

# Comparison between External Locking Plate Fixation and Conventional External Fixation for Extraarticular Proximal Tibial Fractures: A Finite Element Analysis

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## Research article

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# Abstract

## Background

Good clinical outcomes for locking plates as an external fixator to treat tibial fractures have been reported. However, external locking plate fixation is still generally rarely performed. This study aimed to compare the stability of external locking plate fixator with that of conventional external fixator for extraarticular proximal tibial fractures, using finite element analysis.

## Methods

Three models were constructed: (1) external locking plating of proximal tibial fracture with lateral proximal tibial locking plate and 5-mm screws (ELP), (2) conventional external fixation of proximal tibial fracture with an 11-mm rod and 5-mm Schanz screws (EF-11), and (3) conventional external fixation of proximal tibial fracture with a 7-mm rod and 5-mm Schanz screws (EF-7). The stress distribution, displacement at the fracture gap, and stiffness of the three finite element models at 30-, 40-, 50-, and 60-mm plate-rod offset from the lateral surface of the lateral condyle of the tibia were determined.

## Results

The conventional external fixator showed higher stiffness than did the external locking plate fixator. In all models, the stiffness decreased as the distance of the plate-rod from the bone surface increased. The maximum stiffness was 121.06 N/mm in the EF-11 model with 30-mm tibia-rod offset. In the EF-7 model group, the maximum stiffness was 40.00 N/mm in the model with 30-mm tibia-rod offset. In the ELP model group, the maximum stiffness was 35.79 N/mm in the model with 30-mm tibia-plate offset.

## Conclusions

External locking plate fixation is more flexible than conventional external fixation, which can influence secondary bone healing. External locking plate fixation requires the placement of the plate as close as possible to the skin, which allow low-profile design, because the increased distance of the plate from bone can be too flexible for bone healing.

## Background

Proximal tibial fracture, which can be associated with severe soft tissue injuries, requires external fixation [1]. Joint bridging external fixator is usually applied for proximal tibial fractures because it is technically demanding to place a conventional external fixator without bridging the knee. However, most external fixators for the lower extremities are bulky and burdensome for the patients [2]. Thus, some clinicians have used locking plates as an external fixator to treat tibial fractures because of their advantages of low profiles and angular stability [3]. The locking plate has axial and angular stability due to the locking-head mechanism and thus forms a unique construction of the plate, screws, and bone [4]. Recent studies have reported good clinical results of using external locking plates for treating tibial fractures [5, 6, 7]. However,

external locking plate fixation is still not generally acknowledged. Further, only few biomechanical studies of external locking plate fixation have been conducted [8, 9, 10, 11]. Thus, this study aimed to compare the stability of external locking plate fixator with that of conventional external fixator for extraarticular proximal tibial fractures, using finite element analysis.

## Methods

### Three-dimensional modelling

Two-dimensional computed tomography (CT) images were obtained by scanning the composite tibia (Sawbones®, 4th Gen., Composite, 17 PCF Solid Foam Core, Medium) at the Department of Traumatology, Sestre milosrdnice University Hospital Center, Zagreb, Croatia. The slice thickness of the CT images was 0.6 mm in a 512 x 512 matrix. A three-dimensional (3D) model of the tibia was then reconstructed with the CT images using the 3D model reconstruction software Mimics (software version 17.0, Materialise, Leuven, Belgium). The Digital Imaging and Communications in Medicine data set, which consists of 681 CT images, was imported into Mimics to reconstruct the geometry of the tibia including the contours of the cortical and cancellous bone.

The 3D models of the lateral proximal tibial locking plate and screws were designed according to the manufacturer's specifications (Instrumentaria, Zagreb, Croatia) using a computer-aided design (CAD) software (SOLIDWORKS 2017, Dassault Systèmes, Massachusetts, USA). The moment of inertia of the lateral proximal tibial locking plate measured at the cross-sectional area between locking screw holes and combi screw holes was 120.28 mm<sup>4</sup>. The 3D models of conventional external fixators with Schanz pins, rods, and clamps were also designed using the CAD software. The moments of inertia of the 7-mm rod and the 11-mm rod were 117.86 mm<sup>4</sup> and 718.69 mm<sup>4</sup>, respectively. Three models were constructed using the CAD software: (1) external locking plating of proximal tibial fracture with lateral proximal tibial locking plate and 5-mm screws (ELP), (2) conventional external fixation of proximal tibial fracture with an 11-mm rod and 5-mm Schanz screws (EF-11), and (3) conventional external fixation of proximal tibial fracture with a 7-mm rod and 5-mm Schanz screws (EF-7). The ELP model was computed with 30-, 40-, 50-, and 60-mm plate offset from the lateral surface of the lateral condyle of the tibia. Meanwhile, the EF-11 and EF-7 models were computed with 30-, 40-, 50-, and 60-mm rod offset from the lateral surface of lateral condyle of the tibia. The geometry of the locking screws and Schanz screws were simplified to a cylinder (D = 5 mm) to conserve computing time.

### Finite element modelling

After alignment of the tibia and bone fixation systems in the CAD software, the entire solid models were imported into a commercial finite element software (Abaqus/CAE 6.14-5, Dassault Systèmes, Simulia Corp, Rhode Island, USA). In all models, a 10-mm fracture gap was created 60 mm beneath the tibia plateau, which represent multifragmentary extraarticular proximal tibia fracture (AO/OTA classification: 41A3.3) [12]. All models were fixed with three proximal screws and three distal screws from the fracture

gap. All materials were assumed to have linear elastic, homogeneous, and isotropic properties. The Young's modulus of TiAl6V4 was set to 110 GPa and the Poisson's ratio to 0.3 for material properties of the locking plate, locking screws, rods, clamps, and Schanz screws [13, 14]. For the material properties of the tibia, we set the Young's modulus to 17 GPa and 1.1 GPa for the cortical and cancellous bone [13, 15, 16]. Poisson's ratio for both bones was 0.3 [15, 16]. Tied constraints were applied between the locking screws and the bone, the locking screws and the locking plate, the Schanz pins and the bone, and the rod, and the clamps and the Schanz pins.

The finite element models were meshed with ten node quadratic tetrahedral elements. The total number of elements in the finite models ranged from 1,134,416 to 1,413,755, and the total number of nodes ranged from 1,703,188 to 2,111,440, depending on the model.

## **Boundary conditions**

The finite element model generated outer cortical and inner cancellous bones, indicating its validity; thus, material properties were assigned accordingly. In all models, the axial load of the 50 N was applied to the surface of the tibial plateau in direction from proximal to distal, which represent toe-touch weight bearing [17]. To prevent rigid body motion during the analysis, the tibial plafond was fixed in all degrees of freedom (Fig. 1). The stress distribution, displacement at the fracture gap, and stiffness of the three finite element models with 30-, 40-, 50-, and 60-mm plate-rod offset from the lateral surface of the lateral condyle of the tibia were obtained.

## **Mesh sensitivity analysis**

A convergence study was performed to establish the appropriate mesh refinement. Mesh convergence analysis was performed by using a model of intact cortical tibia. The finite element model was optimized and joined through convergence analysis by using the h-refinement method. Both mesh sensitivity analysis between displacement magnitude and number of elements (Fig. 2A) and mesh sensitivity analysis between von Mises stress values and number of elements (Fig. 2B) showed that convergence has been achieved.

## **Results**

### **Stress distribution**

In the ELP model, the maximum von Mises stress was 562.8 MPa, observed in the nearest screw to fracture gap on the proximal side of the fracture gap, in the model with 60-mm tibia-plate offset (Fig. 3A). In the EF-7 model group, the maximum von Mises stress was 270 MPa in the rod, observed around the nearest Schanz screw to fracture gap on the proximal side of the fracture gap, in the model with 60-mm tibia-rod offset (Fig. 3B). In the EF-11 model group, the maximum von Mises stress was 169,8 MPa, observed in the nearest Schanz screw to fracture gap on distal side of the fracture gap in the model with 60-mm tibia-rod offset (Fig. 3C). Table 1 shows the distribution of the maximum von Mises stress in all model groups.

Table 1  
Distribution of the maximum von Mises stress in the three model groups

Plate-rod offset (mm)	Maximum von Mises Stress (MPa)		
	ELP model	EF-7 model	EF-11 model
30	377.9	191.8	138.2
40	444.7	236.2	146.6
50	494.7	241	163.5
60	562.8	270	169.8

## Displacement

Displacement was measured at the medial border of the tibia at the proximal side to the fracture gap (Fig. 4). The maximum displacement was 3.281 mm in the ELP model with 60-mm tibia-plate offset. In the EF-7 model group, the maximum displacement was 2.523 mm in the model with 60-mm tibia-rod offset. In the EF-11 model group, the maximum displacement was 0.984 mm in the model with 60-mm tibia-rod offset. Table 2 shows the distribution of the displacement in all model groups. Figures 5, 6, and 7 show all model groups with distribution of the displacement.

Table 2  
Distribution of the displacement at the medial border of the tibia at the proximal site to the fracture gap in all model groups

Plate-rod offset (mm)	Displacement (mm)		
	ELP model	EF-7 model	EF-11 model
30	1.397	1.250	0.413
40	1.913	1.610	0.563
50	2.542	2.033	0.751
60	3.281	2.523	0.984

## Stiffness

The maximum stiffness was 121.06 N/mm in the EF-11 model with 30-mm tibia-rod offset. In the EF-7 model group, the maximum stiffness was 40.00 N/mm in the model with 30-mm tibia-rod offset. In the ELP model group, the maximum stiffness was 35.79 N/mm in the model with 30-mm tibia-plate offset. Table 3 shows the distribution of the stiffness in all model groups.

Table 3  
Distribution of the stiffness in the three model groups

Plate-rod offset (mm)	Stiffness (N/mm)		
	ELP model	EF-7 model	EF-11 model
30	35.79	40.00	121.06
40	26.14	31.05	88.81
50	19.67	24.59	66.58
60	15.24	19.82	50.81

## Discussion

Evidence on the biomechanical characteristics of external locking plate fixation are still inadequate to support its clinical recommendations as an external locking plate. Our study showed higher stiffness of the conventional external fixator than that of the external locking plate fixator. In all models, the stiffness decreased as the distance between the plate/rod and the bone surface increased. To our best knowledge, this is the first finite element analysis of comparison between external locking plate fixator and conventional external fixator for proximal tibial fractures.

Ideal osteosynthesis involves the optimal balance between biology and mechanics that promotes fracture healing. The concept of biological fracture fixation implies preserving soft tissue and periosteal blood supply and achieving relative stability that promotes callus formation [18]. Internal locking plate fixation can be too stiff to promote optimal fracture healing by callus formation or can cause inconsistent and asymmetric formation of the periosteal callus [19]. Bottlang et al. introduced a modified internal locked plating technology, termed far cortical locking, in 2010 [20]. In this technology, elastic fixation is achieved with cantilever bending of the far cortical locking screw shafts. The mechanism is similar to an external fixator that derives elasticity from fixation pin flexion. Compared with locked plating internal constructs, far cortical locking internal constructs form more callus by providing flexible fixation [20]. External fixators also provide flexible fixation, although too flexible fixation can bring instability and nonunion.

Kloen et al. first use the locking compression plate as an external fixator and named this technique “supercutaneous plating” [21]. External locking plate fixator is a low-profile external fixator with angular stable screw fixation, facilitating mobilization and providing more comfort and better aesthetics than does traditional bar-Schanz pin fixators. Zhang et al. evaluated the outcomes of one-stage external locking plate fixation in 116 tibial fractures [22]. The mean fracture healing time was 12, 20, 14, and 24 weeks for proximal, shaft, distal, and multi-segmental tibial fractures, respectively [22]. Luo et al. conducted a systematic review of 12 studies and reported that external locking plate fixation achieved satisfactory functional outcomes and union rate and low complication rate [3].

However, the few biomechanical studies that investigated the biomechanical aspects of external locking plate fixation were heterogeneous [8, 9, 10, 11]. Zhang et al. reported a finite element analysis of external locking plate fixation with contralateral femoral less invasive stabilization system (LISS) and different plate–bone distances (1, 10, 20, and 30 mm) in the distal tibial metaphyseal fracture [23]. They concluded that the construct with a 30 mm plate–bone distance might be beneficial to induce callus formation. Further, more profound increases in stiffness were observed in the 1-, 10-, and 20-mm groups, indicating the potential of load shielding [23]. Ma et al. conducted a finite element analysis to evaluate the biomechanical performance of external and internal locking plate fixation of the proximal tibial fractures with a LISS plate [24]. They showed that compared to the internal locking plate model, axial stiffness was reduced by 84% for the external locking plate model with a 6-cm offset and by 94% for the external locking plate model with a 10-cm offset [24]. In the clinical application of external fixation, the distance of the external fixator from the bone depends on the soft tissue swelling and the individual soft tissue thickness. In our study, increasing the distance of the plate or rod from the bone surface from 30 mm to 60 mm reduced uniformly the stiffness by more than 50% in all models. The stiffness of the ELP model with a 30-mm tibia plate offset was 57.42% higher than that of the ELP model with a 60-mm tibia plate offset. The stiffness of the EF-7 model with a 30-mm tibia plate offset was 50.45% higher than that of the EF-7 model with a 60-mm tibia plate offset. The stiffness of the EF-11 model with a 30-mm tibia plate offset was 58.03% higher than that of the EF-11 model with a 60-mm tibia plate offset.

In our study, the contact body between the locking screws and the bone; the locking screws and the locking plate; the Schanz pins and the bone; and the rod, clamps and the Schanz pins were set as tied constraints. With regard to tied constraints, the stiffness of the models was most affected by the moment of inertia of the plate or rod, which was  $120.28 \text{ mm}^4$  for the plate. The moment of inertia of the 7-mm rod and the 11-mm rod were  $117.86 \text{ mm}^4$  and  $718.69 \text{ mm}^4$ , respectively. The moment of inertia of the 11-mm rod was 83.26% higher than that of the plate. The stiffness of the EF-11 model with a 30-mm tibia–rod offset was 70.44% higher than that of the ELP model with a 30-mm tibia–plate offset. The stiffness of the EF-7 model with a 30-mm tibia–rod offset was 10.52% higher than that of the ELP model with a 30-mm tibia–plate offset. The ELP model was more flexible than the EF-11 model due to its lower moment of inertia. Further, the stiffness of the ELP model can be improved by increasing the thickness of the lateral proximal tibial locking plate, which in turn leads to an increase in the moment of inertia of the plate.

Few limitations of the present study have to be considered. One limitation is that contact interfaces were tied constraints between the different fixator components and bone. Karunratanakul et al. showed that contact settings between the different fixator components are highly predictive of the external fixator stiffness [25]. However, we compared the external locking plate fixator with the conventional external fixator under ideal contact settings because it is difficult to determine the real contact settings of the locking screw-plate and clamp-rod-Schanz screw without an experimental validation study. The second limitation is that two-dimensional CT images were obtained by scanning the composite tibia despite living bone. However, the use of a commercialize composite model (i.e. Sawbones) appears to be an

acceptable practice to validate finite element models [26]. The fourth-generation composite bones have average stiffnesses and strains that are in the range for natural bones [15]. The third limitation of this study is that finite element analysis cannot evaluate the dynamic stability of models, which is important for understanding the effect of the fixator on fracture healing. Manipulation of the mechanical environment is important to optimize and accelerate fracture healing. One concept is reverse dynamization that postulates that the fracture should initially be stabilized with flexible fixation to promote cartilaginous callus formation [27]. This should be followed by more rigid fixation after adequate fracture callus formation to accelerate healing and the remodeling process [27]. Further experimental fatigue tests with external locking plate fixator–composite tibia models and conventional external fixator–composite tibia models should be performed to determine the influence of locking screw–plate contact settings and clamp–rod–Schanz screw contact settings to the dynamic stability of each model.

## Conclusions

External locking plate fixation is more flexible than conventional external fixation, which can influence secondary bone healing. External locking plate fixation requires the placement of the plate as close as possible to the skin, which allow low-profile design, because the increased distance of the plate from bone can be too flexible for bone healing. Further biological analysis is necessary to evaluate the effect of external locking plate fixation on fracture healing.

## Abbreviations

3D: three-dimensional

CAD: computer-aided design

CT: Computed tomography

ELP: External locking plating of proximal tibial fracture with lateral proximal tibial locking plate and 5-mm screws

EF-11: Conventional external fixation of proximal tibial fracture with an 11-mm rod and 5-mm Schanz screws

EF-7: Conventional external fixation of proximal tibial fracture with a 7-mm rod and 5-mm Schanz screws

LISS: Less invasive stabilization system

## Declarations

## Ethics approval and consent to participate

Not applicable

## Consent for publication

Not applicable

## Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

## Competing interests

The authors declare that they have no competing interests.

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## Contributions

PA and JK are responsible for finite element analysis, DB and PA for data analysis, DB, DV and ZT for manuscript writing, and DB and SS for design of the study and surveillance of method and data quality. All authors have read and approved the manuscript for submission.

## Corresponding author

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## Figures

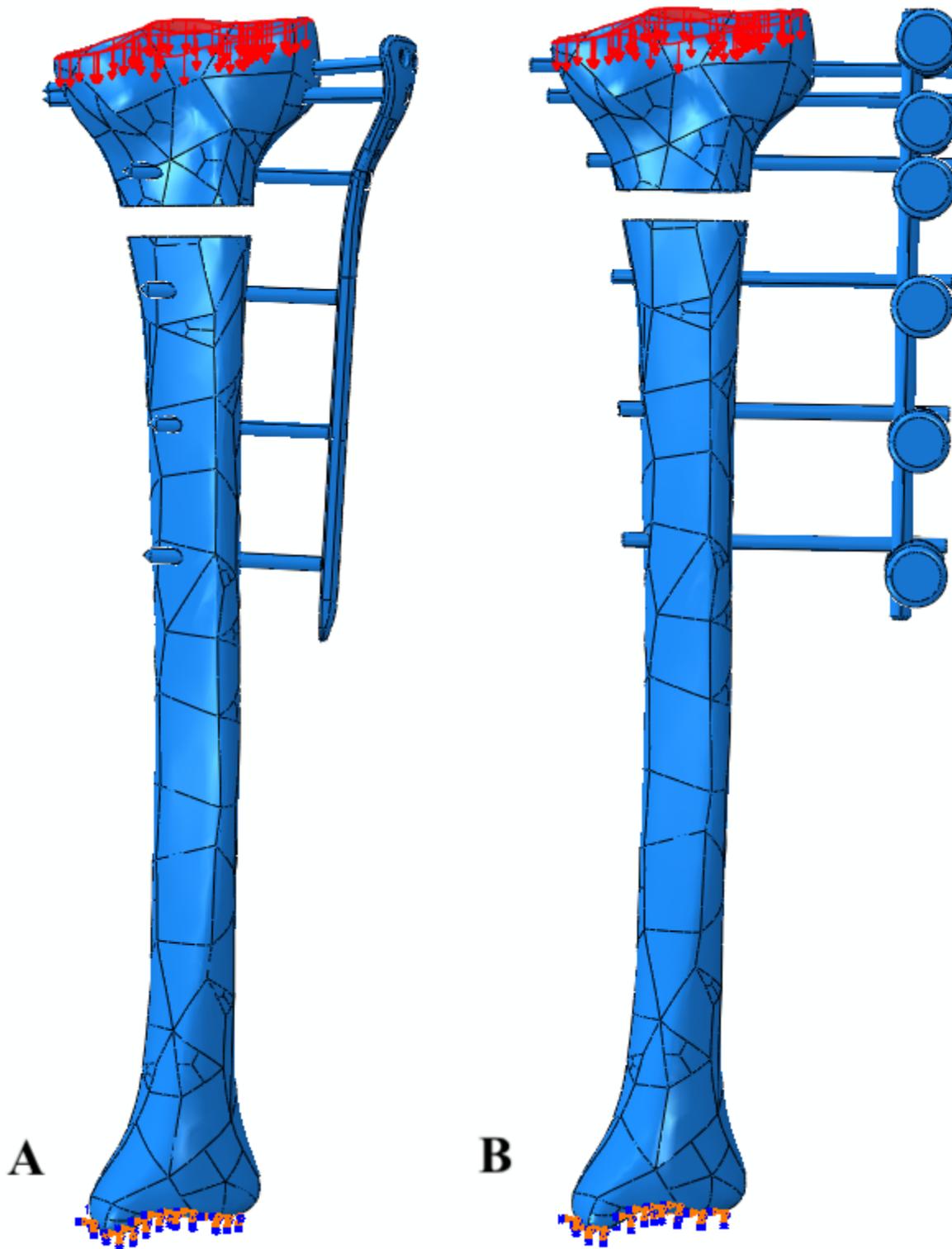
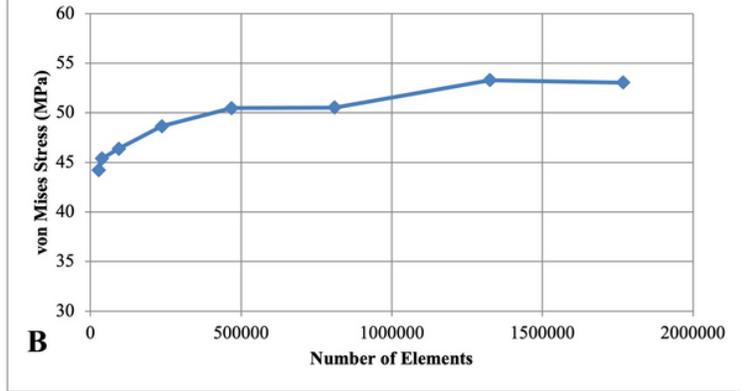
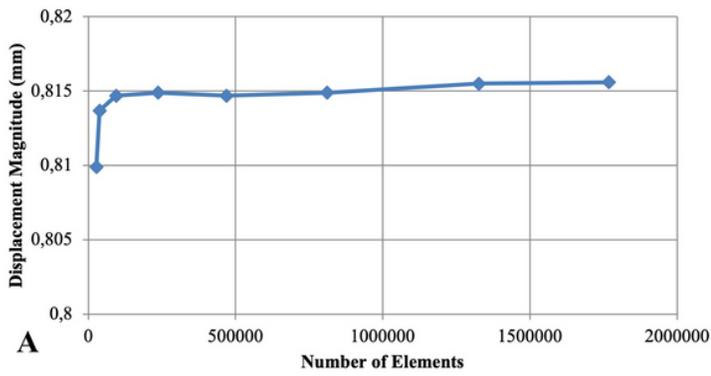


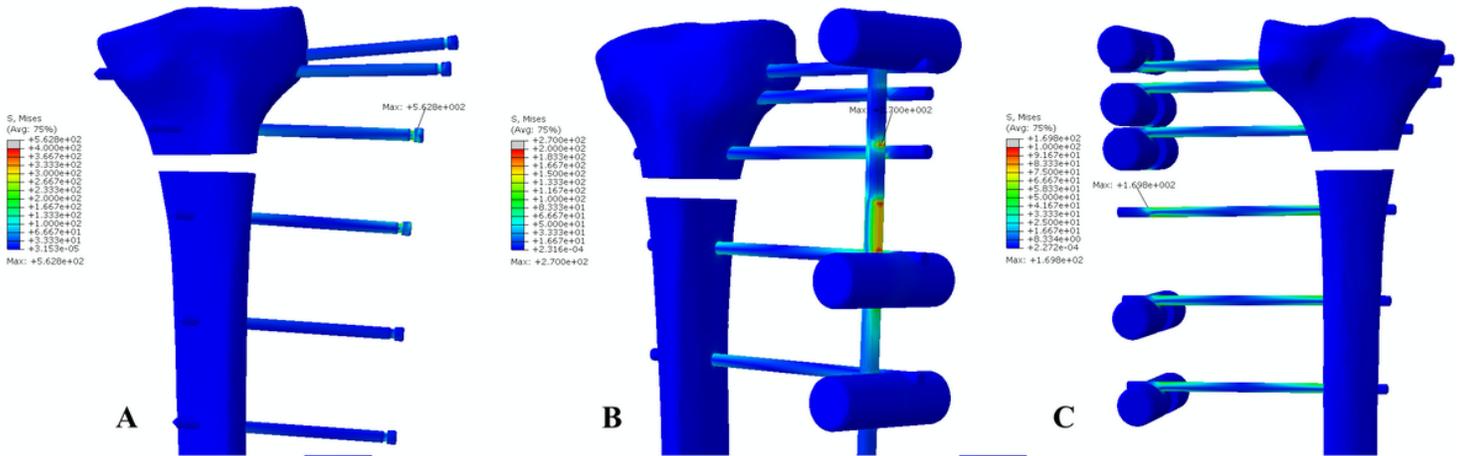
Figure 1

Boundary conditions: (A) external locking plate fixator, (B) conventional external fixator



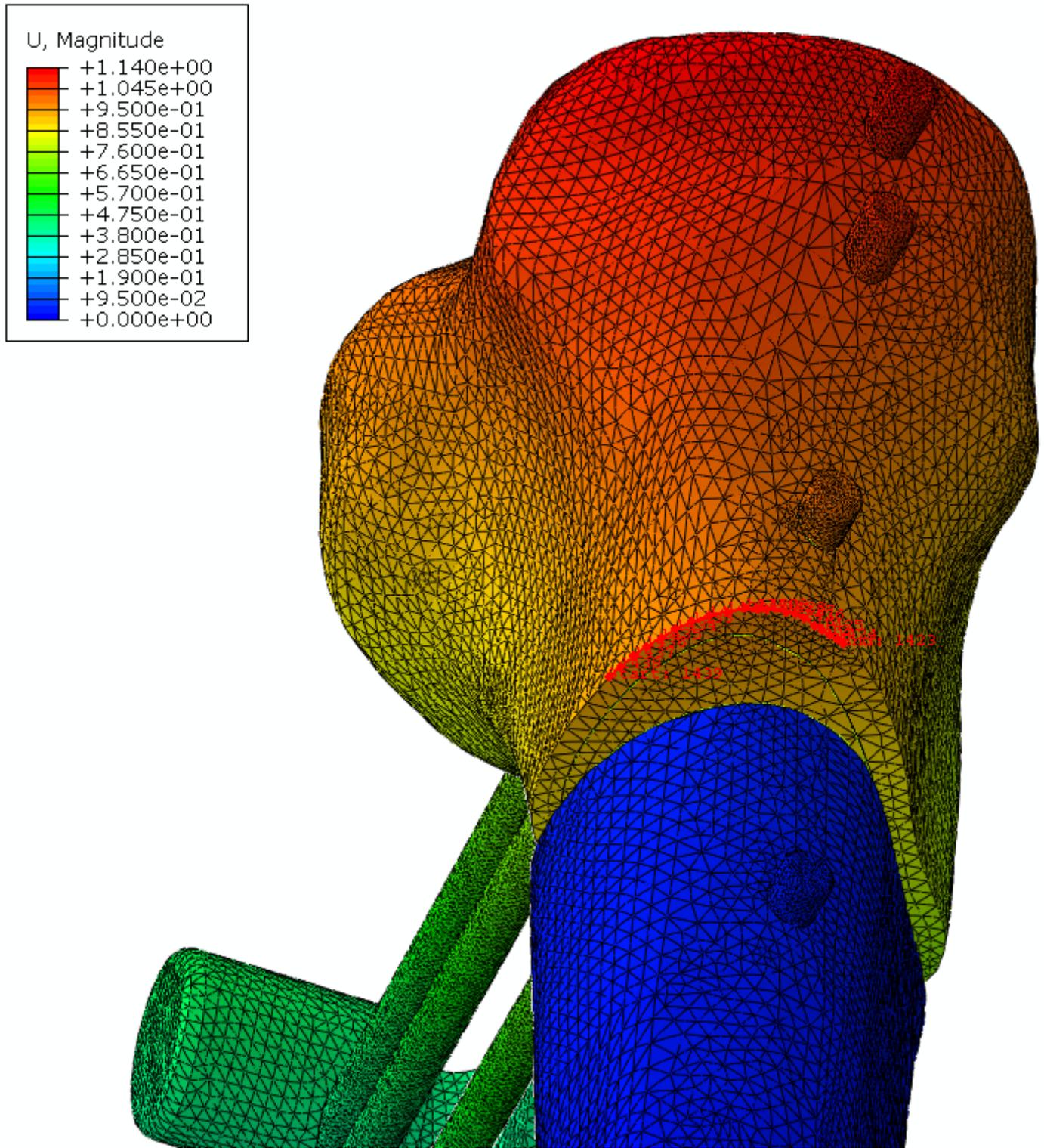
**Figure 2**

Mesh sensitivity analysis (A) between displacement magnitude and number of elements and (B) between Von Mises stress values and number of elements.



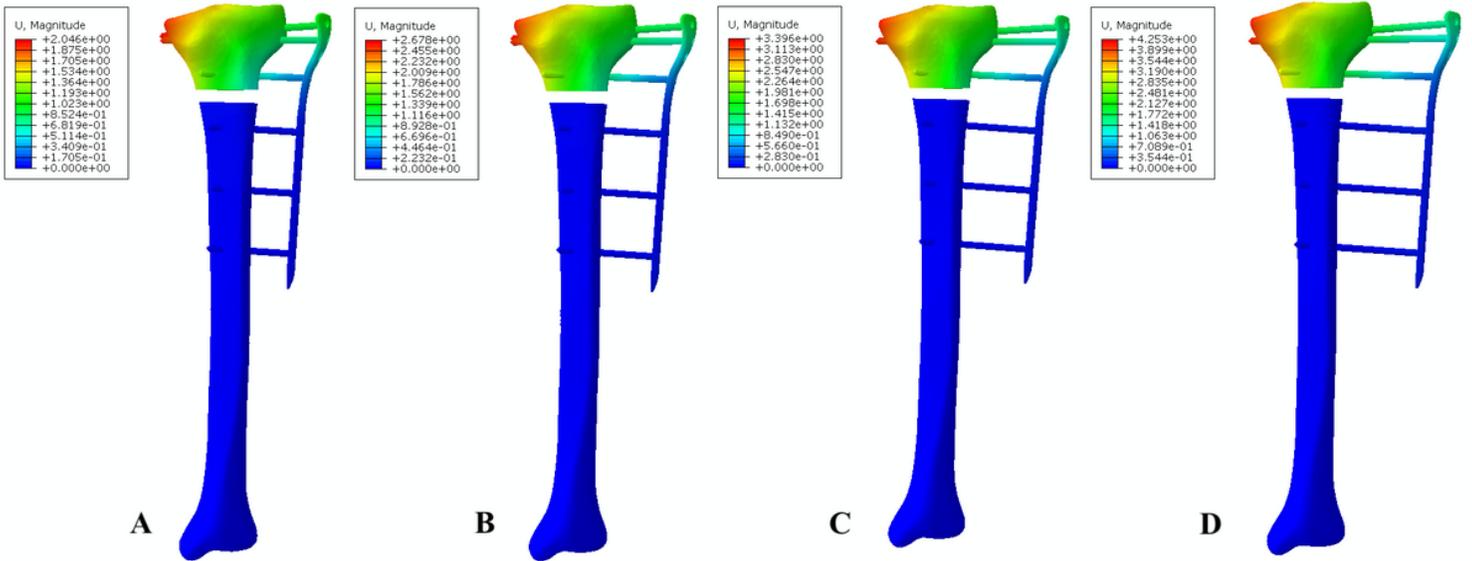
**Figure 3**

Maximum von Mises stress (A) in the ELP model with 60 mm tibia-plate offset, (B) the EF-7 model with 60 mm tibia-rod offset, and (C) the EF-11 model with 60 mm tibia-rod offset.



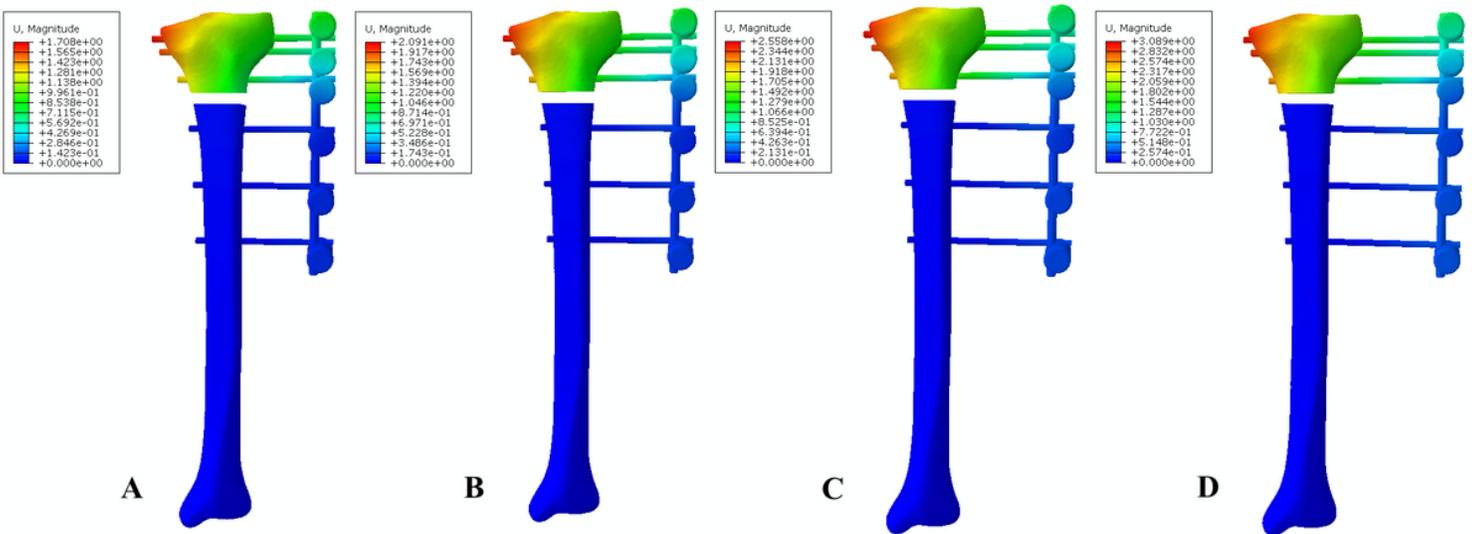
**Figure 4**

Medial border of the tibia at the proximal site to the fracture gap where the displacement was measured, indicated by the red area.



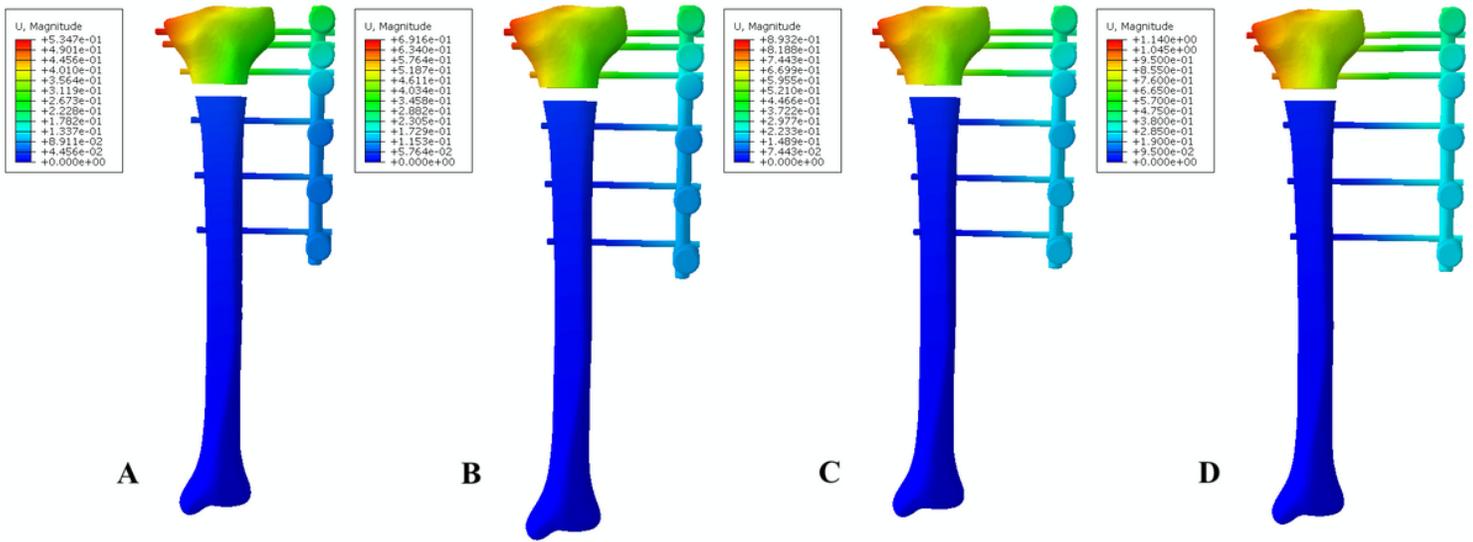
**Figure 5**

Distribution of displacement in the ELP model group. (A) 30-mm offset. (B) 40-mm offset. (C) 50-mm offset. (D) 60-mm offset.



**Figure 6**

Distribution of displacement in the EF-7 model group. (A) 30-mm offset. (B) 40-mm offset. (C) 50-mm offset. (D) 60-mm offset.



**Figure 7**

Distribution of displacement in the EF-11 model group. (A) 30-mm offset. (B) 40-mm offset. (C) 50-mm offset. (D) 60-mm offset.