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ORIGINAL PAPER

Computer-assisted virtual surgical technology in pre-operative design for the reconstruction of calcaneal fracture malunion

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Abstract

Purpose No computer-assisted pre-operative design for calcaneal fracture malunions has been presented. The aim of the study is to evaluate the intra-operative realization of computer-assisted pre-operative planning (CAPP) and the clinical outcomes based on computer-assisted virtual surgical technology for calcaneal malunions.

Methods Between 2010 and 2016, 20 patients with 21 calcaneal fracture malunions were retrospectively reviewed with the average follow-up time of 22.3 months (range, 12 to 43 months), which were operatively treated with the help of CAPP. The CAPP steps included the image segmentation, exostectomy of lateral wall, simulated reconstruction of calcaneal thalamus, morphological evaluation, and the implantation of internal fixation devices. Post-operative outcomes were assessed with the American Orthopaedic Foot and Ankle Society (AOFAS) score, SF-36 physical component summary (PCS), VAS for pain, range of motion of ankle, and the morphological parameters of the calcaneus including the axial length of the calcaneus, the height of the posterior facet, the talocalcaneal angle, Böhler's angle, and Gissane's angle.

Results The mean time required for CAPP was 41.8 minutes. All the surgical processes were carried out according to CAPP. Six patients (6 feet) were treated with the joint-preserving osteotomy. Fourteen patients (15 feet) underwent the subtalar distraction bone block arthrodesis, among which the medial displacement calcaneal osteotomy was additionally performed in six patients (6 feet). At the final follow-up, the average AOFAS, SF-36 PCS, and VAS scores were significantly improved to 77.4, 64.3, and 1.4, respectively ($P < 0.001$). The postoperative calcaneal morphological parameters and the range of motion of ankle were significantly restored ($P < 0.05$).

Conclusion CAPP can assist surgeons in understanding calcaneal malunions, thereby improving intraoperative correction and reconstruction. The satisfying clinical and radiographic outcomes could be provided after treating calcaneal malunions aided by the computer-assisted virtual surgical technology.

Keywords Calcaneal fracture · Malunion · Osteotomy · Computer-assisted surgery · Computed tomography · Three-dimensional imaging

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Introduction

Fractures of calcaneus are the most common tarsal fractures. Calcaneal fractures account for 2% of all fractures, 75% of which are intra-articular [1, 2]. Inappropriate surgical management or conservative treatment of these displaced intra-articular calcaneal fractures may result in a severely disabling fracture malunion and long-standing heel pain. The pathoanatomy of calcaneal malunion includes loss of height, heel widening accompanying with subfibular impingement, calcaneocuboid joint impingement, hindfoot malalignment with deformity, and posttraumatic arthrosis [3–5]. Malunited calcaneal fractures are often accompanied with different complications, which seriously influence patients' quality of life and cause a large economic impact.

The goal of treatment for calcaneal fracture malunion is restoration of a painless foot with satisfying function [6]. A number of surgical techniques have been described for reconstruction of the malunited calcaneus fractures, such as lateral wall decompression, various kinds of subtalar arthrodeses, corrective osteotomy and arthrodesis, triple arthrodesis, and so on [4, 7–11]. Despite the numerous surgical techniques available, management of calcaneal malunion is still technically difficult due to the irregular contour of the calcaneus, the delicate soft tissue envelope, the surrounding neurovascular structures, and the complex mechanics of the subtalar joint [5]. The choice and combination of operative methods for the calcaneal fracture malunion is still a challenge fraught with possible complications.

Pre-operative planning plays an important role in orthopaedic surgery. Precise pre-operative planning can provide radiological assessment and detailed information in performing surgery. Computer assistance has acquired wide acceptance for use in trauma surgery, such as surgical reduction and fixation for humeral fractures, pelvic and acetabular fractures, and tibial plateau fractures [12–15]. Computer-assisted preoperative planning (CAPP) has become an important part of the computer-assisted orthopaedic surgery (CAOS) [16]. With the development of computer technology, three-dimensional (3-D) CT and its interactive segmentation and measurement technique have gradually become popular to improve visualization and quantitative evaluation in calcaneus [17, 18].

To our knowledge, no computer-assisted pre-operative design for calcaneal fracture malunions has been presented. We hypothesized that CAPP would be helpful to make the surgical treatment protocol for calcaneal fracture malunions and to estimate whether the bone excised from the lateral wall was enough for bone graft. And the efficient computer-assisted virtual surgical technology may lead to an improved clinical outcome for the reconstruction of calcaneal fracture malunions. The purposes of the current study were (1) to present the procedure of CAPP for calcaneal fracture malunions, (2) to evaluate the intra-operative realization of pre-operative planning, and (3) to determine the clinical outcomes after treating calcaneal malunions based on computer-assisted virtual surgical technology.

Materials and methods

Patient

Between May 2010 and January 2016, a total of 20 patients with 21 calcaneal fracture malunions were retrospectively reviewed in the study, which were operatively treated with the help of computer-assisted pre-operative planning. The demographic characteristics, mechanism of injury, initial treatment, time from fracture to reconstructive operation, and the classification were recorded (Table 1). All patients had been received initial treatment, including nine treated conservatively and 12 surgically. Twenty patients with a mean age of 44.7 years (range, 24 to 62 years) consisting of six females and 14 males, one of which presented with bilateral calcaneal malunion. The average period from injury to operation was 13.1 months. The patients complained of walking disability, pain along the heel and distal fibula, and loss of the longitudinal arch. According to the Stephens and Sanders Classification of calcaneal malunions, there were three feet with type I malunion, nine feet with type II malunion, and nine feet with type III malunion. The CT and radiographic data were from the medical image database in the hospital. The clinical data were gathered from patients' medical records. This retrospective study was approved by the institutional review committee of the hospital. And written informed consents were obtained.

Computer-assisted pre-operative planning

The CT scanning data were input into the CAPP system (SuperImage Orthopedics Edition 1.1; Cybermed Ltd., Shanghai, China) [15, 19]. Two-dimensional (2-D) multiple

Table 1 Patients' demographic data

Characteristic	
Gender	
Male/female	14/6
Side, *n*	
Left/right	13/8
Mechanism of initial injury, *n*	
Vehicle accident	6
Missing steps	4
Falling from height	11
Reason for malunion, *n*	
Inappropriate surgery	12
Conservative treatment	9

planar reconstruction and 3-D volume rendering of the calcaneus were reconstructed for analyzing injury details, including the congruity of subtalar joint with or without arthrosis (Fig. 1). In accordance with the radiological evaluation, our clinical experience, and the current mainstream surgical treatment for calcaneal malunions, our surgery team chose two basic surgical methods categorized as subtalar arthrodesis and joint-preserving osteotomy [3, 11]. For part of cases with severe valgus malalignment, the surgery was supplemented with a medial displacement calcaneal osteotomy. The CAPP steps were as follows (Fig. 2).

1. Bone segmentation and virtual exostectomy of lateral wall

The 3-D shaded surface display image of the calcaneus with heel widening was distinguished by 3-D interactive and automatic segmentation. The exostosis was excised from the posterior to the anterior of lateral wall via the plane cutting technique of the software. The excised lateral fragment could be the main source of the autograft bone.

2. Simulated reconstruction of calcaneal thalamus

In the subtalar arthrodesis group, the distraction bone block arthrodesis was simulated after the lateral calcaneal wall was exposed subperiosteally and excised to the normal width for lateral decompression. After the distraction of the posterior subtalar joint, an appropriately sized bone graft was prepared for the joint gap. In the joint-preserving osteotomy group, the collapsed and malunited posterior articular facet fragment was separated along the primary fracture line with an osteotomy. If the fracture line was invisible, the tongue osteotomy would be used in the body of the calcaneus [20]. The fragment was distracted upward and backward to restore the congruence of the subtalar joint. The bone excised from the lateral wall was filled in the distraction gap. As the bone graft, the excised fragment with appropriate shape and placement was helpful to correct the varus or valgus deformity.

3. Simulation of medial displacement calcaneal osteotomy

The osteotomy was obliquely at 45° to the plantar from the recess of the tuberosity to the inferior border of the calcaneal body [21]. The osteotomy ran approximately 1.0 cm beneath the peroneal tendons. The cutting plane was perpendicular to the lateral cortical surface to avoid shortening of the heel. Medial displacement was 1.0 to 1.5 cm or nearly one-third the width of the calcaneus.

4. Morphological evaluation for simulated reconstruction

The 3-D morphological evaluation could indicate whether the bone excised from the lateral wall was enough for bone

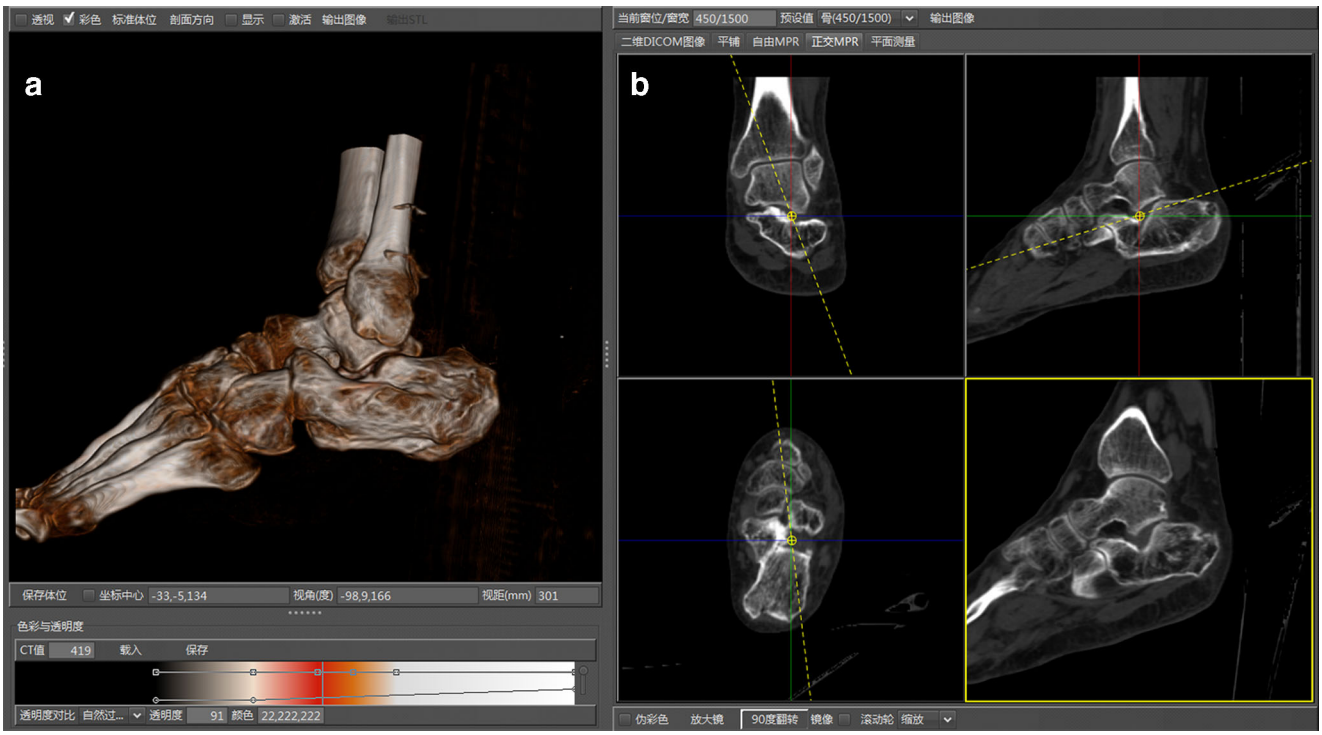

Fig. 1 The pre-operative CT for analyzing injury details. **a** The 3-D image of the malunited calcaneus fracture was reconstructed by volume rendering. **b** The 2-D images were reconstructed by multiple planar reconstruction, which could detect the congruity of subtalar joint with or without arthrosis

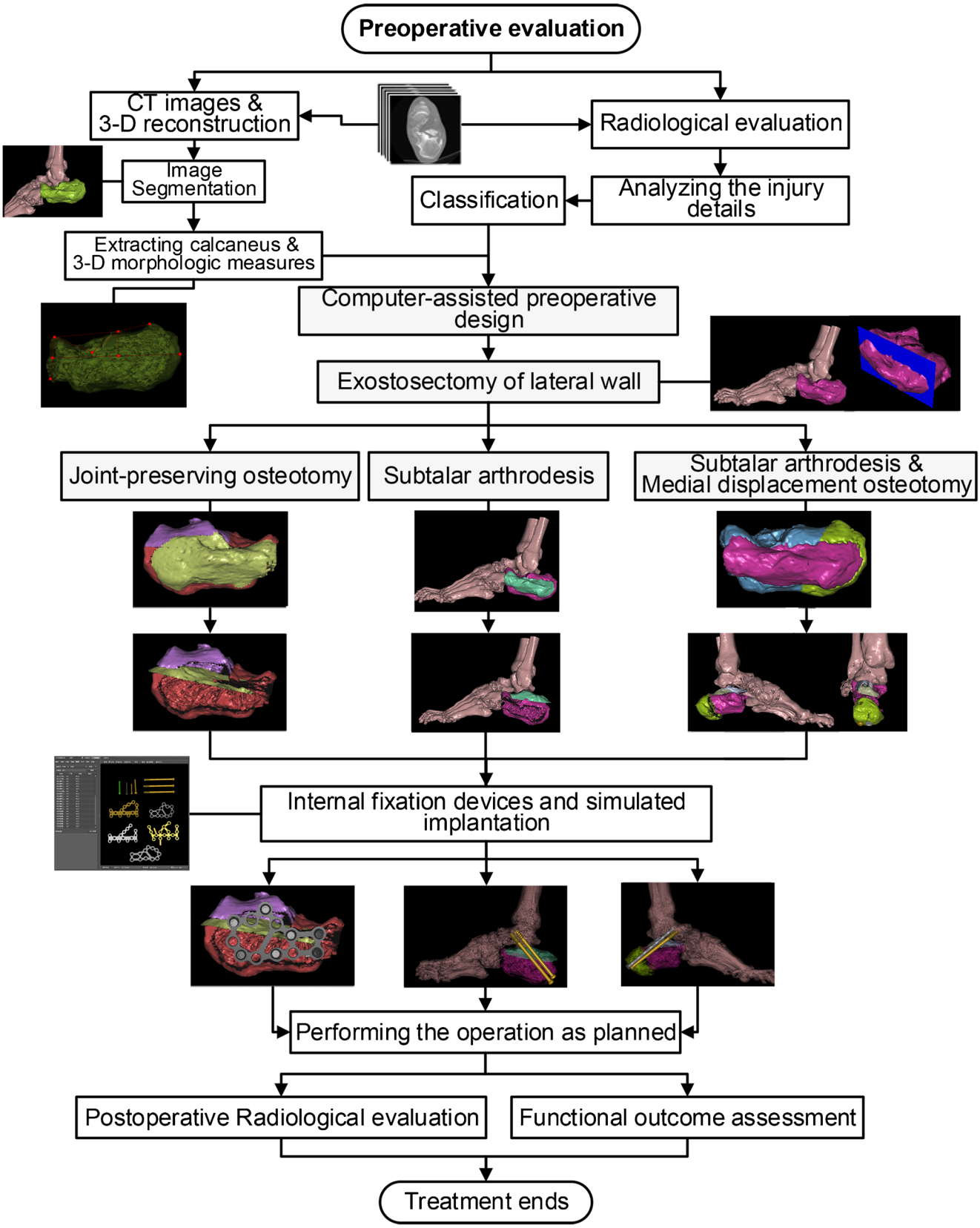

Fig. 2 Flow diagram of computer-assisted pre-operative planning for calcaneal fracture malunions

graft. The Böhler's angle and the Gissane's angle were additionally assessed in the 3-D space in the joint-preserving osteotomy group [17, 19].

5. Internal fixation devices and simulated implantation

The appropriate plates were chosen from the internal fixation device database of the system. After rebuilding the calcaneal morphology, the calcaneal plate and screws with the proper size were placed on the lateral wall in joint-preserving osteotomy group. Patients who underwent the subtalar arthrodesis with use of partially or fully threaded (6.5 or 7.3 mm) cannulated screws.

Surgical protocol and post-operative rehabilitation

Epidural anaesthetic were used for the operation. The calcaneal wall was exposed by the lateral extensile L-shaped incision. The patients with failed surgery had the removal of the previous hardware first. When the intra-operative evaluation was consistent with the pre-operative radiological assessment, the operation was carried out according to the pre-operative protocol. The defect in the subthalamic portion or the distraction gap was filled with bone graft from the excised lateral wall. For part of cases with Achilles tendon contracture, the percutaneous Achilles lengthening was performed additionally. The iliac crest would be harvested for the part of patients, whose bone excised from the lateral wall was not enough according to CAPP. C-arm fluoroscopy was used to determine the intra-operative reconstruction quality.

Patients were encouraged to perform early passive motion of the knee and toes without weight-bearing from the first day after surgery. Full weight-bearing was not recommended until the radiographic union. The axial length of the calcaneus, the height of the posterior facet, and the talocalcaneal angle were assessed in all cases on the lateral radiograph. The post-operative CT scanning was additional performed in the patients with joint-preserving osteotomy to evaluate the Böhler's angle and the Gissane's angle in the 3-D space, as well as the congruence of the subtalar joint [17]. To quantify functional outcomes, a visual analogue scale (VAS) for pain, the American Orthopaedic Foot and Ankle Society (AOFAS) ankle–hindfoot scale, and the SF-36 physical component summary (PCS) were used. The passive range of motion of the ankle was evaluated.

Statistical analysis

The data were analyzed using SPSS 18.0 for Windows software (PASW Statistics, IBM, USA). Data were shown as the range, the mean and standard deviation (SD). The Shapiro–Wilk test of normality in frequentist statistics was used. The nonparametric test such as Wilcoxon signed rank test was used when comparing the matched sample of the range of motion of ankle and Gissane's angle, which were not normally distributed. Differences of the functional outcome scores and the other radiological measurements between the pre-operative and final follow-up results would be determined by the paired samples t test, due to the normally distributed data. A P value less than 0.05 was considered to be significant.

Results

Table 2 presents the time spent in each stage of CAPP for the virtual reconstruction of calcaneal fracture malunions. The mean time required for CAPP was 41.8 minutes (range, 30 to 64 minutes). With regard to the time spent in each stage of CAPP for the virtual reconstruction, the segmentation of fracture fragments was finished in the software with the average time of 6.0 minutes. The virtual exostectomy of lateral wall costs 4.7 minutes on average. The mean time spent in the virtual distraction bone block arthrodesis, joint-preserving osteotomy and medial displacement osteotomy, and evaluation of the simulated reconstruction was 13.7 minutes, 19.0 minutes, 13.0 minutes, and 12.1 minutes, respectively.

All of the surgical processes were carried out strictly according to CAPP (Figs. 3 and 4). Six patients (6 feet) were treated with a joint-preserving osteotomy. Fourteen patients (15 feet) underwent the subtalar distraction bone block arthrodesis, among which the medial displacement calcaneal osteotomy was additionally performed in six patients (6 feet). The mean operating time was 79.3 ± 15.4 minutes. The mean intra-operative blood loss was 95.5 ± 53.0 ml (range, 50 to 250 ml). The greatest blood loss was 250 ml in a patient with the longest operating time that reached the limited time of the thigh tourniquet; therefore, the thigh tourniquet needed to be released. Concerning post-operative complications, a 1-cm wound edge necrosis required daily wound dressing in one foot (4.8%), which finally healed after 22 days. No post-operative haematoma, deep soft tissue infection or deep venous thrombosis occurred.

The 20 patients were available with the average follow-up time of 22.3 months (range, 12 to 43 months). The average AOFAS score improved significantly from 32.3 (range, 20 to 48) pre-operatively to 77.4 (range, 68 to 91) at follow-up ($t = -22.92$, $P < 0.001$). The average SF-36 PCS increased to 64.3 ± 8.0, which was 45.7 ± 11.0 pre-operatively ($t = -8.83$, $P < 0.001$). The average VAS score for pain was 1.4 (range, 0 to 3.8) at the final follow-up, whereas the pre-operative VAS score was 5.9 (range, 4 to 8), of which the difference was significant ($t = 14.84$, $P < 0.001$). The range of motion of the ankle and the radiological measurement are summarized in Table 3. The dorsiflexion and the plantar flexion were significantly improved at the final follow-up ($P < 0.001$). The significant differences could be detected between the pre-

Table 2 The time spent in each stage of computer-assisted preoperative planning (min)

Case	Classification (Stephens and Sanders)	Image segmentation	Virtual exostectomy of lateral wall	Simulated distraction bone block arthrodesis	Virtual joint-preserving osteotomy	Simulation of medial displacement osteotomy	Morphological evaluation	Total time
1	III	12	7	16	–	15	14	64
2	III	6	5	8	–	12	15	46
3	II	5	5	–	15	–	12	37
4	II	4	5	–	24	–	8	41
5	II	5	4	10	–	–	11	30
6	II	7	5	14	–	–	14	40
7	III	9	6	15	–	–	13	43
8	III	8	6	11	–	14	14	53
9	I	2	4	–	16	–	8	30
10	III	6	5	18	–	–	15	44
11	I	4	4	12	–	–	11	31
12	II	5	4	–	20	–	10	39
13	III	8	4	15	–	–	10	37
14	III	9	6	16	–	14	15	60
15	II	3	4	–	21	–	6	34
16	III	6	5	12	–	–	15	38
17	I	2	4	–	18	–	8	32
18	III	6	4	14	–	13	14	51
19	II	3	4	13	–	10	12	42
20	II	9	3	17	–	–	16	45
21	II	7	5	15	–	–	13	40

operative and post-operative parameters including the axial length of the calcaneus, the height of the posterior facet, and the talocalcaneal angle ($P < 0.05$). The Gissane's angle and the Böhler's angle were measured in the cases with joint-preserving osteotomy, which were significantly improved post-operatively ($P < 0.001$).

Discussion

Calcaneal malunion is a common complication suffering from non-operative treatment or inappropriate surgery for calcaneal fractures. The objective deformities are heel widening, residual hindfoot malalignment, and subtalar joint depression. Surgical treatment for calcaneal malunion aims to improve the anatomy of the calcaneus to the nearly normal one by reshaping the calcaneal geometry and recovering the hindfoot function.

As the regular method, the conventional pre-operative planning for calcaneal malunions is based on radiography and CT images (including 2-D and 3-D imaging) in combination with surgeon's experience. Compared with the conventional method, CAPP allows the surgeons more detailed observation, more precise measurement, and more direct understanding of the malunion including the height, the width, and the alignment of the hindfoot. With use of computer-assisted virtual surgical technology, it allows the interactive and direct display of characteristics of the fracture for surgeons [14, 16]. Meanwhile, surgeons can perform the virtual surgery, including simulated reconstruction, osteotomy, and internal fixation implantation. In this study, the computer-assisted virtual surgical technology was very useful for pre-operative planning and intra-operative decision making. It was revealed the long operative time was considered a high risk factor and associated with incision complications infection for calcaneal surgery [22]. Shi et al. [23] reported that the surgical time of the subtalar joint fusion through the modified lateral approach for calcaneal malunions was 85 min, which was without computer-assisted pre-operative planning. In the present study, the mean operation time was 79.3 min. The difference of operating time between the treatment with and without computer-assisted planning for the calcaneal malunion might be related to that the virtual operation gives an important guidance to carry out the reconstruction of calcaneus and to select the suitable internal fixation devices. Optimal reconstruction of the calcaneal malunion depends on the precise and detailed pre-operative planning besides the surgeons with rich experience, or else, repeated adjustments for pursuing adaptable surgical protocol will possibly increase the exposure time of fluoroscopy and prolong the operating time. With the

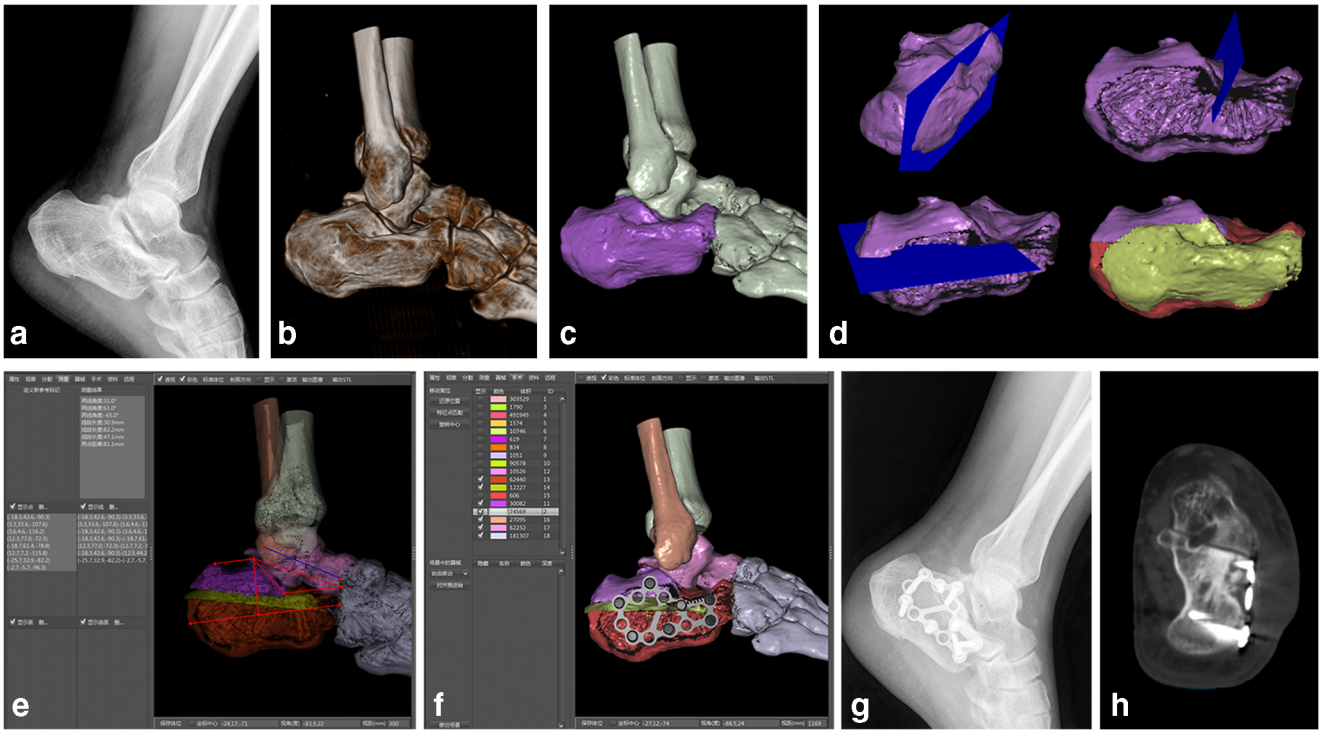

Fig. 3 The computer-assisted pre-operative planning for the reconstruction of calcaneal thalamus for joint-preserving osteotomy. **a** The radiography showed that the calcaneal fracture malunion occurred in a 30-year-old female due to the conservative treatment one year ago. **b** The 3-D volume rendering image revealed the lateral wall blowout and the clear subtalar joint. **c** The shaded surface display image of the calcaneus was labeled by 3D interactive and automatic segmentation. **d** The plane cutting technique for virtual osteotomy. **e** The thalamus fragment was distracted upward and backward to restore the congruence of the joint. The bone excised from the lateral wall was filled in the distraction gap. And then morphological measurement for simulated reconstruction was evaluated. **f** The joint-preserving osteotomy with appropriate internal fixation devices was stimulated. **g** The post-operative lateral radiograph indicated the surgical process was carried out as planned. **h** CT showed the congruence of subtalar joint at 16 months of follow-up

help of CAPP, the stimulated reconstruction of calcaneus can be pre-operatively achieved and fixed by virtual real-sized plates and screws, which will avoid repeating intra-operative adjustments. Furthermore, CAPP is also helpful to estimate whether the bone excised from the lateral wall is enough for bone graft and to determine the placement of the bone graft in advance, which could decrease the exposure time of intra-operative fluoroscopy. However, the pre-operative evaluation of above surgical protocol will not be realized accurately without the computer-assisted planning. In brief, CAPP is advocated, as it may make the virtual reconstruction and osteotomy more quickly and accurately via CAPP associated with the decrease of the operating time.

Individualized surgical planning can be made for each patient with the assistance of the individual 3-D bone models created from CT data. The calcaneal fracture malunions differ from one another. Meanwhile, there are kinds of osteotomy methods for calcaneal malunions. Therefore, choosing the optimal surgery scheme is a challenge for the surgeons. Combining the surgeon's experience and the recommended surgical management from the current literatures [3, 7, 8, 11, 20], we performed the computer-assisted pre-operative planning, before the surgical option for each individual case was decided. Herein in this study, the lateral decompression was performed in all cases due to the lateral wall exostoses. Sixteen feet with type II or III malunions required additional peroneal tenolysis. The joint-preserving osteotomy was performed in six feet with no or slight arthritic changes and nearly normal articular cartilage. The other 15 feet were treated with distraction bone block arthrodesis. The medial displacement osteotomy was also required to correct the severe valgus deformity in six feet according to the preoperative 3-D CT evaluation.

The aims of our study were to determine whether the individualized computer-assisted preoperative design for calcaneal fracture malunions could satisfy the intra-operative decision making and to evaluate the clinical outcomes after treating calcaneal malunions aided by the computer-assisted virtual surgical technology. In this study, the improved AOFAS scores and satisfying functional outcomes for the patients were obtained. The AOFAS score improved significantly from 32.3 pre-operatively to 77.4 at follow-up. In terms of the surgical treatment of the hindfoot deformity, either the correction of the deformity or the preservation of complex hindfoot motion should be taken into account [24, 25]. The previous study confirmed that good subjective results could be predicted and obtained with operative treatment of the displaced intra-articular calcaneal fracture in patients, if

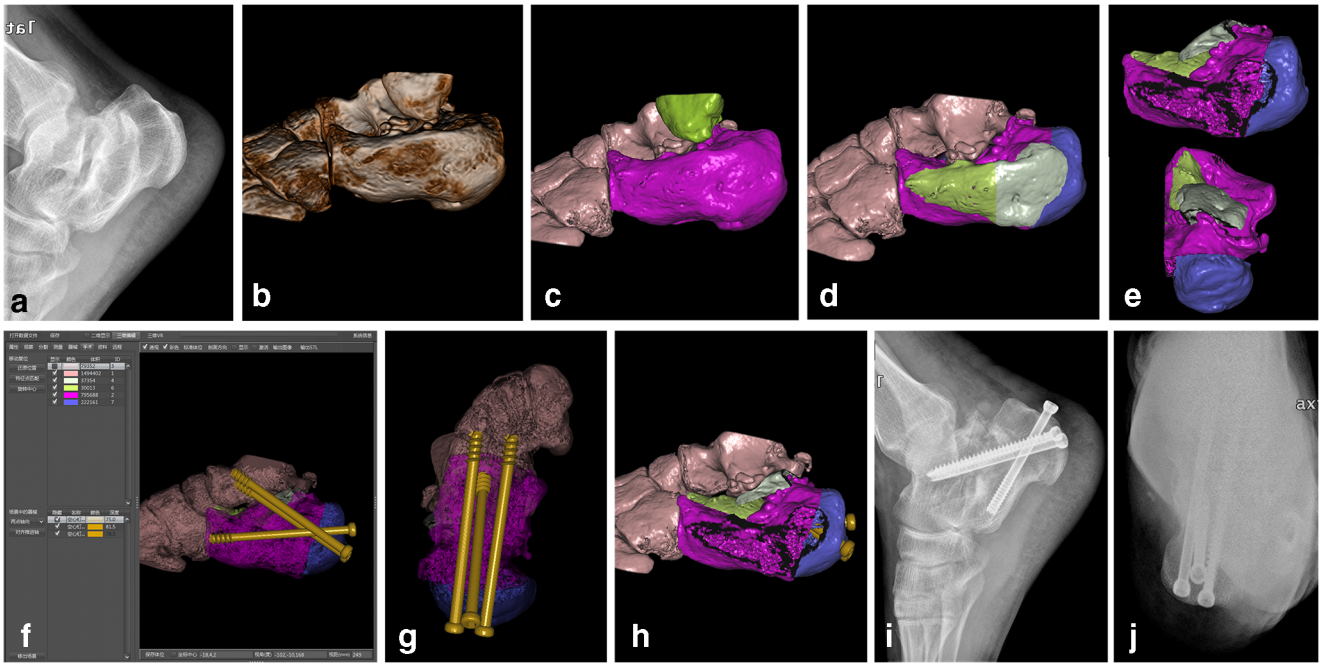

Fig. 4 The subtalar distraction bone block arthrodesis combing the medial displacement calcaneal osteotomy was performed. **a** The lateral view showed that the calcaneal malunion occurred in a 41-year-old male due to the conservative treatment 14 months ago. **b** The 3-D volume rendering image presented the severe deformity of the hindfoot. **c** The shaded surface display image the calcaneus was generated. **d** The plane cutting technique for virtual osteotomy was displayed with different color. **e** The defect in the distraction gap was filled with bone graft. And then medial displacement calcaneal osteotomy was simulated. **f**–**h** The distraction bone block arthrodesis was performed with appropriate screws. **i**, **j** The operation was performed as planned. The post-operative radiographs indicated the lateral wall exostosis had been excised and the hindfoot alignment was nearly normal

anatomic reduction of the three-dimensional outline of the calcaneus was achieved [17]. In the present study, patients were satisfied to have the less pain foot with the acceptable range of motion of the ankle, which might be related to the restoration of the hindfoot morphology, the correction of the alignment, and the relief of the pain. The radiological parameters of the hindfoot were corrected to nearly normal values.

The main weaknesses of this study were its retrospective nature, the minimum follow-up time of 12 months, and the relatively small sample size. Over recent decades, with the development of the current treatment concepts of calcaneal fractures and the internal fixation devices, open reduction and internal fixation have become the mainstream treatment for displaced intra-articular calcaneal fractures in our country, which achieved the acceptable outcomes with the operative management. Therefore, the incidence of calcaneal malunions is in decline, which is also the main reason for the small sample size of our study. However, the patients with the calcaneal malunion usually complain of the symptomatic foot, which seriously affected the quality of life. There is still controversy surrounding the selection of the surgical protocol for calcaneal malunions and the operation is technically

Table 3 The clinical and radiological evaluation

	Pre-operative	Post-operative	*t*/*Z* value	*P* value
Range of motion of ankle				
Dorsiflexion	6.9° ± 3.3°	12.1° ± 5.4°	−3.64	< 0.001†
Plantar flexion	21.7° ± 6.0°	29.8° ± 6.3°	−4.00	< 0.001†
Radiological measurement				
Height of posterior facet (mm)	15.6 ± 4.7	27.1 ± 2.8	−9.38	< 0.001*
Axial length of calcaneus (mm)	69.4 ± 5.6	71.2 ± 4.3	−2.68	0.014*
Talocalcaneal angle	17.4° ± 4.5°	31.3° ± 4.1°	−10.26	< 0.001*
Gissane's angle	98.8° ± 15.5°	124.8° ± 9.0°	−3.84	< 0.001†
Böhler's angle	17.7° ± 5.3°	34.2° ± 4.2°	−13.43	< 0.001*

* The paired samples *t* test

† Wilcoxon signed rank test

demanding. Therefore, we think it is necessary to carry out the precision surgery for calcaneal malunions aided by CAPP so as to improve the patient's symptom.

Conclusion

Our results indicate that the application of computer-assisted preoperative planning can assist the surgeon in understanding the calcaneal fracture malunion, thereby improving intraoperative correction and reconstruction. The satisfying clinical and radiographic outcomes could be provided after treating calcaneal fracture malunion aided by the computer-assisted virtual surgical technology.

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Compliance with ethical standards The retrospective study was approved by the Institutional Review Committee of Shanghai East Hospital, Tongji University School of Medicine, Shanghai, China. And written informed consents were obtained.

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

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