Original Article

Agreement between semiautomatic and manual measurement of selected parameters on weight-bearing computed tomography images in total ankle replacement: a retrospective study

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Abstract

Objective: To assess the agreement between semiautomatic 3D measurements and manual measurements derived from WBCT images in patients with end-stage ankle osteoarthritis (AO) who underwent total ankle replacement (TAR).

Methods: In this retrospective, IRB-approved study (ID #201904825), we evaluated patients who underwent TAR via the lateral trans-fibular approach for end-stage ankle OA. The study included 14 ankles from 14 patients. Raw multiplanar data were analyzed using CubeVue® software. Lateral talar station (LTS) was obtained in the sagittal plane, while hindfoot moment arm (HMA) and talar tilt angle (TTA) were calculated in the coronal view. Semiautomatic 3D measurements were performed using Disior® software. Intra-rater reliabilities were analyzed using the intraclass correlation coefficient (ICC). Agreement between methods was tested with Bland-Altman plots. Each measurement was assessed using the Wilcoxon signed-rank test. Alpha risk was set to 5% (α=0.05). P-values of ≤0.05 were considered significant.

Results: ICC-measured reliabilities ranged from moderate to almost perfect for manual and semiautomatic WBCT measurements in the preoperative and postoperative groups for HMA and LTS. There was high correlation between parameters calculated from manual and semiautomatic measurements, and strong agreement between the readers and software in both groups.

Conclusions: Manual (M) and semiautomatic (SA) 3D measurements expressed excellent agreement for pre- and postoperative groups, indicating a high correlation between the parameters calculated and strong agreement between the readers and the software in both groups.

Level of Evidence III; Therapeutic Studies; Comparative Retrospective Study.

Keywords: Ankle; Osteoarthritis; Arthroplasty, replacement, ankle; Tomography, x-ray computed; Weight-bearing.

Introduction

Ankle osteoarthritis (AO) is a chronic joint disease associated with discomfort, mobility issues, and reduced quality of life[1,2]. Approximately 1% of the population worldwide is affected by AO[3]. Unlike in other joints, primary or idiopathic AO is rare. A post-traumatic etiology is most common[4,5], with rotational ankle fractures and ligamentous injuries comprising the most common traumatic causes[6-8]. Total ankle replacement (TAR) has been advocated over ankle arthrodesis to correct AO, with evolving strategies and revisions each year to reduce complication rates[9-11]. However, bony overlap in conventional radiographs poses a challenge in the 3D evaluation of the ankle, and axial alignment of the ankle joint can be difficult to evaluate in the intraoperative management of AO[12]. Weight-bearing computed tomography (WBCT) has been increasingly adopted as a method well- equipped to assess the rotational elements of the ankle joint in the axial plane, addressing a limitation of standard radiographic evaluation[13-15]. Radiographic parameters obtained from these images can be valuable in the preoperative assessment and postoperative analysis of TAR for AO; thus, improvement in the acquisition, reliability, and accuracy of these measurements can influence treatment approaches and impact patient outcomes after deformity correction[16-19].

The use of semiautomated 3D measurements in WBCT images has recently been demonstrated to be reliable in assessing midfoot and hindfoot disorders[20-23], suggesting the potential for a method to characterize 3D joint morphology quickly and comprehensively. Compared to 2D measurements in weight-bearing radiographs, semiautomatic 3D measurements have proven more reliable in assessing foot and ankle alignment[13]. Kvarda et al.[20] showed that auto-generated 3D measurements using WBCT images of the midfoot and hindfoot were reliable in evaluating healthy individuals and patients with post-traumatic end-stage AO. Further, Lintz et al.[21], in a study on the development of periprosthetic cysts after TAR utilizing 3D multiplanar reconstruction, proposed the potential for 3D biometrics in the improvement of malalignment characterization in the foot and ankle.

No studies have examined the reliability of semiautomatic 3D measurements derived from WBCT in assessing patients who underwent TAR for end-stage AO. Validation of semiautomatic 3D measurements in this analysis may reveal a time-efficient and cost-efficient method to assess and treat patients with end-stage AO, and lay the groundwork for an AI-based evaluation in the future. In this study, we applied semiautomatic 3D measurement software to WBCT images of patients with end-stage AO who underwent TAR. Our aim was to assess the agreement between manual and semiautomatic 3D measurements derived from WBCT images, with the hypothesis that semiautomatic measurement would be as reliable and accurate as measurements performed manually in this setting.

Methods

A retrospective comparative study was performed, which analyzed existing data recorded as part of routine clinical care. The study was approved by the Institutional Review Board (ID #201904825) in accordance with the Health Insurance Portability and Accountability Act (HIPAA) and the provisions of the Declaration of Helsinki.

Subjects included were patients greater than 18 years of age who underwent TAR via a lateral trans-fibular approach for end-stage ankle OA, with at least 5° of coronal and/or sagittal plane deformity, and who underwent preoperative and postoperative WBCT. WBCT was used to assess each patient's ankle as a diagnostic standard. Exclusion criteria included patients who underwent TAR via an anterior ankle approach, patients with no ankle deformity in the coronal or sagittal planes, and patients with less than 9 months of clinical follow-up. The study included a total of 14 ankles (5 right and 9 left) in 14 patients, and the average age and BMI were 63.9 years (range, 43-83) and 32.7 kg/m^2 (standard deviation, 7.5).

Conventional Surgical Procedure

All surgical procedures were performed by a single fellowship-trained foot and ankle orthopedic surgeon with more than 10 years of experience. All patients received the Zimmer-Biomet® (Warsaw, Indiana, US) Trabecular Metal™ TAR (Figure 1).

Imaging acquisitions

WBCT scans were performed utilizing a cone-beam lower extremity CT scanner (pedCAT® Model, CurveBeam®, Warrington, FL, USA). Patients entered the scanner in a bipedal standing position and were instructed to bear weight equally between their lower limbs with their feet shoulder-width apart. Images were taken at 120 kVp and 5 mA with a maximum exposure of 10s. The volume was reconstructed with a 0.37-mm isotopic voxel.

Manual WBCT measurements

A single fellowship-trained foot and ankle orthopedic surgeon performed all WBCT measurements. De-identified, raw multiplanar data were translated into sagittal, coronal, and axial plane images and evaluated utilizing CubeVue® software (CurveBeam, LLC, Warrington PA, USA). Lateral talar station (LTS) was obtained using sagittal plane views, whereas hindfoot moment arm (HMA) and talar tilt angle (TTA) were calculated in the coronal plane (Figure 2).

Semiautomatic 3D WBCT measurements

Semiautomatic 3D measurements were performed utilizing the Disior® Bonelogic® Ortho Foot and Ankle Software (version 2.0; Helsinki, Finland). First, a file is selected in DICOM format for analysis, and the software automatically constructs a 3D isosurface of the bone tissue. Bone segmentation

is performed by placing at least one marker point on each visible bone in the rendered image for analysis. Deformable shape models were applied to obtain a patient-specific shape. Longitudinal axis estimates were generated for each patient-specific model by finding the center of the specific bones and analyzing cross-sections at different locations.

The software applied vigorous line-fitting techniques to select the straight-line representative for the center of the bone. Subsequently, the software automatically registered a mathematical model of the foot and ankle on the image and computed the location of measurement landmarks and longitudinal axes of the bones of interest (Figure 3).
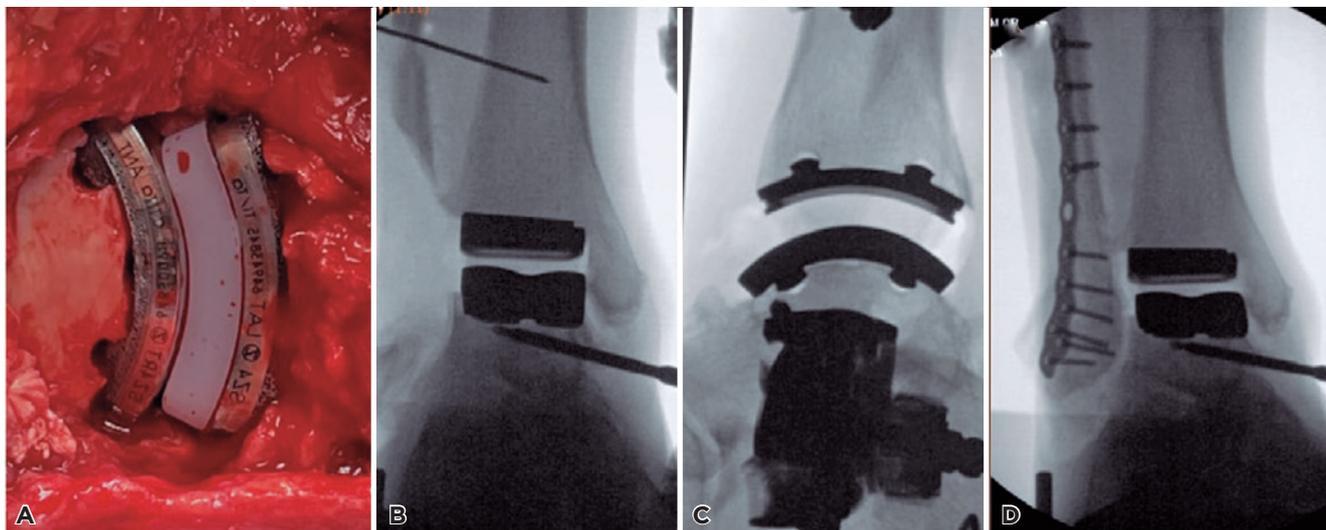
Figure 1. Lateral trans-fibular total ankle replacement. Final implant in place (A), and final positioning checked on the anteroposterior (B) and lateral (C) views. Final view: the fibula was reduced, and bone osteosynthesis was executed (D).
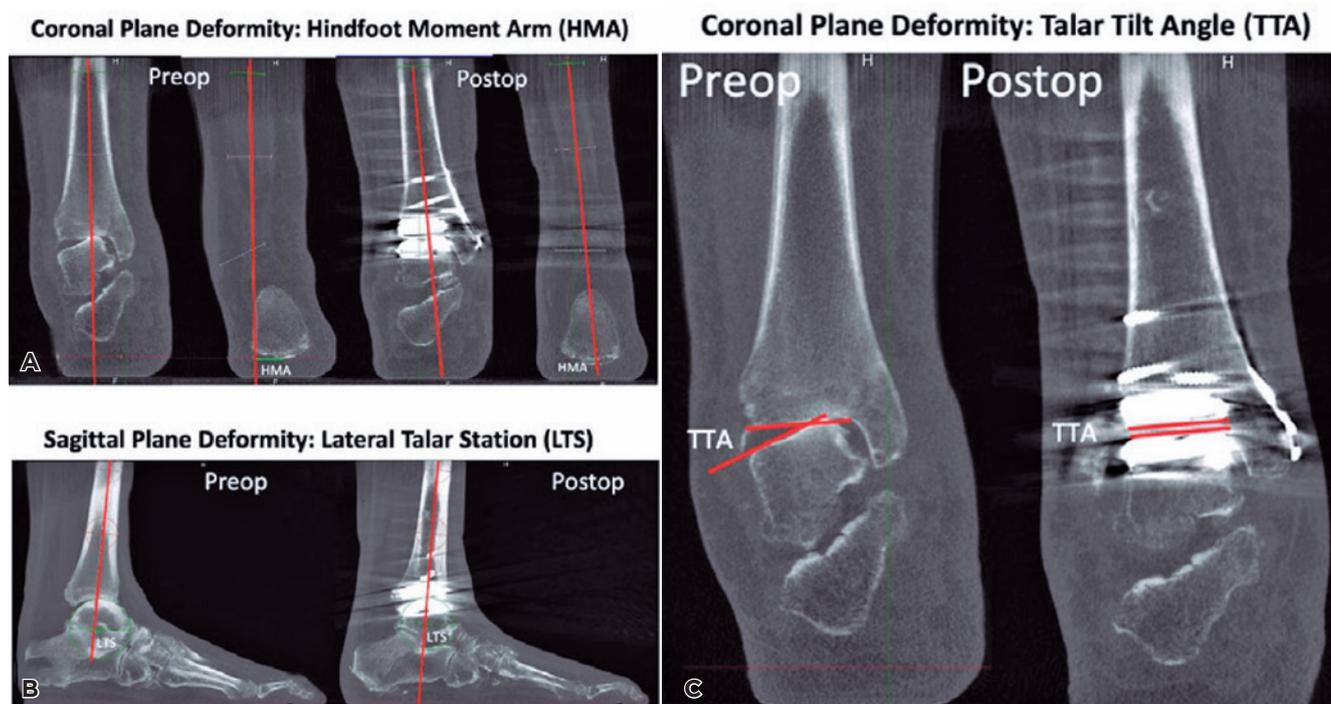
Figure 2. Manual measurements in preoperative and postoperative WBCT images: A) Hindfoot moment arm (HMA), B) Lateral talar station (LTS), and C) Talar tilt angle (TTA).
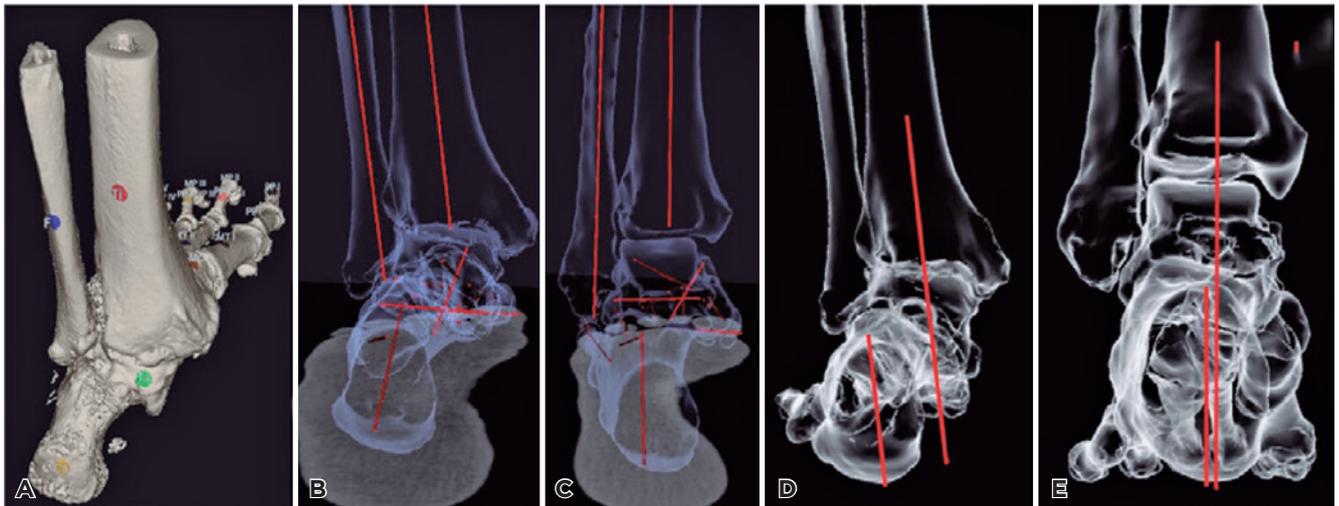
Figure 3. Raw multiplanar nonidentified data were converted into sagittal, coronal, and axial images and evaluated using dedicated software (CubeVue™). Bone segmentation performed using the DISIOR Bonelogic F&A Software (A). The software automatically registered a mathematical model of the foot and ankle on the image and computed the location of measurement landmarks and longitudinal axes of bones of interest producing semiautomatic 3D measurements; preoperative (ankle osteoarthritis) (B) and postoperative (after total ankle replacement) (C). Hindfoot Moment Arm (HMA) measured semiautomatically, in preoperative (D) and postoperative (E) images.

Statistical analysis

Each measurement was evaluated for normality using the Wilcoxon test, and descriptive statistics were obtained (mean and 95% confidence interval values). Intra-rater reliabilities for continuous data were analyzed using intraclass correlation coefficients (ICC).

A Pearson correlation coefficient was utilized to evaluate the linear relationship between the semiautomatic WBCT and manually performed WBCT measurements. Alpha risk was set to 5% ($\alpha=0.05$). Agreement between manual (M) and semiautomatic (SA) methods was evaluated using Bland-Altman plots. P-values of ≤ 0.05 were considered significant.

Results

ICC-measured reliability ranged from moderate to almost perfect for manual and semiautomatic WBCT measurements in the preop and postop groups for HMA and LTS (Table 1).

Mean manual and semiautomatic measurements of HMA, LTS, and TTA showed, as expected, a decrease in value when comparing the preoperative group with the postoperative group, and presented a statistically significant difference for HMA in manual and semiautomatic measurements (Tables 2 and 3).

According to Pearson coefficients, there was a high positive linear correlation between semiautomatic and measurements performed manually in the preoperative group for the two parameters evaluated (HMA, r=0.93, p<0.001; LTS, r=0.64, p=0.01). There was no significant positive linear correlation between the semiautomatic and manual measurements per-

formed for TTA (r=0.01; p=0.936). The same phenomenon occurred in the postoperative group, with a high, positive linear correlation for HMA (r=0.84; p<0.001) and LTS (r=0.66; p=0.01). There was no significant positive linear correlation between the semiautomatic and manual measurements for TTA (r=0.22; p=0.448).

Agreement between manual (M) and semiautomatic (SA) methods was tested for HMA, LTS, and TTA using Bland-Altman plots. This method expressed excellent agreement between manual and semiautomatic segmentation for the preoperative and postoperative groups. In the preoperative group, the plot shows that the mean difference between measurements for HMA was 0.48 degrees, with a 95% confidence interval of -6.81 to 5.86; for LTS, 2.64 mm, with a 95%CI of -5.58 to 10.85; and for TTA, 1.4 degrees, with a 95%CI of -30.83 to 28.03. In the postoperative group, the mean difference between measurements for HMA was 2.9 degrees, with a 95% confidence interval of -11.11 to 5.3; for LTS, it was 3.12 mm, with a 95%CI of -0.43 to 6.68; and for TTA it was 2.62 degrees, with a 95%CI of -12.69 to 17.91. These results indicated a high correlation between the parameters calculated from the manual and semiautomatic measurements, and strong agreement between the readers and the software in both groups (Figure 4).

Discussion

Our study revealed that computer-assisted semiautomatic WBCT image measurements in end-stage OA patients undergoing TAR are reliable and expressed excellent agreement between manual and semiautomatic segmentation for the

Table 1. Intraobserver Agreement and Consistency of Manual vs. Semi-Automatic Measurements Assessed by ICC[a]

	Pre-op			Post-op		
	Agreement (95% CI)	Consistency (95% CI)	P value	Agreement (95% CI)	Consistency (95% CI)	P value
HINDFOOT MOMENT ARM	0.697 (0.143-0.896)	0.706 (0.123-0.901)	0.014*	0.877 (0.522-0.963)	0.91 (0.719-0.971)	<0.001*
LATERAL TALAR STATION	0.725 (0.185-0.908)	0.778 (0.339-0.925)	0.004*	0.496 (0.235-0.842)	0.793 (0.335-0.933)	0.004*
TALAR TILT ANGLE	0.27 (0.00-0.686)	0.26 (0.00-0.673)	0.481	0.229 (0.00-0.596)	0.241 (0.00-0.602)	0.648

M, Manual measurement; SA, semi-automatic measurement.
[a] P values are based on F tests calculated using function icc() of *R* package irr.
*Statistical significance, P<.05.

Table 2. Comparison between Preop vs. Postop group using Manual measurement

	Preop Mean	Postop Mean	Mean difference	P value
HINDFOOT MOMENT ARM	10,61	5,98	4,63	<0.001*
LATERAL TALAR STATION	4,66	3,58	1,08	0,1
TALAR TILT ANGLE	2,87	0,37	2,5	0,176

aP values are based on Wilcoxon test.
*Statistical significance, P<.05.

Table 3. Comparison between Preop vs. Postop group using Semi-automatic measurement

	Preop Mean	Postop Mean	Mean difference	P value
HINDFOOT MOMENT ARM	11,28	8,19	3,09	0.006*
LATERAL TALAR STATION	3,78	1,49	2,29	0,07
TALAR TILT ANGLE	2,99	0,63	2,36	0,231

aP values are based on Wilcoxon test.
*Statistical significance, P < .05.

pre- and postoperative groups. We validated a high positive linear relationship between semiautomatic and manual measurements for HMA and LTS. However, no significant positive linear correlation was found for TTA in either group. This stands in contrast to previous studies, which have only focused on 3D measurements concerning end-stage posttraumatic AO or the assessment of foot and ankle alignment, not on how these measurements can be applied to evaluate a surgical approach[13, 20,21].

This study used semiautomatic WBCT measurements to evaluate patients with end-stage AO who underwent a lateral trans-fibular TAR. Previous studies have illustrated the superiority of WBCT over conventional radiography for assessing the foot and ankle[24,25], suggesting that this imaging method can more accurately characterize 3D joint morphology in comparison to 2D radiographs. It has been demonstrated that hindfoot alignment can be poorly evaluated in the cli-

nic[26] and that 2D radiographs have poor reproducibility[27,28]. Further, a study performed by de Cesar Netto and Richter[14] suggested that WBCT can mitigate certain flaws inherent to 2D imaging, such as errors in patient positioning, overlapping structures, and operator-related bias. These critiques are supported by others[13-15,22].

Bernasconi et al.[23] evaluated semiautomatic 3D measurements of WBCT images to assess hindfoot alignment in pes cavovarus, and found high intra- and inter-observer reliability regarding these measurements.

In a recent study, Kvarda et al.[13] examined 3D measurements generated from WBCT images of the midfoot and hindfoot by semiautomated software and assessed the reliability of these measurements in patients with posttraumatic end-stage AO. They concluded that this technique provided an accurate assessment of the hindfoot and midfoot, irrespective of the observer, and found that the automatically generated 3D measurements were reliable both in healthy patients and in patients with posttraumatic end-stage AO. They suggested that acquiring these measurements can impact patient outcomes and provider decision-making.

These studies confirmed our impression that semiautomatic 3D WBCT measurements expressed high intra-rater reliability in assessing foot and ankle hindfoot deformities.

While our study yielded significant findings, some limitations must be addressed: (1) we used a retrospective design; (2) while the software utilized to collect semiautomatic measurements calculates the parameters automatically, selection of the bone structures within the interface was done manually; (3) we did not measure image acquisition time, a software parameter subject to variability depending on the computer, and this must be accounted for; (4) this software is currently limited to select research institutions, and is still under development. Thus, there are some barriers to improving access to this novel technology.

Further research will need to be conducted for this technology to be integrated into clinical practice as a tool that can improve the time efficiency and accuracy of diagnosis, treatment planning, and decision-making by orthopedic surgeons.
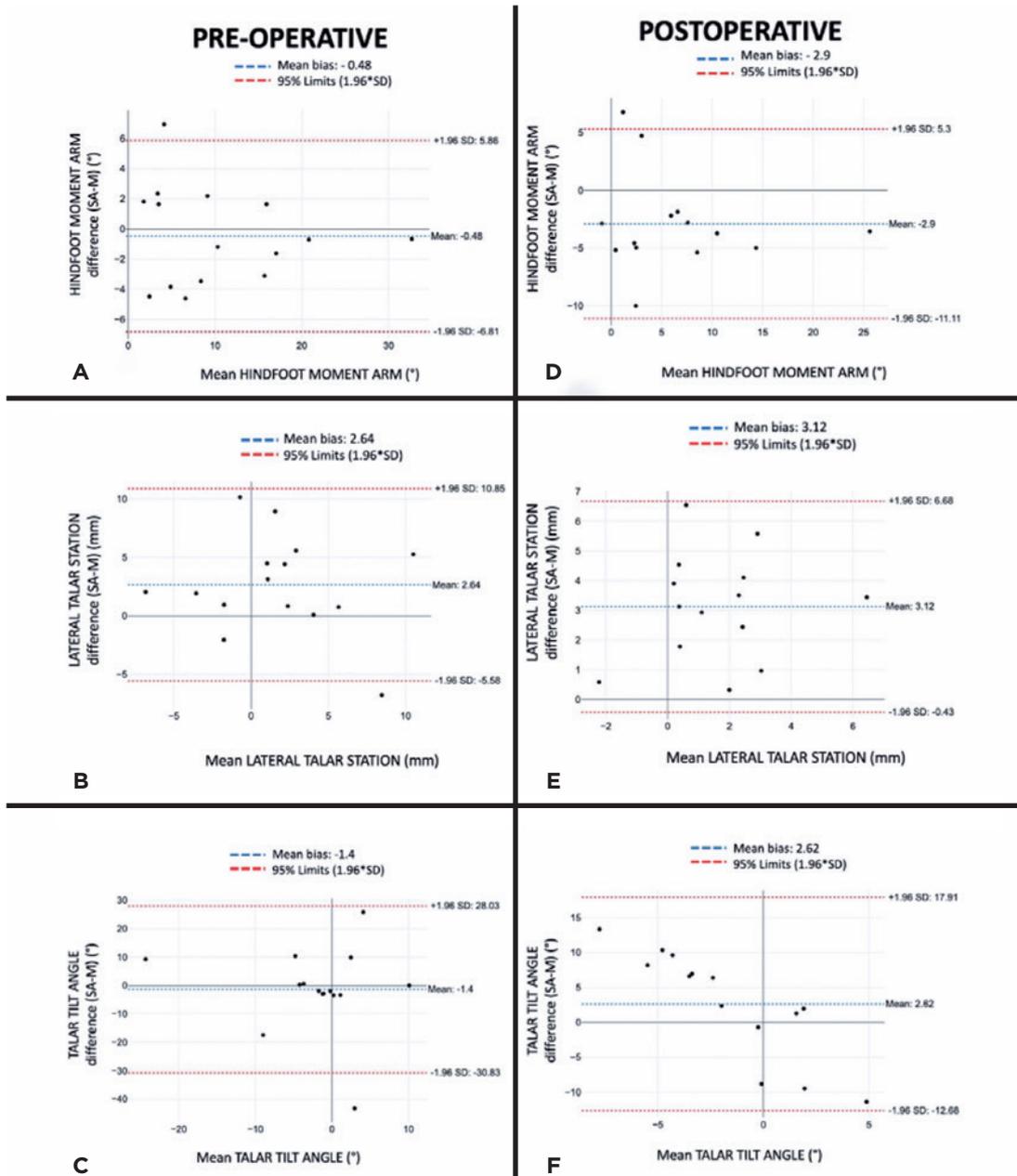
Figure 4. Bland-Altman plots for preoperative group: A) hindfoot moment arm, B) lateral talar station, and C) talar tilt angle; and for postoperative group: D) hindfoot moment arm, E) lateral talar station, and F) talar tilt angle. The mean for each pair of semiautomatic (SA) and manual (M) measurements is shown on the x-axis. The corresponding difference (bias) between each SA and M measurement (SA minus M) is shown on the y-axis. Dashed blue line represents the mean difference. Dashed red lines represent 95% limits of agreement (mean difference ± 1.96 standard deviation [SD] of the difference).

Conclusion

Our hypothesis that semiautomatic measurement in the setting of patients with end-stage AO who underwent TAR would be as reliable and accurate as measurements perfor-med manually was confirmed. Manual (M) and semiautomatic (SA) 3D measurements expressed excellent agreement for pre-and postoperative groups, indicating a high correlation between the calculated parameters, and strong agreement between the readers and the software in both groups.

Authors' contributions: Each author contributed individually and significantly to the development of this article: VM *(https://orcid.org/0000-0002-8612-5941) Conceived and planned the activities that led to the study, interpreted the results of the study, participated in the review process and approved the final version; RJ *(https://orcid.org/0000-0003-3448-1300) Data collection and interpreted the results of the study; MJ *(https://orcid.org/0000-0003-0773-7286) Data collection and interpreted the results of the study; CV *(https://orcid.org/0000-0002-7797-6111) Data collection and interpreted the results of the study; KAMC *(https://orcid.org/0000-0003-1082-6490) Interpreted the results of the study, participated in the review process and approved the final version; KCK *(https://orcid.org/0000-0002-3731-8448) Data collection and interpreted the results of the study; NSBM *(https://orcid.org/0000-0003-1067-727X) Interpreted the results of the study and approved the final version; KD *(https://orcid.org/0000-0002-8061-4453) Interpreted the results of the study and approved the final version; CCN *(https://orcid.org/0000-0001-6037-0685) Interpreted the results of the study and approved the final version. All authors read and approved the final manuscript. *ORCID (Open Researcher and Contributor ID) ⓘD.

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