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Computed Tomography Imaging-Based Preoperative Virtual Simulation for Calcaneal Fractures Reduction

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ABSTRACT

Reduction of calcaneal fractures via a small incision approach at the sinus tarsi is technically difficult. This study was undertaken to determine if preoperative virtual simulation based on computed tomographic data improves reduction and reduces complications. Fifty-five patients with calcaneal fractures were treated via the sinus tarsi approach with minimally invasive plates between February 2013 and December 2015. DICOM files obtained from computed tomographic imaging preoperatively were imported into Superimage software, and virtual surgery was performed. Preoperative planning time, operative time, and complications were recorded. Clinical function was analyzed with radiology and with the American Orthopaedic Foot and Ankle Society and visual analogue scale scores. As a result, preoperative planning time was 30.7 ± 4.1 minutes, which increased with the severity of the fracture (Sanders III vs Sanders II: 34.2 ± 2.5 minutes vs 27.8 ± 2.7 minutes), which was in line with the real surgery, with a mean operative time of 86.7 ± 4.5 minutes (Sanders III vs Sanders II: 89.5 ± 2.7 minutes vs 84.3 ± 4.4 minutes). Radiologic results indicated that the calcaneal width, length, height, Böhler angle, and Gissane angle were significantly corrected from preoperatively to postoperatively. After a mean follow-up of 21.5 ± 6.1 months, no complications were observed. The mean American Orthopaedic Foot and Ankle Society score was 88.7 ± 4.0 , with an excellent/good rate of 94.5% (52 of 55). The mean visual analogue scale score was 0.8 ± 0.9 . In conclusion, preoperative virtual simulation may be efficient to promote accomplishment of sinus tarsi surgery, and this step may help improve outcomes for calcaneal fractures.

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Displaced intra-articular calcaneal fractures, predominantly Sanders types II and III (1), are the most common tarsal bone injuries, but their surgical management remains a challenge for surgeons. In consideration of a high wound-related complication rate (approximately 10% to 50%) induced after a conventional open reduction and internal fixation approach through an L-shaped extensile incision (2,3), various minimally invasive techniques have been developed and gained wide popularity recently, including a small incision approach over the sinus tarsi (4–6). Several comparable trials have demonstrated a significantly lower risk of wound complications (approximately 0% to 6%) by this procedure than with the lateral extended approach (7–11). Nevertheless, the poor

visualization of the fracture site via this small incision makes it difficult to completely and precisely perform bone reduction and insert the fixation plate (12), which may result in inadequate reduction and still cause inevitable complications, such as sural nerve injury, medial plantar injury, and subtalar stiffness (10,11). Additionally, experienced surgeons are required. Thus, we propose that if the surgeons deeply understand the fracture characteristics and are acquainted with the whole reduction process in advance, reduction difficulty can be prevented and the complication rates may be further decreased. This hypothesis may be realized by preoperative evaluation via 3-dimensional computed tomographic (CT) scanning with computerized virtual surgical simulation. Recently, several scholars have tried to perform preoperative planning based on CT scans and preoperative virtual surgery, and they have reported excellent results in reduction of acetabular (13,14), humeral shaft (15,16), and condylar fractures (17,18). However, studies focusing on calcaneal fractures rarely have been reported.

The goal of this study was to retrospectively evaluate the effect of computerized virtual surgery planning on the sinus tarsi approach for patients with displaced intra-articular calcaneal fractures.

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Patients and Methods

Patients

The study protocol was approved by the institutional review board of Shanghai Pudong New Area Zhoupu Hospital, and written informed consent was obtained from all participants. The eligible patients met the following inclusion criteria:

1. Admission for treatment of displaced intra-articular calcaneal fractures between February 2013 and December 2015;
2. With acute (defined as being repaired within 3 weeks of the injury), closed, Sanders type II or III fractures (1) of the calcaneus;
3. With fractures reduction via the small sinus tarsi approach and fixed by the minimally invasive percutaneous plate; and
4. With a minimum of 12 months of clinical follow-up.

The exclusion criteria were the following:

1. Sanders type IV fractures;
2. Open calcaneal fractures;
3. Old fractures (defined as being repaired after 3 weeks of the injury);
4. Accompanied by other fractures in the affected limb; and
5. Accompanied by hemiplegia sequelae in the affected limb that was caused by cerebral infarction before injury.

Preoperative Preparation

After admission, the affected limbs of patients were elevated and immobilized to prevent the exacerbation of injuries. Ice compress and drugs were applied to achieve edema control when the injury occurred within 24 hour. Mandatory smoking cessation and fasting blood glucose control to <8.0 mmol/L by oral metformin were also advocated for some patients to prevent their influence on the fracture healing. Surgery was scheduled when the lateral calcaneal skin began to show wrinkle and flexibility, with a mean interval from injury to surgery of 6.69 ± 1.07 days.

All patients underwent lateral and axial radiography (4 mA, 60 kV) (Fig. 1A, B; Fig. 2A, B) and horizontal CT scans (section thickness 1 mm; tube voltage 120 kV; a Toshiba

Activion 16 [Toshiba Medical Systems, Otawara, Japan]) (Fig. 1C–F; Fig. 2C, D) to reveal the calcaneal fractures.

Computer-Assisted Preoperative Planning

DICOM data obtained from CT scanning were imported into Superimage software (Cybermed Ltd., Shanghai, China), and 3-dimensional visualized models of calcaneal fractures were reconstructed using the quick surface reconstruction function of Superimage software.

Intelligently automatic and manual segmentation functions of Superimage software were used to segment the fragments of calcaneus: automatic segmentation was first performed for the bones around the calcaneus (Fig. 1G; Fig. 2E). When an independent virtual object was formed, these bones were then concealed. Otherwise, manual etching was performed (Fig. 1H; Fig. 2F), followed by automatic segmentation and concealment (Fig. 1I). Only the main calcaneal fracture blocks were retained, which further underwent intelligent segmentation. Different colors were assigned to different fracture fragments. For the fracture blocks with close or overlapped edges, manual partitioning was also performed.

After the segmentation process, each fracture fragment became a separate virtual object. The fracture type, the course for the fracture line, the shape of fracture blocks, and the subtalar articular surface could be observed and assessed by movement, rotation, zoom (magnification and minimization), and other functions. Then the fracture fragments were virtually reduced by the movement function to restore anatomical positions (Fig. 1J, K; Fig. 2G, H).

Once the reduction succeeded, virtually minimally invasive percutaneous plates were chosen from the instrument library of the Superimage software. The plate and fracture imaging were matched using the fitting function of the Superimage software, with the plate placed on the lateral surface of the lateral cortex of the calcaneus (Fig. 2I, J). Screws of the appropriate length were inserted into the plate or across the fracture with the perspective and length measurement function of the Superimage software (Fig. 1L, M; Fig. 2K, L).

Surgical Procedure

All patients were operated in a lateral decubitus position under epidural or subarachnoid anesthesia. A lateral incision was made from the tip of the lateral malleolus to the proximal cuboid to expose the lateral cortex of the anterior process of the calcaneus. According to the virtual surgical plan, the subtalar articular surface was elevated by using a special periosteal elevator. Meanwhile, a 3.5-mm Steinmann pin was inserted into the bone block under the articular surface to correct the Böhler angle, Gissane angle, and

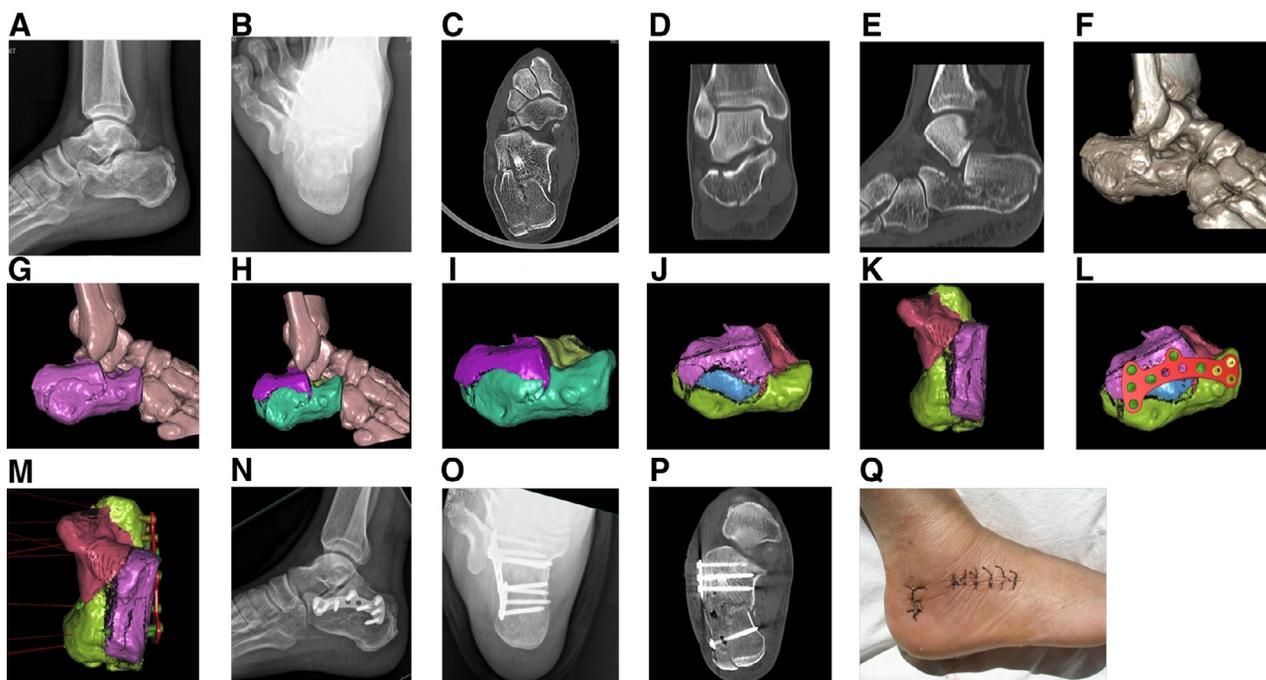


Fig. 1. A male, aged 49 years, was admitted for treatment of calcaneal fractures and underwent preoperative virtual simulation. Preoperative lateral (A) radiographs showed reduced calcaneal height and decreased Böhler angle and Gissane angle, preoperative axial (B) radiographs showed increased calcaneal width, and a preoperative plain computed tomographic (CT) scan (C) indicated right calcaneal fractures, with the bulging around the lateral wall, articular surface embedded in the calcaneus and obvious varus deformity. A preoperative coronal CT scan (D) indicated subtalar articular surface fractured, a preoperative sagittal reconstruction (E) indicated concave subtalar articular surface, and a preoperative 3-dimensional reconstruction (F) indicated bulked lateral wall and a displacement in the subtalar articular surface. A preoperative automatic segmentation for the bones around the calcaneus (G), manual etching for the bones around the calcaneus (H), automatic segmentation and concealment (I), virtual reduction (J), reduction confirmation (K), plate insertion (L), and plate and screw confirmation (M) are shown. Postoperative lateral (N) radiographs showed obvious corrections of the calcaneal height, Böhler angle, and Gissane angle. Postoperative axial (O) radiographs showed obvious corrections of calcaneal width and a postoperative plain CT scan (P) showed excellent fracture reduction. The wound was healing well at 14 days after surgery (Q).

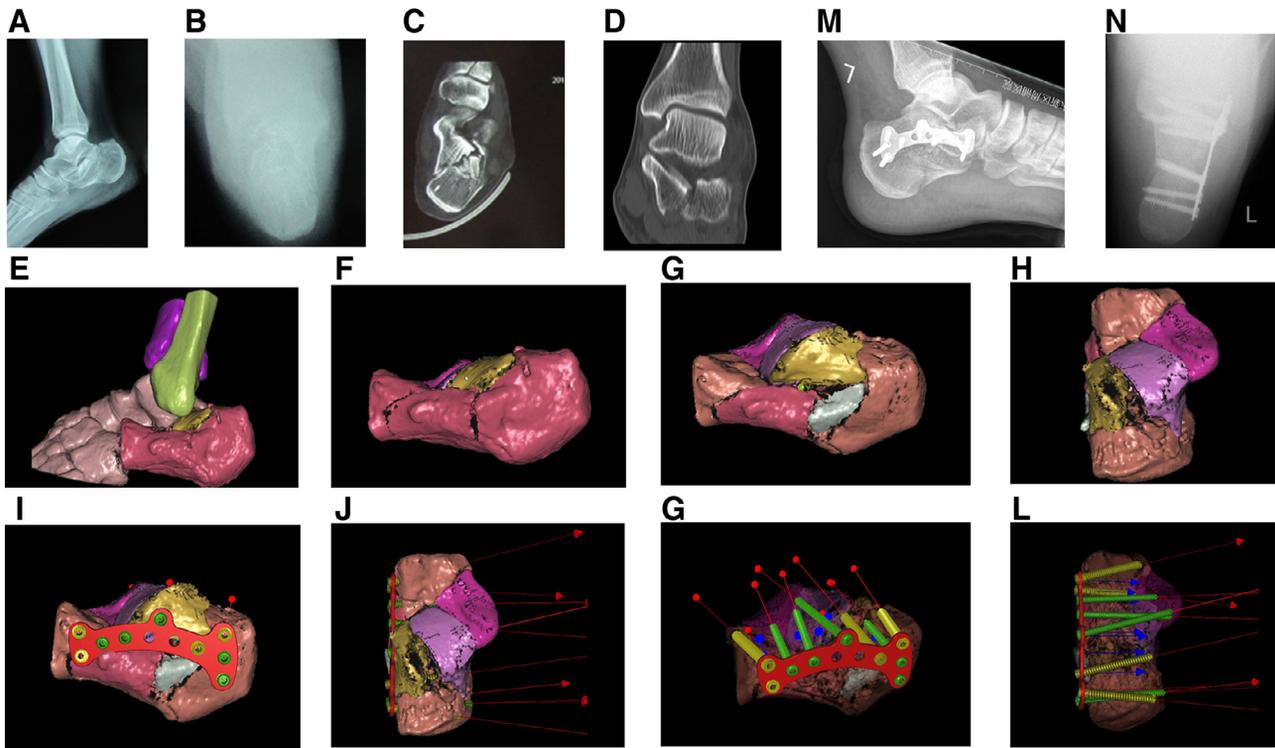


Fig. 2. A male, aged 50 years, was admitted for treatment of calcaneal fractures and underwent preoperative virtual simulation. Preoperative lateral (A) radiographs showed decreased calcaneal height and decreased Böhler and Gissane angle. Preoperative axial (B) radiographs showed increased calcaneal width, a preoperative plain computed tomographic (CT) scan (C) indicated right calcaneal fractures, with the bulging around the lateral wall, articular surface embedded in the calcaneus, and obvious varus deformity. A preoperative coronal CT scan (D) indicated subtalar articular surface fractured and a preoperative automatic segmentation for the bones around the calcaneus (E). Automatic segmentation and concealment (F), virtual reduction (G, H), virtual fixation (I, J), reduction confirmation (K, L), and postoperative lateral radiographs (M) showed obvious corrections of the calcaneal height, and Böhler and Gissane angles. Postoperative axial (N) radiographs showed obvious corrections of calcaneal width.

calcaneal length, height, and width, which was then temporarily held in place. When a larger defect was present in the cancellous bone, β -tricalcium phosphate artificial bone (Shanghai Beiaolu Bio-Materials Ltd., Shanghai, China) was implanted. After a satisfactory reduction was achieved under C-arm fluoroscopy, the appropriate locking plate corresponding with the virtual plan was used to fix the subtalar articular surface, anterior process of the calcaneus, and the sustentaculum tali. Once a rigid fixation was achieved under C-arm fluoroscopy, the incision was closed in a layered fashion.

Postoperative Management

Within 48 hours after operation, prophylactic antibiotics were given to prevent infection, and elevation of the affected limb was performed for edema control. Dressing changing was done every 3 days, and sutures were removed at 2 weeks after the operation. Patients were encouraged to do toe flexion and dorsiflexion exercises at 24 hours after the operation, and weightbearing exercise was initiated at 3 months after the operation.

Outcome Evaluation

The preoperative planning time (needed to accomplish fracture fragments' segmentation, virtual fracture reduction, and virtual fixation in minutes), operative time (measured from the cut to the suture of the incision in minutes), and the occurrence of complications were recorded. Lateral and axial radiographs were also obtained preoperatively and postoperatively to assess the reduction of the calcaneus, including the Böhler angle, Gissane angle, and calcaneal height, width, and length (19). Measurement of the reduction parameters was accomplished using the Image-pro plus software (version 5.0; Media Cybernetics, Silver Spring, MD). Clinical functional outcomes were evaluated every 6 months by the American Orthopaedic Foot and Ankle Society (AOFAS) score (20,21) and a visual analogue scale (VAS) score. The AOFAS is a 100-point scoring system, with a score between 90 and 100 considered to be an excellent result, between 80 and 89 good, between 70 and 79 fair, and < 69 poor. The VAS for pain ranges from 0 (no pain) to 10 (severe pain).

Statistical Analysis

All data were expressed as n (%) or mean \pm standard deviation and analyzed by SPSS statistical software (version, 18.0; SPSS Inc., Chicago, IL). The comparison

between preoperative and postoperative results was performed with a 2-tailed, paired, Student's *t* test, whereas the comparison between different Sanders classifications was performed by the 2-tailed, independent, Student's *t* test. A *p* value of < .05 was considered to indicate a significant difference.

Results

According to the inclusion and exclusion criteria, 55 patients (49 males and 6 females) with calcaneal fractures showing loss of Böhler angle, and Gissane angle, decreased calcaneal height, length, and increased calcaneal width (Fig. 1A, B; Fig. 2A, B), were enrolled in this study. Their mean age at the time of the calcaneal fracture was 48.6 ± 10.8 years. The mechanism of injury included falling from a height in 52 (94.5%) cases and traffic accidents in 3 (5.5%) cases. All fractures were closed and unilateral, with the left side affected in 23 (41.8%) cases and the right side affected in 32 (58.2%) cases. Eleven (20%) patients had a smoking history of > 5 years who were required to quit smoking; 2 (3.64%) patients had diabetes who received blood sugar control before surgery. According to the Sanders CT scan classification system, there were 30 (54.5%) patients with type II fractures (9 [16.4%] type IIa and 21 [38.2%] type IIb) and 25 (45.5%) with type III fractures (21 [38.2%] type IIIab, 1 [1.82%] type IIIac, and 3 [5.45%] type IIIbc) (Table 1; Supplemental Table 1).

Preoperative virtual surgery, including segmentation, simulated reduction and fixation, was performed in all 55 patients, with the mean time required for virtual planning of 30.7 ± 4.1 minutes and the time increased with the severity of the fracture (Sanders III vs Sanders II: 34.2 ± 2.5 minutes vs 27.8 ± 2.7 minutes; *p* < .05) (Table 2). This finding seemed to be in line with the real surgery, with the mean operative time also longer in Sanders III than Sanders II (89.5 ± 2.7 minutes vs 84.3 ± 4.4 minutes; *p* < .05) (Table 2).

Table 1
Demographic data of 55 patients with calcaneal fractures

Parameters	Mean ± SD or no. (%)
Age (y)	48.6 ± 10.8
Gender, male	49 (89.1)
History	
Smoking	11 (20.0)
Diabetes	2 (3.64)
Injury mechanism	
Falling from a height	52 (94.5)
Traffic accidents	3 (5.5)
Location	
Left	23 (41.8)
Right	32 (58.2)
Sanders classification	
Type II	30 (54.5)
IIa	9 (16.4)
IIb	21 (38.2)
Type III	25 (45.5)
IIIab	21 (38.2)
IIIac	1 (1.82)
IIIbc	3 (5.45)
Time from injury to surgery (d)	6.69 ± 1.07

Abbreviation: SD, standard deviation.

Referring to the virtual surgical plan, surgery was successfully achieved in all patients, with the calcaneal width, length, height, and Böhler and Gissane angles significantly corrected from preoperatively to postoperatively, regardless of overall or different Sanders types (Table 3). After a mean follow-up of 21.5 ± 6.1 months, no screw loosening or breakage of internal fixation was observed and none of the patients developed incision infection, incisional margin necrosis, incision split, or other complications. Sural nerve and long or short peroneal tendon injuries were not present. All patients were able to walk normally, with excellent appearance and without discomfort when wearing shoes.

Functional outcomes were also evaluated. According to the AOFAS scoring system, 30 patients (54.5%) were assessed as excellent, 22 (40.0%) as good, and 3 (5.5%) fair, with a mean AOFAS score of 88.7 ± 4.0 and an excellent/good rate of 94.5%. The mean VAS score was 0.8 ± 0.9. Further comparison showed a higher AOFAS score (91.0 ± 2.5 vs 85.8 ± 3.6; $p < .05$) and lower VAS (0.2 ± 0.6 vs 1.5 ± 0.9; $p < .05$) in Sanders type II than type III fractures after surgery but no significant difference in the excellent and good rate (100% vs 88%; $p = .088$; Table 4). Typical cases are presented in Figs. 1 and 2.

Discussion

In present study, we used virtual planning to preoperatively understand the calcaneal fracture characteristics and designed the sinus tarsi reduction procedure to improve reduction effects and prevent injuries, which to our knowledge was reported for the first time. In line with treatment for other fractures (15,16,22), surgeons also benefit from virtual operating for calcaneal fractures, which was reflected in the following ways.

First, no complications occurred after follow-up, which was obviously favorable to current reports without preoperative simulation. For example, Basile et al (7) reported painless ambulation owing to hindfoot varus malreduction in 1 (2.6%) patient and peroneal tendons irritation

Table 2
Time recorded preoperatively, intraoperatively, and postoperatively (N = 55)

	Total	Sanders II	Sanders III	p Value
Preoperative planning time (min)	30.7 ± 4.1	27.8 ± 2.7	34.2 ± 2.5	<.001
Operative time (min)	86.7 ± 4.5	84.3 ± 4.4	89.5 ± 2.7	<.001
Follow-up time (mo)	21.5 ± 6.1	20.9 ± 5.5	22.3 ± 6.8	.421

Values are mean ± standard deviation.

Table 3
Radiologic and function results before and after operation (N = 55)

	Preoperative	Postoperative	p ₂ Value
Böhler angle (°)			
Total	2.6 ± 3.9	26.5 ± 3.1	<.001
Sanders II	2.8 ± 4.3	26.1 ± 2.8	<.001
Sanders III	2.4 ± 3.6	27.0 ± 3.3	<.001
p ₁ value	.660	.307	
Gissane angle (°)			
Total	97.7 ± 7.5	119.4 ± 4.5	<.001
Sanders II	97.9 ± 5.7	119.5 ± 4.9	<.001
Sanders III	97.4 ± 9.4	119.2 ± 4.0	<.001
p ₁ Value	.836	.781	
Calcaneal width (mm)			
Total	41.0 ± 2.8	32.8 ± 1.8	<.001
Sanders II	40.9 ± 3.0	32.3 ± 1.5	<.001
Sanders III	41.1 ± 2.5	33.4 ± 2.0	<.001
p ₁ Value	.807	.029	<.001
Calcaneal length (mm)			
Total	62.4 ± 4.2	67.1 ± 3.6	<.001
Sanders II	63.0 ± 4.3	67.6 ± 3.6	<.001
Sanders III	61.6 ± 3.9	66.5 ± 3.7	—
p ₁ Value	.193	.274	—
Calcaneal height (mm)			
Total	32.0 ± 3.4	38.2 ± 2.5	<.001
Sanders II	32.2 ± 3.8	38.7 ± 2.5	<.001
Sanders III	31.8 ± 3.0	37.6 ± 2.4	<.001
p ₁ Value	.463	.126	

in 1 (2.6%) patient in the sinus tarsi treatment group. Cao et al (23) observed postoperative superficial infections and subtalar arthritis in 4 (12.1%) patients, which were resolved with systemic antibiotics and oral indomethacin, respectively. Wu et al (10) showed the complication rate in minimally invasive group was 6.6% (14 of 213), including superficial infection in 4 (1.9%), sural nerve injury in 3 (1.4%), and medial plantar nerve injury and restricted movement of flexor hallucis longus tendons in 7 (3.3%) cases.

Second, the operative time seemed to be shorter compared with the study of Basile et al (7) (86.7 ± 4.5 vs minutes 122.15 ± 8.32 minutes) and Abdelazeem et al (4) (86.7 ± 4.5 minutes vs 90 [range 70 to 120] minutes). The longer operative time may be attributed to repeated reduction attempt and confirmation by radiographic fluoroscopy. In addition, preoperative planning time was relatively shorter (approximately 30 minutes) (15) when using Superimage software in comparison with other platforms (24,25), and its supplement may not increase more time for surgery, indicating its feasibility.

Third, clinical outcomes also seemed to be better, with an AOFAS score of 88.7 ± 4.0 and an excellent/good rate of 94.5% (52 of 55). However, the mean AOFAS score was only 82.5 ± 5.7 (82 [range 80 to 99]) minutes versus 82.17 ± 11.50 minutes. In the studies of Feng et al (26), Cao et al (23), and Basile et al (7), the excellent/good rates were 89.5% (34 of 38), 93.9% (31 of 33), and 72.2% (13 of 18), respectively. Although 3 (5.5%) patients reported a "fair" outcome in our study, their scores resulted from a subjective evaluation of pain and not gait analysis (their

Table 4
Function results before and after the operation (N = 55)

	Total	Sanders II	Sanders III	p Value
AOFAS				
Score	88.7 ± 4.0	91.0 ± 2.5	85.8 ± 3.6	<.001
Excellent/good rate	52 (94.5)	30 (100)	22 (88.0)	.088
VAS	0.8 ± 0.9	0.2 ± 0.6	1.5 ± 0.9	<.001

Abbreviations: AOFAS, American Orthopaedic Foot and Ankle Society; VAS, visual analogue scale.

Values are mean ± standard deviation or no. (%).

imaging examination results were also normal). These 3 patients were workers and prolonged standing was needed at work, which may have resulted in an increased likelihood of out of control pain as compared with other patients (27). In addition, the development of post-traumatic arthritis may also cause pain (23). However, joint space narrowing was not observed in our shorter follow-up period. Thus, long-term follow-up is still necessary to further confirm our complications. As for the VAS, a similar conclusion was also obtained, with lower scores when compared with the studies of Cao et al (23) (0.8 ± 0.9 vs 1.6 ± 1.4) and Li et al (28) (0.8 ± 0.9 vs 1.5 ± 0.7). Although recent studies have demonstrated an equivalent anatomical reduction with the sinus tarsi approach compared with the extended lateral approach (2,3,9,11), we believe that this finding may be owing to the fact that all surgeries were performed by experienced calcaneal fracture surgeons who knew the anatomy well and were experts in the sinus tarsi approach (9). For younger and less experienced surgeons, preoperative virtual planning may be important to attain perfect reduction results, shorten the learning curve, and increase the knowledge of the anatomical variations to prevent intraoperative unexpected difficulties for all surgeons (29). As expected, in our study, the calcaneal width, length, height, and Böhler and Gissane angles were significantly corrected from preoperatively to postoperatively, with no loss during follow-up.

Our study has some limitations. First was its retrospective nature, which led to the patients not being randomized to receive virtual planning and sinus tarsi surgery. Second, we did not have a direct control group (especially younger and less experienced surgeons) who performed surgery without preoperative planning to confirm the effects on learning curve shortening and reduction improvement (30) but only reviewed the literature. Third, our sample size of 55 was relatively small and the follow-up was short, which may result in the underestimation of the complication rate and long-term reduction effects. Fourth, only Sanders II and III calcaneal fractures were evaluated, not Sanders IV. Therefore, further clinical investigation with a larger sample size, more complex fracture types, longer follow-up period, and a randomized controlled design is necessary to obtain a more precise efficacy evaluation.

In conclusion, our results confirm that preoperative virtual simulation can be a useful method to assist surgeons in preoperative planning and intraoperative accomplishment of sinus tarsi surgery, thereby aiding in improving clinical outcomes for calcaneal fractures.

Supplementary Materials

Supplementary material associated with this article can be found in the online version at <https://doi.org/10.1053/j.jfas.2018.08.054>.

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