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Surgical treatment of type IV Zwipp – Rammelt calcaneal fractures using customized resection templates

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Abstract

Introduction Calcaneal fractures account for approximately 2 % of all fractures and are common in younger population. Treatment of the patients can be challenging with involved articular and soft tissue component. Conventional methods can be ineffective for complex and rare type IV and type V Zwipp – Rammelt fractures necessitating development of new surgical approaches.

The **objective** was to explore short-term (10 months of observation) outcomes of patients with type IV Zwipp – Rammelt calcaneal fractures using a new technology. The technique suggested improved accuracy of remodeling osteotomy due to three-dimensional reconstruction of the broken foot during preoperative planning and creation of customized resection templates with additive technologies.

Material and methods A prospective, hypothesis-generating study was performed for 13 patients with type IV Zwipp – Rammelt calcaneal fractures. There were 6 males and 7 females with the mean age of 45.5 ± 13.02 years. The patients were treated with the new method which employed 3D reconstruction of the broken foot using MSCT images, fabrication of customized resection templates using FDM printing, their sterilization with ethylene oxide, precision osteotomy of the calcaneus through an L-shaped approach and subtalar arthrodesis. The results were assessed at 77 weeks using AOFAS, EFAS, FFI and VAS scales.

Results Functional parameters significantly improved at ten months with the EFAS increased by 2.5 times (to 34.0 scores, $p = 0.0002$), AOFAS improved by 1.6 times (to 80.0 scores, $p = 0.0002$), FFI increased by 1.57 times (to 38.0 scores, $p = 0.0002$). Pain improved with the VAS decreasing by half from 60 mm to 30 mm ($p = 0.001$).

Discussion The technique demonstrated several advantages with the possibility of multiplanar osteotomies, precise template fixation and control of resection parameters facilitating anatomical restoration.

Conclusion Short-term outcomes of patients with type IV Zwipp – Rammelt calcaneal fractures showed that custom-made resection templates were practical for accurate surgical technology, improved functional outcomes, pain relief using the effective technique.

Keywords: malunited calcaneal fracture, posttraumatic deformity of the hindfoot, subtalar arthrosis, subtalar arthrodesis, calcaneus, correcting osteotomy of the calcaneus, customized resection templates, additive technologies

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INTRODUCTION

Calcaneal fractures account for approximately 2 % of all skeletal fractures, accounting for 70 % of tarsal fractures, and are associated with spinal fractures in 10–12 % of cases [1]. The fractures are common in younger population. There are still no epidemiological studies on large sample sizes on the incidence of disability resulting from calcaneal fractures [2]. The consequences of calcaneal fractures remain a complex problem for diagnosis and treatment due to a combination of severe extra-articular deformities of the heel and injury to soft tissues including vessels and nerves of the foot [3, 4]. A consensus has emerged among professionals on the need to improve methods for diagnosing and treating the consequences of calcaneal fractures [5].

Conservative treatment, although ineffective, is acceptable as a preoperative preparation of the patient for surgical treatment, which is the major option.

Diagnostic and clinical treatment strategy relies on current classifications of post-traumatic deformities of the calcaneus including Zwipp – Rammelt grading system [6]. There is a common opinion among medical community that subtalar arthrodesis *in situ* is indicated for subtalar osteoarthrosis resulting from Zwipp – Rammelt type 1 injury, and distraction subtalar arthrodesis is indicated for lesions Zwipp – Rammelt types 2-3 (including simultaneous osteotomies according to Dwyer, Romash, etc.). Improvement of surgical treatment methods allows the use of arthroscopic, percutaneous and other techniques, as evidenced by literature data [7]. In select circumstances, joint-preserving surgical techniques may be considered even at a long term (1 year or more) [8]. There is a possibility to avoid bone grafting of calcaneal defects in the hope of the spontaneous repair with stable bone fixation to be provided using screws and plates [9].

The unequivocal ineffectiveness of the above-mentioned surgeries is driving researchers worldwide to seek new approaches to treating this severe condition. With the known patterns of calcaneal fracture, there are a variety of options for the consolidation of malpositioned bone, requiring an individualized approach to surgical planning.

Reconstructive surgery of calcaneal injuries suggests a pathogenetic approach in the treatment of the lesions, characterized by the intention to return the deformed calcaneus to the anatomical shape as close as possible. The founder of this direction is M.M. Romash initiated the approach in 1993 using oblique osteotomy of the calcaneus and continues the development of the approach using the advantages of current diagnostic methods [10, 11]. Yu Guang-Rong reported reconstruction of the thalamic part of the calcaneus as an attempt to reconstruct the original anatomy of the calcaneal fracture Zwipp – Rammelt types 4–5 [12, 13].

Despite accumulated global experience, diagnostic and treatment difficulties have been observed in the management of malaligned calcaneal fractures, classified as Zwipp – Rammelt type 4–5 lesions, which are most severe and rare. The injuries can be complicated by aseptic necrosis of the calcaneus, degenerative changes in adjacent joints, abnormal spatial orientation of the talus, etc. aggravating the clinical scenario and treatment approaches.

The **objective** was to explore short-term (10 months of observation) outcomes of patients with type IV Zwipp – Rammelt calcaneal fractures using a new technology. The technique suggested improved accuracy of remodeling osteotomy due to three-dimensional reconstruction of the broken foot during preoperative planning and creation of customized resection templates with additive technologies.

MATERIAL AND METHODS

Characteristics of the Study Population

The study included data from 13 patients with posttraumatic calcaneal deformities of Zwipp – Rammelt type 4 recruited between April 2023 and April 2025. The patient follow-up period was at least 10 months from the date of surgical treatment. The authors obtained consent from the patients to participate in the study and publish the results without identifying the patients.

Fifteen patients meeting the inclusion criteria were identified through screening. Of these, 13 patients were included in the final analysis of the results in full compliance with the study protocol. The study did not involve blinding or randomization procedures due to the expected small number of patients and was designed as a prospective, hypothesis-generating case series with a continuous enrollment of patients meeting the inclusion criteria.

The study included six men (46.2 %) and seven women (53.8 %), with an average age of 45.5 ± 13.02 years and a body mass index (BMI) of 27.4 ± 5.84 kg/m^2, being considered as overweight (pre-obese).

The median follow-up period was 77 weeks (minimum 41 weeks, maximum 106 weeks), or approximately 1.5 years from the date of surgery.

Inclusion criteria for the study included age from 18 to 70 years, regardless of gender; post-traumatic deformities of the calcaneus Zwipp – Rammelt type 4.

Exclusion criteria included active infection, uncontrolled diabetes mellitus with concomitant neuropathy, Charcot arthropathy, critical limb ischemia, obliterating atherosclerosis, neuromuscular disorders with paralysis, decompensated systemic diseases, psychoneurological disorders.

Methods of clinical and instrumentation measurements

Radiographic findings, multispiral computed tomography (MSCT), scales and questionnaires for assessing the functional and clinical condition of the foot and ankle including AOFAS Ankle-Hindfoot (American Orthopedic Foot & Ankle Society), EFAS (European Foot and Ankle Society), FFI (Foot Function Index), and the VAS visual analog pain scale were used to evaluate the treatment results [17–20]. These diagnostic tools were used both before treatment and during the follow-up period of patients.

Biostatistical analysis

Descriptive statistics were used to describe the indicators selected during the study. For interval variables, the median and quartiles, mode, and minimum and maximum values in the sample were calculated due to the small samples. Intragroup comparisons of interval variables were performed using the nonparametric Wilcoxon signed-rank test. With the small size of the study sample, tabulated results for interval variables were presented using nonparametric statistics as the median and first and third quartiles (Me [Q1; Q3]). A minimum sample size was not calculated due to the exploratory, hypothesis-generating nature of the study. Given the case series design, no control group was included in the study (results were compared with available literature), and blinding and randomization procedures were not produced. Statistical analysis of the study data was performed using IBM SPSS v25.0 software.

Technology for the production of a custom-made calcaneal resection template [16]

The first stage involved preparation of a custom-made resection template to be used during the surgical procedure. For this purpose, a virtual model of the calcaneus was created using design software based on the patient's MSCT scan (Fig. 1). During the second stage, the actual resection block was manufactured using FDM 3D printing technology from plastic (PA2200) (Fig. 2a). The block was tested on a plastic model of the injured foot to verify the congruence of the product's surfaces and the anatomical structures of the foot (Fig. 2b). The finished implant was sterilized using ethylene oxide gas sterilization in accordance with GOST ISO 11135 at a temperature of 30 to 55 °C.

To precisely position the instrument during resection, the template is equipped with filing guides for the pendulum saw blade. Their orientation corresponds to the fracture consolidation lines determined during 3D reconstruction of the foot. The model features three key fixation points: the anterior process of the calcaneus, the distal pole of the fibula, and the calcaneal tuberosity, ensuring stability during surgery.

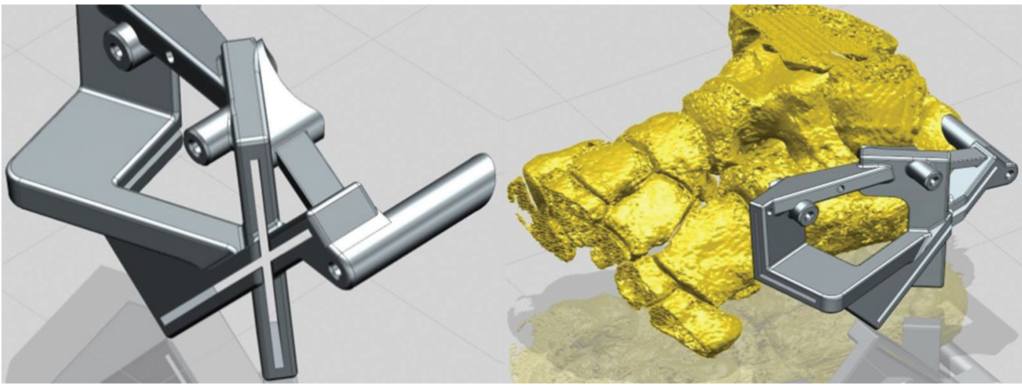

Fig. 1 Custom-made resection block of the calcaneus: a computer 3D model of the resection template and a virtual diagram of intraoperative positioning of the custom-made resection template on a 3D reconstruction of the patient's calcaneus

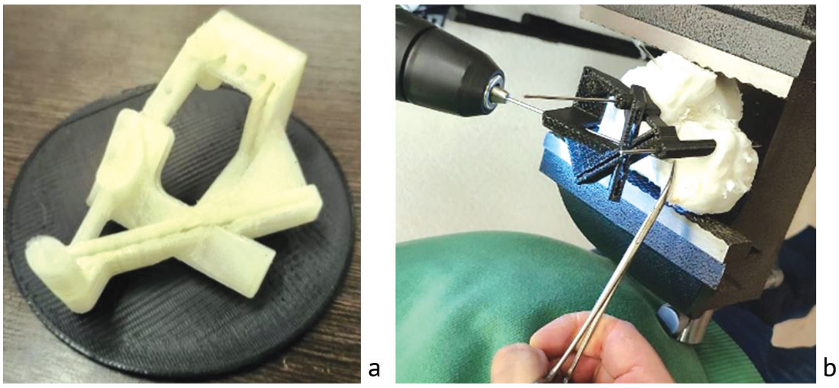

Fig. 2 A custom-made PA2200 cutting block (a); preoperative testing of the block on a plastic model of the patient's injured foot (b)

Surgical Technique

The leg is prepared in a clean operating room with the patient in the intact lateral position, exsanguinating the limb using a pneumatic tourniquet. The surgical field is prepared according to a standard protocol, including double antiseptic skin preparation with povidone-iodine (10 %) or chlorhexidine bigluconate (0.5 %). An L-shaped approach to the calcaneus is performed and the skin, subcutaneous fat, and fascia are dissected layer by layer, preventing damage to the sural nerve. The calcaneus is skeletonized with a single fasciocutaneous flap to its lateral wall, the distal pole of the fibula and subtalar joint are exposed. A custom resection template is placed at the fixation points selected during preoperative planning using 2 mm Kirschner wires.

Using an oscillating saw, osteotomies are produced along the grooves in the template corresponding to the consolidation lines with the calcaneus fragments being mobilized (Fig. 3). Remnants of the articular cartilage and scar tissue are removed from the articulating surfaces of the subtalar joint down to the bleeding subchondral bone using a thin osteotome, curettes, and round and oval burs of various diameters. Following this, multidirectional osteoperforation of the articular surfaces is performed using a 2 mm Kirschner wire.

After osteoperforation, final reduction of the calcaneus and subtalar arthrodesis are performed using internal metal constructs in a position close to the anatomically correct position. The resulting bone defects are filled with the autograft obtained during surgery. The pneumatic tourniquet is removed, hemostasis established, the wound closed layer by layer with interrupted tension-free sutures, drained, and a sterile dressing is applied. Immobilization of the foot and ankle is performed with a deep posterior removable plaster cast with the foot in a neutral position.

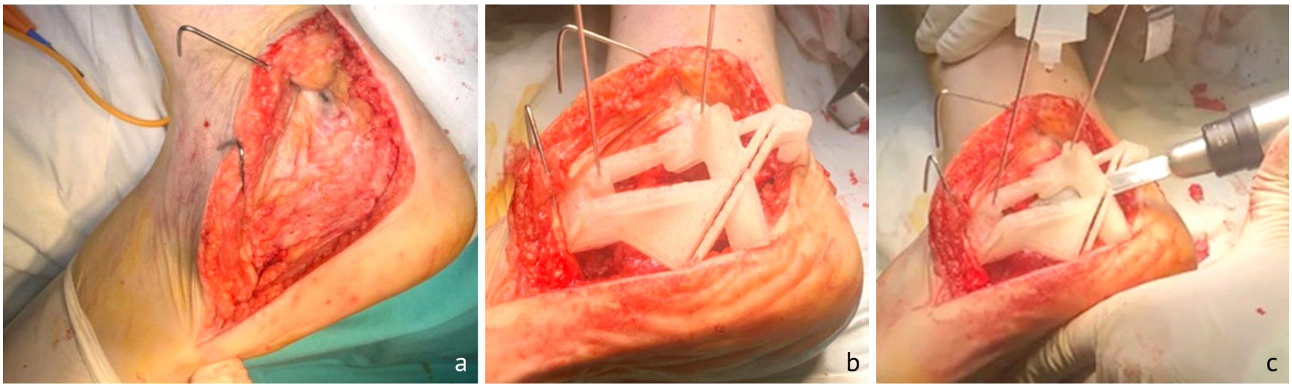

Fig. 3 Stages of surgical intervention: (a) performing an extended L-shaped approach to the calcaneus with the formation of a cutaneous-fascial flap; (b) positioning and fixing a custom-made resection template on the support points using 2 mm Kirschner wires; (c) performing a multi-plane (remodeling) osteotomy of the calcaneus using an oscillating saw in accordance with the template guides.

RESULTS

The descriptive statistics for the scale parameters in the patients who underwent operative treatment with the method we developed, are presented in Table 1. Baseline preoperative patient characteristics showed a high median value on the FFI scale, indicating significant limitations in the patients' functional and daily activities. This was confirmed by the low median values measured with the AOFAS Ankle-Hindfoot and EFAS scales and high median pain VAS score of 60 mm (Table 1), indicating significant functional limitations and severe pain, as well as their negative impact on the overall well-being of the patients.

The surgical outcomes at the end of patients' participation in the study were characterized by a significant improvement in the indicators on all the scales (Table 1). The median value on the EFAS scale increased almost 2.5 times compared to the initial value, up to 34.0 [33.00; 38.00] scores (Z-score = –3.182; $p = 0.0002$). The median values increased 1.6 times on the AOFAS Ankle-Hindfoot scale, up to 80.0 [76.00; 91.00] scores (Z-score = –3.184; $p = 0.0002$). The median parameters improved 1.57 times on the FFI scale, up to 38.0 [34.00; 47.00] scores (Z-score = –3.180; $p = 0.0002$).

Patients' pain sensations according to the VAS scale decreased significantly: from the initial "moderate pain", subjective pain sensations decreased by half to "mild pain" in the form of a median value of 30.0 [20.00; 30.00] mm (Z-score = –2.952; $p = 0.001$).

Some patients reported the highest pain scores on the VAS scale at the start of the study (90–100 mm, "unbearable pain") due to damage to both heels. In such cases, the reduction in pain after surgery could have been even more pronounced, which should have a positive impact on the patients' quality of life.

Table 1
Descriptive statistics values for scale parameters in the study population pre- and postoperatively (*n* = 13)

Scale	Period	Scoring							
		The mean	Standard deviation	Max	Min	Mode	Median	Q1	Q3
EFAS	pre-op	13.0	4.74	23	5	15.0	14.0	11.00	15.00
	post-op	35.2	5.55	43	22	34.0	34.0	33.00	38.00
AOFAS Ankle-Hindfoot	pre-op	48.9	11.46	80	32	45.0a	49.0	42.00	52.00
	post-op	81.6	12.22	102	56	76.0a	80.0	76.00	91.00
FFI	pre-op	87.2	20.46	120	39	75.0	91.0	75.00	99.00
	post-op	39.2	11.63	63	20	20.0a	38.0	34.00	47.00
VAS	pre-op	62.3	18.78	100	30	50.0a	60.0	50.00	70.00
	post-op	25.4	16.13	50	0	30.0	30.0	20.00	30.00

Note: The sample contains several mode values, the smallest of which is shown.

As a ***clinical example*** of the use of the technology we developed, the treatment result of a patient with post-traumatic Zwipp – Rammelt type 4 calcaneal deformity is presented at 12 months of surgery. The patient was 53 years old with, had no bad habits, was engaged in physical labor, normosthenic body build (weight 95 kg, height 195 cm; BMI 25.8 kg/m², which corresponded to the upper limit of the norm), and led an active lifestyle associated with regular physical labor. The patient's professional activity (construction worker) required systematic heavy physical activity, which placed greater demands on the musculoskeletal system.

The patient's history of chronic diseases revealed the following: stage 1 hypertension with a risk of cardiovascular complications of 4; permanent atrial fibrillation; gastroesophageal reflux disease. The patient received regular therapy with Concor at a dosage of 5 mg once daily. In 2002, broken fibula of the left ankle joint was repaired with metal osteosynthesis.

In 2018, the patient sustained a comminuted intra-articular fracture of the left calcaneus as a result of a domestic accident (a fall from a three-meter height). The injury was treated surgically at a local clinic. Open reduction and internal metal fixation of the left calcaneus was performed for the patient. The postoperative period was uneventful. External immobilization of the operated limb to be fully unloaded was recommended for eight weeks. The patient initiated gradual weight-bearing on the lower limb after immobilization. Physiotherapy, massage and exercise therapy were administered as part of his rehabilitation at a local clinic.

However, no significant improvement in the patient's condition was noted at one-year follow-up: pain and swelling persisted, and the hallux valgus of the rear left foot progressed. A year after the surgery, the patient sought examination and treatment at the S.S. Yudin City Clinical Hospital's Foot Surgery Center, aimed at improving his quality of life, facilitating his professional and daily physical activities.

At the time of presentation, the patient reported severe pain at the back of his left foot, localized in the subtalar joint and fibular pole, as well as decreased functional activity. His unassisted ambulation was limited to 3,000 steps per day, after which he was forced to take nonsteroidal anti-inflammatory drugs to reduce pain. The patient developed progressive limitation of dorsiflexion in his left ankle and discomfort with use of standard shoes, due to persistent deformity of the posterior portion of his left foot (Fig. 4). The complaints indicated persistent functional impairment in his left foot, requiring a thorough diagnostic examination and a comprehensive approach to further treatment strategy.

Fig. 4 Appearance of the left foot of the patient: (a) a rear view (hallux valgus of the hindfoot on the left side); (b) medial side (post-traumatic flatfoot); (c) lateral surface (soft tissues swollen at the calcaneofibular site) [16]

Radiographic examination revealed post-traumatic osteoarthrosis of the subtalar joint of the left foot (Kellgren – Lawrence grade 3); a negative Bohler angle indicating impaired anatomy of the calcaneus; "horizontalization" of the talus and a decreased talocalcaneal height caused by post-traumatic changes; a consolidated fracture of the left calcaneus, Zwipp – Rammelt type 4 and fixation with screws healed bone fusion in a displaced position; a consolidated fracture of the fibula, fixed with a metal construct (plate and screws) after an injury in 2002. The phenomenon of "horizontalization" of the talus caused a progressive limitation of dorsiflexion in the left ankle joint, which led to the formation of anterior impingement at the site (Fig. 5).

MSCT of the left calcaneus was produced to clarify the course of the fracture lines, bone alignment and degree of consolidated calcaneus. The scan indicated the initial articular-depression nature of the fracture, pronounced calcaneofibular impingement demonstrating the shape and relative position of the consolidated calcaneal fragments and metal constructs (Fig. 6).

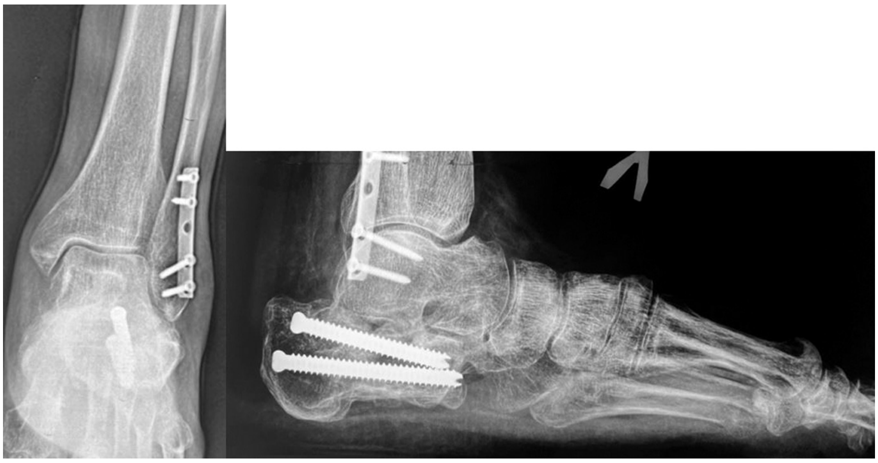

Fig. 5 Coronal and lateral weight-bearing radiographic views of the left foot

Fig. 6 MSCT of the left foot in the coronal, sagittal and axial planes [16]

The patient was finally diagnosed with post-traumatic deforming osteoarthrosis of the left subtalar joint Kellgren – Lawrence grade 3; Zwipp – Rammelt type 4 malaligned consolidated fracture of the left calcaneus; consolidated fracture of the fibula of the left ankle joint fixed with a locking plate; fixed valgus deformity of the left calcaneus with calcaneofibular conflict; anterior impingement of the left ankle joint and contracture of the left ankle joint.

Definitive diagnosis was established and indications for surgical intervention identified to include removal of the metal constructs, remodeling osteotomy of the calcaneus with simultaneous subtalar arthrodesis, internal screw fixation, autologous bone grafting, and percutaneous Vulpius achillotomy. There were some difficulties during preoperative planning related to identifying the lines of the previous calcaneus fracture. This created potential difficulties in accurate reproduction of the profiled osteotomy lines in the operating room, which could have impacted the duration and accuracy of the surgical procedure.To explore the spatial characteristics of the calcaneus fragments, a plastic model was created using a three-dimensional reconstruction and 3D printing technology. The approach allowed for the use of a visual-tactile analysis method, facilitating a more detailed understanding of the injury (Fig. 7).

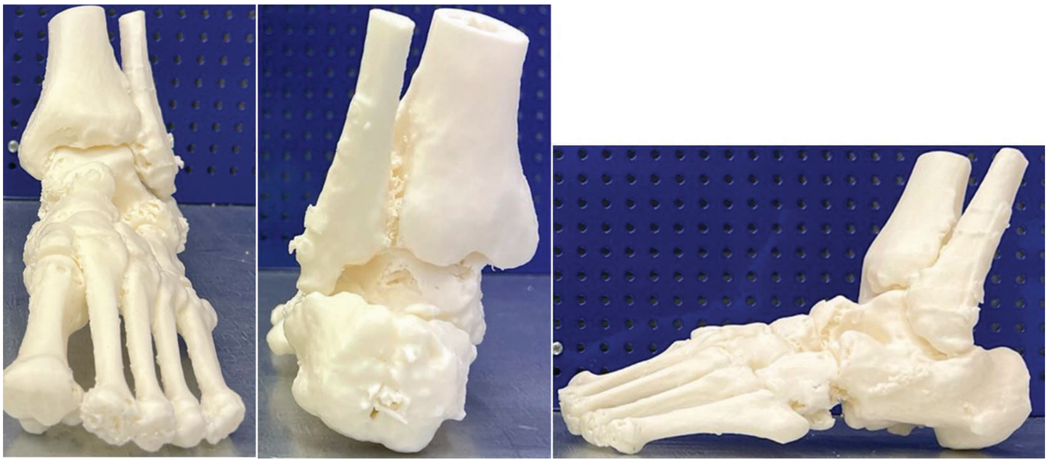

Fig. 7 3D model of a broken left foot made of plastic: front, back and side views

A model of the damaged bone structures of the foot revealed lateral calcaneofibular impingement and valgus deformity of the hindfoot on the left. The surgical treatment indicated included remodeling osteotomy of the left calcaneus, corrective subtalar arthrodesis, internal fixation with metal constructs, bone autografting of the calcaneus defects and a Vulpius achillotomy. The scope of surgical intervention is determined by the need to correct the hindfoot deformity on the left and lateral calcaneofibular impingement, and eliminate anterior impingement in the left ankle joint. The condition caused pain and created inconvenience in the patient's daily life, difficulties in the use of standard footwear and significantly reduce the patient's quality of life.

Preoperative planning was associated with significant difficulties in analyzing the primary, secondary, and tertiary healing lines of the calcaneus at the site of previous fracture lines. These lines can be easily visualized even in consolidated fractures, which is the basis for planning remodeling osteotomy. With difficulties anticipated for the osteotomy, a custom resection template was created to help determine healing lines in the wound, given bone consolidation and previous surgery.

With a custom-made resection block made, the patient underwent surgery using the method developed to achieve the deformity correction (Fig. 8). Given the in following bone reduction, a percutaneous Vulpius achillotomy was performed for the Achilles tendon significantly tensioned and resulted in almost completely restored range of motion in the left ankle.

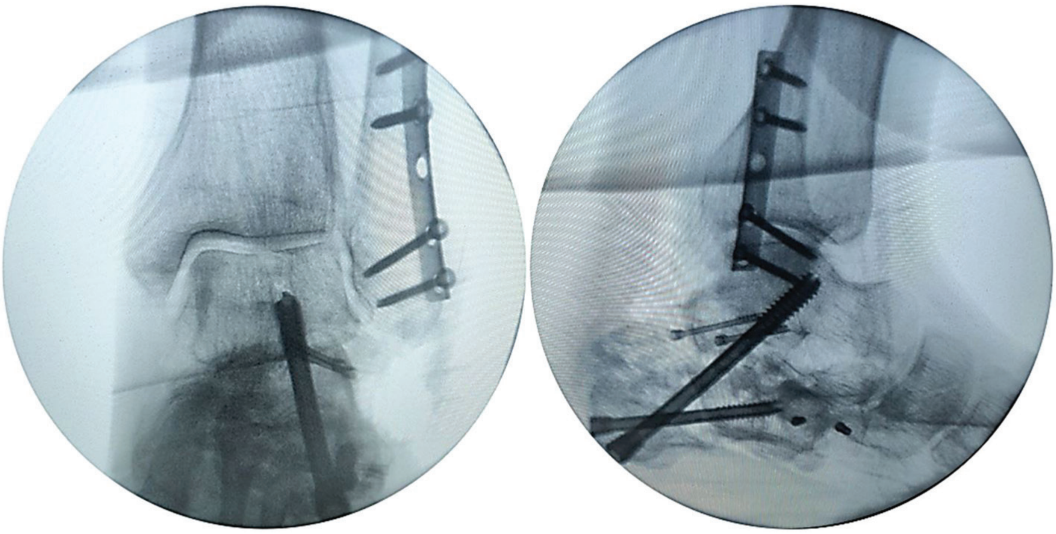

Fig. 8 Intraoperative control using image intensifier in anteroposterior and lateral projections

The calcaneus deformity was corrected based on preoperative planning. The position of the bone fragments and the metal construct placed was assessed as satisfactory.

The patient's postoperative period was uneventful, the wound healed by primary intention, and the sutures were removed after 21 postoperative days. With the wound healed and postoperative swelling settled, the plaster cast was replaced with a circular polymer cast, with immobilization continued for two months. Then the patient underwent a follow-up examination with radiographs and MSCT of the operated left calcaneus. The diagnostic procedures indicated bone union of the artificial left calcaneus fracture, formation of a subtalar bone fusion and stable positioning of the metal constructs. The patient was allowed to bear some weight on the operated limb, prescribed restorative and rehabilitation treatment recommended to include physiotherapy, massage and exercise therapy in a rehabilitation center.

The patient could regain axial loading on the limb within a month and return to work. Dynamic observation of the patient was continued, and the final treatment result was assessed at 12 months after the surgery. The follow-up examination showed the correction of the hindfoot on the left maintained, there was no lateral calcaneofibular impingement, and the talar deviation angle, calcaneal inclination angle, Meary angle, malleolar growth, and calcaneal width restored (Fig. 9a). MSCT demonstrated a consolidated artificial fracture of the left calcaneus with the formation of a subtalar bone fusion with screw fixation, and a consolidated fibula fracture fixed with locking plate (Fig. 9b).

The surgical outcome was visually evaluated with a 3D reconstruction of the left foot using MSCT obtained at 12 months after surgery. Using these data, a plastic model of the foot was created using additive manufacturing (3D printing) and compared with the original plastic model printed prior to surgery during the preoperative planning stage (Fig. 10). Lateral calcaneofibular impingement and hallux valgus were corrected. Photographs of the left foot models demonstrated ankle growth increased by 10 mm as compared to the preoperative model (Fig. 10b).

Comparison of the measurements of topographic-anatomical parameters of preoperative and postoperative foot models showed the values being closer to corresponding to the anatomical norm of the healthy contralateral limb (Table 2).

Fig. 9 Radiography and MSCT imaging of the patient's left foot at 12 months of surgery: weight-bearing AP and lateral views (a), MSCT reconstruction in the coronal, sagittal and axial planes (b)

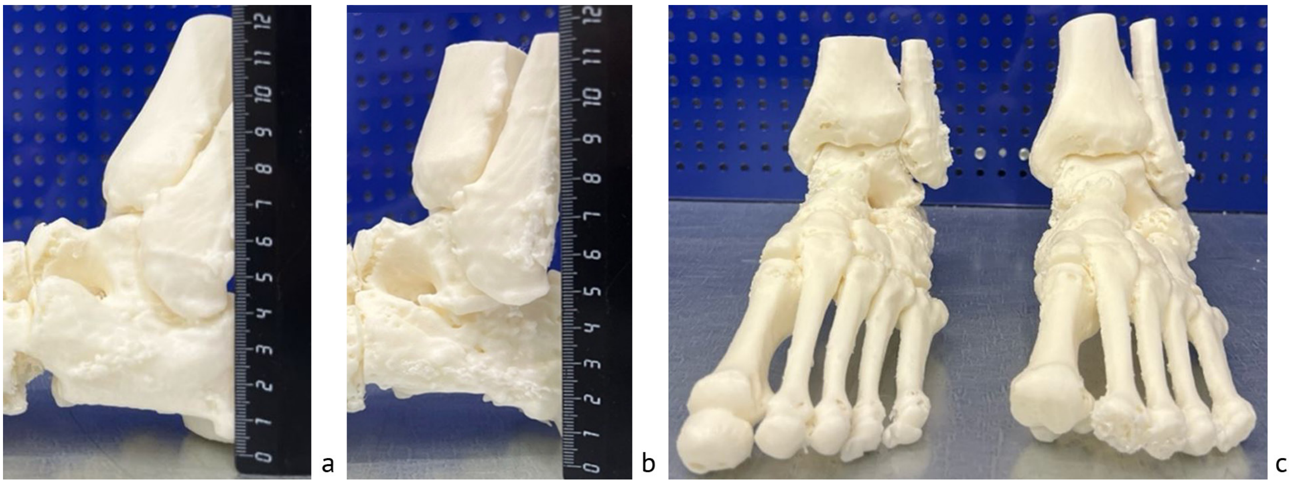

Fig. 10 Photographs of the simulated left foot showing (a) preoperative side view; (b) side view at 12 months; (c) front view of both models (on the left: control postoperative model of the operated foot, on the right: preoperative model)

Table 2

Evaluation of anatomical parameters of the foot

Description	Hindfoot of the left (injured) foot		Hindfoot of the right (normal) foot
	pre-op	at 12 months of surgery	
Angle of deviation of the talus, °	11	20	22
Calcaneal inclination angle, °	11	16	18
Miri angle, °	9	4	2°
Talocalcaneal height, mm	67	73	76
Calcaneal width, mm	53	43	34
Ankle growth, mm	35	45	46

The postoperative results demonstrated a significant improvement in the condition of the injured foot compared to baseline values obtained before the corrective reconstructive surgery on the left calcaneus (Table 3). The patient showed a high level of physical activity at 12 months, taking up to 12,700 steps per day. He was able to return to his normal work activities indicating positive changes in his quality of life.

Table 3

Assessment of the clinical and functional condition of the patient's left foot

Scale/Questionnaire	Assessment, score	
	Pre-op	At 12 months post-op
AOFAS Ankle-Hindfoot	45	76
EFAS	12	22
FFI	101	50
VAS	5	2

None of the 13 patients experienced any complications. One patient experienced postoperative wound healing by secondary intention due to superficial skin necrosis, which resolved within one month.

DISCUSSION

Surgical treatment of patients with post-traumatic calcaneal deformity is challenging. Effective management of the cohort of patients is difficult to be arranged in trauma and orthopedic departments, given the current structure of specialized trauma and orthopedic care. Improved outcomes for this category of patients treated at a specialized foot and ankle surgical centers are associated with the institution's organizational technologies, specialists' expertise in foot biomechanics, diagnostic and therapeutic techniques, experience and creative and innovative approaches to treatment [21].

It is generally accepted that while patients with moderate consequences of calcaneal fractures (Zwipp – Rammelt types 1-3) can be successfully treated with well-known methods (distraction subtalar arthrodesis or subtalar arthrodesis *in situ*), patients with Zwipp – Rammelt types 4-5 injuries require an individual approach and different technical methods and operations for correction.

This type of injury is rare. Zwipp et al. reported 245 patients with calcaneal fractures with 12 % of patients having consequences of Zwipp – Rammelt type 4 injuries and 7 % of patients having consequences of type 5 injuries, i.e. 29 and 3 patients, respectively [22]. Our series of 13 patients with similar types of injuries appears sufficiently representative for a hypothesis-generating study considering the rarity of the diseases and the impossibility of randomization due to the unethical nature of forming comparison groups with surgical intervention options that are obviously inferior in terms of expected treatment outcomes.

Many authors suggested a procedure combining subtalar arthrodesis and Dwyer osteotomy for this cohort of patients, which is acceptable for type 2-3 injuries, but leads to the formation of a "zigzag" deformity of the calcaneus in type 4-5 injuries. Moreover, the formation of varus deformity of the calcaneus, described as a typical complication [13], in our experience, can result in failure of suturing the surgical wound. Specific diagnostic and treatment techniques can be applied for the group of patients with consequences of Zwipp - Rammelt type 4-5 injuries. The technology was first reported by M.M. Romash, who offered an original osteotomy of the calcaneus along the primary fracture line in 1993, which had a scientific and practical role at that time [10].

Fracture lines are complex and may run in different directions, creating typical fracture patterns. This can pose a challenge for surgical planning, as the fracture lines become invisible after one year or more from the injury, leaving the surgeon with no reference points for osteotomies. However, these lines are visible on computed tomography (CT) images which can be practical for preoperative osteotomy planning. The simultaneous use of custom-made resection blocks allows for adjustment of the direction and depth of the osteotomy in the surgical wound. Based on this fact, we offered an original operation of remodeling osteotomy of the calcaneus, which can be combined with subtalar arthrodesis [14] and have been successfully using since 2009, 8–12 months after the injury, while the lines of consolidated bone remain available for identification [15].

Our research aimed at improving the accuracy of shaped osteotomies of the calcaneus and bring them into precise correspondence with the planned anatomical landmarks during preoperative planning led to the creation of a surgical treatment method using individually manufactured resection templates we patented in the Russian Federation [16]. There are publication reporting the use of resection blocks in a similar scenario. Lee et al. used intraoperatively a custom-made resection template for Zwipp – Rammelt type 4 post-traumatic calcaneal deformity with good clinical and radiographic results [23]. The disadvantages of the method used by colleagues from Singapore include the inability to firmly fix the template during manipulations and fix the angle of attack of the oscillating saw blade, and the limitation of resection to one plane. The disadvantages were adjusted by incorporating several sawing planes, fixation points, and programmed directions for osteotomies into the template [16]. Identifying consolidation lines during preoperative planning allows for calcaneal osteotomies to be performed along "old" fracture lines correcting multiplanar hindfoot deformities. We believe that reduction of displaced bone fragments and subtalar arthrodesis in a functionally advantageous anatomical position can improve patient outcomes.

Functional results could be compared with published results of treatment of this cohort of patients due to the absence of a comparison group in our study. Schepers et al. [24] reported the findings of 21 studies in the systematic review (average follow-up period of 40 months) with a total of 456 patients with late complications of consolidated comminuted intra-articular calcaneal fractures with bone displacement. The patient underwent arthrodesis of the subtalar joint with bone grafting and distraction (in 93 % of cases as a salvage intervention). Functional outcomes measured with the modified AOFAS scale at final follow-up averaged 73 scores (range, 64 to 83). Almost all studies included in the review were retrospective case series with level IV evidence. Subtalar joint arthrodesis with bone grafting and distraction was performed in 93 % of cases.

In our series, the AOFAS-Hindfoot scores were recorded with a median of 80.0 [76.00; 91.00] scores (Z-score = -3.184; p = 0.0002) at the time of postoperative observation, which even exceeded the pooled average values on the AOFAS scale published by Schepers et al. [24]. The value of the minimum clinical significance of changes on the AOFAS scale has not been determined for this type of lesions in world practice, and no conclusion can be made about the significance of a difference of 7 scores.

We concluded that patients with Zwipp – Rammelt type 4 injuries can be treated with open reduction, internal fixation and deformity correction if the cartilage is intact (assuming a high risk of complications), while primary arthrodesis and osteotomy can be recommended for patients with a destroyed joint. Multistage reconstruction is practical for severe deformities, and corrective osteotomy is critical for restoring biomechanics.

Qiang et al. [25] suggested that primary subtalar or triple arthrodesis is recommended for irreparable cartilage damage, that type 4 severe intra-articular calcaneal fractures accompanied by a deformity require precise anatomical reconstruction to restore subtalar function, and modern surgical treatment methods (minimally invasive osteosynthesis, 3D navigation) can facilitate accurate reduction. Therefore, our method improves clinical efficacy and provides more predictable treatment outcomes for patients with post-traumatic deformity due to Zwipp – Rammelt type 4 injuries. The use of customized resection templates for calcaneal remodeling osteotomy in this patient population is practical, as the clinical and prognostic outcomes of other surgical approaches described in the literature will be inferior to those treatment method proposed by the authors.

Limitations of the Study

The main limitation of the study is the relatively small patient sample, which is due to the rare nature of the injury type. Therefore, the study was designed as a hypothesis-generating prospective case series, without a comparison group or statistical power calculation. Therefore, the primary focus is on descriptive statistics and a comparison of pre- and post-treatment patient condition, which may aid in calculating the sample size required for future studies of the patient population.

The second limitation is the lack of comparison groups and failure of randomization due to the unethical nature of forming groups based on surgical intervention options that are obviously inferior in terms of expected treatment outcomes.

CONCLUSION

The use of additive technologies in reconstructive calcaneus procedures allows for the creation of precise 3D models of the injured foot, facilitating a detailed analysis of the spatial and geometric structure of the deformity and the development of an optimal correction strategy. The creation of custom-made cutting blocks for precision osteotomies according to the preoperative plan facilitates accurate restoration of the anatomy of the injured calcaneus. Analysis of surgical outcomes demonstrates significant improvements in functional and pain scores measured with the EFAS, AOFAS Ankle-Hindfoot, FFI and VAS scales. A significant reduction in pain in patients with initially severe pain has a positive impact on their quality of life.

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