Long Bone Fracture Reduction and Deformity Correction Using the Hexapod External Fixator With a New Method: a Feasible Study and Preliminary Results

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Abstract

Background: The hexapod external fixator (HEF), such as the Taylor spatial frame (TSF), offering the ability of simultaneous correction of the multidirectional deformities without frame modification, whereas there are so many parameters for surgeons to measure and subjective errors will occur inevitably. The purpose of this study was to evaluate the effectiveness of a new method based on computer-assisted three-dimensional (3D) reconstruction and hexapod external fixator for long bone fracture reduction and deformity correction without calculating the parameters needed by the computer program.

Methods: This retrospective study consists of 25 patients with high-energy tibial diaphyseal fractures treated by the HEF at our institution from January 2016 to June 2018, including 22 males and 3 females with a mean age of 42 years (range 14-63 years). Hexapod external fixator treatments were performed due to primary and definitive management of multiplanar posttraumatic deformity and/or severe soft-tissue damage that were not suitable for internal fixation in the tibia. Computer-assisted 3D reconstruction and trajectory planning of the reduction by Mimics were applied to perform virtual fracture reduction and deformity correction. The electronic prescription derived from the length changes of the six struts were calculated by SolidWorks. Fracture reduction was conducted by adjusting the lengths of the six struts according to the electronic prescription. The standard anteroposterior (AP) and lateral X-rays after reduction were taken to evaluate the effectiveness.

Results: All patients acquired excellent functional reduction (most cases achieved anatomical reduction) in our study. The mean coronal plane translation (1.0±1.1 mm), coronal plane angulation (0.8±1.2°), sagittal plane translation (0.8±1.0 mm) and sagittal plane angulation (0.3±0.8°) after correction were all less than those (6.1±4.9 mm, 5.2±3.2°, 4.2±3.5 mm, 4.0±2.5°) before correction (P<0.05).

Conclusion: The computer-assisted three-dimensional reconstruction and hexapod external fixator-based method allows surgeons to conduct long bone fracture reduction and deformity correction without calculating the parameters needed by the computer program. Considering the radiologic exposure, this method is suggested to apply in those unusually complex cases with extensive soft tissue damage and internal fixation is impossible or inadvisable.

Background

External fixation played an important role over the years in the treatment of open fractures, bone infections, deformity correction, or to reconstruct missing or short bones, especially those with extensive soft tissue damage[1–4]. Prior to external fixation, closed reduction must be done to realign the fracture fragments. The accurate anatomic reduction was reported to have beneficial effects in reducing the time to union[5], lowering the possibility of malunion and nonunion[6], and improving the function and appearance of the limb[7]. Given that the three-dimensional(3D) spatial deformities in actuality, the conventional approach for fracture reduction using an external fixator based on the two-dimensional(2D) fluoroscopic with limited field of view and static remains a challenge, often results in the surgeons making a compromise between the quality of reduction and time taken[8, 9]. The conventional procedure is subjective, time-consuming, and experience-dependent.

The hexapod external fixator (HEF), such as the Taylor spatial frame (TSF), combining gradual distraction principles of the Ilizarov method with deformity analysis provided by a computer program[3, 10]. This frame is an symmetric configuration of the Stewart platform, which consists of 2 rings or partial rings connected by 6 telescopic struts at special universal joints[11]. It offers the versatility of correcting multiplanar deformities simultaneously without frame modification[3, 10, 12–14], and makes the reduction process more objective and experience-independent. However, the effectiveness depends on the measurement accuracy of the input parameters which calculated by 2D X-rays. In general usage, for TSF, surgeons must measure 13 parameters precisely, including six deformity parameters, four mounting parameters, and three frame parameters. There are many factors that can affect effectiveness, and errors in any one parameter will affect the entire preoperative plan. Of all these parameters, the axial rotational deformity is easier to error because the 2D radiographs can't contain axial spatial information and it determined by clinical examination[15–17]. Additionally, limb rotation on radiographs changes the measured anatomical and mechanical angles significantly[18, 19].

These practical constrains ground the premise of the current study. Based on previous published data and our previous exploration, the purpose of this study was to propose a new method based on computer-assisted 3D reconstruction and hexapod external fixator for long bone fracture reduction and deformity correction without calculating the parameters needed by the computer program.

Methods

This retrospective study consists of 25 trauma patients who suffered tibial diaphyseal fracture treated by the hexapod external fixator at our institution from January 2016 to June 2018, including 22 males and 3 females with a mean age of 42 years (range 14–63 years). Informed consent was obtained from all patients for their data to be recorded in our study (included hospital data, radiographs, and photographs). This study was approved by the Ethical Committee of our institution.

Hexapod external fixator treatments were performed due to primary and definitive management of multiplanar posttraumatic deformity and/or severe soft-tissue damage that were not suitable for internal fixation in the tibia. Postoperative deformities with an angular deformity greater than 5° in any anatomical plane or a translational deformity greater than 10mm[9] needed to be corrected. Fractures associated with vascular and nerve injury, and patients with poor compliance were excluded.

Planning procedure of electronic prescription

The postoperative computed tomographic (CT) data of the bilateral extremities were imported into Mimics 17.0 (Materialise, Belgium) for 3D reconstruction, registration, and virtual trajectory planning of the reduction. The reference (proximal) ring and distal ring which contains the spatial positional information at each critical point in the trajectory were exported as STL (Standard Template Library) files by Mimics and then imported into SolidWorks 2016 (Dassault Systemes, USA) to calculate the lengths of the six struts.

The electronic prescription derived from the length changes of the six struts.

Technique and case example

A 54-year-old man suffered tibiofibular fractures in a traffic accident with multiplanar posttraumatic deformity. He had severe hemorrhagic fracture blisters on presentation to our institute 2 days after the injury. In this case, computer-assisted 3D reconstruction and virtual trajectory planning of the reduction with Mimics were applied to perform fracture reduction and deformity correction based on hexapod external fixation (Fig. 1 to 4).

The 3D model of the injured limb, contralateral healthy limb, and external fixator were reconstructed based on postoperative CT data by threshold division, bone separation, and image editing in Mimics. The proximal bony fragment and ring were defined as reference bony fragment and reference ring, which were motionless relatively. The mirrored 3D model of the contralateral healthy limb was regarded as the reference for reduction, and it was registered with the reference bony fragment. To eliminate the visual interference caused by metal artifacts on the actual external frame, two standard ring models which are the same size as the actual ring of the HEF were created in STL format by SolidWorks, loading them into Mimics and registered with the 3D model of the actual proximal and distal ring. The bony fragment and its corresponding standard ring were merged into one part, the whole model was divided into two parts, and the position of the bony fragment relative to its corresponding standard ring was locked in each part (Fig. 1).

The proximal part was motionless relatively, the virtual trajectory of fracture reduction was planned by adjusting the spatial position of the distal part with the function of move and rotation in Mimics. Three steps with three critical points performed the reduction. Firstly, the distal part was moved at an appropriate distance to the distal end, providing sufficient space for the relative movement of the two bony ends. Secondly, the distal part was moved and rotated in multiple planes to correct the spatial deformities referred to the mirrored 3D model of the contralateral healthy limb. Thirdly, the bony end of the two parts was docked with a comprehensive reference to the profile of the docking site and the mirrored 3D model of the contralateral healthy limb (Fig. 2).

The relative position of the bony fragment and its corresponding ring was locked in each part, the position changes in the bony fragment could be replaced by those in ring. The relative position information of the two bony fragments at each critical point during the procedure of virtual reduction was obtained. Each part was separated into bony fragment and ring at every critical point, and these rings were named in the order and saved. The two rings of the same group which contain the information of spatial position were imported into SolidWorks for an assembly model, and six virtual struts were created based on the actual situation in this assembly model. The lengths of the six virtual struts were the electronic prescription needed by HEF (Fig. 3).

Reduction management and effectiveness evaluation

Fracture reduction was conducted by adjusting the lengths of the six struts according to the electronic prescription. The standard anteroposterior (AP) and lateral X-rays after reduction were taken to evaluate the effectiveness. The coronal plane translation, coronal plane angulation, sagittal plane translation, and sagittal plane angulation were documented and analyzed.

Statistical analysis

Statistical analysis was performed with the SPSS 22.0 (IBM Corp, USA). Continuous variables were analyzed by paired-samples T-tests and expressed as the mean and standard deviation (SD). Statistically significant difference was set at $P < 0.05$.

Results

The differences before and after reduction are shown in Table 1. All patients acquired excellent functional reduction which was evaluated by AP and lateral X-rays (most cases achieved anatomical reduction) in our study. The mean coronal plane translation, coronal plane angulation, sagittal plane translation and sagittal plane angulation before correction were 6.1 ± 4.9 mm, 5.2 ± 3.2°, 4.2 ± 3.5 mm and 4.0 ± 2.5°, respectively. Mean coronal plane translation, coronal plane angulation, sagittal plane translation and sagittal plane angulation after correction were 1.0 ± 1.1 mm, 0.8 ± 1.2°, 0.8 ± 1.0 mm and 0.3 ± 0.8°, respectively. All the differences between the residual deformities before and after correction were statistically significant ($p < 0.05$). (Typical cases were shown in Fig. 4–5)

Table 1
Comparison of the residual deformities before and after correction

Parameters	Before	After	t	P-value
Coronal plane translation	6.1 ± 4.9	1.0 ± 1.1	5.614	P < 0.001
Coronal plane angulation	5.2 ± 3.2	0.8 ± 1.2	7.426	P < 0.001
Sagittal plane translation	4.2 ± 3.5	0.8 ± 1.0	5.006	P < 0.001
Sagittal plane angulation	4.0 ± 2.5	0.3 ± 0.8	6.942	P < 0.001
Values are presented as mean ± SD. Translation in mm and angulation in degree (°).				

Discussion

The major risk factor for fracture healing is poor reduction. Fractures that healed with an angular deformity greater than 5°in any anatomical plane or a translational deformity greater than 10 mm are regarded as malunion[9]. Even minor degrees of alteration in the mechanical axis has been demonstrated to significantly affect the progression to arthritis in both knee and ankle[20, 21]. It is generally accepted that anatomic reduction is a crucial step for most fracture treatments.

To improve reduction accuracy, many computer-assisted techniques have been developed. Koo et al.[22, 23] performed an algorithm for closed fracture reduction using a unilateral external fixator, whereas there lacked a device which could facilitate its implementation in clinical practice. Hofstetter et al.[24, 25] and Weil et al.[26] developed fluoroscopy-based navigation techniques in which the bone fragments are displayed through superimposed line graphics to provide the real-time spatial relationship between the bone fragments, and navigation systems based on CT were also developed for the accurate reduction[27, 28].

The hexapod external fixation offers the ability of simultaneous correction of the multidirectional deformities without frame modification, and was widely used for limb lengthening, deformity correction, and fracture reduction in recent years[3, 4, 11–13, 16, 29, 30]. In contrast, there are still some inherent limitations that can affect effectiveness. The postoperative adjustments are based on the measurements of standard orthogonal AP and lateral radiographic[31], whereas they are often conducted subjectively by radiologists and position the limbs for taking the orthogonal radiographs especially in patients with severe deformities is challenging. Besides, lots of published data demonstrated that radiographs performed with malrotation of the limb will lead to wrong measurements of the mechanical axis, the mechanical femorotibial axis (mFTA), the femoral anatomic mechanical angle (AMA), the mechanical lateral distal femoral angle (mLDFA) or the mechanical medial proximal tibial angle (mMPTA) [18, 19, 32, 33]. As described, malrotation on radiographs can lead to wrong anatomical measurements, however the assessment of this malrotation is difficult. It can be assumed that rotation-related changes in the measured anatomic alignment can influence the degree of deformity correction as well as the treatment success.

Moreover, the reference ring must be perpendicular to the reference bony fragment in AP and lateral view, which is a challenge for surgeons during the surgical installation. For the mounting parameters, the whole reference ring must be visible on the radiographs, while the lateral border of the reference ring was incomplete or obscured in most radiographs in our retrospective analysis. The spatial information, especially for the rotational deformities, can't be obtained from the radiographs which are shown in the 2D planes, and they were calculated by clinical examination in traditional usage which is not accurate[17]. Additionally, there are 13 parameters for surgeons to measure and subjective errors will occur inevitably, the majority of residual deformities have been reported due to inaccurate mounting parameters[34]. The aforementioned situations may result in a time-consuming process, which is often followed by repeated radiographs including further radiation exposure for the patient.

To prevent the miscalculation of the parameters needed by the hexapod external fixation system, several techniques have been proposed[31, 34–36]. Kucukkaya et al.[34] calculated the mounting parameters using the tomographic images in CT, they demonstrated its advantages, especially in deformities with a rotational deformity. Gantsoudes et al.[36] declared it is easily reproducible in the operating room and allows for accurate measurement of the mounting parameters when conducted intraoperative measurement. Ahrend et al.[37] used rotation rod to control limb rotation before taking radiographs and enhance the standard radiographic procedure, they concluded that the variability of rotation on radiographs was lower with the rotation rod, and more reproducible and better comparable radiographs can be conducted. However, these techniques are all dependent on the measurements in 2D planes.

The presented new method which uses a postoperative CT scans to establish the relationship between the bone and ring, and replaced the spatial changes in bony fragments with that in the two rings. In our study, there was no need to conduct orthogonal AP and lateral X-rays to measure so many parameters for surgeons, and this way may be a potential benefit to prevent wrong measurements. Besides, surgeons conducted virtual reduction under the direct vision by Mimics, and the three-point trajectory of "extend-rotate-reduct" can easily avoid the collision and interference between the irregular bony end in the process of fracture reduction. In this method, the most important one for surgeons is just keeping the stable fixation in bony fragment and its corresponding ring, and there was no need to ensure that the reference ring was perpendicular to the reference bony fragment.

The present study had several limitations. Firstly, the new method here may be limited by the two software, Mimics and SolidWorks, which required the surgeons to have a basic knowledge of these software. The procedures are tedious and time-consuming in inexperienced hands, especially under the influence of metal artifacts for 3D reconstruction. A practical software which contains the aforementioned comprehensive function need to be developed for these limitations. Secondly, the control group in which conduct parameters measurement on 2D radiographs is needed to compare the accuracy of the present method, whereas the clinical outcomes have demonstrated the effectiveness of our new method. Thirdly, considering the higher radiologic exposure in CT than X-rays, our method is suggested to apply in severe open fractures or those unusually complex cases with severe deformities, especially in those with extensive soft tissue damage and internal fixation is impossible or inadvisable.

Conclusions

The computer-assisted three-dimensional reconstruction and hexapod external fixator-based method allows surgeons to conduct long bone fracture reduction and deformity correction without calculating the parameters needed by the computer program. Considering the radiologic exposure, this method is suggested to apply in those unusually complex cases with severe deformities, especially in those with extensive soft tissue damage and internal fixation is impossible or inadvisable.

Abbreviations

HEF: hexapod external fixator;

TSF: Taylor spatial frame;

3D: three-dimensional;

2D: two-dimensional;

AP: anteroposterior;

CT: computed tomographic;

STL: Standard Template Library;

SD: standard deviation.

Declarations

Ethics approval and consent to participate

This retrospective study was approved by the Ethics Committee of The First Affiliated Hospital of Xinjiang Medical University. Written informed consent was obtained from all patients for their data to be recorded in our study.

Consent for publication

Written informed consent was obtained from all patients for their data to be publicated in this study.

Availability of data and materials

The datasets analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no conflict of interest.

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Author's contributions

YSL: Conducted the study. Collected, analyzed and interpreted the data. Wrote the manuscript.

HL: Provided software assistance. Interpreted and analyzed the data. Edited the manuscript.

JLL: Interpreted and analyzed the data. Edited the manuscript.

XPZ: Conducted the study. Collected, analyzed and interpreted the data.

MY: Created and statistical analyzed the data. Edited the manuscript.

ZHL: Provided software assistance.

CM: Planned the project. Reviewed the manuscript.

AY: Planned the project. Reviewed the manuscript.

Final approval of the version to be submitted: YSL, HL, JLL, XPZ, MY, ZHL, CM, AY

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Figures

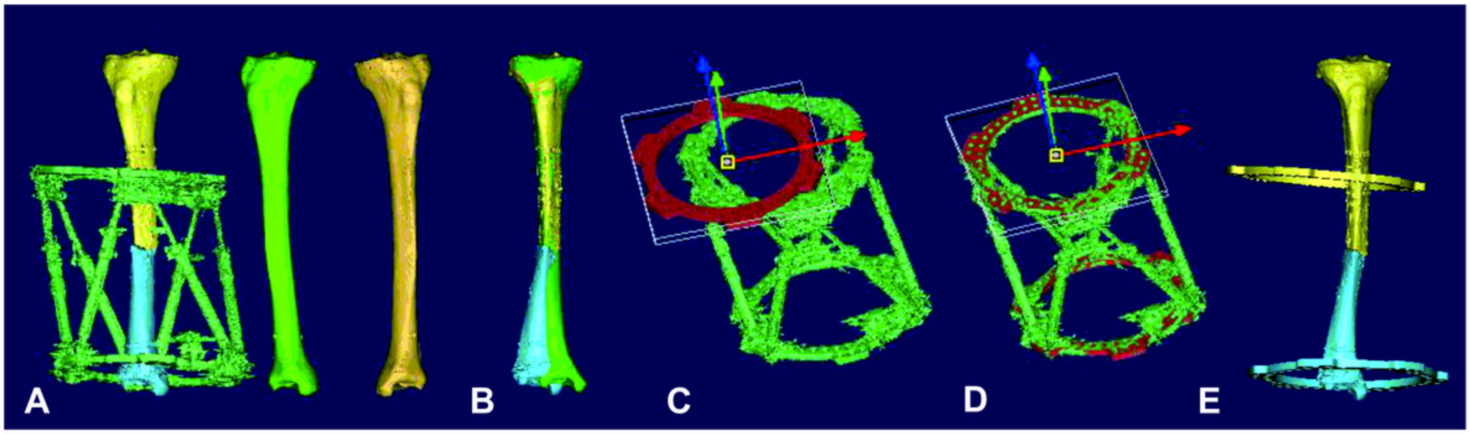

Figure 1

3D reconstruction and registration of the whole model. a 3D reconstruction of the bilateral tibia and the TSF. The green tibia is the mirror of the contralateral tibia. b Registration of the proximal bony fragment and mirrored image of the contralateral tibia. (c, d) Registration of the standard ring and the 3D model of the actual ring. e Merge of the bony fragment and the corresponding ring.

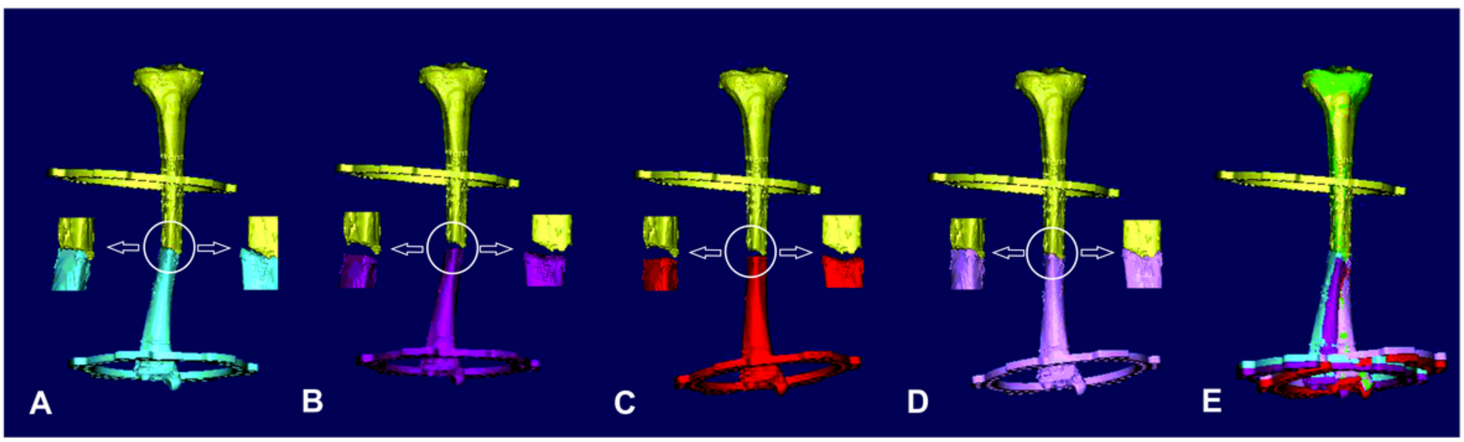

Figure 2

Flowchart of the trajectory planning for fracture reduction. a Original position of the whole model. b Extension of the distal part. c Rotation of the distal part. d Reduction of the distal part. e Schematic image of the whole planning.

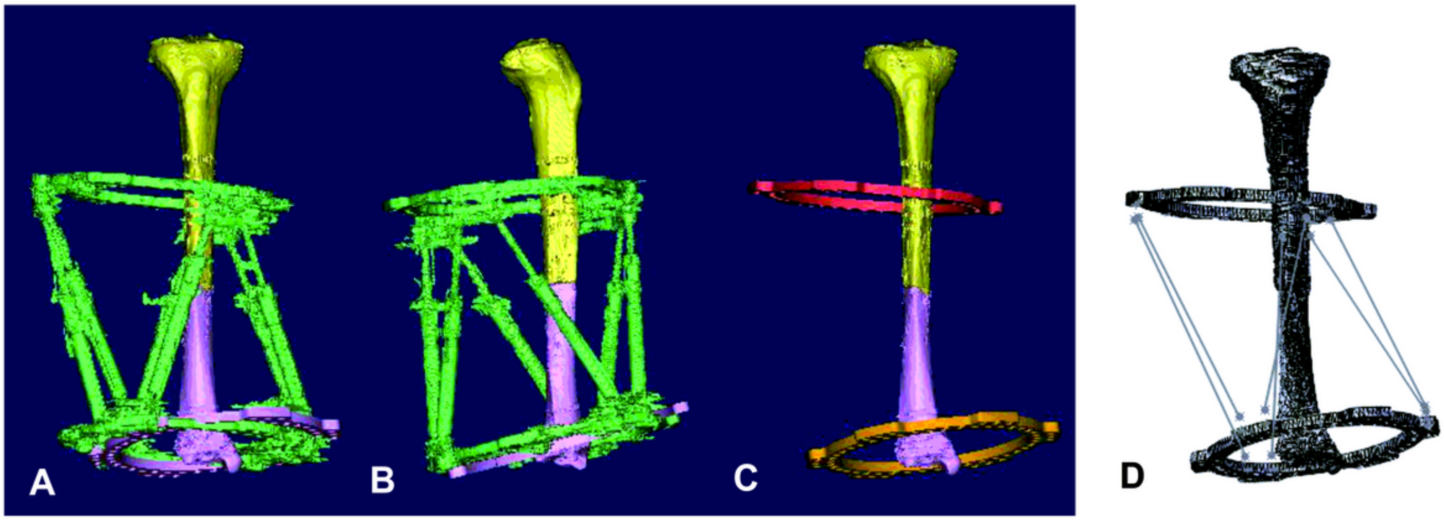

Figure 3

Position changes of the distal ring before and after reduction. a AP view of the whole model. b Lateral view of the whole model. c Separation of the bony fragment and the corresponding ring from the two parts. d Calculate the length of the six struts in SolidWorks.

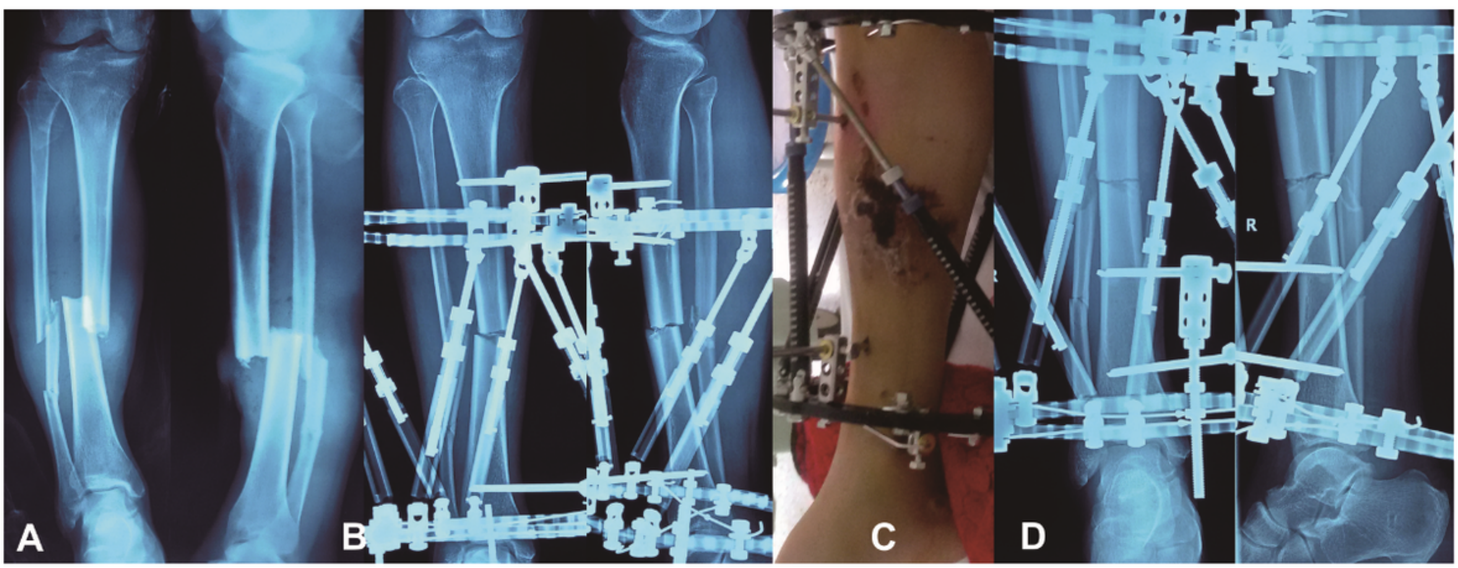

Figure 4

Images of a 54-year-old man with posttraumatic multidimensional deformities in tibia and fibula treated by the hexapod external fixation (HEF). a Posttraumatic AP and lateral views of X-rays. b Radiographs immediately after application of HEF. c Patient in HEF with preoperative hemorrhagic fracture blisters seen. d Radiographs after final correction.

Figure 5

Follow-up images of the same patient after removing the HEF. a Radiographs one month later. b, c Clinical images of the patient, obtained at 13 months after HEF removal.