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Automatic software-based 3D-angular measurement for weight-bearing CT (WBCT) is valid

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ABSTRACT

Background: The purpose of this study was to compare automatic software-based angular measurement (AM) with validated measurement by hand (MBH) regarding angle values and time spent for Weight-Bearing CT (WBCT) generated datasets.
Methods: Five-hundred WBCT scans from different pathologies were included in the study. 1st - 2nd intermetatarsal angle, talo-1st metatarsal angle dorsoplantar and lateral, hindfoot angle, calcaneal pitch angle were measured and compared between MBH and AM.
Results: The 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 did not differ between MBH and AM (each $p > 0.36$). The time spent for MBH / AM was 44.5 / 1 s on average per angle ($p < .001$).
Conclusions: AM provided angles which were not different from validated MBH and can be considered as a validated angle measurement method. The time spent was 97% lower for AM than for MBH.
Levels 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 [1–4]. The measurement by hand (MBH) has demonstrated adequate inter- and intraobserver reliability but high time spent for the investigator [1–3]. Therefore, the need for faster automatic measurement was formulated [3]. In 2020, automatic software-based angular measurement (AM) was introduced (Autometrics, Curvebeam AI, Hatfield, PA, USA) [4]. A previous study was performed to compare AM with MBH regarding angle values and time spent for the investigator [4]. In this previous study, AM provided different angles as MBH and was not considered as a validated angle measurement method [4]. The further conclusion of this previous study was that the AM system would have to become reliable (especially in distinguishing positive and negative angle values as defined) and valid which would have to be proven by studies in the future [4]. The AM system was modified several times until a new version (Autometrics 2.0, Curvebeam AI, Hatfield, PA, USA) was deployed. The purpose of this study was to compare the updated version of AM with MBH regarding angle values and time spent for the investigator with the same method as before [4]. The null hypothesis was that the different angles and the investigator time spent for the measurements did not differ between AM and MBH.

2. Methods

In this retrospective comparative study, our weightbearing CT database from more than 14,000 scans between February 2013 and December 2020 was used. The same methods including case selection and measurements as in a previous study were repeated [4]. No WBCT scans were performed for the study but existing scans were included and anonymized following the request from the institutional authority for data protection [4]. Five-hundred bilateral WBCT scans were randomly extracted [4]. No exclusion criteria were defined. The foot/ankle side with pathology was included in the study, i.e. one foot per patient [4]. The pathology was defined based on clinical, radiological and pedographic findings in the institution´s outpatient clinic [4]. The pathology was classified into the following pathology groups: ankle osteoarthritis/instability, Haglund deformity/Achillodynia, forefoot deformity, Hallux rigidus, flatfoot, cavus

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

Parameter	MBH		AM		t-test, p
	mean	STD	mean	STD	
IM	9.1	3.5	9.2	3.7	0.55
TMT dorsoplantar	-3.4	12.0	-2.7	12.7	0.37
TMT lateral	-6.4	9.2	-6.0	11.2	0.47
Hindfoot angle	4.6	7.5	4.4	6.7	0.61
Calcaneal pitch angle	20.4	5.4	20.7	5.7	0.52

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

foot, osteoarthritis except ankle [4]. Five angles as shown in Table 1 were measured with MBH and AM on the specified side [1,2,4].

2.1. Measurement by hand (MBH)[1]

The results from MBH from the previous study were included in this study [4]. The angles were digitally measured with specific software (Cubevue, version 3.7.0.3, Curvebeam AI, Hatfield, PA, USA).

The following angles were measured 1st - 2nd intermetatarsal angle, talo-metatarsal 1-angle (TMT) dorsoplantar and lateral projection, hindfoot angle, calcaneal pitch angle [1,4–6].

All bone axes (Tibia, talus, metatarsals) were defined as the straight line between the centres 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 (Fig. 1a) [1].

The TMT angle was defined as the angle created between the axis of the 1st metatarsal and the talus (Fig. 1b-c) [1,5]. The dorsoplantar TMT angle was measured in the axial / horizontal reformation (Fig. 1b) [1]. The lateral TMT angle was measured in the parasagittal reformation (Fig. 1c) [1]. The TMT angles were defined to be negative for abduction for dorsiflexion (Fig. 1c) and positive for abduction (Fig. 1b) and plantarflexion [5].

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 in paracoronal reformation (Fig. 1d) [1]. This angle was defined to be positive for hindfoot valgus and negative for hindfoot varus [1].

The calcaneal pitch angle was defined as the angle created between the line between the lowest part of the posterior calcaneal process and the lowest part of the anterior calcaneal process, and a horizontal line in parasagittal reformation [1].

2.2. Automatic measurement (AM)

AM included software generated 3D models with automatic bone specification of tibia, fibula, talus, calcaneus, navicular, cuboid, cuneiform 1–3 and metatarsal 1–5, medial and lateral sesamoid, proximal/base phalanx 1–5, middle phalanx 2–5 and distal/end phalanx 1–5 (Fig. 2a and b) [4]. The same angles with the same definition as MBH were measured with AM (Result illustrated in Fig. 3a-e) [4]. Four angles (IM angle, TMT dorsoplantar and lateral and hindfoot angle) included the automatic definition of bone axes (Tibia, talus and 1st metatarsal), one angle (Calcaneal inclination) included the definition of a tangential line of a bone (Calcaneus), one angle (Hindfoot angle) included the automatic definition of a line between the center of two bones (Tibia and calcaneus) and one angle (Calcaneal inclination) the automatic definition of a line parallel to the floor.

2.3. Time spent

The time spent of the investigator for the measurements was recorded [4]. The software calculation time for AM was not measured or considered as investigator time spent [4]. To allow for statistical comparison between MBH and A, a time spent of 1 s per angle for A was defined [4].

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) [4]. The null hypothesis at a significant level of 0.05 was formulated that the different angles and the investigator time spent for the measurements did not differ between the two methods [4]. For non-significant findings, a power analysis was indicated [4]. Sufficient power was defined as ≥0.8 [4].

3. Results

3.1. Patients

Mean age of the patients 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%). Metal implants were detected in 48 (10%) scans (for example Fig. 3d, c and e).

3.2. Angle measurement - differences between methods

The angles did not differ between MBH and AM (each $p > 0.05$) (Table 1). The null hypothesis was rejected. The power was 0.92. Tables 2–4 show specific angles for different specific deformities (Forefoot deformity, flatfoot, cavus foot). The null hypothesis that the different angles for the measurements did not differ between AM and MBH was not rejected. The power was 0.98.

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 that the investigator time spent for the measurements did not differ between AM and MBH was rejected.

4. Discussion

In an earlier study, we expected that the artificial intelligence of AM would provide valid angles, i.e. no differences in comparison with MBH [4]. However, all angles measured with AM significantly differed from MBH [4]. Significantly different angles in some cases as for example lateral TMT angle −8.2° versus 72.7° were found [4]. Some AM angle values that massively differed from the real angle between the lines defined (angle value 144.66°; angle between lines 20°) were also found [4]. 1350 (54%) of all angles measured by AM were more than ± 100% different from angles measured by MBH [4]. The findings with massively different and obviously wrong angles were caused by incorrect bone segmentations as part of the AM process [4]. The results of the earlier study were in contrast to the findings or Day et al. regarding automatic measurement of 1 st-2nd intermetatarsal angle [7]. They reported much less differences between MBH and AM in 128 feet in 93 patients with the same method we used (mean 1st-2nd intermetatarsal angle MBH, 15.44; AM, 16.80) [7]. They also reported problems with the bone segmentation

Fig. 1. a-e [4]. Monitor views showing an example of some angle measurements by hand. 1st - 2nd intermetatarsal angle, 18.8° (Fig. 1a), talo-metatarsal 1-angle (TMT) dorsoplantar, 24.8° (Fig. 1b) and lateral, −8.2° (Fig. 1c), hindfoot angle, 0° (Fig. 1d), and calcaneal pitch angle, 16.8° (Fig. 1e).

with AM especially in cases with implants like plates and/or screws [7].

In the current study, the angle values between MBH and AM did not differ for the group of all patients (n = 500) with sufficient statistical power (Table 1). The angles of subgroups with forefoot deformity (n = 108; IM angle), flatfoot (n = 35, TMT dorsoplantar and lateral, hindfoot angle and calcaneal inclination) and cavus foot (n = 10, TMT dorsoplantar and lateral, hindfoot angle and calcaneal inclination) did also not differ between MBH and AM. One could argue that the case numbers in the subgroups flatfoot (n = 35) and cavus foot (n = 10) are too low with consequent insufficient statistical power, but the same angles (TMT dorsoplantar and lateral, hindfoot angle and calcaneal inclination) were also compared in the entire group (n = 500) without differences between MBH and AM and sufficient statistical power. Furthermore, the absolute angle differences between MBH and AM were low (mean and single values) with neglectable clinical relevance as discussed before [4]. AM could correctly distinguish between positive and negative values in this study which was not the case in the initial study [4]. This is important as positive angle values of TMT dorsoplantar means midfoot/forefoot adduction, of TMT lateral cavus, and of hindfoot angle varus. In contrast, negative angle values of TMT dorsoplantar means midfoot/forefoot abduction, of TMT lateral dorsiflexion (comparable flatfoot), and of hindfoot angle valgus. Consequently, AM could correctly distinguish between flatfoot and cavus foot, midfoot/forefoot adduction and abduction and hindfoot varus and valgus. We included 5 different angles in this study. Four angles (IM angle TMT dorsoplantar and lateral and hindfoot angle) included the definition of bone axes (Tibia, talus and 1st metatarsal), one angle (Calcaneal inclination) included the definition of a tangential line of a bone (Calcaneus), one angle (Hindfoot angle) included a line between the center of two bones (Tibia and calcaneus) and one angle (Calcaneal inclination) a line parallel to the floor. With this variety of different axes and line definitions, other angles could also be measured as for example Hallux valgus angle. As in the earlier study, we did not exclude cases/scans with (metal) implants in the current

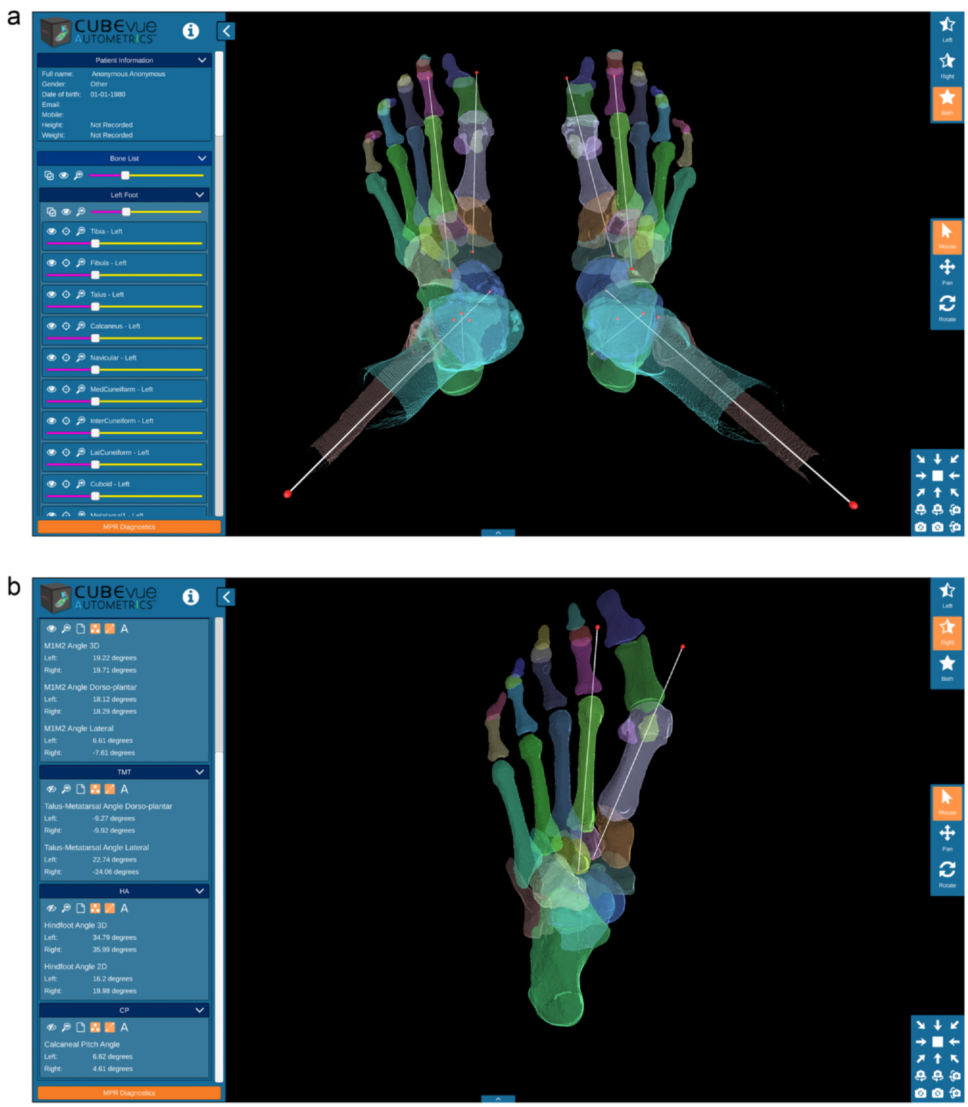

Fig. 2. Automatic measurement software monitor view (Autometrics 2.0, Curvebeam, Warrington, PA, USA). The software generates a 3D model with automatic bone specification of tibia, fibula, talus, calcaneus, navicular, cuboid, cuneiform 1–3 and metatarsal 1–5, medial and lateral sesamoid, proximal/base phalanx 1–5, middle phalanx 2–5 and distal/end phalanx 1–5 (Fig. 2a) [4]. The software automatically defined the longitudinal axes of the relevant bones and automatically measures the angles between these axes. Fig. 2b shows the same case as Figs. 1a and 3a. On the left part of the screen, the automatically measured angles are displayed such as the 1st - 2nd intermetatarsal angle in the so-called dorsoplantar plane (18.29).

study [4]. Consequently, the currently investigated AM generation could deal with metal implants (Fig. 3b, c and e) which was considered as problematic with the initial AM generation [4,7].

4.1. Shortcomings of the study

Potential shortcomings of the study are low case number and questionable validity of MBH [4]. Five measured angles in 500 feet sum up to 2,500 angles in addition to highly significant differences between measurement types ensures adequate case number. MBH as used in this study was performed exactly as previously published [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]. We did not observe clinically relevant angle differences between MBH and AM in this study. However, we still do recommend that the human investigator reviews the AM data and corresponding images to detect implausible angles which have been observed in the past and could still be observed, despite obvious improvements in the current version of the software [4]. No angles with articular angle such as distal metatarsal angle was included in the study. MBH was not validated for the type of angle and therefore we did not include this type of angle in this and the previous study [4]. We would expect that AM would be able to define the articular axis as bone axis, tangential line of a bone or a line between the center of two bones as in this study. The time spent was only analyzed for the investigator but not for processing times of AM [4]. The repeated AM with updated software versions showed that processing times massively decreased (data not shown). Analysis of these times would probably be obsolete before finishing the analysis.

In conclusion, AM measured angles which were not different from validated MBH and can be considered as validated angle measurement method. The investigator time spent for the measurements is 97% lower for AM (1 s per angle) than for MBH (44.5 s per angle). As a future research direction, the further development and validation of automated 3D measurements should also focus on articular angles, such as the distal metatarsal angle.

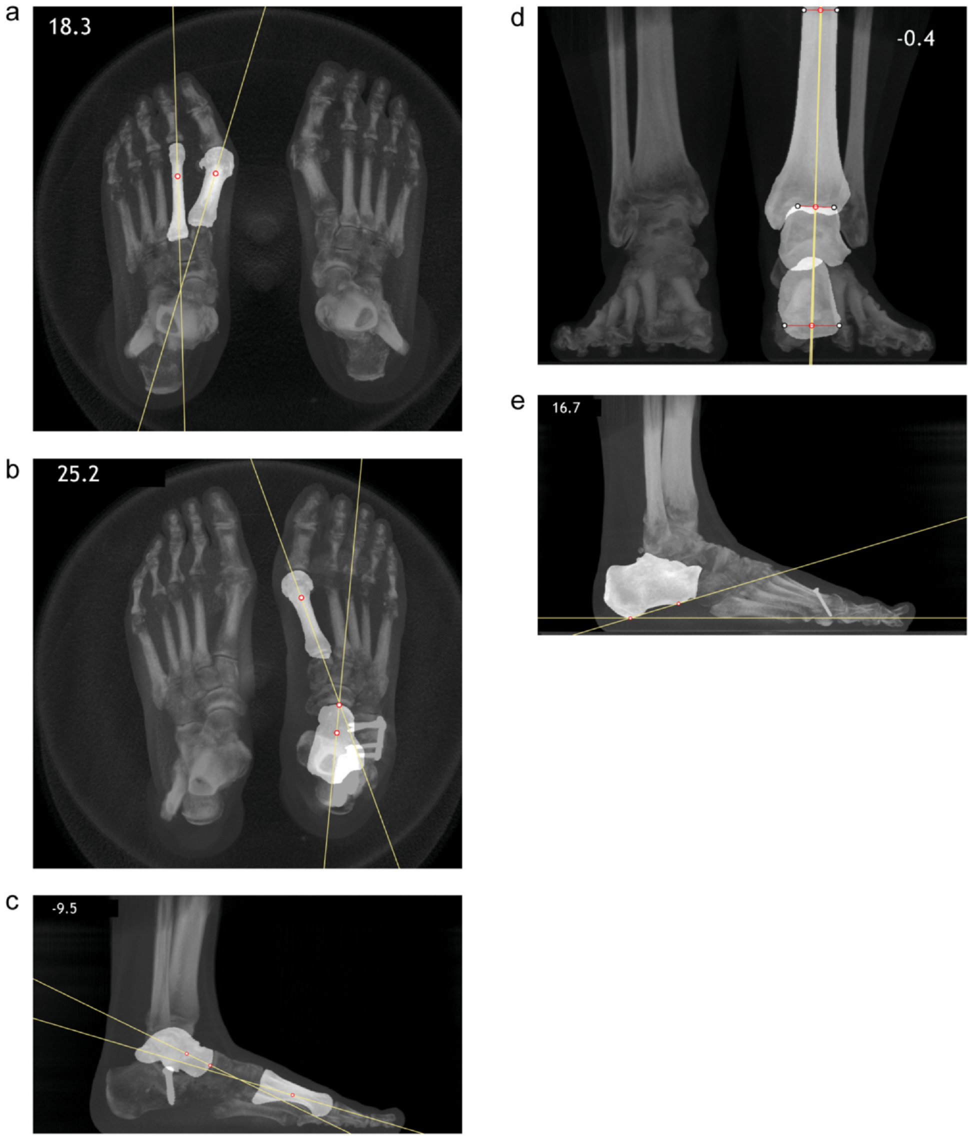

Fig. 3. a-e. Automatic measurement (AM). The figures illustrate the results of the AM process. Same cases/angles as measurements by hand (MBH, Fig. 1a-e): 1st - 2nd intermetatarsal angle, 18.3° (Fig. 3a), talo-metatarsal 1-angle (TMT) dorsoplantar, 25.2° (Fig. 3b) and lateral, − 9.5 (Fig. 3c), hindfoot angle, − 0.4° (Fig. 3d), and calcaneal pitch angle, 16.7° (Fig. 3e).

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

Parameter	MBH		AM		t-test, p
	mean	STD	mean	STD	
IM	10.7	3.8	11.0	4.3	0.52

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

Table 3
Angles measurement by hand (MBH) versus automatic measurement (AM) in patients with flatfoot deformity (n = 35).

Parameter	MBH		AM		t-test, p
	mean	STD	mean	STD	
TMT dorsoplantar	-15.3	12.6	-15.2	13.0	0.95
TMT lateral	-16.8	6.6	-18.1	8.9	0.49
Hindfoot angle	13.1	6.0	11.3	5.9	0.20
Calcaneal pitch angle	17.1	6.8	16.9	6.5	0.93

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

Table 4
Angles measurement by hand (MBH) versus automatic measurement (AM) in patients with Cavus foot deformity (n = 10).

Parameter	MBH		AM		t-test, p
	mean	STD	mean	STD	
TMT dorsoplantar	15.5	16.0	19.5	14.7	0.58
TMT lateral	6.5	10.0	10.4	7.4	0.33
Hindfoot angle	-9.6	6.4	-8.1	6.7	0.61
Calcaneal pitch angle	24.5	4.2	25.2	6.5	0.76

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

Declaration of Competing Interest

None of the authors or the authors´ institution received funding in relation to this study. The first and corresponding author is consultant of Curvebeam AI, Geistlich, Intercus, Ossio and Implants International, proprietor of R-Innovation, and shareholder of Curvebeam AI.

References

[1] Richter M, Seidl B, Zech S, Hahn S. PedCAT for 3D-imaging in standing position allows for more accurate bone position (angle) measurement than radiographs or CT. Foot Ankle Surg 2014;20:201–7.

[2] Richter M, Zech S, Hahn S, Naef I, Merschin D. Combination of pedCAT for 3D imaging in standing position with pedography shows no statistical correlation of bone position with force/pressure distribution. J Foot Ankle Surg 2016;55(2):240–6.

[3] Richter M., Lintz F., Cesar de Netto C., Barg A., Burssens A., Ellis S. Weight Bering Cone Beam Computed Tomography (WBCT) in the Foot and Ankle. A Scientific, Technical and Clinical Guide, Springer Nature, Cham, Switzerland, 2020.

[4] Richter M, Schilke R, Duerr F, Zech S, Andreas Meissner S, Naef I. Automatic software-based 3D-angular measurement for Weight-Bearing CT (WBCT) provides different angles than measurement by hand. Foot Ankle Surg 2022;28(7):863–71.

[5] Richter M, Zech S. Lengthening osteotomy of the calcaneus and flexor digitorum longus tendon transfer in flexible flatfoot deformity improves Talo-1st metatarsal-index, clinical outcome and pedographic parameter. Foot Ankle Surg 2012;19(1):56–61.

[6] Saltzman CL, el-Khoury GY. The hindfoot alignment view. Foot Ankle Int 1995;16(9):572–6.

[7] Day J, de Cesar Netto C, Richter M, Mansur NS, Fernando C, Deland JT, et al. Evaluation of a weightbearing CT artificial intelligence-based automatic measurement for the M1-M2 intermetatarsal angle in hallux valgus. Foot Ankle Int 2021;42(11):1502–9.