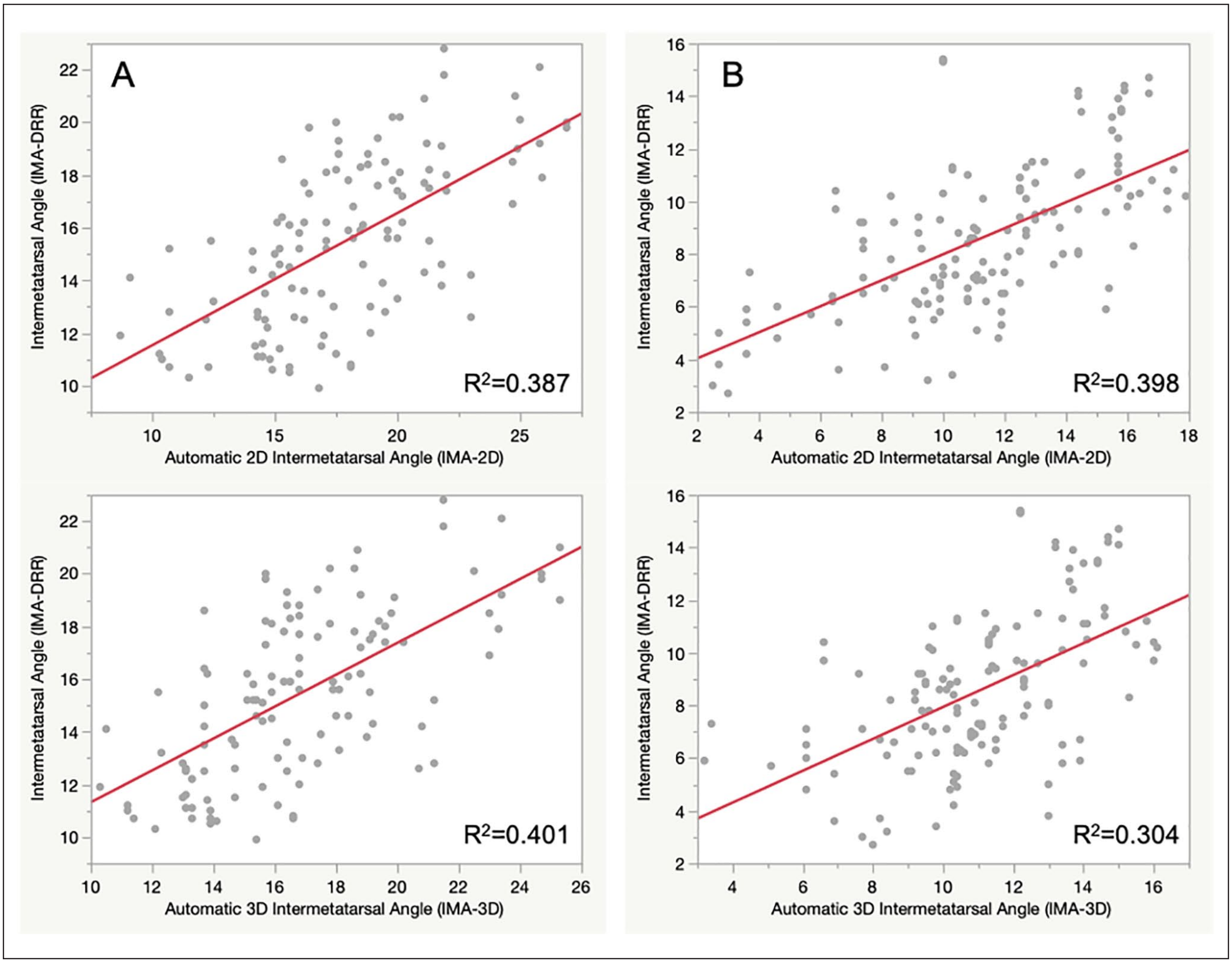

Figure 3. Correlation between manual and automatic measurements. Bivariate fits demonstrating the correlation (R^2, coefficient of determination) between manual and automatic 2- and 3-dimensional (2D and 3D) intermetatarsal angle (IMA) measurements in (A) patients with hallux valgus and (B) controls.

other measurements in the foot and ankle in the evaluation of multiplanar deformity.

Finally, because the software utilizes deep learning, it is constantly evolving. While the current version has yielded reliable results for a single measurement, it is still considered a beta version. Over time, as the software amasses more data, it can "learn" to become more precise and accurate. We found that a trained observer takes around 24 seconds to perform IMA measurement on left and right feet with the manual Cobb angle measurement tool on dorsoplantar DRR views, while the software takes around 14 seconds to produce both auto 2D and auto 3D measurements on a bilateral scan. A 10-second difference may seem small, but the software provides a 3D measurement of the IMA, which would be painstaking to obtain manually from landmark coordinates and require further calculations. Furthermore, future iterations are likely to speed this process up and therefore make it even more user-friendly in the clinical setting. One illustration of this learning process is that the test-retest reliability was very close (0.99 for auto 2D, 0.99 for auto 3D) but not actually equal to 100%, which would be surprising if the software were a traditional linear-type algorithm. A neural network, functioning more like a human brain, does not necessarily use the same neural pathway to reach the result, hence the very subtle differences observed in the test-retest.

The authors acknowledge the following limitations. First, this was a retrospective study that utilized patients as controls rather than a matched cohort of healthy volunteers, which would be considered the gold standard comparison. However, enrolling healthy volunteers was deemed not feasible for the purposes of this study given the unnecessary exposure and cost of the WBCT scans. Another limitation is the AI software itself, which is currently unable to perform automatic segmentation in the setting of metal hardware in the foot. Therefore, while this software yields promising results, it may have limited applications in the postoperative setting when hardware is already present in the foot, at least for the time being. Furthermore, despite excluding patients with hardware from this study, the software had an observed failure rate of 22.4% (n = 26), and these scans were also excluded from the study analysis. While the specific reasons for failure could not be specifically investigated because of the small sample size, possible explanations range from the presence of external objects captured in the scan (observed in 7 cases, which all resulted in failures, repeatedly) to motion artifacts or any cause that may impede the automatic segmentation process. With respect to the software, these failures point to the infancy of this beta version and the potential for improvements to be made through the deep learning process. The AI in this case is based on a neural network. Therefore, the output of the algorithm may vary slightly, depending on the neural pathways used, explaining the infinitesimal differences observed in the test-retest reliability. As more data become available with the diffusion of WBCT into daily practice, the more efficient the deep learning process will become through this virtuous circle.

In this study, only 1 radiographic parameter of HV was measured. In that respect, future studies should aim to utilize this software in assessing additional measures of deformity, such as the HV angle (HVA) and sesamoid rotation. This will help create a more complete picture of the multiplanar deformity that is HV. Furthermore, the current study was limited to patients with a primary diagnosis of HV; patients with severe first metatarsal osteoarthritis and/or PCFD were excluded. Future studies should aim to evaluate this software in cases of arthritic changes and complex deformity. The authors postulate that the AI software—in its current state—may not be as efficient in recognizing and performing automatic segmentation of shorter bones or bones with more complex shapes. However, as alluded to earlier, this too may become more accurate and efficient as deep learning analyzes growing numbers of data sets.

Conclusion

The results of the current study demonstrate the reliability and validity of an AI-based, automatic measurement tool for the IMA, with the capability of identifying patients with HV using WBCT. The current AI software is still in the beta testing phase, and therefore future studies to evaluate clinical usability are warranted. Automatic measurement tools provide an intuitive and clinically meaningful way to harness 3D WBCT data with the potential of optimizing foot and ankle orthopedic care.

Declaration of Conflicting Interests

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