3D Printed Models Improve Surgical Planning for Correction of Severe Postburn Ankle Contracture With External Fixator

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Research

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Abstract

Background: Gradual distraction with external fixators such as Ilizarov frame has been widely used for the treatment of severe postburn ankle contracture (PAC). However, the application of external fixator is complex and conventional surgical planning based on 2D imaging is compromised due to a lack of spatial geometry and tactile feedback. The purpose of this study was to evaluate the surgical planning with patient-specific 3D-printed models (3DPM) for the treatment of PAC with external fixators.

Methods: A two-centered retrospective cohort study, composed of consecutive patients who underwent external fixation for the treatment of severe PAC, was implemented. Patients were divided into two cohorts (3DPM group vs. Control group) according to whether 3DPM was used for preoperative surgical planning. The primary outcome variable was operation duration. Other outcome variables included improvement in metatarsal-tibial angle (MTA), range of motion (ROM), American Orthopedic Foot and Ankle Society (AOFAS) scores, and complications.

Results: Between January 2008 and June 2018, ten patients with an average age of 23.8±14.1 yeas were treated for PAC at two centers. 3DPM were used for surgical planning in 5 patients. 3DPM group had significantly shorter operation duration than the control group (2±0.3 hours vs. 3.2±0.3 hours, p=0.0001). The comparison of preoperative, after removal of external fixator, and follow-up MTA, ROM, and AOFAS between the 3DPM and control group showed no significant differences. A plantigrade foot was achieved and gait was substantially improved in all patients at the final follow-up. Pin-tract infections occurred in 2 patients (one in each group) during distraction and were treated with wound care and oral antibiotics.

Conclusion: The results of this study show that surgical planning using patient-specific 3DPM significantly reduced the operation duration while providing similar improvements in MTA, ROM, and AOFAS scores compared to traditional surgical planning for the correction of severe PAC with external fixators.

Background

Postburn ankle contracture

Postburn ankle contracture (PAC) can be a disabling deformity due to excessive hypertrophic scarring and limited range of motion (ROM), thus significantly impairs the patient’s activity of daily living and quality of life [1]. Severe PAC is often associated with substantial shortening of tendons, ligaments, and neurovascular bundles [2]. Acute complete correction of severe PAC is unfeasible because it may overstretch these contracted tissues, increase the risks of neurovascular injury, skin necrosis, ischemia, and even amputation [3]. Gradual distraction with external fixator is required to lengthen the contracted tissues and correct deformities to achieve a plantigrade, painless and stable foot and ankle [4].

Treatment with external fixator

Since Ilizarov et al. [5] first introduced the Ilizarov technique based on the principle of distraction histogenesis, Ilizarov frame and several other external fixators (e.g. hexapod frame, unilateral, bilateral, and combined-type external fixator) have been widely used in the treatment of foot and ankle deformities caused by trauma, burn, infection, congenital malformation, and neuromuscular pathology [6]. The gradual distraction offered by external fixators allows simultaneous correction of all tissues of the deformed ankle, including lengthening of neurovascular bundles, muscles, tendons, ligaments, skin and bones. Of all types of external fixators, Ilizarov apparatus is the most commonly used for the treatment of severe PAC due to its stability, accessibility, and capability of multiplanar correction [7]. Khodzhakulov et al.[8] reported improvement of weight-bearing function in 81% of 82 PAC patients treated with Ilizarov method. van Roermund et al. [4] observed a decrease in pain and improvement of joint function in 3 patients with ankle joint stiffness. Similarly, Said Saghieh et al. [9] described their successful experience in treating severe PAC with Ilizarov technique in 3 patients.

However, the assembly and installation of Ilizarov frame and other external fixators are complex and challenging, which require a great deal of experience and knowledge of the anatomical structure [10]. Furthermore, several attempts of K-wire insertion and frame adjustments may be required intraoperatively until the frame is satisfactorily applied, leading to prolonged surgical time and increased risk of complications e.g. pin-tract infection, osteomyelitis, pain, fixation failure, and re-contracture [11]. The surgical time and associated complications could be minimized via more accurate preoperative planning. Nevertheless, traditional preoperative surgical planning mainly depends on two-dimensional (2D) images, such as X-rays, computed tomography (CT), and magnetic resonance imaging (MRI). Although they provide helpful information of the area and severity of the PAC, they are unable to accurately reflect the complex three-dimensional deformities, reproduce the actual spatial geometry, and offer tactile feedback [12, 13]. Surgical planning is then compromised and preoperative rehearsal is impossible based on conventional 2D-imaging modalities.

3D printed models

As the development of three-dimensional (3D) printing technology, 3D-printed models (3DPM) have gained global popularity owing to their individualization, visualization, and tangibility with actual dimensions and spatial geometry [14,15,16,17,18,19,20]. Previous studies have shown that the use of 3DPM is associated with decreased surgical time and intraoperative X-ray exposure, as well as increased operative accuracy and safety compared to traditional imaging in the treatment of ankle deformities [21, 22]. Duan et al. [23] found that preoperative planning with 3DPM facilitated accurate drilling of K-wires into the appropriate position, reduced the operation time and intraoperative radiation in 29 patients who underwent subtalar joint arthrodesis. A randomized controlled trial by Zheng et al.[24] showed that 3DPM-assisted surgical planning had shorter operation duration, less blood loss and X-ray exposure, as well as better anatomic reduction and clinical outcomes than conventional surgery in 100 patient with Pilon fractures. However, few studies have used 3DPM in combination with external fixators for the treatment of lower extremity deformity [25, 26, 27]. To the best of our knowledge, no study has reported the application of 3DPM in the correction of PAC with external fixators.

Purpose, hypothesis and aims

The purpose of this retrospective study is to evaluate the surgical planning with patient-specific 3DPM on the treatment of PAC with external fixators. We hypothesized that 3DPM-assisted surgical planning would reduce the operation duration compared to traditional planning with 2D imaging. The specific aims are to compare the 3DPM-assisted and traditional surgical planning in operation duration, ROM, American Orthopedic Foot and Ankle Society (AOFAS) scores and complications.

Patients And Methods

Study Design

After approved by the Institutional Ethics Committees, the investigators implemented a two-centre retrospective cohort study composed of consecutive patients who underwent external fixation for the treatment of PAC at Department of Plastic and Reconstructive Surgery, Chinese PLA General Hospital, Beijing, China; Department of Plastic Surgery and Department of Orthopedic Surgery, Xijing Hospital, Xi’an, China, from January 1, 2008 to June 1, 2018. Patients were identified from the institutional Patient Data Registry.

Participants

Inclusion criteria were: 1)Postburn ankle contracture; 2)External fixator (e.g. Ilizarov frame, hexapod frame, combined external fixator) was used to correct the deformity; 3)Availability of complete medical records that included medical history, physical examination, operation note, imaging, and a minimum of 2-year follow-up. Exclusion criteria were: 1) Contractures caused by other etiologies, such as trauma, congenital malformation, syndromes, neuropathy, and haemophilia; 2)Other joint contractures, such as knee, shoulder, elbow, wrist, and hand; 3)Incomplete information. Participants were divided into two cohorts (3DPM group vs. Control group) according to whether 3DPM was used for preoperative surgical planning.

Production of 3DPM

Thin-layer CT scan with 0.6-mm slice thickness (Siemens, Germany) of the ankle and foot was routinely performed. The DICOM (Digital Imaging and Communications in Medicine) data was processed using the MIMICS (Materialise Interactive Medical Image Control System Software) (Materialise, Leuven, Belgium) to create a 3D model. The dataset was saved in Stereolithography Language (STL) format and imported into a 3D printer (iSLA880, ZRapid Tech, Beijing, China). The model was printed using photosensitive resin as a raw material using Stereolithography Apparatus technology with shell thickness from 0.8 mm to 2 mm and layer height of 0.05 mm.

Surgical Planning with 3DPM

In the control group, traditional surgical planning was performed by viewing CT scans (**Figure 1**). In the 3DPM group, surgical planning and rehearsal were performed on the 3DPM including assembly and configuration of the external fixators, ring placement, and the drilling location and direction of pins and wires (**Figure 2**). Once determined, the fixator was sterilized for intraoperative use.

Surgery and Postoperative Distraction

Patient was in supine position and received epidural or general anesthesia. Scars were excised. Conservative correction of the articular position was performed. Exposure and overstretch of the ankle joint and neurovascular bundle were avoided. The subsequent defect caused by scar resection was covered by skin grafting or local/free flaps. The preconstructed external fixator was applied and wires were inserted as preoperatively planned (**Figure 3**).

Gradual distraction was started after a 10-day latency for grafted skin or flaps healing. Distraction was performed over 4 to 6 weeks by manually rotating the nuts to lengthen or shortening the distraction rods at a rate of 1-4 mm per day. The distraction rate was adjusted according to the patient's pain tolerance and skin reaction (numbness, swelling, temperature, and color). The external fixator was maintained in situ for another 4 to 8 weeks depending on the severity of the deformities. X-rays were performed to confirm that satisfactory correction was achieved (**Figure 4**). The external fixator was then removed, and a short-leg walking splint was applied for 6 weeks, followed by an ankle foot orthrosis for 3 months. First partial then full weight-bearing was encouraged to improve the gait. Physiotherapy was recommended to prevent recurrence and regain maximum function. Patients were followed up annually (**Figure 5**).

Data Collection

The following data were collected from the Electronic Medical Records: 1) Demographics: gender, age, type of ankle deformity (e.g. plantarflexion, dorsiflexion, plus varus, and/or valgus); 2) Type of external fixator used (e.g. Ilizarov frame, hexapod frame, or combined external fixator); 3) Operation duration; 4) Preoperative, after removal of the frame, and a ≥ 2-year follow-up metatarsal-tibial angle (MTA), ROM, and American Orthopedic Foot and Ankle Society (AOFAS) ankle and hindfoot scores. MTA was measured as the angle between the diaphysis of tibia and the diaphysis of the first metatarsal using a lateral goniometer according to the established protocol [28]. ROM was calculated as follows: MTA at the maximum plantar-flexion position minus the MTA at the maximum dorsiflexion position; 5)

Complications: intraoperative blood loss, pin-tract infection, fixation failure, neurosensory disturbance, and re-contracture. The primary predictor variable is whether 3DPM was used for preoperative surgical planning (3DPM group vs. Control group). The primary outcome variable was operation duration. Other outcome variables included improvement in MTA, ROM, AOFAS scores, and complications.

Data Analysis

Continuous variables were expressed as mean±standard deviation, or median (range) depending on their distributions. Categorical variables were expressed as percentages and proportions. T-test was performed to compare the normally-distributed continuous variables and Fisher's Exact test was performed to compare the categorical variables between two groups. A p value < 0.05 was considered statistically significant. Statistical analysis was performed using Stata v15.1 (StataCorp, College Station, Texas, USA). This study is reported in accordance with the STROBE Guidelines [29].

Results

Between January 2008 and June 2018, ten patients (5 males and 5 females, with an average age of 23.8±14.1 yeas) with PAC were treated with external fixators at the two centers (5 patients at each center). There were 5 patients with dorsiflexion deformity, 3 plantarflexion, 1 plantarflexion with varus, and 1 dorsiflexion with varus. Ilizarov frames were used in 6 patients and combined-type external fixator were used in 4 patients. 3DPM were used for surgical planning in 5 patients (**Table 1**).

3DPM group had significantly shorter operation duration than the control group (2±0.3 hours vs. 3.2±0.3 hours, p=0.0001). The comparison of preoperative, after removal of external fixator, and follow-up MTA, ROM, and AOFAS between the 3DPM and control group showed no significant differences. Substantial increase in ROM was observed from preoperatively to the removal of the fixator in both groups (3DPM group: from 6±5.5 degree to 32±23.1 degree; Control group: from 4±4.2 degree to 31±16.4 degree). The ROM was well maintained at 36.5±19.7 degree until the last follow-up at an average of 7.6±4 years (**Figure 6**). In addition, the AOFAS significantly increased from 33.4±11 preoperatively to 64.4±4.7 after the removal of the fixator, and further increased to 84.4±9 over the follow-up (**Figure 7**). A plantigrade foot was achieved and gait was substantially improved in all patients at the final follow-up. Pin-tract infections occurred in 2 patients (one in each group) during distraction and were treated with wound care and oral antibiotics. No other complications occurred.

Discussion

Major findings

The results of this study show that preoperative surgical planning using patient-specific 3DPM significantly reduced the operation duration while providing similar improvements in MTA, ROM, and

AOFAS scores compared to traditional surgical planning for the correction of severe PAC with external fixators.

Operation duration

Operation duration plays an essential role in the surgical outcomes. Previous literature have demonstrated that surgical planning using 3DPM significantly reduced the operation time in the treatment of a variety of ankle trauma and deformity [30]. Yang et al. [31] found shorter operation time (71 mins vs. 98 mins) in 15 patients with 3DPM-assisted surgical planning than 15 counterparts with conventional planning in the treatment of trimalleolar fractures. A randomized trial by Zheng et al. [24] showed shorter operation time in the 3DPM-assisted group than the conventional group (74 mins vs. 90 mins) in the treatment of Pilon fractures in 100 patients. Duan et al. [23] noted shorter time for accurate drilling of a K-wire to the satisfactory position (2.1 mins vs. 4.6 mins) and fewer number of re-drills (2 cases vs. 8 cases) in 14 joints under 3DPM assistance than 16 joints using traditional method during subtalar joint arthrodesis. In addition, Corona et al. [27] reported that the average surgical time in 9 patients who underwent 3DPM-assisted preoperative surgical planning was about half of the time in 10 patients with traditional planning (172 mins vs. 329 mins) in the treatment of post-traumatic tibial malunion and non-union using circular external fixation. Similarly, the study by Liu et al. [32] also demonstrated a shorter surgical time in 12 patients with preoperative surgical planning using individualized 3DPM of complex hypertrophic scars.

In accordance with these studies, we found significantly shorter operation time in the 3DPM group than the control group. This was achieved via accurate preoperative installation of the external fixators and surgical rehearsal on the 3DPM. In the control group, frames were installed and K-wires were drilled intraoperatively according to surgeons' experience. Adjustment of fixator configuration and re-drilling may be required, leading to prolonged operative time. Using 3DPM, surgeons are able to pre-assemble the external fixator, optimize its configuration, and simulate the placement, as well as determine the size, drilling location and direction of K-wires prior to the surgery. Therefore, intraoperative modification of the frame configuration and K-wire re-drills were minimized or avoided, which substantially saving operation time.

MTA & ROM

Appropriate fixator construction and installation, as well as accurate insertion of wires and screws are crucial for fixation stability and predictable outcome for the treatment of severe PAC using external fixators. According to the American Association for Orthopedics Surgeons, the normative values for ankle dorsiflexion and plantarflexion was 20°-30° and 40°-50° from the neutral position at 90° of MTA, respectively [33]. Korp et al. [34] defined functional ROM as follows: 1) Dorsiflexion: 14°-20° mild contracture, 7°-13° moderate contracture, <6° severe contracture; 2) Plantarflexion: 33°-49° mild contracture, 17°-32° moderate contracture, <16° severe contracture. We found significant increases in

MTA and ROM in all patients as showed in Table 1. No significant differences in MTA and ROM between 3DPM and control group were detected. This finding agreed with Zhang et al. [35], indicating that 3DPM-assisted surgical planning offered similar effectiveness of correction compared to conventional surgical planning. This might be explained because most of operations including frame installation and application were performed by a group of experienced surgeons. Since they were already familiar with these procedures, the benefit of 3DPM might be limited for them. It is noteworthy that the use of 3DPM significantly shortened the learning curve for junior surgeons in previous studies [30, 31, 32]. In our study, one surgery in the 3DPM and one in the control group were performed by a junior surgeon who reported an easier learning process with more confidence using the 3DPM due to the preconstructed frame and preoperative simulated operation.

AOFAS

AOFAS ankle and hindfoot scale is a comprehensive, well accepted method to evaluate the ankle function. AOFAS has a total of 100 points, including 40 points of pain, 50 points of function (i.e. activity limitation and support requirement, maximum walking distance, walking surfaces, gait abnormality, sagittal motion, hindfoot motion, and ankle stability), and 10 points of alignment [36]. Duan et al. [23] demonstrated comparable AOFAS scores between the 3DPM and control group in the treatment of ankle deformities. In the study by Zhang et al. [35], comparable AOFAS scores between the 3D printing group and the conventional group (87.4 vs. 84.7) were noted. In agreement with these studies, we found no significant difference in AOFAS between two groups. The AOFAS significantly increased after removal of the external fixator, and even slightly increased to an average of 84.4 at the final follow-up. It is noteworthy that ankylotic ankle will still be stiff after correction into a plantigrade position, though the AOFAS may improve. Therefore, it is crucial to discuss with patients preoperatively about this potential ankle stiffness. 3DPM is helpful in patient communication due to the visible and tactile model, thus improving patient’s understanding and compliance with surgery and postoperative rehabilitation.

Complications

Complications associated with the correction of PAC with external fixators included intraoperative blood loss, fixation failure, pain, pin-tract infection, osteomyelitis, joint instability, neurovascular injury, and re-contracture. Of these, pin-tract infection was the most commonly reported complication in previous studies [9, 37, 38, 39]. In the present study, pin-tract infections developed in 2 patients (one in each group). They were controlled with oral antibiotics and local dressings without any serious sequelae. Re-contracture is another common complication following correction of severe ankle contracture. To prevent recurrence, rigid ankle orthosis and physiotherapy were performed after removal of the external fixator until complete stabilization and remodeling was achieved.

Limitations

This study has several limitations. Although 3D printing has become more accessible and affordable over the past decade, the time (usually in 24 hours) and cost (more than 2000 RMB ≈ 300 USD) for manufacturing the 3DPM cannot be neglected. In addition, all patients in our study were hospitalized until the removal of external fixators to adjust the distraction rate and minimize complications. This inevitability prolonged the hospital stay and further increased the overall cost. Another major limitation is the small sample size. The number of patients with PAC has been dramatically decreased in our hospitals due to lower incidence of burns and higher proportion of early interventions for prevention of contracture in burned joints. Despite these limitations, this is the first study compared the operation duration, ROM and AOFAS scores between 3DPM-assisted and traditional surgical planning for the treatment of severe PAC using external fixators. A future randomize controlled trial with adequate sample size will better elucidate the benefit of 3DPM-assisted surgical planning in the treatment of PAC and other ankle deformities.

Conclusion

The results of this study show that preoperative surgical planning using patient-specific 3DPM significantly reduced the operation duration while providing similar improvement in ROM and AOFAS scores compared to traditional surgical planning for the correction of severe PAC with external fixators.

Abbreviations

PAC: Postburn ankle contracture;3DPM: 3D-printed models; ROM: range of motion; MTA: metatarsal-tibial angle; CT: computed tomography; MRI: magnetic resonance imaging; AOFAS: American Orthopedic Foot and Ankle Society.

Declarations

Ethics approval and consent to participate

This study was approved by the following Ethics Committees: Chinese PLA General Hospital, Beijing, China and Xijing Hospital, Xi’an, China. Informed consent was obtained from all patients.

Consent for publication

Written consent was sought prior to publication from patients.

Availability of supporting data

All the data supporting the conclusions of this article is included in the present article.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

YBC, ZHN and WQJ drafted the manuscript and designed the study. YBC, ZHN and WQJ collected the data and performed the data analysis. YH, YHL and LLG performed part of the surgeries. WSX, BQS, LYH, QXZ measured MTA, ROM, AOFAS and hindfoot scores, YH designed the study. All authors read and approved the final manuscript.

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Not applicable.

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Tables

Due to technical limitations, table 1 is only available as a download in the Supplemental Files section.

Figures

Figure 1

Traditional surgical planning based on CT scans

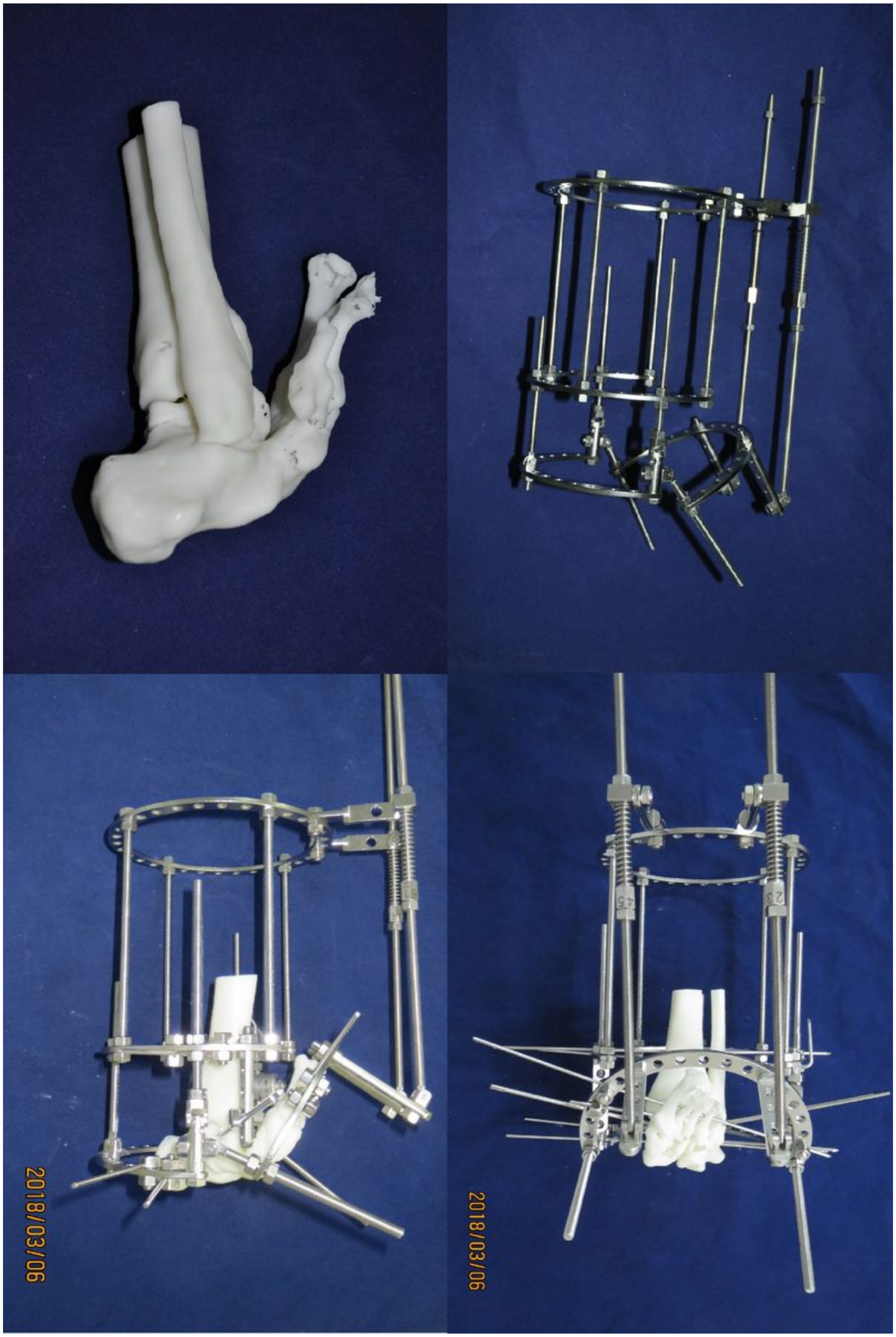

Figure 2

In the 3DPM group, surgical planning and rehearsal were performed on the 3DPM including assembly and configuration of the external fixators, ring placement, and the drilling location and direction of pins and wires. A: Lateral view of the 3DPM; B. Preconstructed Ilizarov frame; C: Lateral view after the frame was successfully applied on the 3DPM via rehearsal surgery. D: Anterior view

Figure 3

A: Design of Fish-bone incision for contracture release. B: Conservative correction of the articular position was performed to avoid exposure and overstretch of neurovascular bundle (Lateral view); C: Anterior view; D: The preconstructed external fixator was applied and wires were inserted as preoperatively planned.

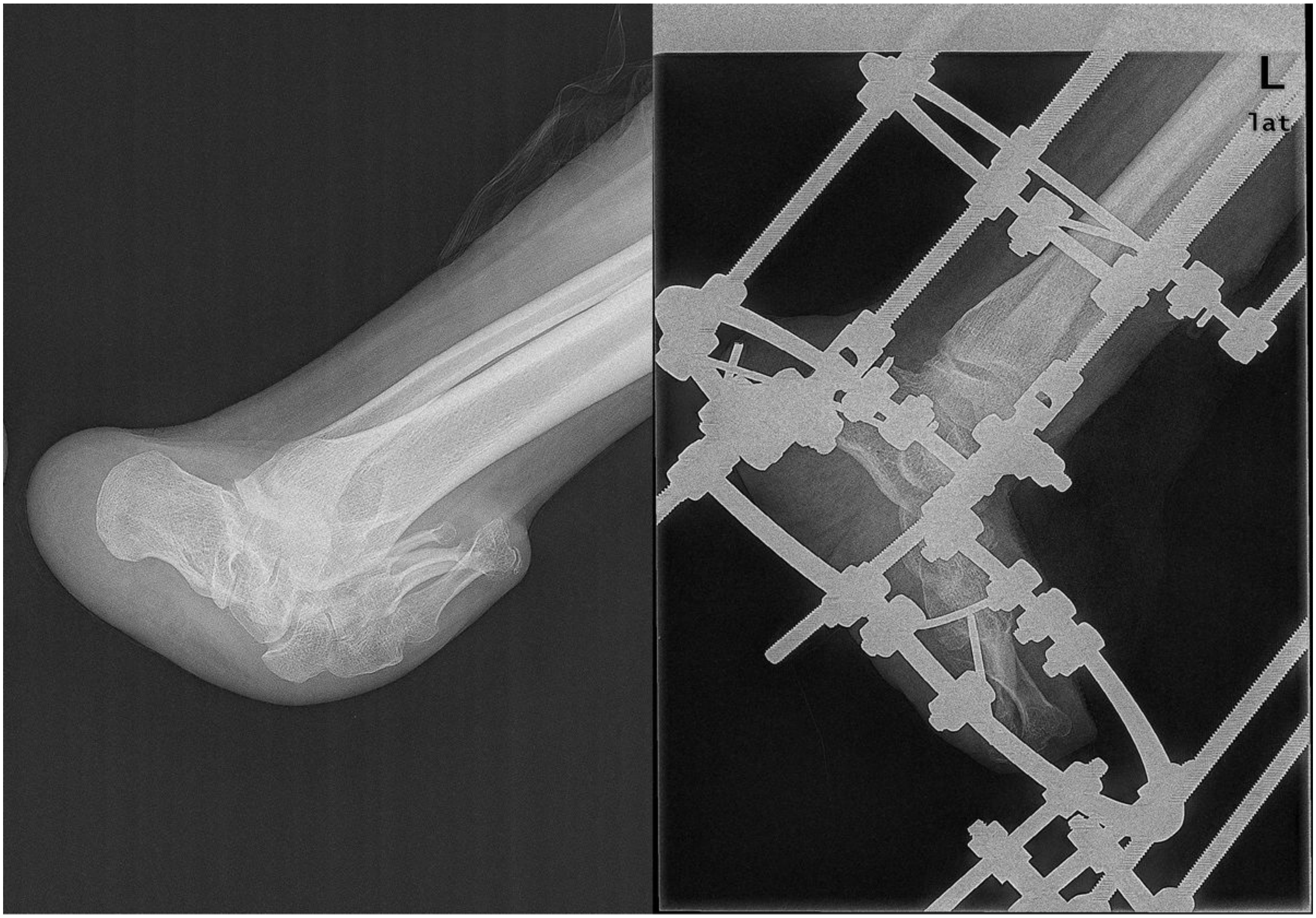

Figure 4

A: Preoperative lateral X-ray; B: X-ray was performed to confirm that satisfactory correction was achieved before the removal of frame.

Figure 5

A: Lateral view and B: anterior view before the removal of the circular frame; C: Lateral view and D: anterior view after the removal of the frame; E: Lateral view and F: anterior view of the ankle at 2.5-year follow-up.

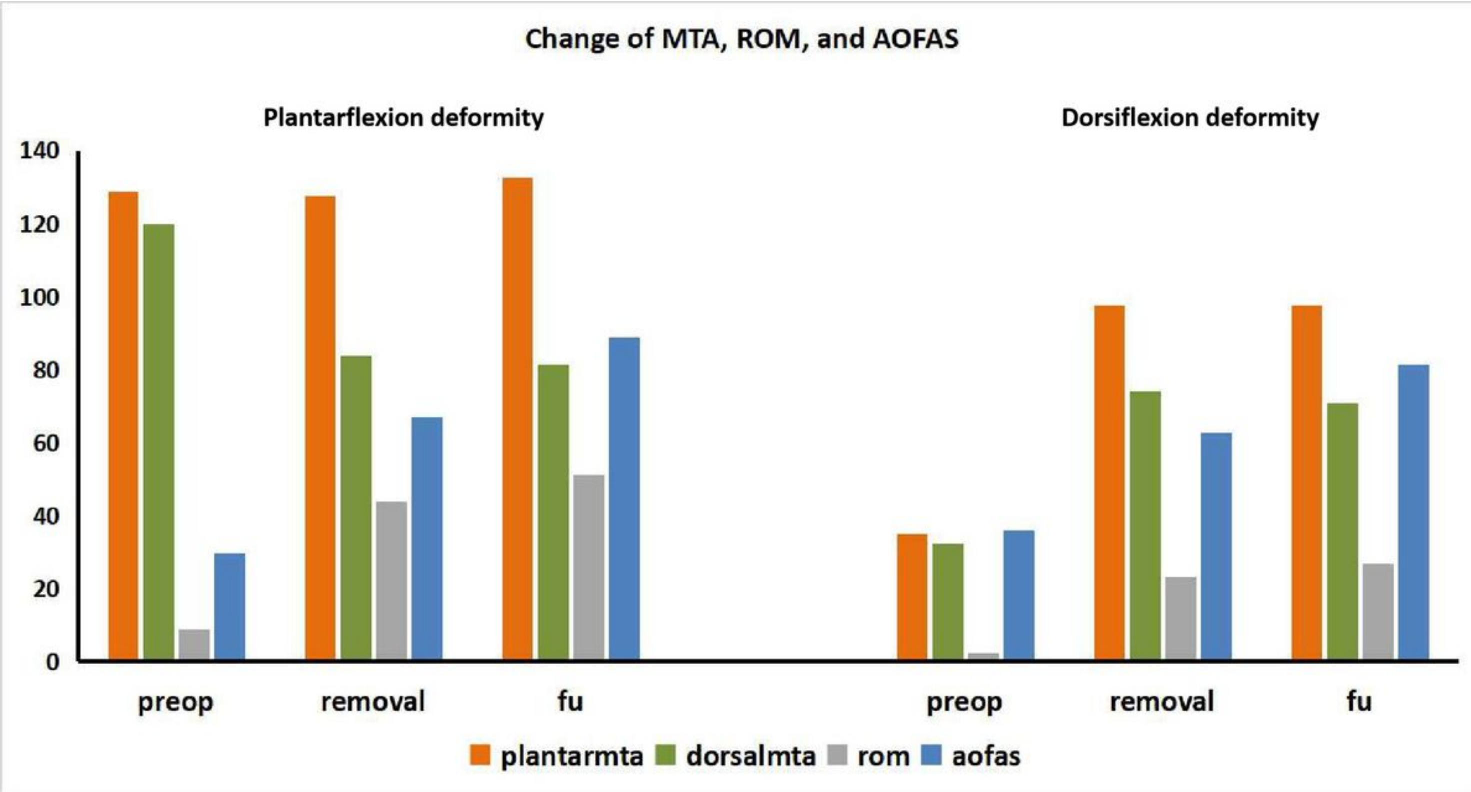

Figure 6

Change of MTA, ROM, and AOFAS. MTA: metatarsal-tibial angle, ROM: range of motion, AOFAS: American Orthopedic Foot and Ankle Society ankle and hindfoot scores, preop: preoperative, removal: after removal of the external fixator, fu: at the final follow-up, plantamta: MTA at the maximum plantarflexion, dorsalmta: MTA at the maximum dorsiflexion

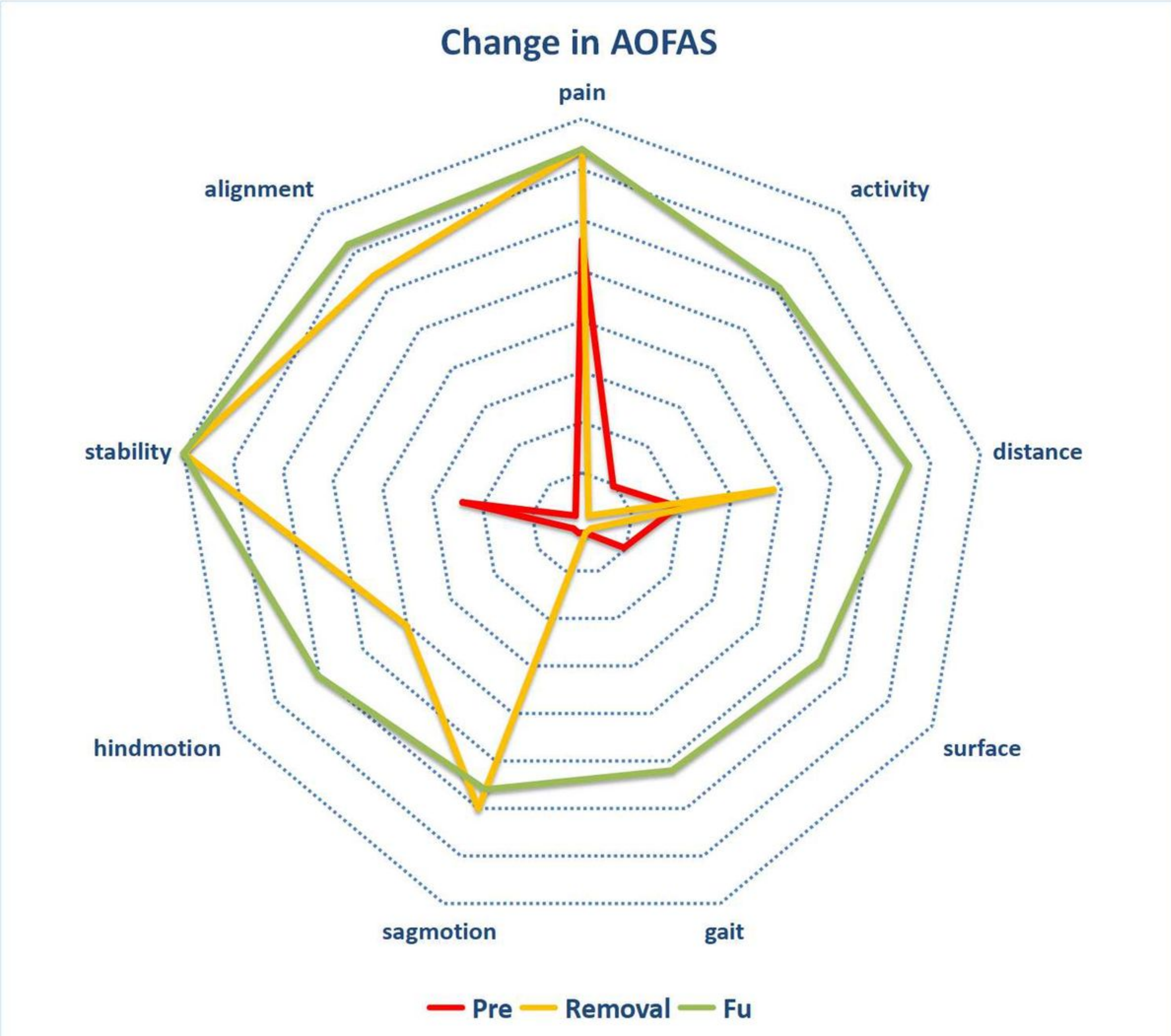

Figure 7

Changes in AOFAS. activity: activity limitations and support requirement, distance: maximum walking distance, surface: walking surfaces, gait: gait abnormality, sagmotion: sagittal motion (flexion and extension) , hindmotion: hindfoot motion (inversion and eversion), stability: ankle-hindfoot stability (anteroposterior, varus-valgus).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Table1.xlsx