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Comparison of the Usefulness of Computer-Assisted Three-Dimensional Analysis and Weight-Bearing Radiographs in Ankle Osteoarthritis

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Background: To evaluate the degree of deformation in patients with ankle osteoarthritis (OA), it is essential to measure the three-dimensional (3D), in other words, stereoscopic alignment of the ankle, subtalar, and foot arches. Generally, measurement of radiological parameters use two-dimensional (2D) anteroposterior and lateral radiographs in a weight-bearing state; however, computer-aided 3D analysis (Disior) using weight-bearing cone-beam computed tomography (CBCT) has recently been introduced.

Methods: In this study, we compared the 2D human radiographic method with a stereoscopic image in patients with ankle arthritis. We enrolled 57 patients diagnosed with OA (28 left and 29 right) and obtained both standing radiographs and weight-bearing CBCT. Patients were divided by the Takakura stage. The interclass correlation coefficient (ICC) for each result was confirmed.

Results: On the ICC between 2D radiographs and 3D analysis, the tibiotalar surface angle and lateral talo-1st metatarsal angle showed a good ICC grade (> 0.6), while other parameters did not have significant ICC results. Three-dimension was superior to radiographs in terms of statistical significance.

Conclusions: We demonstrated that 2D and stereoscopic images are useful for the diagnosis of OA. Our study also confirmed that the radiographic features affected by ankle OA varied. However, according to the results, the typical radiography is not sufficient to diagnose and determine a treatment plan for ankle OA. Therefore, the method of using 3D images should be considered.

Keywords: *Osteoarthritis, Radiologic picture, Three-dimensional, Disior, Cone-beam computed tomography*

Approximately 1% of the adult population is affected by ankle osteoarthritis (OA), resulting in pain, dysfunction, and impaired mobility.[1-3] The etiology of hip and knee OA is well understood and has been highlighted in numerous clinical studies; however, research on ankle OA remains limited.[2,4,5] To evaluate the degree of deformation in patients with ankle OA, it is essential to measure the three-dimensional (3D) alignment of the subtalar joint and the ankle joint.[6] Weight-bearing radiographic imaging is also required for the diagnosis of ankle OA because it is difficult to accurately confirm joint spacing using non-weight-bearing techniques.[7] The treatment method of ankle OA is determined on the basis of the severity, which is classified using the Takakura staging system. For stages 1 and 2, nonsurgical treatment options are considered, while stage 3A or higher is considered a candidate for surgical treatment. In the latter, three surgical methods are considered: supramalleolar osteotomy, total ankle replacement arthroplasty (TAR), and ankle arthrodesis.[8-11] In patients with stages 2 and 3A ankle OA, supramalleolar osteotomy

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is used for correcting the alignment of the lower end of the tibial surface. TAR or ankle arthrodesis is generally indicated in patients with end-stage arthropathy (stages 3B and 4).[12] The use of TAR to treat end-stage ankle OA is becoming increasingly common, with biomechanical excellence and improved clinical results.[13] In addition, when ankle OA is present, the condition of the foot may cause diseases related to the arch of the foot and the ankle joint. The angles related to the diagnosis of foot and ankle disease can be obtained from radiographic images of the anteroposterior (AP), lateral (Lat), and hindfoot alignment views. The angle that can be measured in an ankle weight-bearing AP view for the assessment of ankle OA is the tibiotalar surface angle (TTS).[9,14-16] The tibial lateral surface angle (TLS), which can be measured in ankle weight-bearing lateral radiography, is also used for the diagnosis of ankle OA.[9,16-18] In foot diseases, flatfoot associated with ankle OA is defined as a weight-bearing foot with an abnormally low or absent longitudinal arch and a valgus heel position.[19] Foot standing AP views can be used to measure the talo-1st metatarsal angle (AP-TFMA) and AP talocalcaneal angle (AP-TCA), which are both indicators of flat feet. In addition, the lateral talo-1st metatarsal angle (Lat-TFMA) and talocalcaneal angle (Lat-TCA) are measured in a standing foot Lat view. The Lat-TCA is widely used in children as a diagnostic parameter for clubfoot.[6,17,19-22] Finally, hindfoot alignment views can be used to check the hindfoot alignment angle (HAA) to diagnose heel valgus or varus.[18,20,23,24] These measurements are commonly used in the assessment of hind- and midfoot deformities.

Radiological indicators are commonly measured using two-dimensional (2D) anterior-posterior and lateral radiographs under weight-bearing conditions, but 2D images tend to miss the important characteristics captured only in a stereoscopic view. In addition, 2D images limit bone superimposition and lack reproducibility. Computer-aided 3D analysis using weight-bearing cone-beam computed tomography (CBCT) has been introduced because deformities in each patient are more individual and complex.[25] Because 3D scans can compensate for these problems of 2D, stereoscopic scans using modern CBCT with weight-bearing are particularly valuable for foot and ankle studies.[26,27] However, quantitative analysis of the overall skeletal geometry of the foot using CT requires careful reconstruction of the 3D bone models, starting from a series of image slices. The best possible software would support the user in accurately defining these 3D bone models and at the same time would not require extensive manual work from an expert operator. For each clinical or biomechanical application, a good compromise should be found between the automation of the process and the quality of the result. Among these software packages for 3D bone reconstruction, Bonelogic Ortho Foot and Ankle (Disior) is the most modern tool for the fully automatic segmentation of foot bones.[7,18]

Analysis of ankle OA is important for selecting the best treatment strategy and is key to achieving satisfactory long-term results and avoiding postoperative complications. Therefore, this study aimed to confirm how similar the 3D analysis was to the 2D analysis and to examine

Table 1. Demographic Characteristics of the Patient Population

Variable	Value
Age (yr)	67.5 (46–86)
Sex (n = 29)	
Male	14 (48)
Female	15 (52)
Takakura stage (n = 57)	
Group 1 (n = 36)	
Normal	21 (37)
1	4 (7)
2	11 (19)
Group 2 (n = 21)	
3A	5 (9)
3B	5 (9)
4	11 (19)

Values are presented as median (range) or number (%).

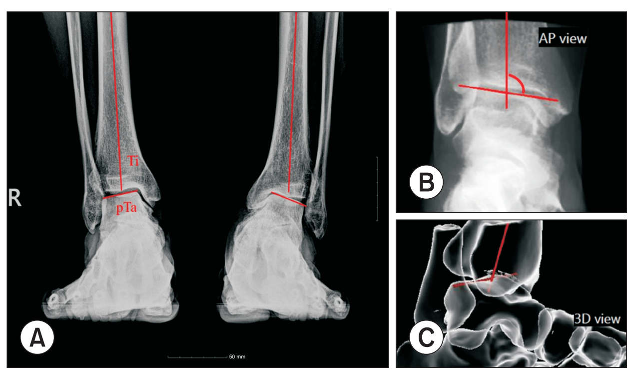

Fig. 1. Method of measurement of the tibiotalar surface angle in weight-bearing ankle anteroposterior views. (A) The angle between the axis of the tibia (Ti) and the plafond of the talus (pTa) was measured as the tibiotalar surface angle in an anteroposterior (AP) view. (B) Tibiotalar surface angle in a Disior anteroposterior view. (C) Three-dimensional (3D) view in Disior.

whether the stereoscopic analysis was useful in classifying ankle OA patients.

METHODS

Patients

We retrospectively reviewed the data from April 2019 to June 2020 after obtaining Institutional Review Board approval (No. DSMC 2019-10-003). Informed consent was obtained from all patients. There was a total of 29 patients (both ankles of all patients were affected, except for 1 patient), including 14 men and 15 women with a mean age of 67.5 years (range, 46.3–86.2 years). Patients with ankle OA who underwent both standing radiography and weight-bearing CBCT (57 feet [28 left and 29 right]) were enrolled. The distribution of patients, based on the modified Takakura classification, is summarized in Table 1. To analyze the radiographic differences based on the ankle OA stage, we divided the patients into group 1 (stages 0–2) and group 2 (stages 3A–4).

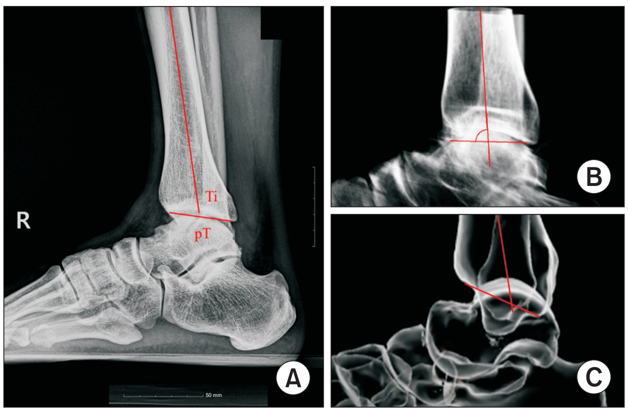

Fig. 2. Method of measurement of the tibial lateral surface angle in weight-bearing ankle lateral views. (A) The angle between the axis of the tibia (Ti) and the plafond of the distal tibia (pT) was measured as the tibial lateral surface angle in a lateral view. (B) Tibial lateral surface angle in a Disior lateral view. (C) Three-dimensional view in Disior.

Radiographic Features

The radiographic features measured using 3D imaging software (Disior) were based on the angle used for evaluating ankle OA; these are especially useful when judged by a clinician. Three observers (two orthopedic surgeons [SWL and CJY] and one anatomist [YRH]) assessed these weight-bearing radiographs and plain radiographs preoperatively in the AP, Lat, and hindfoot alignment views. The following measurements were obtained: (1) TTS, the angle between the axis of the tibia and the dome of the talus (Fig. 1) in the ankle weight-bearing AP view; (2) TLS, the angle between the axis of the tibia and the distal plafond (Fig. 2) in the foot standing Lat view; (3) AP-TFMA, the angle between the axis of the1st metatarsal bone and the axis of the talus; (4) AP-TCA, the angle between the axis of the talus and the axis of the calcaneus (Fig. 3) in the standing lateral foot; (5) Lat-TFMA; and (6) Lat-TCA (Fig. 4). In the hindfoot alignment view, (7) HAA, the angle between the axis of the tibia and the axis of the calcaneus (Fig. 5), was measured. In addition, 3D analysis using weight-bearing CBCT was repeated 10 times for comparison.

Statistical Analysis

All data were analyzed using the SPSS ver. 21.0 (IBM Corp.). Continuous variables, including TTS, TLS, AP-TFMA, AP-TCA, Lat-TFMA, Lat-TCA, and HAA, are presented as mean ± standard deviation and were analyzed using the interclass correlation coefficient (ICC).[28] Inter-

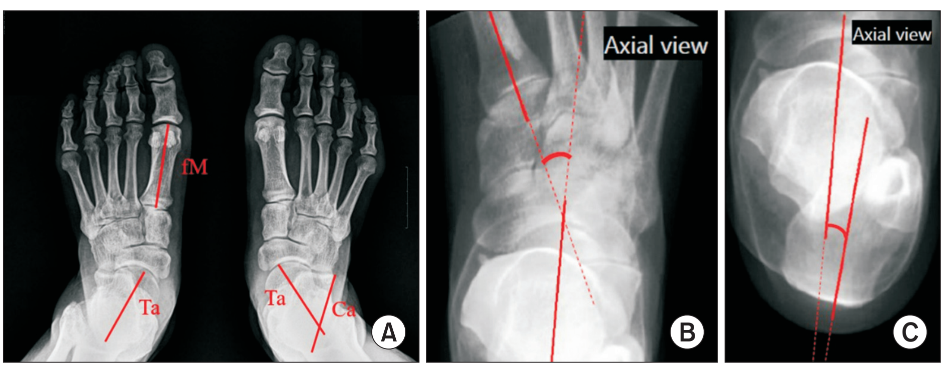

Fig. 3. Method of measurement of the anteroposterior talo-1st metatarsal angle and talocalcaneal angle in foot standing anteroposterior (AP) views. (A) The angle between the axis of the first metatarsal (fM) and the axis of talus (Ta) was measured as the talo-1st metatarsal angle. The angle between the Ta and the axis of calcaneus (Ca) was measured as the talocalcaneal angle. (B) AP talo-1st metatarsal angle in a Disior axial view. (C) AP talocalcaneal angle in a Disior axial view.

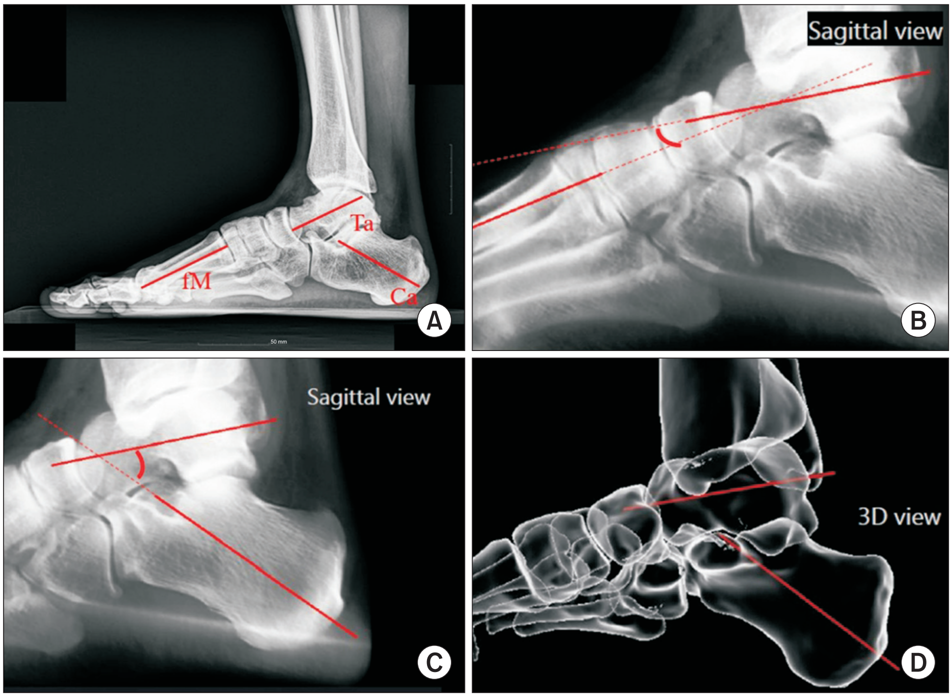

Fig. 4. Method of measurement of the lateral talo-1st metatarsal angle and talocalcaneal angle in foot standing lateral views. (A) The angle between the first metatarsal (fM) and the axis of talus (Ta) was measured as the talo-1st metatarsal angle in a lateral view. The angle between Ta and the axis of calcaneus (Ca) was measured as the talocalcaneal angle in a lateral view. (B) Talo-1st metatarsal angle in a Disior sagittal view. (C) Talocalcaneal angle in a Disior sagittal view. (D) Three-dimensional (3D) view in Disior.

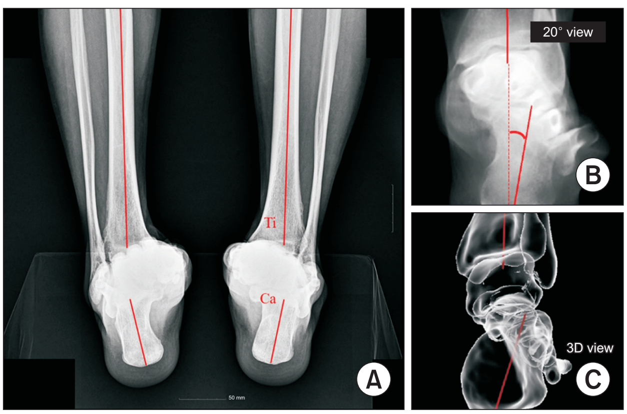

Fig. 5. Method of measurement of the hindfoot alignment angle in hindfoot alignment views. (A) The angle between the axis of tibia (Ti) and the axis of calcaneus (Ca) was measured as the hindfoot alignment angle in a hindfoot alignment view. (B) Hindfoot alignment angle in a Disior hindfoot alignment view. (D) Three-dimensional (3D) view in Disior.

group comparisons were performed using an independent *t*-test and the Mann-Whitney analysis. Differences were considered statistically significant at $p < 0.05$.

RESULTS

ICC Analysis of Foot Radiographic Measurements in Three Observers

In all measurements, the mean values of TTS, TLS, AP-TFMA, AP-TCA, Lat-TFMA, Lat-TCA, and HAA were 85.79 ± 5.8, 84.59 ± 5.49, 18.32 ± 9.4, 36.62 ± 5.41, –6.86 ± 11.78, 51.28 ± 5.71, and 2.84 ± 9.41, respectively. Based on the ICC grade, AP-TFMA, Lat-TFMA, and HAA were excellent with an ICC of 0.75 or higher, and TTS and TLS were good with an ICC of 0.6–0.75. However, AP-TCA and Lat-TCA were only considered fair with an ICC of 0.4–0.6 (Table 2). When the patients were stratified into the Takakura stage, only Lat-TFMA and Lat-TCA were statistically significant ($p < 0.05$) (Table 3).

Comparative Analysis of 2D Radiographs and 3D Measurements of Foot Angles by ICCs

In 3D analysis (Disior), the average angle measurements for the TTS, TLS, AP-TFMA, AP-TCA, Lat-TFMA, Lat-TCA, and HAA were 87.93 ± 7.01, 84.59 ± 5.13, 19.57 ± 13.71, 41.00 ± 9.34, –4.58 ± 16.14, 52.65 ± 8.20, and –2.57 ± 11.88, respectively. The ICCs of 2D radiographs and stereoscopic image measurements are summarized in Table 4. AP-TCA and Lat-TCA were excluded from the analysis because they had only fair interobserver grades. TTS and Lat-TFMA showed good ICC grades (> 0.6); however, the other parameters did not have meaningful ICC results.

When patients were stratified according to the Takakura stage, TTS, AP-TFMA, Lat-TFMA, Lat-TCA, and HAA were found to be statistically significant ($p < 0.05$) (Table 5). The overall mean angle measurements in 2D radiographs, stereoscopic image measurements, and correlations in group classification by the Takakura stage

Table 2. Interobserver Agreement and Interclass Correlation Coefficients for Average Values in Foot Angle Measurements

Variable	Observer 1	Observer 2	Observer 3	Average	ICC	Grade
TTS	86.02 ± 6.06	86.57 ± 6.54	84.77 ± 6.67	85.79 ± 5.80	0.708	Good
TLS	79.31 ± 6.21	80.59 ± 5.67	80.72 ± 5.11	84.60 ± 5.49	0.678	Good
AP-TFMA	18.57 ± 10.25	19.34 ± 10.70	17.05 ± 9.33	18.32 ± 9.40	0.788	Excellent
AP-TCA	35.52 ± 6.05	39.88 ± 7.29	34.46 ± 6.62	36.62 ± 5.41	0.429	Fair
Lat-TFMA	–5.73 ± 12.44	–8.56 ± 12.80	–6.24 ± 13.25	–6.84 ± 11.78	0.756	Excellent
Lat-TCA	48.13 ± 6.54	50.69 ± 6.58	51.87 ± 5.83	51.28 ± 5.71	0.471	Fair
HAA	4.74 ± 10.57	1.70 ± 8.60	2.08 ± 10.27	2.84 ± 9.41	0.847	Excellent

Values are presented as mean ± standard deviation.
ICC: interclass correlation coefficient, TTS: tibial surface angle, TLS: tibial lateral surface angle, AP-TFMA: anteroposterior talo-first metatarsal angle, AP-TCA: anteroposterior talocalcaneal angle, Lat-TFMA: lateral talo-1st metatarsal angle, Lat-TCA: lateral talocalcaneal angle, HAA: hindfoot alignment angle.

Table 3. Mean Angle Measurements in 2D Radiographs and Correlations in Group Classification by Takakura Stage

Variable	Group 1 (n = 36)	Group 2 (n = 21)	*p*-value
TTS	86.89 ± 4.92	83.90 ± 6.77	0.090
TLS	80.74 ± 4.60	80.51 ± 6.05	0.877
AP-TFMA	18.81 ± 8.97	17.48 ± 10.26	0.610
AP-TCA	37.07 ± 4.86	35.86 ± 6.42	0.424
Lat-TFMA	–9.79 ± 11.01	–1.78 ± 11.56	0.012
Lat-TCA	52.87 ± 6.42	48.56 ± 6.18	0.005
HAA	4.18 ± 8.98	0.54 ± 9.90	0.145

Values are presented as mean ± standard deviation.
2D: two-dimensional, TTS: tibial surface angle, TLS: tibial lateral surface angle, AP-TFMA: anteroposterior talo-first metatarsal angle, AP-TCA: anteroposterior talocalcaneal angle, Lat-TFMA: lateral talo-1st metatarsal angle, Lat-TCA: lateral talocalcaneal angle, HAA: hindfoot alignment angle.

Table 4. Mean Angle Measurements in 2D Radiographs and 3D scans and Correlations in Group Classification by Takakura Stage

Variable	2D	3D	ICC	Grade
TTS	85.79 ± 5.80	87.93 ± 7.02	0.627	Good
TLS	84.59 ± 5.49	80.65 ± 5.13	0.253	Fair
AP-TFMA	18.32 ± 9.40	19.57 ± 13.70	0.597	Fair
Lat-TFMA	–6.84 ± 11.78	–4.58 ± 16.14	0.678	Good
HAA	2.84 ± 9.41	–2.57 ± 11.88	0.504	Fair

Values are presented as mean ± standard deviation.
2D: two-dimensional, 3D: three-dimensional, ICC: interclass correlation coefficient, TTS: tibial surface angle, TLS: tibial lateral surface angle, AP-TFMA: anteroposterior talo-first metatarsal angle, Lat-TFMA: lateral talo-1st metatarsal angle, HAA: hindfoot alignment angle.

Table 5. Mean Angle Measurements in 3D Radiographs and Correlations in Group Classification by Takakura Stage

Variable	Group 1 (n = 36)	Group 2 (n = 21)	*p*-value
TTS	89.72 ± 5.10	84.88 ± 8.77	0.028
TLS	85.00 ± 3.37	83.90 ± 7.98	0.553
AP-TFMA	23.13 ± 12.51	13.48 ± 13.79	0.009
AP-TCA	41.82 ± 7.74	39.59 ± 11.84	0.448
Lat-TFMA	–11.33 ± 11.64	6.99 ± 16.42	< 0.001
Lat-TCA	52.54 ± 7.53	39.49 ± 13.86	< 0.001
HAA	0.16 ± 11.67	–7.24 ± 10.97	0.047

Values are presented as mean ± standard deviation.
3D: three-dimensional, TTS: tibial surface angle, TLS: tibial lateral surface angle, AP-TFMA: anteroposterior talo-first metatarsal angle, AP-TCA: anteroposterior talocalcaneal angle, Lat-TFMA: lateral talo-1st metatarsal angle, Lat-TCA: lateral talocalcaneal angle, HAA: hindfoot alignment angle.

are summarized in Table 6. Examples of 2D radiograph and 3D image analysis results are shown in Fig. 6.

DISCUSSION

Our study demonstrated that 3D computer-aided analysis (Disior) can be used to assess ankle OA, which is quite different from 2D radiography. Additionally, the TTS and Lat-TFMA were found to be statistically significant. Ankle OA is less common than OA of other major joints of the lower extremities (e.g., knee or hip). However, the clinical importance of ankle OA should not be underestimated. Patients with ankle OA have a lower quality of life and substantial functional limitations.[5,12,16,27] Unlike the hip

Table 6. Overall Mean Angle Measurements in 2D Radiographs and 3D scans and Correlations in Groups Classified by Takakura Stage

Variable	Group 1 (n = 36)		*p*-value	Group 2 (n = 21)		*p*-value
	2D	3D		2D	3D	
TTS	86.89 ± 4.92	89.72 ± 5.10	0.003	83.90 ± 6.77	84.88 ± 8.77	0.014
TLS	80.74 ± 4.60	85.00 ± 3.37	< 0.001	80.51 ± 6.05	83.90 ± 7.98	0.130
AP-TFMA	18.81 ± 8.97	23.13 ± 12.51	0.097	17.48 ± 10.26	13.48 ± 13.79	0.292
AP-TCA	37.07 ± 4.86	41.82 ± 7.74	0.003	35.86 ± 6.42	39.59 ± 11.84	0.213
Lat-TFMA	–9.79 ± 11.01	–11.33 ± 11.64	0.566	–1.78 ± 11.56	6.99 ± 16.42	0.052
Lat-TCA	52.87 ± 6.42	52.54 ± 7.53	0.827	48.56 ± 6.18	39.49 ± 13.86	0.011
HAA	4.18 ± 8.98	0.16 ± 11.67	0.053	0.54 ± 9.90	–7.24 ± 10.97	0.688

Values are presented as mean ± standard deviation.
2D: two-dimensional, 3D: three-dimensional, TTS: tibial surface angle, TLS: tibial lateral surface angle, AP-TFMA: anteroposterior talo-first metatarsal angle, AP-TCA: anteroposterior talocalcaneal angle, Lat-TFMA: lateral talo-1st metatarsal angle, Lat-TCA: lateral talocalcaneal angle, HAA: hindfoot alignment angle.

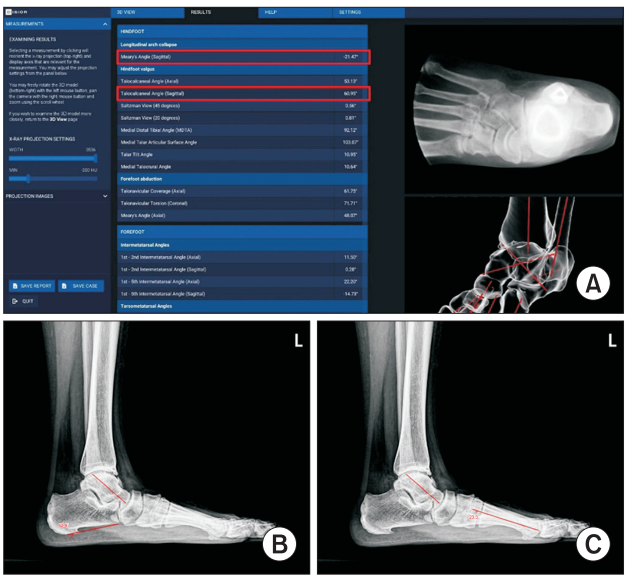

Fig. 6. Classic examples of image analysis using radiographs and Disior. (A) Image of patient results in Disior. The upper red box is the lateral talo-1st metatarsal angle (Lat-TFMA: –21.47°) and the lower red box is the lateral talocalcaneal angle (Lat-TCA: 60.95°). (B) A radiograph of the same patient showing the Lat-TCA of 52.8°. (C) A radiograph of the same patient showing the Lat-TFMA of –23.3°.

and knee joints, the ankle joint is often affected by post-traumatic OA. The diagnosis of the osteoarthritic ankle joint begins with a clinical assessment of the alignment, stability, and measurement of the range of motion. Different radiographic modalities may help recognize and analyze the underlying reasons of ankle OA.[2,29-31]

The stereoscopic image analysis is available for these analyses, using modern tools with limited effort.[32] It is expected to show the true orientation of the bones and joints of the foot during physiological loading. However, in many previous studies on CBCT scans, angles were still taken in planar views, that is, in the most appropriate single images and not exactly from 3D models of the foot bones, as in the present work. Ortolani et al.[7] compared Disior and Mimics in a 3D analysis.[18] In the current study, we determined whether the angle for the diagnosis of ankle joint disease was useful for diagnosis by using the traditional method and stereoscopic image analysis, that is, Disior.

Most ICC values of the angle represented good or excellent interobserver agreement. However, in AP-TCA and Lat-TCA, the ICCs were found to be fair. The reason for this result was the recognition of the calcaneal bone. On radiography, the boundaries of the calcaneus are not clear because of the overlapping of the tibia, talus, and fibula. Therefore, it is difficult for an observer to measure the lines and angles. Although the TTS and TLS showed good ICC grades, they did not show better concordance, probably because of variables such as osteophytes. In most angles, the ICC was not very good when using 2D radiographs and stereoscopic image measurements. However, TTS and Lat-TFMA were estimated to manifest good ICC grades. The HAA had a fair ICC grade because in the hindfoot alignment, the criteria for classifying positive and negative numbers may be different. Guidelines for determining the centerline of each bone are more complicated in stereoscopic images than in 2D. In 3D analysis, the software scans the bone and determines its cross-section at various locations. The weighted counterpoint was computed for each cross-section. Robust line-fitting routines were used to obtain a straight line representative of the cross-section points. Additionally, in the talus, projections of the joint facets and tendon insertion were used to determine the bone alignment. Moreover, 3D reconstruction uses CBCT so that not all feet are visualized, especially in the AP and Lat views. Therefore, 3D analysis has more variables than 2D analysis does. These variables are considered to affect the ICC between stereoscopic and 2D images.

On radiography, when the patients were stratified by the Takakura stage, Lat-TFMA and Lat-TCA were statistically significant. For stereoscopic measurements, the TTS, AP-TFMA, Lat-TFMA, Lat-TCA, and HAA were statistically significant. According to the results, when deciding the treatment and severity, 3D assessment is more useful than radiography or conventional radiologic assessment.

This study has some limitations. First, only a small number of patients were included in this study. And, it is difficult to make an accurate judgment because there is no reference value for the parameter indicating disease in 3D analysis. However, we found that it is important to improve diagnostic accuracy by performing both conventional radiologic assessment and stereoscopic analysis when evaluating ankle OA.

The radiographic parameters affected by ankle OA measured using the 2D and stereoscopic modalities were quite different. However, 3D analysis using weight-bearing CBCT showed relatively good agreement in the evaluation of the transverse arch, hindfoot alignment, and ankle arthritis in radiographic index measurements of the foot and ankle joint. Therefore, 3D analysis is useful for diagnosing ankle OA and valuable as a prognostic program. However, guidelines for stereoscopic analysis are needed.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

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