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Automatic software-based 3D-angular measurement for Weight-Bearing CT (WBCT) provides different angles than measurement by hand

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ABSTRACT

Background: Purpose of this study was to compare automatic software-based angular measurement (AM, Autometrics, Curvebeam, Warrington, PA, USA) with previously validated measurement by hand (MBH) regarding angle values and time spent for the investigator for Weight-Bearing CT (WBCT).
Methods: Five-hundred bilateral WBCT scans (PedCAT, Curvebeam, Warrington, PA, USA) were included in the study. Five angles (1st - 2nd intermetatarsal angle, talo-metatarsal 1-angle (TMT) dorsoplantar and lateral projection, hindfoot angle, calcaneal pitch angle) were measured with MBH and AM on the foot/ankle (side with pathology). Angles and time spent of MBH and AM were compared (*t*-test, homoscedatic).
Results: The specific pathologies were ankle osteoarthritis/instability, n = 147 (29%); Haglund deformity/Achillodynia, n = 41 (8%); forefoot deformity, n = 108 (22%); Hallux rigidus, n = 37 (7%); flatfoot, n = 35 (7%); cavus foot, n = 10 (2%); osteoarthritis except ankle, n = 82 (16%). The angles differed between MBH and AM (each $p < 0.001$) except the calcaneal pitch angle (p = 0.05). The time spent for MBH / AM was 44.5 ± 12 s / 1 ± 0 s on average per angle ($p < 0.0011$).
Conclusions: AM provided different angles as MBH and can currently not be considered as validated angle measurement method. The investigator time spent is 97% lower for AM (1 s per angle) than for MBH (44.5 s per angle). Cases with correct angles in combination with almost no time spent showed the real potential of AM. The AM system will have to become reliable (especially in diminishing positive and negative angle values as defined) and valid which has to be proven by planned studies in the future.
Level of evidence: Level III

1. Introduction

Weight-bearing CT (WBCT) has been proven to allow for more precise and valid measurement of bone position (angles) than conventional weight-bearing radiographs and conventional CT without weight-bearing [1–3]. The measurement by hand (MBH) has demonstrated adequate inter- and intraobserver reliability but high time spent [1–3]. Therefore, the need for faster (semi-)automatic measurement was formulated [3]. Recently, an automatic software-based angular measurement (AM) has been developed (Autometrics, Curvebeam, Warrington, PA, USA). The purpose of this study was to compare AM with MBH regarding angle values and time spent for the investigator.

2. Methods

Five-hundred bilateral WBCT scans (PedCAT, Curvebeam, Warrington, PA, USA) were randomly extracted from a local institutional database with more than 14,000 scans. The foot/ankle side with pathology was included in the study, i.e. one foot per patient. The pathology was defined based on clinical, radiological and pedographic findings in the institution´s outpatient clinic. The pathology was classified into the following pathology groups: ankle osteoarthritis/instability, Haglund deformity/Achillodynia, forefoot deformity, Hallux rigidus, flatfoot, cavus foot, osteoarthritis except ankle. Five angles as shown in Table 1 were measured with MBH and AM on the right foot/ankle [1,4,5].

2.1. Measurement by hand (MBH) [1]

The angles were digitally measured with specific software (Cubevue, version 3.7.0.3, Curvebeam, Warrington, USA).

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Table 1
Angles measurement by hand (MBH) versus automatic measurement (AM) entire population (n = 500).

Parameter	MBH		AM		*t*-test, p
	mean	STD	mean	STD	
IM-angle	9.1	3.5	13.5	6.1	< 0.001
TMT dorsoplantar	-3.4	12.0	10.6	8.7	< 0.001
TMT lateral	-6.4	9.2	9.0	8.9	< 0.001
Hindfoot angle	4.6	7.5	22.5	6.2	< 0.001
Calcaneal pitch angle	20.5	5.4	21.4	5.3	0.005

IM, 1st - 2nd intermetatarsal angle; TMT, talo - 1st metatarsal - angle; STD, standard deviation.

The following angles were measured 1st - 2nd intermetatarsal angle, talo-metatarsal 1-angle (TMT) dorsoplantar and lateral projection, hindfoot angle, calcaneal pitch angle [1,6,7].

All bone axes (Tibia, talus, metatarsals) were defined as the straight line between the centers of the bones proximally and distally [1]. These bone centers were defined by linear measurements (Fig. 1a-d) [1].

The 1st - 2nd intermetatarsal angle was defined as the angle created between the axis of the 1st and the 2nd metatarsal in axial / horizontal reformation. The plane for the measurement was virtually rotated within the 3D-datase to achieve an exact congruency to the bone axes of 1st and 2nd metatarsals (Figs. 1a and 3a) [1].

The TMT angle was defined as the angle created between the axis of the 1st metatarsal and the talus (Fig. 1a and b) [1,6]. The dorsoplantar TMT angle was measured in the axial / horizontal reformation (Fig. 1b) [1]. The lateral TMT angle was measured in the parasagittal reformation (Figs. 1c and 3b) [1]. The plane for the measurement was virtually rotated within the 3D-datase to achieve an exact congruency to the bone axis of talus and 1st metatarsal [1].

Fig. 1. a-e. Monitor views showing an example of some angle measurements by hand (Cubevue, version 3.7.0.3, Curvebeam, Warrington, USA). 1st - 2nd intermetatarsal angle (Fig. 1a), talo-metatarsal 1-angle (TMT) dorsoplantar (Fig. 1b) and lateral projection (Fig. 1c), hindfoot angle (Fig. 1d), and calcaneal pitch angle (Fig. 1e).

The TMT angles were defined to be negative for abduction in the dorsoplantar radiograph and for dorsiflexion in the lateral radiographs [6].

The hindfoot angle was defined as the angle created between the axis of the distal tibia and the line between the center of the talar dome and the posterior calcaneal process (Figs. 1d and 3c) [1]. This angle was defined to be positive for hindfoot valgus and negative for hindfoot varus [1]. It was measured in the coronal reformation (Figs. 1d and 3c) [1]. The plane for the measurement was virtually rotated within the 3D-dataset to achieve an exact congruency to the bone axis of the tibia and the axis of the hindfoot (Fig. 1d) [1]. This was typically the case when this plane was congruent with the axis of the ankle, i.e. a line between medial and lateral malleolus comparable to a Mortise orientation but within a 3D-space [1]. Fig. 1d shows the orientation within the 3D dataset as described above with the adjusted rotation with the fibula and tibia aligned in the same virtual plane comparable to a Mortise view [1]. The calcaneal pitch angle was defined as the angle created between line between the lowest part of the posterior calcaneal process and the lowest part of the anterior calcaneal process, and a horizontal line. It was measured in the parasagittal reformation (Fig. 1e) [1]. The measurement was virtually rotated within the 3D-datase to achieve an exact congruency to an exactly parasagittal plane [1].

2.2. Automatic measurement (AM)

AM included software generated 3D models with automatic bone specification of tibia, fibula, talus, calcaneus, navicular, cuboid, cuneiforms and metatarsals (Autometrics, Curvebeam, Warrington, PA, USA)(Fig. 2a). The software automatically defined the longitudinal axes of these bones and automatically measures the angles between these axes: 1st - 2nd intermetatarsal angle (Figs. 2b and 3a), talometatarsal 1-angle (TMT) dorsoplantar (Fig. 2c) and lateral projection (Figs. 2d and 3c), and hindfoot angle (Figs. 2e and 3c). The calcaneal pitch angle was defined as the angle created between line between the lowest part of the posterior calcaneal process and the lowest part of the anterior calcaneal process, and a horizontal line (Fig. 2f).

2.3. Time spent

The time spent of the investigator for the measurements was recorded. The software calculation time for AM was not measured or considered as investigator time spent. To allow for statistical comparison between MBH and A, a time spent of 1 s per angle for A was defined.

2.4. Statistics

IBM SPSS Statistics Version 25 (IBM, Armonk, NY, USA) was used for the statistical evaluation. The angles and time spent of MBH and AM were compared (*t*-test, homoscedatic). The null hypothesis at a significant level of 0.05 was formulated that the different angles did not differ between the two methods. For non-significant findings, a power analysis was indicated. Sufficient power was defined as ≥ .8.

3. Results

3.1. Subjects

Mean age of the subject was 49 years (range, 18–85), 214 (43%) were male. 243 (49%) right and 257 (51%) left feet were analyzed with the following specific pathologies: ankle osteoarthritis/instability, n = 147 (29%); Haglund deformity/Achillodynia, n = 41 (8%); forefoot deformity, n = 108 (22%); Hallux rigidus, n = 37 (7%); flatfoot, n = 35 (7%); cavus foot, n = 10 (2%); osteoarthritis except ankle, n = 82 (16%).

3.2. Angle measurement - differences between methods

The angles differed between MBH and AM (each $p < 0.05$) (Table 1). The null hypothesis was rejected. The power was 0.91. Tables 2–4 show specific angles for different specific deformities (Forefoot, flatfoot, cavus foot). All angles differed between MBH and AM except calcaneal pitch angles in flatfoot and cavus foot deformity and TMT dorsoplantar angles in cavus foot deformities. Table 5 shows the same analysis as Table 1 with absolute angle values. TMT dorsoplantar and lateral angles and calcaneal pith angles did not differ between MBH and AM.

3.3. Time spent

The time spent for MBH / AM was 44.5 ± 12 s / 1 ± 0 s on average per angle ($p < 0.001$). The null hypothesis was rejected. The power was 0.98.

4. Discussion

Most studies about WBCT focused on bone position measurement accuracy and/or pathology detection [1,8–46]. However, all these studies included MBH by investigators. Only Lintz et al. introduced an semiautomatic measurement method with the so-called TALAS [47]. AM for commonly used angles as for example 1 st-2nd intermetatarsal angle in the 3D environment has been available since 2020, and has not been validated so far. We compared five angular measurements by hand that were validated before in 500 patients with AM [1–3]. We expected that the artificial intelligence of AM would provide valid angles, i.e. no differences in comparison with MBH. However, all angles measured with AM differed significantly from MBH. This finding was surprising but bit shocking for us. We were unsure if the previously validated MBH could have been executed wrongly, and therefore performed a detailed qualitative analysis in cases with different angular measurement results as shown in Figs. 3b and 3c. We found massively different angles in some cases as for example lateral TMT angle −8.2° versus 72.7° (Fig. 3b). We also found that some AM angle values that did massively differ from the real angle between the lines defined (Fig. 3c, angle value 144.66°; angle between lines 20°). Both findings are disturbing. For this discussion, we ran an analysis to find out how many of the 2500 angles differ more than ± 20%, ± 50%, ± 100% between MBH am AM. The result was 1350 (54%) were more than ± 100% different, 1642 (66%) more than ± 50%, and 2009 (80%) more than ± 20%. The findings with massively different and obviously wrong angles (Example Fig. 3b) were caused by false bone segmentations during AM. The reason for the difference between values and "lines" are unclear. Finally, AM seemed to work fine in some cases as for example shown in Fig. 3a but not in others, and it was not foreseeable when AM gives accurate angles and when not. Whatsoever, a valid AM shall not produce results like this. Our results are in contrast to the findings or Day et al. regarding automatic measurement of 1st-2nd intermetatarsal angle [48]. They observed accurate and reliable AM in 128 feet in 93 patients with the same method we used [48]. This study and cases from our study with correct AM angles in combination with almost no time spent showed the real potential of AM. The AM system will have to become reliable and valid which has to be proven by further studies in the future. Additionally, it needs to be defined how accurate angle measurements need to be. For example, the average calcaneal pitch angles with MBH was 20.5° and with AM 21.4° resulting in a difference of 0.9° respectively 3.6%. This difference of 0.9° (3.6%) with 500 feet measured resulted in the *t*-test with $p = 0.005$ which is highly

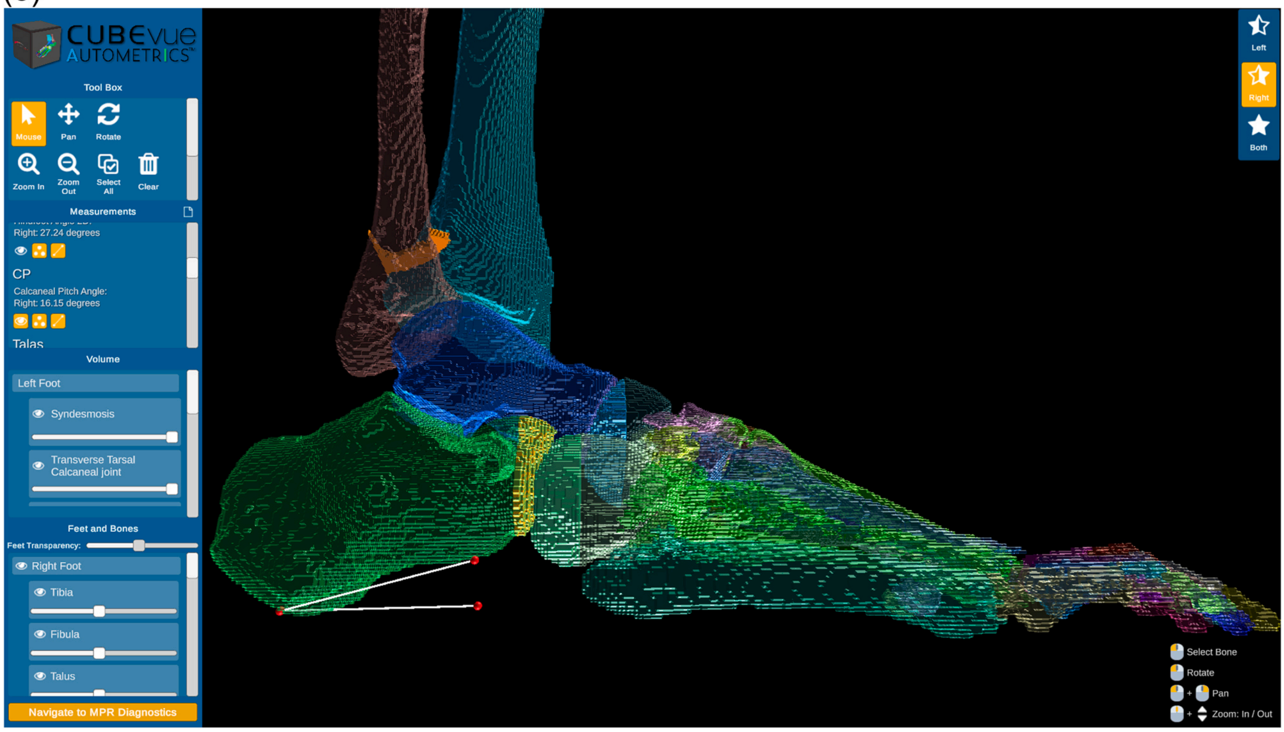
Fig. 2. a-f. Automatic measurement software monitor view (Autometrics, Curvebeam, Warrington, PA, USA)(Fig. 2a). The software generates a 3D model with automatic bone specification of tibia, fibula, talus, calcaneus, navicular, cuboid, cuneiforms, metatarsals and base phalanxes (Fig. 2a). The software automatically defines the longitudinal axes of these bones and automatically measures the angles between these axes: 1st - 2nd intermetatarsal angle (Fig. 2b), talo-metatarsal 1-angle (TMT) dorsoplantar (Fig. 2c) and lateral projection (Fig. 2d), and hindfoot angle (Fig. 2e). The calcaneal pitch angle was defined as the angle created between line between the lowest part of the posterior calcaneal process and the lowest part of the anterior calcaneal process, and a horizontal line (Fig. 2 f).

significant. Consequently, AM did not measure the same angles as MBH by statistical definition. On the other hand, one could argue that a difference of 0.9° is clinically not relevant. One could further argue that also MBH might result in different values when repetitively measured as shown in the initial validation studies [1,2]. The conclusion could be that AM measured the calcaneal pitch angles good enough or even valid despite the significant differences with MBH. However, for the four other angles, this conclusion would not be appropriate. The 1st - 2nd intermetatarsal angles with MBH was 9.1° on average and with AM 13.5°, i.e. 4.4° or 48% more ($p < 0.001$). One could not argue that this difference is clinically not relevant or that AM was still somehow good enough despite significant

Fig. 2. (*continued*)

differences in comparison with MHB as for the calcaneal pitch angle. The same for the hindfoot angles with 4.6° on average with MBH and 21.4°, i.e. 16.8° or 365% more on average with AM. 1st - 2nd intermetatarsal angles and hindfoot angles were at least the same principal direction relating positive and negative. A positive hindfoot angle reflects hindfoot valgus and MBH and AM resulted both in positive values. This was not the case for the talo - 1st metatarsal - angles (TMT). TMT dorsoplantar and lateral were negative with MBH (−3.4°/−6.4°) but positive with AM (10.6°/9.0°) on average. This means that the measurements with MBH resulted in midfoot/forefoot dorsiflexion respectively flatfoot (negative TMT lateral) and midfoot/forefoot abduction (negative TMT dorsoplantar). In contrast, the measurements with AM resulted in midfoot/forefoot plantiflexion respectively cavus foot (positive TMT lateral) and midfoot/forefoot adduction (positive TMT dorsoplantar). This means (approved by a qualitative case-to-case-analysis) that AM cannot

(e)



(f)

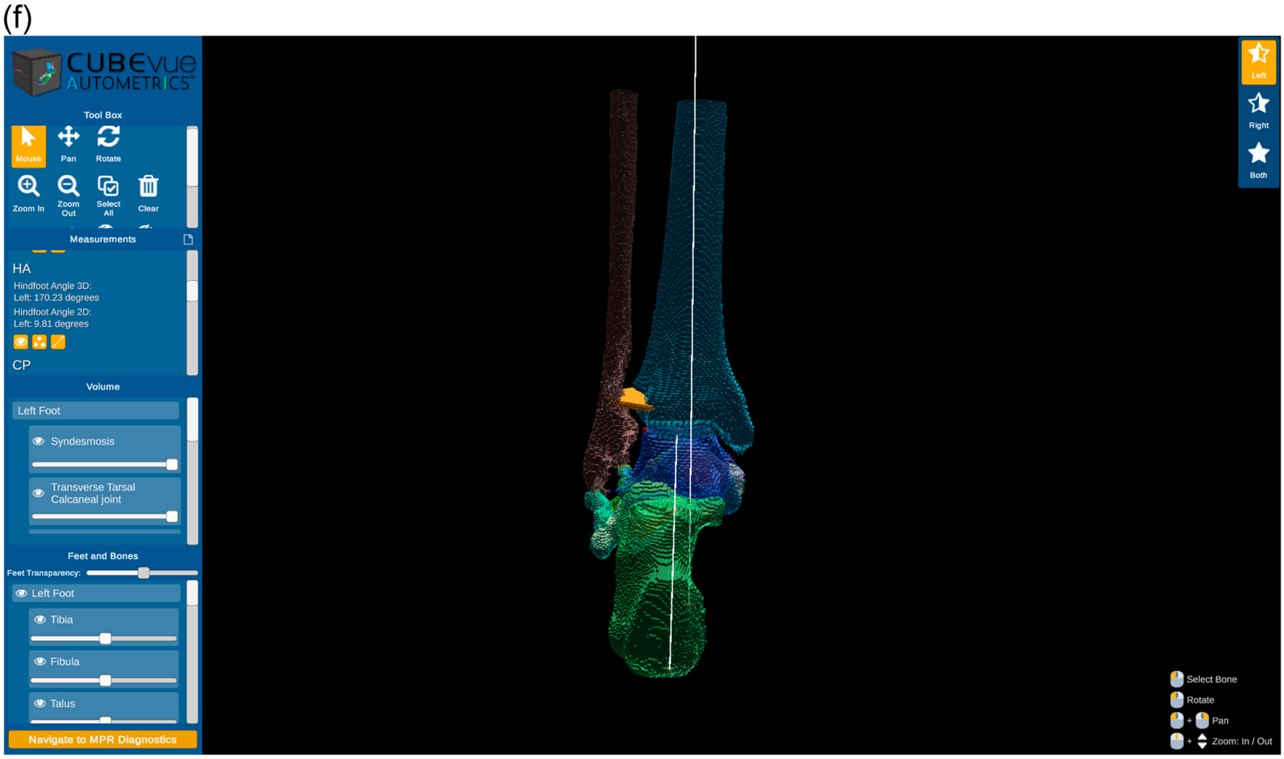


Fig. 2. (*continued*)

Table 2
Angles measurement by hand (MBH) versus automatic measurement (AM) in cases with forefoot deformity (n = 108).

Parameter	MBH		AM		*t*-test, p
	mean	STD	mean	STD	
IM-angle	10.7	3.8	14.3	3.4	< 0.001

IM, 1st - 2nd intermetatarsal angle; STD, standard deviation.

correctly diminish between flatfoot/cavus foot and midfoot/forefoot ab-/adduction. When looking into specific deformities and specific angles, the situation changes a little. The 1st - 2nd intermetatarsal angles did still differ between MBH and AM in forefoot deformities (n = 108) (Table 2). In flatfoot deformities (n = 35), the calcaneal pitch angles did not differ between MBH and AM but TMT dorsoplantar and lateral angles and hindfoot angles did still differ (Table 3). In hindfoot deformities (n = 10), the calcaneal pitch angles and TMT dorsoplantar angles did not differ between MBH and AM but TMT

Table 3
Angles measurement by hand (MBH) versus automatic

measurement (AM) with flatfoot deformity (n = 35)Parameter	MBH		AM		*t*-test, p
	mean	STD	mean	STD	
TMT dorsoplantar	-15.3	12.6	16.3	8.8	< 0.001
TMT lateral	-16.8	6.6	10.9	5.9	< 0.001
Hindfoot angle	13.1	6.0	27.7	5.9	< 0.001
Calcaneal pitch angle	17.1	6.8	17.4	6.5	0.842

TMT, talo - 1st metatarsal - angle; STD, standard deviation.

Table 4
Angles measurement by hand (MBH) versus automatic

measurement (AM) with Cavus foot deformity (n = 10)Parameter	MBH		AM		*t*-test, p
	mean	STD	mean	STD	
TMT dorsoplantar	15.5	16.0	13.9	12.9	0.803
TMT lateral	6.5	10.0	15.8	8.4	0.037
Hindfoot angle	-9.6	6.4	15.2	5.0	< 0.001
Calcaneal pitch angle	24.5	4.2	29.3	6.4	0.059

TMT, talo - 1st metatarsal - angle; STD, standard deviation.

Table 5
Angle measurement by hand (MBH) versus automatic

measurement (AM) entire population (n = 500) with absolute values parameter	MBH		AM		*t*-test, p
	mean	STD	mean	STD	
IM-angle	9.1	3.5	13.5	6.1	< 0.001
TMT dorsoplantar	9.7	7.9	10.6	8.7	0.067
TMT lateral	8.9	6.9	9.0	8.9	0.793
Hindfoot angle	7.0	5.2	22.5	6.2	< 0.001
Calcaneal pitch angle	20.5	5.4	21.4	5.3	0.005

IM, 1st - 2nd intermetatarsal angle; TMT, talo - 1st metatarsal - angle; STD, standard deviation.

lateral angles and hindfoot angles did still differ (Table 4). However, the statistical power of this deformity specific analysis was only sufficient for forefoot deformities, i.e. the missing differences in some angles might be caused by too low case numbers. One issue could be that AM was just not able to determine negative angle values. We therefore analyzed also absolute values (without +/-) (Table 5). However, this did not change the significances for 1st - 2nd intermetatarsal angles, hindfoot angles and calcaneal pitch angles. Interestingly, TMT dorsoplantar and lateral angles did not differ between MBH and AM despite sufficient statistical power. It seems that the insufficient detection of negative has partly caused the significances. This is of theoretical value because a method that is not able to diminish between positive and negative angles would not be useful and never valid.

4.1. Shortcomings of the study

Potential shortcomings of the study are low case number and questionable validity of MBH. Five measured angles in 500 feet sum up to 2500 angles in addition to highly significant differences between measurement types ensures adequate case number. MBH as used in this study was performed exactly as used before [1,2]. In these earlier studies, MBH showed excellent intra- and interobserver reliability, and adequate validity was therefore concluded [1,2]. One could argue that high intra- and interobserver reliability does not ensure adequate validity as discussed before [1,2]. A qualitative analysis as performed in this study support the validity of MBH.

In conclusion, AM provided different angles as MBH and can currently not be considered as validated angle measurement method. The investigator time spent is 97% lower for AM (1 s per angle) than for MBH (44.5 s per angle). Cases with correct angles in

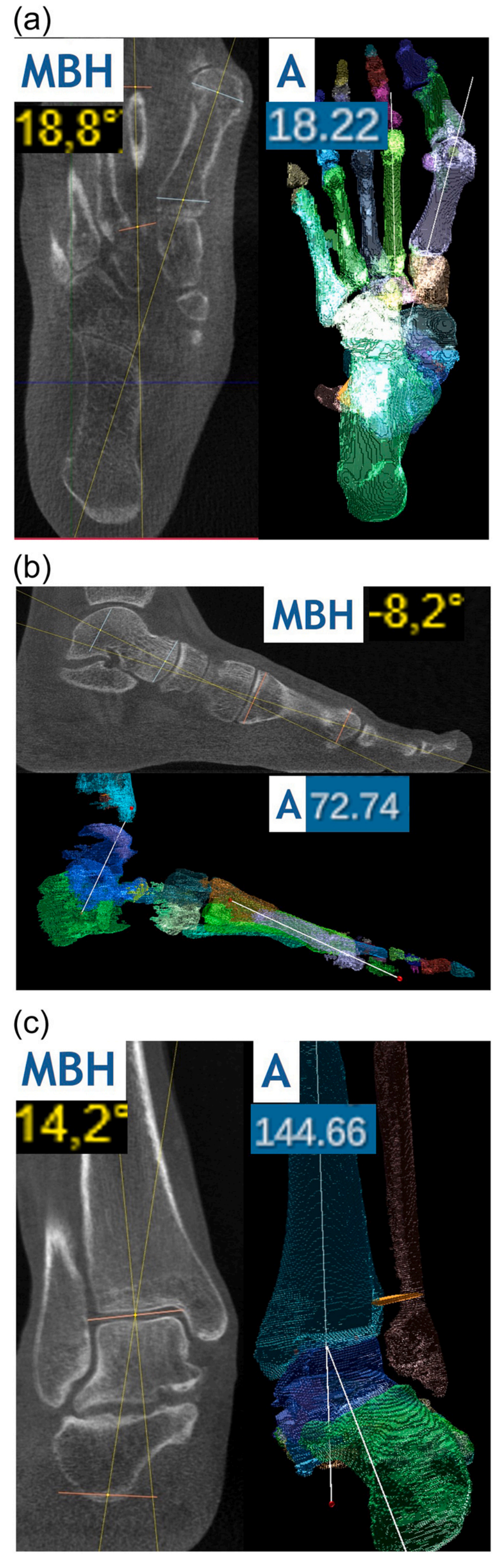


Fig. 3. a-c. Comparison measurements by hand (MBH) with automatic measurement (A) 1st - 2nd intermetatarsal angle (Fig. 3a), talo-metatarsal 1-angle (TMT) lateral projection (Fig. 3b), and hindfoot angle (Fig. 3c) in different feet. The angle values are shown as provided by the measurement software as described in Figs. 1 and 2. The 1st - 2nd intermetatarsal angle (Fig. 3a) was 18.8° provided with MBH and 18.22° with A. The talo-metatarsal 1-angle (TMT) lateral projection (Fig. 3b) was −8.2° provided with MBH and −72.74° with A. The hindfoot angle (Fig. 3c) was 14.2° provided with MBH and 144.66° with A. The 144.66° hindfoot angle value does not correspond to the image in which an angle of approximately 20° is shown.

combination with almost no time spent showed the real potential of AM. The AM system will have to become reliable (especially in diminishing positive and negative angle values as defined) and valid which has to be proven by planned studies in the future. Until then, manual checking of automatic measurement results is obligatory.

Conflict of interest statement

None of the authors or the authors´ institution received funding in relation to this study. The first and corresponding author is consultant of C, G, I, O and II, proprietor of R, and shareholder of C (Company names abbreviated to enable blinded review).

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