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ORIGINAL PAPER

Post-operative radiological predictors of satisfying outcomes occurring after intra-articular calcaneal fractures: a three dimensional CT quantitative evaluation

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Abstract
Purpose No functional outcome related to 3-D CT evaluations for calcaneal fractures has been presented. The aims of this study are to analyze the post-operative morphological parameters of calcaneal fractures in 3-D space and to correlate the 3-D morphological parameters with functional outcomes.
Methods Between 2009 and 2015, 156 patients operatively treated for displaced calcaneal fractures were retrospectively reviewed with an average follow-up time of 32.4 months. Böhler's angle, Gissane's angle, the length of calcaneal axis, the height of posterior facet, the length of posterior facet, and the subtalar joint congruity were evaluated post-operatively in accordance with 3-D CT. Each parameter was quantified, and then its association with the clinical outcomes assessed by the AOFAS score and Short Form-36 questionnaire was evaluated.
Results The restoration of the length of calcaneal axis, the height of posterior facet, and the length of posterior facet had no significant correlation with the clinical outcomes ($P > 0.05$). The restoration of Böhler's angle and Gissane's angle had significant correlation with the better AOFAS score ($P < 0.001$), while no correlation was found with the SF-36 physical component summary score ($P > 0.05$). No significant association emerged between the clinical outcomes and reconstruction of the posterior facet congruity ($P > 0.05$).
Conclusion The predictable functional outcome is related to the reconstruction of post-operative morphological characteristics of the calcaneus as evaluated on 3-D CT, especially the Böhler's angle and Gissane's angle. Despite post-operative step-off of the posterior facet exiting, the clinical outcomes appear to be not related to the posterior facet congruity.

Keywords Calcaneal fracture · Computed tomography · Three-dimensional imaging · Outcome

Introduction

Calcaneal fractures are the most common tarsal bone fractures, comprising about 2% of all fractures and approximately 75% of calcaneal fractures are intra-articular [1]. Operative treatment is generally recommended for the displaced intra-articular calcaneal fracture (DIACF). Surgical reduction and fixation tends to decrease both the socioeconomic burden and late consequences of the calcaneal fractures [2, 3]. Operative treatment includes open reduction and internal fixation (ORIF), a variety of minimally invasive osteosynthesis with or without arthroscopic-assisted reduction, and so on [4]. Within the past few years, there has still been some controversy with respect to the operative treatment. ORIF as the gold standard is considered the ideal method of restoring calcaneal morphology and achieving anatomic reduction of the articular surface [5–7]. However, the soft-tissue complications sometimes cannot be neglect, when ORIF is accepted. ORIF has its main indication in complex intra-articular fractures which sometimes cannot be reduced well by minimally invasive methods. The minimal risk of wound complication is a major advantage of the less-invasive treatment. Conversely, the reduction accuracy is worse achieved by less invasive methods than by ORIF, especially when articular restoration is involved. In recent years, lots of studies utilized the minimally invasive methods for the operation of calcaneal fractures, and

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achieved satisfactory clinical results [8–10]. Therefore, the correlation between the postoperative morphological characteristic of calcaneal fracture and the ankle-hindfoot function would be a critical focus for whether ORIF or minimally-invasive treatment is an option for some specific calcaneal fractures.

Post-operative outcome evaluations of calcaneal fractures are various. The outcome evaluations include the clinical radiological evaluations. The American Orthopedic Foot and Ankle Society (AOFAS) ankle hindfoot scale and Short Form-36 (SF-36) questionnaire are commonly used to evaluate the functional outcome after the treatment of calcaneal fractures. Recent studies have evaluated the surgical reduction and fixation on the basis of X-ray and two-dimensional (2-D) computed tomography (CT), concluding the post-operative morphological characteristics for calcaneal fractures [11–13]. There remains a lack of clear consensus on the prognostic morphological factors related to the outcome according to the X-ray and 2-D CT.

The evaluation of CT scans of calcaneal fractures was improved by the additional use of three-dimensional (3-D) reconstruction [14]. With the development of computer technology, 3-D CT and its interactive segmentation and measurement technique have gradually become popular to improve visualization and quantitative evaluation in calcaneus [15, 16]. Gutekunst et al. developed the method to define bone axes using landmarks on quantitative CT bone surface meshes to assess 3-D hind foot bone orientation angles, which presented the angular measurement with moderate to high reliability [15]. The previous study analyzed the normal anatomy of the calcaneus with 3-D CT, and the measurements of the clinically relevant morphological parameters in 3-D space were obtained [16]. There was a statistically significant impact of the use of 3-D CT on the reliability and reproducibility of the calcaneal morphological measurement. Furthermore, 3-D CT with shaded surface display (SSD) or volume rendering (VR) could enable a better assessment of the exact fracture geometry, severity of injury, and the post-operative morphological characteristics compared with radiographs or 2-D CT.

To our knowledge, no functional outcome related to 3-D CT evaluations for calcaneal fractures has been presented. In this study, 3-D CT was applied to assess the radiological outcomes after the treatment of DIACFs. We hypothesized that certain 3-D CT images rendered by different image processing would help to evaluate the post-operative 3-D morphological characteristics of calcaneal fractures, such as the Böhler's angle, Gissane's angle, lengths and heights of the main parts of the calcaneus, and the articular facet congruency. The purpose of the current retrospective study was (1) to analyze the post-operative morphological parameters of the calcaneus worked out in 3D space and (2) to correlate the post-operative 3-D morphological parameters with the clinical functional outcomes at the final follow-up.

Materials and methods

Patient

Between January 2009 and May 2015, 267 patients with DIACF were admitted to our level 1 trauma center and were treated operatively. The inclusion criteria were as follows: (1) unilateral DIACF; (2) age ≥ 18 years old; (3) injury-to-surgery interval within two weeks; (4) receiving CT scans during follow-up. Patients with pathological fractures, with open fractures, or with multiple traumas were excluded. According to the inclusion and exclusion criteria, 204 patients were retrospectively reviewed. One hundred and eighty-five cases underwent ORIF. Nineteen cases underwent minimally-invasive treatment. Of the 204 patients included, 48 could not be contacted during the follow-up period or had incomplete medical records. The remaining 156 patients with a mean age of 44.6 years (range, 21 to 72 years), consisting of 41 females and 115 males, were analyzed. The average follow-up time was 32.4 months (range, 18–63 months). Causes of fractures included falling from a height in 87 patients, missing steps in 26 patients, and vehicle accident in 43 patients. According to the Sanders Classification, there were 53 (34.0%) Sanders type II, 72 (46.1%) Sanders type III, and 31 (19.9%) Sanders type IV fractures. All clinical data were obtained from medical records. The CT and radiographic data were from the medical image database in the hospital. This retrospective study was approved by the institutional review committee of the hospital and performed with the written informed consents from all patients.

Clinical outcome assessments

To quantify functional outcomes, the AOFAS ankle-hindfoot scale and SF-36 questionnaire were used. The AOFAS scale consists of a subjective component and an objective clinical component, which was classified into three major parts: pain, function, and alignment. The AOFAS score was classified as excellent (90 to 100 points), good (80 to 89), fair (70 to 79), and poor (less than 70 points). The SF-36 physical component summary (PCS) specific to the daily physical activities were mainly assessed in this study.

Radiological technique

The CT data from the Department of Radiology were collected and saved as DICOM 3.0 format (.dcm). CT was performed by using with a 16–detector row CT scanner (GE Light-Speed CT; USA). The thin-slice CT transverse images of calcaneal fractures were input into the digital orthopaedic clinical research platform (SuperImage orthopedics edition 1.0, Cybermed Ltd., Shanghai, China). The 3-D images of calcaneus for measuring the morphological parameters were

reconstructed by SSD with a reconstruction interval of 0.625 mm. The 3-D VR reconstructions were used to observe the congruity of the subtalar facet. The 3-D interactive and automatic segmentation technique was applied to generate the calcaneus.

Radiological evaluation

All CT scans for the injured foot were obtained at the final follow-up. The congruency of the posterior articular facet was used to assess the reduction quality, in accordance with calcaneal 3-D VR reconstruction. The posterior subtalar facet congruity was categorized as anatomic (no joint surface step-off), nearly anatomic (step-off <2 mm), or non-anatomic (step-off ≥2 mm) (Fig. 1).

We assessed the radiological parameters based on literature review [11, 12], including the length of the calcaneus, the height of the posterior facet, the length of the posterior facet, the Gissane's angle, and the Böhler's angle. However, the difference was that we measured them in the 3-D space based on CT image post-processing. Before we started 3-D measurement, the anatomic landmarks on bone surface meshes were selected to produce clinically relevant parameters including (Fig. 2a, b):

Point A: the highest point of the posterior articular facet.
Point B: the bottom of the posterior articular facet at the lateral surface intersecting the anterior process of the calcaneus.
Point C: the highest point of the calcaneocuboid joint.
Point D: the lowest point of calcaneocuboid joint.
Point E: the most posterior point of the calcaneal tuberosity.
Point F: the highest point on the superior edge of the calcaneal tuberosity.

The length of the calcaneal axis was measured as the distance from point G (the middle point of line segment CD) to point E. The height of the posterior facet (line AH) was measured as the perpendicular distance from point A to the calcaneal axis. The length of the posterior facet was measured as the distance between point A and point B. The Gissane's angle was the angle formed by the intersection of line AB and line BC. The Böhler's angle was formed by the intersection of line AC and line AF. All above morphological parameters were measured in 3-D space according to combined measurement techniques including essential elements of point and line (Fig. 2c).

Statistical method

The data were analyzed using SPSS 18.0 for Windows software (PASW Statistics, IBM, USA). Gender differences in 3-D morphological parameters and clinical outcomes were tested using the independent samples *t*-test. Before the Pearson product-moment correlation test was used to analyze the correlation between the postoperative 3-D morphological parameters and the clinical outcomes of calcaneal fractures, the absolute value of the difference between follow-up measurements and reference values in 3-D morphological parameters was calculated.

$$\Delta Value = |Measurements - Reference \quad values|$$

The Chi-square test was determined for the relationship between the subdivided AOFAS score and the posterior subtalar facet congruity. The SF-36 among different groups of subtalar joint congruence were compared by one-way analysis of variance (ANOVA) and least significant difference (LSD). A P value of <0.05 was considered to be significant.

Results

In comparison to the female group, the post-operative Böhler's angle, Gissane's angle, length of the calcaneal axis, height of the posterior facet, and length of the posterior facet were greater in the male group than those in the female group.

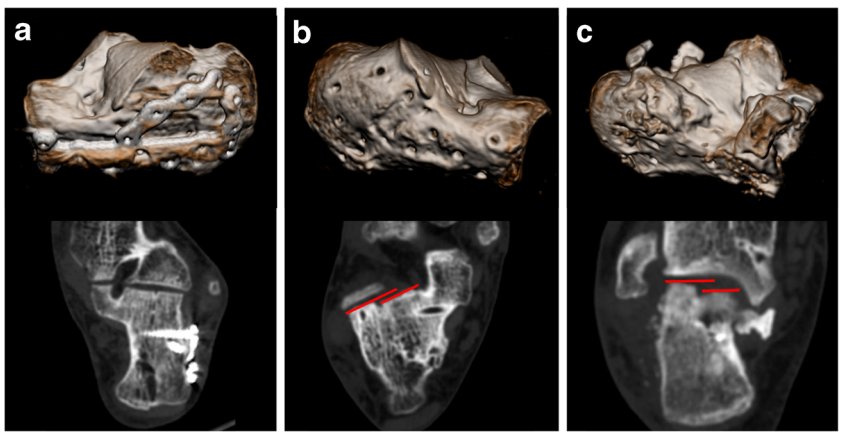

Fig. 1 The congruity of the posterior subtalar facet was assessed at the final follow-up. **a** Anatomic reduction (no joint surface step-off). **b** Nearly anatomic reduction (step-off <2 mm). **c** Non-anatomic reduction (step-off ≥2 mm)

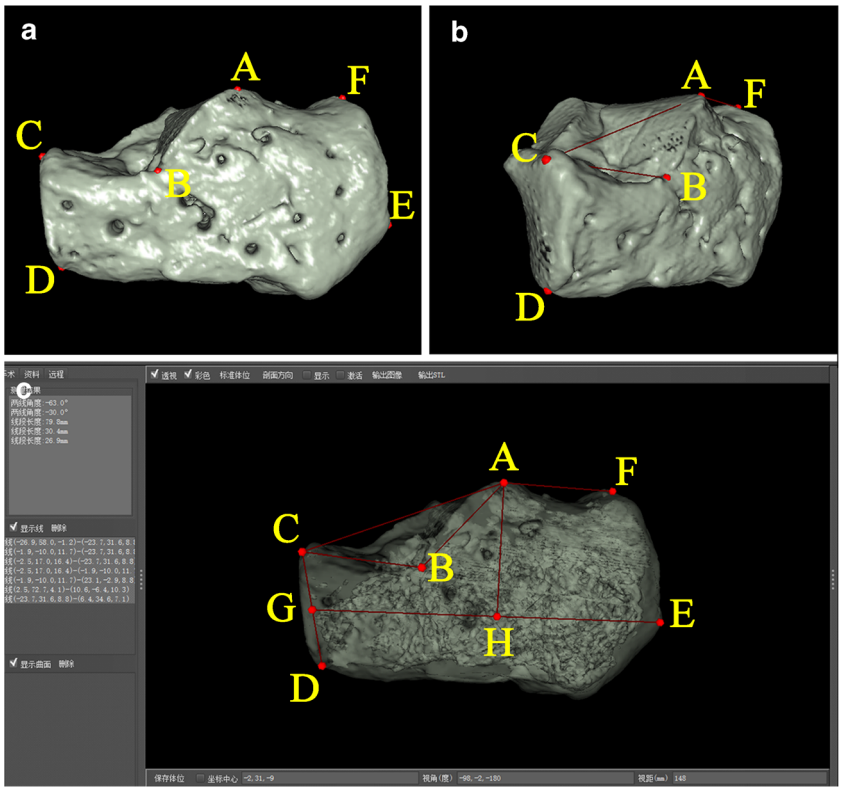

Fig. 2 The post-operative morphological parameters of the calcaneal fracture were measured in 3-D space. **a, b** Location of measurement points was illustrated. *A* = highest point of posterior facet; *B* = bottom of the posterior facet at lateral surface intersecting anterior process; *C* = highest point of calcaneocuboid joint; *D* = lowest point of calcaneocuboid joint; *E* = most posterior point of calcaneal tuberosity; *F* = highest point on the superior edge of calcaneal tuberosity. **c** The 3-D postoperative morphological parameters of calcaneus were shown. 180°-∠CAF = Böhler's angle;∠ABC = Gissane's angle; GE = length of calcaneal axis; AH = height of posterior facet; AB = length of posterior facet

The gender-related differences of the above 3-D morphological parameters were statistically significant ($P < 0.05$). Although the mean AOFAS score in female group (86.2 ± 6.9) was greater than that in male group (84.9 ± 6.1). No significant gender differences could be detected in AOFAS scores ($t = 1.20$, $P = 0.248$) or in SF-36 PCS scores ($t = 1.03$, $P = 0.303$) at the final follow-up visit (Table 1).

Table 2 presented correlations between the restoration of 3-D morphological calcaneal parameters and the clinical outcomes determined by Pearson correlations analyses. The restoration of the length of the calcaneal axis, the height of the posterior facet, and the length of the posterior facet (Δ value) had no significant correlation with the AOFAS score ($r = 0.01$, −0.10, −0.11; all $P > 0.05$, respectively) or the SF-36 PCS score ($r = 0.02$, −0.10, −0.04; all $P > 0.05$, respectively). The absolute value of the difference between the final follow-up Böhler's angle and the reference value (Δ Böhler's angle) had a significant correlation with the AOFAS score ($r = -0.57$; $P < 0.001$), but no correlation was found with the SF-36 PCS score ($r = -0.11$; $P = 0.170$) (Fig. 3). The Δ

Table 1 Post-operative radiological evaluation and clinical outcomes

	Male ($n = 115$)		Female ($n = 41$)		P value*
	Follow-up measurement	Reference value†	Follow-up measurement	Reference value†	
Böhler's angle (deg)	31.2 ± 6.1	39.6	26.5 ± 5.3	30.7	< 0.001
Gissane's angle (deg)	133.1 ± 8.9	127.7	129.6 ± 9.1	123.5	0.032
Length of calcaneal axis (mm)	77.7 ± 3.7	80.0	66.4 ± 2.3	69.2	< 0.001
Height of posterior facet (mm)	28.4 ± 2.0	31.5	23.6 ± 1.7	25.9	< 0.001
Length of posterior facet (mm)	27.4 ± 3.0	28.6	21.6 ± 2.0	22.4	< 0.001
AOFAS	84.9 ± 6.1	NA	86.2 ± 6.9	NA	0.248
SF-36 PCS	75.6 ± 8.3	NA	74.0 ± 8.5	NA	0.303

The values are given as the mean ± standard deviation. NA, not applicable

* Gender difference of the 3-D Parameters and functional score at the follow up were determined by t-test

† Values from a normative population sample from the previous study [16]

Table 2 Correlations between 3-D morphological parameters and clinical outcomes

	AOFAS		SF-36 PCS	
	r value	*P* value	*r* value	*P* value
Δ Böhler's angle	−0.57	< 0.001	−0.11	0.170
Δ Gissane's angle	−0.68	< 0.001	−0.12	0.142
Δ Length of calcaneal axis	0.01	0.955	0.02	0.773
Δ Height of posterior facet	−0.10	0.235	−0.10	0.204
Δ Length of posterior facet	−0.11	0.184	−0.04	0.589

Δ Value = |Measurements- Reference values|

Gissane's angle was correlated with the AOFAS score ($r = -0.68$; $P < 0.001$), while no correlation was found between the Δ Gissane's angle and the SF-36 PCS score ($r = -0.12$; $P = 0.142$) (Fig. 4).

The congruency of posterior subtalar articular facet was evaluated post-operatively via 3-D CT reconstruction. There were 58 cases with anatomic reduction of the posterior facet, 71 cases with nearly anatomic reduction, and 27 with incongruent articular surface. The functional outcome results including the mean AOFAS and SF-36 PCS score were presented in three groups (Fig. 5). The AOFAS questionnaire revealed excellent or good results in 51 patients and fair results in seven patients in the anatomic reduction group. The results in the nearly anatomic reduction group were excellent or good in six patients and fair in eight. In the non-anatomic reduction group, 25 patients acquired excellent or good results, and the remaining two patients acquired fair results. The Chi-square test showed no significant association between the posterior facet congruity and the AOFAS score ($P > 0.05$). There was

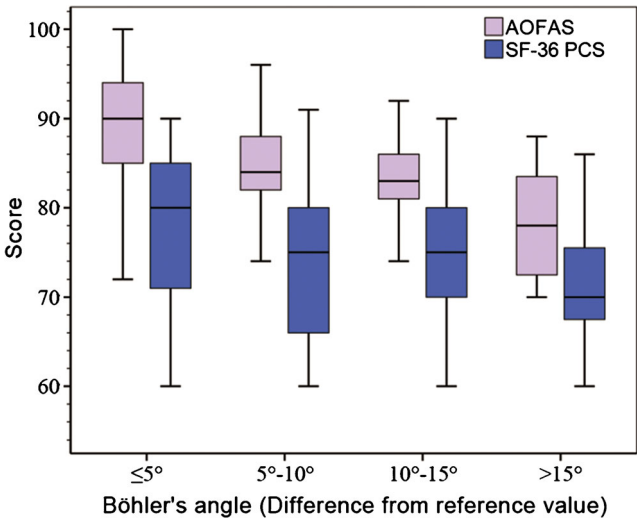

Fig. 3 The restoration of the Böhler's angle was associated with better AOFAS score, while no correlation was found with the SF-36 physical component summary score. Horizontal line is the median; the box top and bottom boundaries indicate the 25 and 75 percentile; whiskers represent the minimum and maximum values

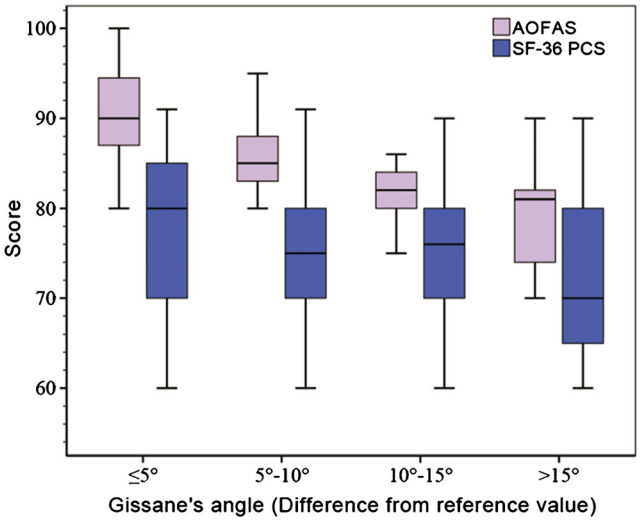

Fig. 4 The restoration of Gissane's angle had a significant correlation with the AOFAS score. No correlation was identified with the SF-36 physical component summary score. Horizontal line is the median; the box top and bottom boundaries indicate the 25 and 75 percentile; whiskers represent the minimum and maximum values

no significant difference in SF-36 PCS among the three groups either ($F = 0.35$; $P > 0.05$) (Table 3).

Discussion

The integrity of calcaneal anatomical morphology is important to maintain normal function of the hindfoot, to support modality of the arch, and to ensure stress conduction for weight bearing [5, 17]. Some studies in the literature on calcaneal fractures strongly suggest that a better reduction provides a better middle to long term outcome following the intra-

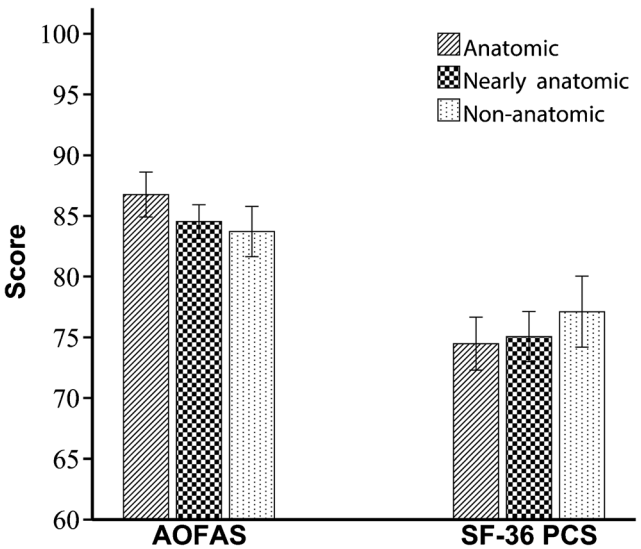

Fig. 5 The functional outcome results including the mean AOFAS and SF-36 PCS score presented in three groups

Table 3 Clinical outcomes among different groups of the posterior facet congruity

	Posterior facet congruity			*P* value
	Anatomic reduction (*n* = 58)	Nearly anatomic reduction (*n* = 71)	Non-anatomic reduction (*n* = 27)	
AOFAS score				0.320*
Excellent	19 (32.7%)	18 (25.4%)	4 (14.8%)	
Good	32 (55.2%)	45 (63.4%)	21 (77.8%)	
Fair	7 (12.1%)	8 (11.3%)	2 (7.4%)	
SF-36 PCS (M ± SD)	74.5 ± 8.3	75.1 ± 8.7	77.1 ± 7.4	0.704†

* Chi-square test. † One-way analysis of variance

articular calcaneal fracture [7, 18–20]. Magnan et al. revealed that a better reduction as measured by CT scanning, may result in a better outcome result [13]. They demonstrated that anatomically reduced calcaneal fractures had a good clinical score. The calcaneal morphological parameters included relevant angles, distances, and articular surface. The optimal post-operative radiological evaluation should take into consideration the whole 3-D morphological characteristics of calcaneus and should be reliable and easy to carry out. Conversely, the less accurate and precise the measurement is, the more it may limit its reproducibility. The radiographic evaluation for calcaneal fractures used today have a few limitations. Radiographs may be limited by the position of the patient's ankle and the angle of the beam, which may not be completely controlled [21]. Furthermore, the selection of axial CT scan images may be affected by the reconstruction interval besides the position of the foot. CT scanning and its 3-D rendering have found wide acceptance in clinical practice. 3-D CT are useful tools that help assess the fracture pattern and enable comparability in 3-D space between scientific studies.

The present retrospective study confirms the hypothesis that good subjective results can be predicted and obtained with operative treatment of DIACFs in patients, if anatomic reduction of the Gissane's angle and Böhler's angle are achieved. The Böhler's and Gissane's angles are the common parameters in calcaneal fractures, which indicate the severity of the injury. Böhler's angle is formed by the superior edges of the tuberosity, the subtalar joint, and the anterior process on lateral radiographs. Especially, the restoration of Böhler's angle is one of the important prognostic factors that correlate with a satisfying outcome [6, 18]. This study also obtained a similar result. Gissane's angle is composed of the posterior facet and anterior facet, and the reconstruction of Gissane's angle enables surgeons to restore the relationship of the articular surfaces to some extent. In this study, three landmarks (point A, B, C) decided the Gissane's angle in 3-D space (Fig. 2). The restoration of Gissane's angle was also significantly correlated with AOFAS score in this trail. This result was not consistent with those available in the published literature where the Gissane's angle was measured on lateral radiographs of the calcaneus [11]. Moreover, when correlating the distance differences with the outcome scores, no distance parameter in 3-D space correlated significantly with the functional outcomes except for the angular parameters.

Comparing pre-operative and post-operative radiographs for anatomical reduction were still imperfect due to the lack of the clear visualization in the articular surface, although Broden's view was recommended to show the extent of pre-operative damage to the subtalar joint and assess post-operative joint congruity. It was convenient to observe and evaluate articular facets with the 3-D CT post-processing technique. In this study, we mainly focused on the underlying relationship between the reduction quality of the subtalar joint facet and the prognosis of calcaneal fractures.

Biomechanical studies have shown that the step-offs or displacement more than 1–2 mm would lead to a pressure redistribution within the posterior joint facet in simulated calcaneal fractures [22, 23]. The quality of reduction of the subtalar joint facet, especially the posterior facet after operative management, was related to outcome of calcaneal fractures. The clinical study showed that patients with anatomic reduction of the posterior facet or the incongruity less than 2 mm had better functional outcomes [18]. Rammelt et al. have revealed that the AOFAS score tended to be lower with the increasing step-offs in the posterior facet, while no significant or strong correlation was shown [20]. As demonstrated in the other study, the step-off on postoperative CT scan in calcaneal fracture patients was correlated with the SF-36 PCS score, while no correlation was found with the AOFAS score [24]. The present study implied that the AOFAS score was not correlated with the step-off of the posterior facet, which was consistent with the previous findings [13, 20, 24]. This may be due to the restoration of the Böhler's angle and Gissane's angle after operation, and then the step-off in subtalar joint within a certain range would be acceptable.

With respect to the limitations of our study, the main weaknesses of the present study were its retrospective nature and the relatively low follow-up rate. The reason for the low

follow-up rate could be explained by the residential mobility of a few patients without permanent addresses due to the vast area of our country. Second, in addition to post-operative morphological parameters, radiological assessment of calcaneal fractures includes pre-operative evaluation of the fracture classification, fracture geometry, and the severity of injury. The value of 3-D CT on the pre-operative evaluation of above factors has not been mentioned in the current study. 3-D CT may have other benefits not researched in this study and may give useful information not captured by current radiological evaluation.

Conclusion

In conclusion, the present study demonstrated that the functional outcome as reported by the patients after calcaneal fractures during follow-up was related to the 3-D morphological characteristics as evaluated on post-operative 3-D CT, especially the Gissane's angle and Böhler's angle. Although the different congruency of the posterior subtalar facet did exist after the surgical treatment, the clinical outcomes at the final follow-up appear to not be related to the congruency of the posterior facet. The results will provide the clinical basis and objective reference for deciding whether the ORIF or less invasive treatment is optional after intra-articular calcaneal fractures.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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