Research Square

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Comparison of CT-Guided Digital Hexapod External Fixation and Intramedullary Nailing for Tibial Shaft Fractures: A Retrospective Study

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Abstract

Background:

The surgical management of tibial shaft fractures remains a challenge, particularly in balancing reduction accuracy with soft tissue preservation. Intramedullary nailing (IMN) is a standard treatment but is associated with approach-related knee pain and inferior torsional control. The Qiao Spatial Frame (QSF) is a CT-guided digital hexapod fixator designed to improve reduction precision. This study compared the clinical and radiographic outcomes of QSF-based fixation, a modified QSF-assisted unilateral external fixation (UEF) technique, and IMN.

Methods:

We retrospectively reviewed 166 patients with tibial shaft fractures treated between 2017 and 2022. Patients were divided into three groups: QSF (n = 46), QSF-assisted UEF (n = 57), and IMN (n = 63). Radiographic reduction (translation and angulation), fracture healing time, functional recovery via the Lower Extremity Functional Scale (LEFS), and complication rates were compared among the groups.

Results:

Radiographic assessments showed that both the QSF and QSF-assisted UEF groups achieved significantly better reduction accuracy in terms of AP, lateral, and axial translation compared to the IMN group ($p < 0.001$). The QSF-alone group achieved the most precise angular alignment ($p < 0.001$). While overall healing times were similar across groups, a sub-analysis revealed that Type C and open fractures in the IMN group required significantly longer to heal than those in the QSF group ($p = 0.013$). Functional LEFS scores at final follow-up showed no significant differences between the three modalities. Complication profiles varied: 30.2% of IMN patients reported chronic anterior knee pain, while the QSF-assisted UEF technique significantly reduced the incidence of pin-tract pain compared to the circular QSF-alone group (2 cases vs. 15 cases).

Conclusion:

The CT-guided QSF technique achieves superior radiographic reduction compared to intramedullary nailing and offers the flexibility of conversion into a low-profile unilateral external fixator. With clinical outcomes comparable to those of intramedullary nailing, this approach provides a minimally invasive and effective treatment strategy for both closed and open tibial shaft fractures.

Introduction

Tibial shaft fractures are among the most common long-bone injuries, with an annual incidence of approximately 20 per 100,000 [1]. Due to the sparse anteromedial soft tissue envelope of the tibia, these injuries are frequently open fractures. Furthermore, many closed fractures exhibit significant occult soft tissue damage, which may lead to delayed healing, infection, and nonunion.

The surgical treatment of tibial diaphyseal fractures generally encompasses internal and external fixation modalities. Internal fixation techniques include compression plating and intramedullary nailing (IMN). Plating is characterized by superior primary stability and the ability to achieve anatomical reduction; however, the necessary periosteal stripping increases the incidence of surgical site infections and wound dehiscence. While IMN is a more biologically friendly approach, it is often criticized for inferior torsional control and a high prevalence of iatrogenic anterior knee pain. Furthermore, in the context of open fractures, internal hardware may further devitalize the soft tissue envelope, resulting in late-stage ischemic necrosis [2].

With the continuous advancement of external fixators, these devices are no longer restricted to the temporary stabilization of open fractures; they are increasingly utilized as definitive treatment, yielding favorable clinical outcomes [3–6]. In 2017, our team refined the working principles of the Taylor Spatial Frame (TSF) to develop a digital six-axis external fixator guided by CT data. Named the Qiao Spatial Frame (QSF; Xinzhong Medical Equipment Co., Ltd., Tianjin, China), its primary advantage lies in the computational accuracy of its digital prescriptions, which surpasses that of TSF protocols based on traditional X-ray data. We previously employed the QSF for the correction of knee joint deformities and achieved successful clinical results [7].

To minimize the hardware volume for tibial shaft fractures, we implemented a modified technique: 4- to 6-hole Rancho cubes were placed at the proximal and distal ends of the fracture, ensuring each segment was stabilized with at least three half-pins. Following the installation of the ring frames and successful reduction via the QSF, the proximal and distal Rancho cubes were connected using two rods. The ring frames were then removed, converting the construct into a unilateral external fixator（UEF）. We have termed this approach the "QSF-assisted UEF" technique. The purpose of this study was to retrospectively compare the clinical outcomes of QSF-based external fixation versus intramedullary nailing for the treatment of tibial shaft fractures. We hypothesized that both QSF-based reduction/fixation and QSF-assisted UEF fixation would achieve therapeutic results equivalent to those of intramedullary nailing.

Patients and methods

This study was approved by the Ethics Review Committee of Xi'an Honghui Hospital (IRB Approval Number 202312001) and conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants. We retrospectively reviewed cases of tibial shaft fractures treated at our institution between January 2017 and December 2022. Patients were categorized into three groups: the IMN group (intramedullary nail fixation alone), the QSF group (reduction and fixation

using a QSF), and the QSF-assisted UEF group (reduction with QSF followed by fixation with a Unilateral External Fixator).

Inclusion criteria were based on radiographic displacement, defined as a >5° coronal angle, >10° sagittal angle, >1 cm shortening, or translation exceeding 50% of the tibial diaphysis. Exclusion criteria included: (1) age <14 years; (2) concomitant fractures of the knee, hip, or ankle; (3) old fractures or non-unions; (4) pathological fractures; (5) fractures without significant displacement; (6) incomplete clinical data; and (7) a follow-up period of less than 12 months. Ultimately, 166 patients were included: 46 in the QSF group, 57 in the QSF-assisted UEF group, and 63 in the IMN group. Demographic details, including average age and follow-up duration, are summarized in Table 1.

Surgical technique

Intramedullary Nail Technology.

A transpatellar approach was employed, splitting the patellar ligament longitudinally to expose the entry site on the tibial plateau. Under fluoroscopic guidance, a starting pin was inserted at the anterior margin of the plateau, positioned just medial to the lateral tibial spine on the anteroposterior (AP) view and at the anterior cortical downslope on the lateral view. Following the preparation of the proximal entry portal, the fracture was reduced manually. A guidewire was then advanced across the fracture site and its position was confirmed via fluoroscopy. In cases where closed reduction proved difficult, pointed reduction clamps were applied through limited incisions to facilitate alignment. After achieving satisfactory reduction, sequential intramedullary reaming was performed. An appropriately sized nail was then inserted, and 2–3 distal locking screws were placed. If a fracture gap persisted, the nail was back-driven to achieve interfragmentary compression. Finally, the proximal locking screws and an end cap were implanted.

QSF technology

The QSF external fixator was pre-assembled based on the patient's tibial morphology and the specific fracture characteristics (location and orientation). Ring sizes and strut lengths were selected accordingly, with shorter struts utilized for transverse fractures and longer struts for long oblique or spiral patterns. The construct consisted of two main rings connected by six adjustable telescopic struts.

The affected limb was centered within the rings, ensuring a circumferential clearance of approximately 3 cm between the skin and the frame. Under fluoroscopic guidance, three to four 5.0 mm threaded Schanz pins were inserted percutaneously into the proximal and distal segments and secured to the rings using Rancho cubes. For segmental fractures, an additional intermediate ring was integrated into the construct. Initial gross reduction was achieved through manual traction and manipulation, after which the strut nuts and locking screws were tightened to stabilize the assembly.

Postoperatively, a full-length CT scan of the tibia was performed. The imaging data were processed using dedicated software to simulate the reduction and generate a digital adjustment schedule

(electronic prescription). In the ward, the struts were adjusted according to this schedule to achieve precise fracture alignment. Reduction was verified via follow-up radiographs. If the alignment was suboptimal, the digital prescription was recalculated, and the frame was re-adjusted until satisfactory anatomical reduction was achieved (Fig. 1).

QSF -assisted UEF technology

The external fixator construct was planned by configuring two Rancho cube half-pin complexes based on the fracture topography. A minimum of three 5.0 mm threaded Schanz pins were inserted into both the proximal and distal fracture fragments under fluoroscopic guidance. These Rancho cubes were then coupled to the QSF spatial frame using two specialized wing-shaped adapters. Following temporary reduction and stabilization, a postoperative full-length CT scan of the tibia was obtained. Dedicated software was utilized to simulate anatomical reduction and generate a digital prescription.

in the ward, the QSF struts were adjusted according to the prescription, with alignment verified via radiography. Once satisfactory reduction was achieved, two carbon fiber rods were secured to the proximal and distal Rancho cubes to provide definitive stabilization. The QSF frame and wing-shaped adapters were then removed, leaving a low-profile, unilateral half-pin-carbon fiber rod construct in situ. If follow-up imaging indicated suboptimal alignment, the QSF was re-attached and the digital prescription recalculated for iterative correction until anatomical alignment was achieved (Fig. 2).

Postoperative Management and Rehabilitation

Postoperatively, all patients immediately commenced active range of motion (ROM) exercises, specifically focusing on knee and ankle flexion and extension.[1] Toe-touch weight-bearing (TTWB) was permitted immediately after surgery, with a gradual progression to weight-bearing as tolerated (WBAT) and full weight-bearing (FWB) based on clinical and radiographic evidence of union. Radiographic assessments were conducted at four-week intervals. Fracture healing was defined as the presence of bridging callus in at least three of the four cortical regions on anteroposterior (AP) and lateral radiographs. Following radiographic confirmation of union, the external fixator was removed in both the QSF and QSF-assisted UEF groups.

Radiographic Evaluation

All radiographic measurements were performed using a Picture Archiving and Communication System (PACS; Synapse, Fujifilm Inc., Tokyo, Japan). Fracture alignment in the coronal, sagittal, and axial planes was assessed four weeks postoperatively. Coronal (AP view) and sagittal (lateral view) angulations were calculated based on the longitudinal axes of the proximal and distal fragments. Translation in the AP and lateral views was measured relative to the axis of the reference fragment. Axial translation (shortening or distraction) was determined using lines perpendicular to the reference fragment axis. As postoperative CT scans were not obtained after final reduction, axial rotational displacement could not be accurately assessed via plain radiography and was therefore excluded from the analysis.

To ensure data reliability, all measurements were performed by two independent observers who were not involved in the surgical procedures. One observer repeated the measurements after a three-week interval to assess intra-observer reliability. The Intraclass Correlation Coefficient (ICC) was utilized to determine measurement consistency. ICC values were interpreted as follows: poor agreement (<0.40), fair to good agreement (0.40–0.75), and excellent agreement (>0.75) [8].

Clinical Evaluation

Clinical outcomes were assessed at the final follow-up using the Lower Extremity Functional Scale (LEFS) [9]. The LEFS is a validated 20-item questionnaire designed to evaluate a patient's ability to perform activities of daily living. Each item is scored on a 5-point scale (0–4), yielding a maximum total score of 80 points. Higher scores indicate superior lower extremity function, with 80 representing the highest level of functional recovery.

Statistical Analysis

Statistical analysis was performed using SPSS version 26.0 (IBM Corp., Armonk, NY, USA). Data normality was assessed using the Kolmogorov-Smirnov test. Normally distributed continuous variables are expressed as mean ± standard deviation (SD) and were compared using one-way analysis of variance (ANOVA). Non-normally distributed continuous data are presented as medians with interquartile ranges (IQR; 25th and 75th percentiles) and were analyzed using the Kruskal-Wallis rank-sum test. Categorical variables (enumeration data) are presented as frequencies and percentages, with inter-group comparisons performed using the chi-square test. A p-value < 0.05 was considered statistically significant.

Results

Radiographic Outcomes

The Kolmogorov–Smirnov test confirmed that all continuous data followed a normal distribution. Intraclass correlation coefficients (ICCs) for the reproducibility of all radiographic parameters exceeded 0.80, indicating excellent inter-observer reliability (Table 2).

Regarding fracture translation, the QSF and QSF-assisted UEF groups demonstrated significantly less displacement in the AP, lateral, and axial planes compared to the IMN group (all $p<0.001$, except lateral translation QSF vs. IMN, $p=0.003$). No statistical differences were observed in translation between the QSF and QSF-assisted UEF groups. In terms of angulation, the QSF group achieved significantly better alignment (smaller angles) in both AP and lateral views compared to both the QSF-assisted UEF and IMN groups (all $p<0.001$). No significant difference in angulation was found between the IMN and QSF-assisted UEF groups. Comprehensive radiographic data are summarized in Table 3.

Fracture Healing and Functional Recovery

There were no significant differences in overall fracture healing time or final LEFS scores among the three groups. However, sub-analysis revealed distinct healing patterns: in the QSF and QSF-assisted UEF groups, healing times were consistent regardless of whether the fracture was open or closed, or its AO/OTA classification (Types A, B, or C). Conversely, in the IMN group, open fractures and Type C fractures required significantly longer healing times compared to closed and Type A or B fractures, respectively. Notably, the healing time for Type C fractures in the IMN group was significantly longer than for those in the QSF group (p=0.013; Table 4).

Complications

Soft tissue irritation and "pin-tract pain" during ambulation occurred in 15 patients in the QSF group and 2 patients in the QSF-assisted UEF group. This was attributed to K-wires or Schanz pins transfixing muscle or tendon units; symptoms resolved completely following frame removal. Superficial pin-site infections occurred in 6 patients in the QSF group and 7 in the QSF-assisted UEF group, all of which were successfully managed with a short course of oral antibiotics.

One patient in the QSF-assisted UEF group experienced a loss of reduction following a fall four weeks postoperatively. The QSF frame was re-applied, and the fracture was successfully re-reduced using a new digital correction prescription. In the IMN group, one patient with an open fracture developed a postoperative infection requiring multiple debridements and targeted antibiotic therapy; however, the internal fixation was successfully retained until union. Additionally, 19 patients in the IMN group reported anterior knee pain related to the surgical approach; these symptoms either resolved or significantly improved within one year of follow-up.

Discussion

Tibial shaft fractures remain a clinical challenge due to their high incidence of open injuries and soft tissue compromise, which often complicate fracture healing and functional recovery [10]. This retrospective study compared the clinical and radiographic outcomes of three surgical strategies for tibial shaft fractures: intramedullary nailing (IMN), Qiao spatial frame (QSF) alone, and QSF-assisted unilateral external fixation (QSF-assisted UEF). Our primary hypothesis—that QSF and QSF-assisted UEF would achieve therapeutic effects comparable to IMN—was supported by the results, with the former two modalities demonstrating superior radiographic reduction accuracy and comparable functional outcomes, while offering unique advantages in managing complex fractures.

The most striking finding was the superior radiographic reduction of QSF and QSF-assisted UEF compared to IMN. Specifically, both QSF groups exhibited significantly smaller coronal translation, sagittal translation, and axial translation than the IMN group. Furthermore, QSF alone achieved the smallest coronal and sagittal angulation (0.3±0.7° and 0.1±0.4°, respectively), which were significantly lower than those of QSF-assisted UEF and IMN. This precision can be attributed to QSF's unique design: unlike the Taylor Spatial Frame (TSF), which relies on X-ray data for reduction planning [11], QSF uses post-operative CT scans and specialized software to generate a digital "electronic prescription" for strut

adjustment. This CT-based approach eliminates the limitations of 2D X-ray imaging [7,12], enabling millimeter-level correction of displacement and angulation.

In terms of fracture healing time, no significant differences were observed among the three groups for overall cases. However, IMN showed a notable disadvantage in complex fractures: the healing time of open fractures in the IMN group (29.2±12.4 weeks) was significantly longer than that of closed fractures (24.0±6.1 weeks), and AO/OTA type C fractures in the IMN group (34.0±6.0 weeks) healed significantly slower than type C fractures in the QSF group (24.0±8.2 weeks, P=0.013). This aligns with previous reports that IMN may exacerbate medullary cavity pressure during reaming [2], potentially compromising blood supply to the fracture site—especially in open fractures or comminuted (type C) fractures, where soft tissue and bony perfusion are already impaired. In contrast, QSF and QSF-assisted UEF employ "elastic fixation": the external frame allows micro-movement at the fracture site, which stimulates callus formation without disrupting vascular ingrowth [13,14]. This mechanical environment is particularly beneficial for complex fractures, explaining the consistent healing times across fracture types in the QSF groups.

Functionally, all three groups achieved excellent lower extremity function, with no significant differences in the Lower Extremity Functional Scale (LEFS) scores at final follow-up. This indicates that despite differences in fixation modality, all approaches effectively restore limb function—likely due to early post-operative mobilization. Notably, QSF-assisted UEF addressed a major limitation of traditional circular external fixators (e.g., QSF alone): by converting to a unilateral external fixator (UEF) after QSF-mediated reduction, the fixation volume was reduced, and needle tract pain was significantly alleviated (15 cases in QSF vs. 2 cases in QSF-assisted UEF). This improves patient compliance with rehabilitation and reduces the burden of long-term external fixation—a key consideration for outpatient management.

Comparison with Existing Literature

Our results are consistent with prior studies on external fixators for tibial fractures. For example, Zhao et al. [15] reported that CT-guided external fixation achieved better reduction accuracy than IMN in distal tibial fractures, with early full weight bearing, early bone union and alignment. Similarly, our data confirm that QSF's CT-based planning outperforms IMN in correcting translational and angular deformities. Regarding IMN-associated knee pain, we observed anterior knee pain in 19 IMN patients (30.2% of the group), which is consistent with the 10–36% incidence reported in the literature [16]. This complication arises from the patellar tendon split approach required for IMN insertion, which can irritate the infrapatellar nerve or disrupt soft tissue around the knee—an issue avoided by QSF and QSF-assisted UEF, which require no knee-specific incisions.

Notably, QSF-assisted UEF represents a novel modification of circular external fixation. Traditional UEFs are limited by poor reduction accuracy, while circular frames are often bulky and associated with higher needle tract complications [17]. By combining QSF's precise reduction with UEF's simplicity, QSF-assisted UEF bridges this gap: our data show that it retains the reduction accuracy of QSF while reducing

needle tract pain and maintaining functional outcomes. This is a valuable innovation for patients who require external fixation but cannot tolerate the bulk of circular frames.

Limitations

This study has several limitations that should be acknowledged. First, its retrospective design introduces inherent selection bias: for example, patients with more severe soft tissue damage may have been preferentially assigned to QSF groups, while those with simple closed fractures may have been more likely to receive IMN. A prospective, randomized controlled trial (RCT) is needed to validate our findings. Second, the follow-up duration of the QSF-assisted UEF group (24.1±8.1 months) was shorter than that of the QSF (55.5±13.3 months) and IMN (48.0±17.2 months) groups. Longer follow-up is required to assess long-term outcomes such as post-traumatic arthritis—particularly for QSF-assisted UEF, a relatively new technique. Third, we did not assess axial rotational displacement because X-ray imaging cannot reliably quantify this parameter; future studies should incorporate post-reduction CT scans to evaluate rotational alignment, a key predictor of functional recovery. Finally, we did not collect data on patient-reported outcomes (PROs) such as pain severity, quality of life, or satisfaction with treatment—metrics that are increasingly prioritized in orthopedic research.

In conclusion, the QSF technique not only achieves better radiographic reduction than intramedullary nailing, but can also be flexibly converted into a small unilateral external fixator for fixation, achieving clinical outcomes comparable to intramedullary nailing. It provides a minimally invasive and effective treatment option for closed and open tibial shaft fractures.

Declarations

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Availability of data and materials

The data analyzed for the current study are available from the corresponding author on reasonable request.

Human Ethics and Consent to Participate declarations

This retrospective study was approved by the Ethics Review Committee of Xi'an Honghui Hospital (IRB Approval Number: 202312001) and was conducted in strict accordance with the principles of the Declaration of Helsinki Written informed consent was obtained from all individual participants.

Clinical trial number: not applicable

Consent for publication

All patients and all authors gave their consent for publication.

Competing interests

The authors declare that they have no competing interests

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Tables

Table 1
A summary of patient demographics.

Characteristics	**QSF**	**QSF-assisted UEF**	**IMN**
Ages(years)	40.5 ± 14.3	40.0 ± 15.1	43.4 ± 13.7
Male/female	36/10	38/19	40/23
Side(right/left)	21/25	31/26	34/29
BMI (kg/m^2)	23.8 ± 2.7	23.4 ± 2.6	24.0 ± 2.7
Fracture healing time(weeks)	24.7 ± 8.0	24.1 ± 8.1	24.8 ± 7.5
Follow-up(months)	55.5 ± 13.3	17.9 ± 2.9	48.0 ± 17.2
LEFS	77.1 ± 3.7	78.2 ± 3.1	77.4 ± 3.4
AO/OTA Classification(A/B/C)	18/20/8	28/26/3	39/20/4
open/closed fracture	15/31	13/44	10/53

Table 2
Intraclass correlation coefficient analysis of five parameters of fracture displacement after surgery

Intraobserver	**Post-op. CT**	**Post-op. CA**	**Post-op. ST**	**Post-op. SA**	**Post-op. AT**
	0.93	**0.96**	**0.93**	**0.93**	**0.88**
Interobserver	0.91	0.94	0.91	0.90	0.86

CT Coronal translation, CA Coronal angulation, ST Sagittal translation SA Sagittal angulation AT Axial translation.

Table 3
postoperative fracture displacement

AP view translation (mm)	**QSF**	**QSF-assisted UEF**	**IMN**
	1.0 ± 1.3	**0.6 ± 1.0**	**2.1 ± 1.9**
AP view angulation(°)	0.3 ± 0.7	1.4 ± 1.6	1.7 ± 1.4
lateral view translation (mm)	1.0 ± 1.7	0.6 ± 1.1	2.0 ± 2.0
Sagittal angulation(°)	0.1 ± 0.4	1.4 ± 1.6	2.0 ± 1.7
Axial translation (mm)	1.0 ± 1.4	0.8 ± 0.9	2.0 ± 1.5

Table 4

Healing time of three groups of different types of tibial shaft fractures

Classification	QSF		QSF-assisted UEF		IMN	
	N	Union time(wk) (95% CI)	N	Union time(wk) (95% CI)	N	Union time(wk) (95% CI)
A	18	25.5 ± 7.2 (21.1–27.2)	28	24.2 ± 9.7(20.4–28.0)	39	23.8 ± 5.7 (21.9–25.7)
B	20	24.4 ± 8.8 (21.5–30.7)	26	23.3 ± 6.3(20.7–25.8)	20	24.9 ± 9.7 (20.3–29.4)
C	8	24.0 ± 8.2 (16.6–28.3)	3	30.0 ± 4.5(18.6–41.3)	4	34.0 ± 6.0 (24.3–43.6)
closed	31	24.4 ± 7.6 (21.6–27.2)	44	23.2 ± 7.2(21.0-25.5)	53	24.0 ± 6.1 (22.3–25.6)
open	15	25.4 ± 8.9 (20.4–30.3)	13	26.9 ± 10.6(20.4–33.3)	10	29.2 ± 12.4 (20.3–38.0)
Total	46	24.7 ± 8.0 (22.3–27.1)	57	24.1 ± 8.1(21.9–26.2)	63	24.8 ± 7.5 (22.9–26.7)

Figures

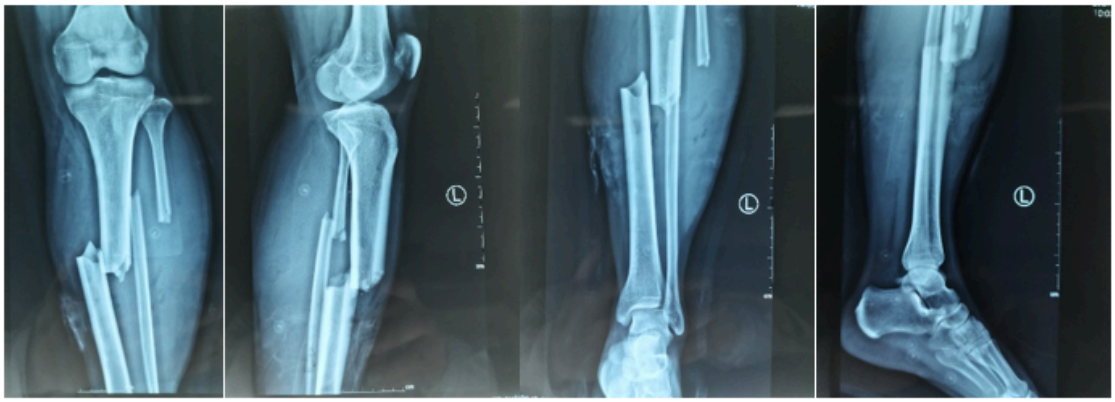


Figure 1A Figure 1B Figure 1C Figure 1D

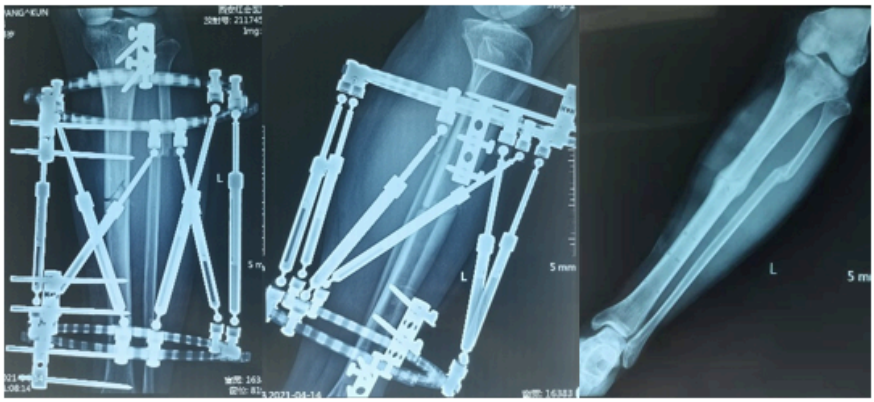


Figure 1E Figure 1F Figure 1G



Figure 1H Figure 1I Figure 1J

Figure 1

losed tibial and fibular diaphyseal fracture in a 33-year-old male. (A–D) Preoperative views. (E, F) Anatomical reduction achieved via digital QSF prescription. (G, H) Radiographic union and frame removal at 17 weeks postoperatively. (I, J) Functional results (standing and squatting) at 6 months.

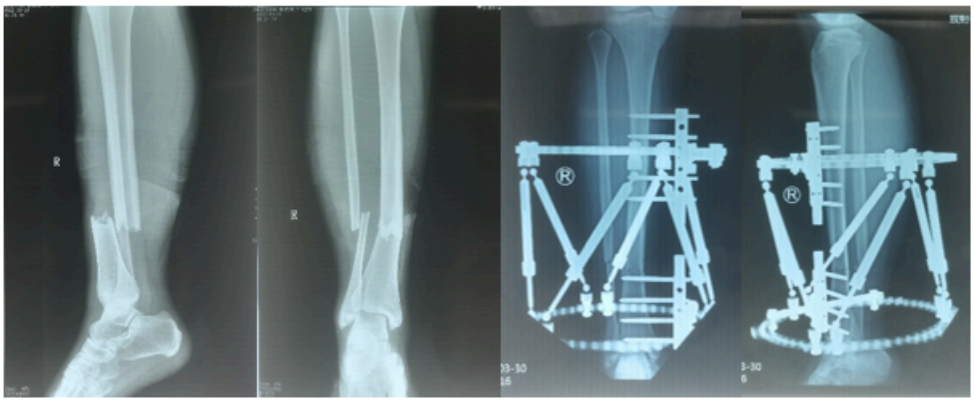


Figure 2A Figure 2B Figure 2C Figure 2D

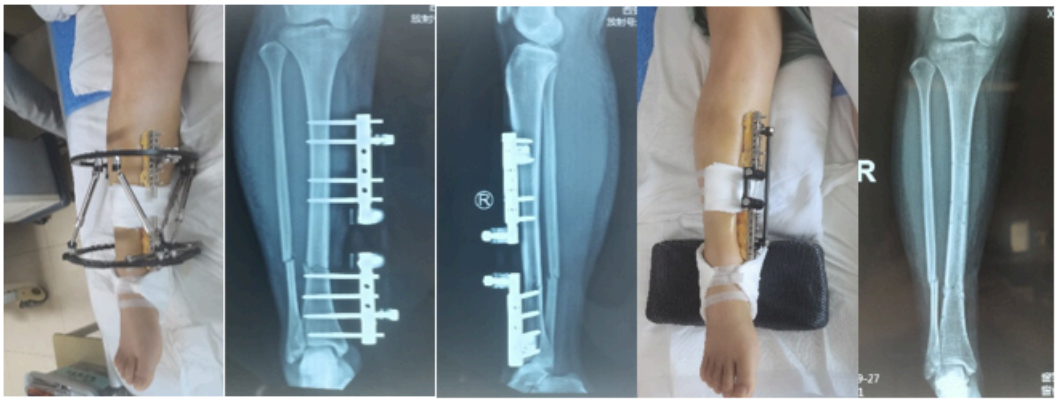


Figure 2E Figure 2F Figure 2G Figure 2H Figure 2I



Figure 2J Figure 2K Figure 2L

Figure 2

Open tibial and fibular diaphyseal fracture in a 29-year-old female. (A, B) Preoperative views. (C, D) Reduction using the QSF technique. (E) Clinical appearance post-reduction. (F, G) Conversion of QSF to UEF for stabilization. (H) Low-profile UEF construct. (I, J) Fracture union and fixator removal at 26 weeks. (K, L) Functional results at 8 months.