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Preliminary exploration of finite element biomechanical preoperative planning for complex tibial plateau fractures

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The aim of this study was to compare the clinical outcomes, biomechanical performance, and cost-effectiveness of finite element planning (FEP) with those of traditional (Trad) methods in the treatment of complex tibial plateau fractures in middle-aged and elderly patients to ultimately optimize treatment protocols, improve surgical efficiency, and reduce the economic burden on patients. Sixteen patients with complex tibial plateau fractures were randomly divided into FEP and Trad groups, with eight patients in each group. The FEP group underwent preoperative finite element analysis for personalized surgical planning and dual-plate fixation; the Trad group participated in traditional preoperative discussions and underwent a multi-plate fixation. Perioperative and postoperative indicators were collected from both groups, and the stress distribution and displacement under different internal fixation modes were evaluated using finite element analysis. Additionally, a cost-effectiveness analysis was conducted to compare the total costs of internal fixation and hospitalization. The surgical times were significantly shorter in the FEP group than in the Trad group (170.00 ± 59.52 vs. 240.00 ± 59.04 min, $p = 0.033$), and patients in the Trad group had shorter times to ambulation (12.88 ± 0.99 vs. 14.25 ± 1.49 days, $p = 0.047$). There were no significant differences between the groups in terms of postoperative orthopaedic scores, mobility indices, fracture healing times, or radiological indicators. Biomechanical analysis revealed that the multiplate fixation mode provided a more uniform stress distribution, but this difference was not statistically significant. In the FEP group, the total costs of internal fixation (4772.25 ± 217.31 vs. 8991.88 ± 2811.25 yuan, $p = 0.004$) and hospitalization (34796.75 ± 9749.19 vs. 65405.14 ± 28684.80 yuan, $p = 0.013$) were significantly lower. While ensuring clinical effectiveness, FEP demonstrated greater cost-effectiveness by shortening the surgery time and reducing internal fixation costs. Although the multiplate fixation mode was biomechanically superior to the dual-plate mode, it did not result in significant clinical advantages and was more costly. FEP improves the economic efficiency of treatment for complex tibial plateau fractures in middle-aged and elderly patients and is recommended. This study has certain limitations, such as a small sample size and a short follow-up period. Thus, larger-scale studies with longer-term follow-up data are needed to further validate these findings and explore whether all patient populations can benefit from these practices or if the benefits are limited to specific groups, such as elderly patients or those with certain types of fractures.

Keywords Complex tibial plateau fractures, Planning of finite elements, Clinical efficacy, Cost-effectiveness, Finite element analysis

Abbreviations

FEP	Finite element planning
Trad	Traditional

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FEA	Finite element analysis
3D	Three-dimensional
Harris	Harris hip score
VAS	Visual analog scale for pain
CER	Cost-effectiveness ratio
ICER	Incremental cost-effectiveness ratio

Tibial plateau fractures are a type of intra-articular fracture primarily caused by high-energy trauma, such as traffic accidents and falls, and constitute 1.0% of all fractures[1]. These fractures often involve varying degrees of depression, displacement, and surgical complications, affecting the stability and mobility of the knee joint. Currently, tibial plateau fractures are classified using traditional systems, such as the Schatzker classification and the AO classification, as well as CT classifications, which are based on the three-dimensional geometric morphology of the fracture. Luo et al.[2] proposed three-column classification using multidimensional reconstructed images of the tibial plateau, which has since deepened our understanding of tibial plateau fractures. An epidemiological study of tibial plateau fractures revealed that single-column fractures are relatively rare, with an incidence of only 12.54%, whereas the incidence of posterolateral column fractures is 62.69%[3]. For efficient disease management, Schatzker types V and VI fractures, along with the double-column (medial + lateral/lateral + posterior/medial + posterior) and triple-column (medial + lateral + posterior) fractures, are categorized as complex comminuted tibial plateau fractures in clinical settings.

Complex tibial plateau fractures are severe injuries that, without timely treatment, can lead to lower limb varus/valgus deformities due to platform collapse, resulting in irreversible joint degeneration and osteoarthritis[4]. Treatment goals include anatomical reconstruction of the joint surface, restoration of coronal and sagittal alignment, and stable fixation, allowing for an adequate range of motion[5]. These unstable types of complex tibial plateau fractures are typically treated with flexible surgical fixation methods on the basis of the specific fracture type. However, the final treatment plan considers not only the patient's specific condition but also the costs of surgery and high-value consumables, which likewise affect the patient's decision. Some patients and their families, unable to afford expensive treatment, opt for conservative treatment instead of surgery, which clearly leads to poor outcomes. The rational combination of internal fixation devices such as steel plates and screws may result in the best fixation results[6,7].

Owing to increasingly scarce medical resources, the identification of optimal treatment methods that lead to satisfactory outcomes in the context of limited health care funds is a challenge that government agencies and all health care professionals must consider and address. To address this issue, scholars have proposed analyses to ascertain the cost-effectiveness, expenditure and health outcomes of various treatment methods[8–12]. Traditional cost-effectiveness evaluations typically focus on the relationship between costs and treatment effects, but with advancements in medical research, more comprehensive evaluation methods have become a focus of attention. To achieve the best treatment outcomes, this study compared the biomechanical performance and clinical applicability of dual-plate fixation with those of multiplate fixation. Previous experience indicated that dual-plate fixation is suitable for simple fractures, such as simple double-column fractures, whereas multiplate fixation is more suitable for complex comminuted fractures or multicolumn fractures. However, despite the better biomechanical performance of multiplate fixation in some cases, such a method is associated with higher material costs and longer surgical times, which impose a significant economic burden on patients and their families. Therefore, a reasonable choice of fixation method not only ensures treatment effectiveness but also significantly reduces medical expenses and optimizes resource usage. Most fixation evaluation projects rely on patient cooperation and the doctor's clinical experience, which introduces a certain degree of subjectivity. The impact of different internal fixation methods on the healing of complex tibial plateau fractures is still not fully understood. Using biomechanical research methods to test the rationality of internal fixation plans is an effective approach. Finite element analysis (FEA) can effectively evaluate multiple variables through finite element simulation, thus optimizing orthopaedic design, screening, prediction, and treatment. Moreover, FEA can be used for both prospective evaluation and retrospective validation; complication and failure prevention; and assessment of implants, procedures, and techniques in a time- and cost-efficient manner. This approach helps doctors better understand the advantages and disadvantages of each plan, providing a scientific basis for clinical decision-making.

Materials and methods

All methods in this study were conducted in accordance with relevant guidelines and regulations. All experimental protocols were approved by the Institutional Ethical Review Committee of Zhangjiagang Fifth People's Hospital (Reference Number: yx11202404008). Figure 1 illustrates the cost-effectiveness optimization process of surgical planning for complex tibial plateau fractures. This prospective cohort study incorporated simulation software for biomechanical analysis.

Clinical research

Inclusion and exclusion criteria

The inclusion criteria were as follows: (1) patients who were diagnosed with tibial plateau fractures on the basis of CT evidence of bicolumnar/tri-columnar fractures or Schatzker type IV, V, or VI fractures; (2) had previous fractures where the time from injury to the hospital was less than 2 weeks; (3) were aged 18 to 70 years; (4) had no significant skin lacerations, avulsions, wound infections, or open fractures; and had (5) no preexisting deformities or functional impairments of the knee joint prior to injury.

The exclusion criteria were as follows: (1) patients who had osteoporosis or pathological fractures; (2) severe underlying medical conditions (such as osteoporosis, diabetes, chronic kidney disease, etc.) or were unable to

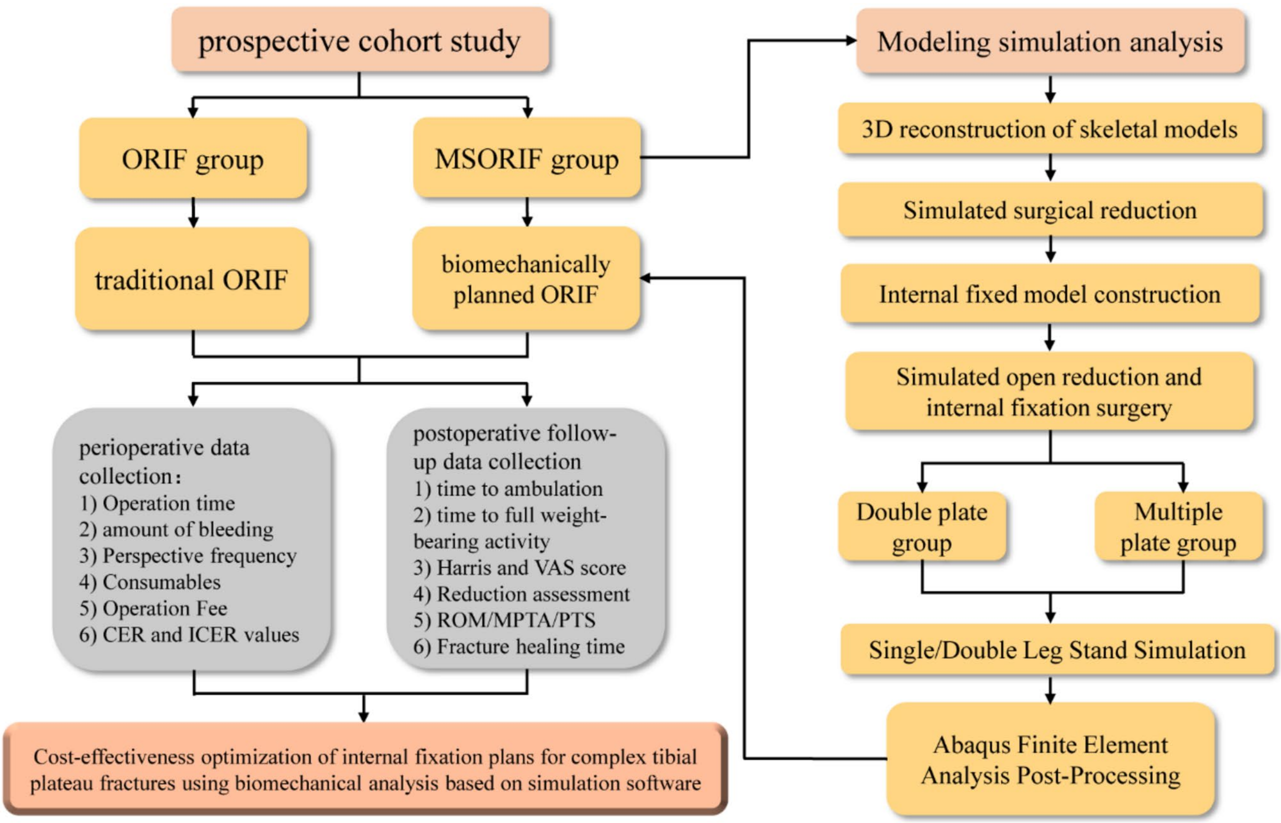

Fig. 1. Flow diagram outlining the study process.

tolerate surgery; (3) had severe lower limb vascular or nerve injuries; (4) refused follow-up visits or did not consent to participate in this clinical study; and (5) had incomplete follow-up data.

Patient baseline data

A prospective analysis of clinical data from 16 patients who were treated for tibial plateau fractures at our hospital from June 2022 to March 2024 and met the criteria mentioned above was conducted. According to the plan, 8 underwent preoperative finite element planning and dual-plate fixation, whereas the other 8 patients underwent multiplate fixation following traditional preoperative discussions. The general preoperative data for both groups are shown in Table 1. There were no statistically significant differences between the two groups in terms of age, sex, body mass index (BMI), mechanism of injury, injured limb, Schatzker classification, CT classification, or follow-up duration ($P > 0.05$).

Surgical methods

General anaesthesia was induced, and a tourniquet was applied at the root of the thigh of the affected limb. The surgical approach, either anterolateral or posteromedial, was chosen on the basis of the patient's fracture type. Those who underwent the anterolateral approach were positioned supine, whereas those who underwent the posteromedial approach were positioned prone. After routine sterilization of the surgical field, the skin was incised, and the layers were carefully dissected to protect the surrounding vessels and nerves and to fully expose the fracture site. Anatomical reduction of the fracture ends was performed on the basis of the actual condition of the fracture, which was temporarily fixed with Kirschner wires, and efforts were made to restore the smoothness of joint surface. If the joint surface was collapsed, lever reduction was performed, and after satisfactory alignment, bone grafting was performed in the void. The alignment of the joint surface and fracture reduction were confirmed using C-arm fluoroscopy, with attention given to restoring the mechanical axis of the lower limb. The preoperative plan was used to confirm and select the appropriate plate for fixation, with the screws being implanted at a safe distance from the joint surface to avoid damaging the articular cartilage. Postoperatively, C-arm fluoroscopy was performed again to confirm the reduction and proper placement of the plate and screws. If the meniscus and cruciate ligaments were damaged, they were repaired, and secondary treatment was provided if the cruciate ligaments were completely torn. A negative pressure drainage tube was placed after surgery, the incision was closed layer by layer, and the limb was immobilized and elevated with an elastic bandage or cast. The drainage tube was removed 24 to 48 h after surgery on the basis of the drainage condition.

Variable	FEP group	Trad group	p value
Cases	8	8	
Age (years)	47.00 ± 10.10	55.50 ± 10.37	0.119
Sex (female/male)	3/5	4/4	0.614
BMI (kg/m^2)	22.75 ± 1.34	21.96 ± 1.33	0.257
Mechanism of injury			0.302
Fall from height	6	4	
Motor vehicle collision	2	4	
Involved side (left/right)	5/3	6/2	0.590
Schatzker type			0.435
IV	1	0	
V	2	1	
VI	5	7	
CT classification			0.055
Bicondylar fractures	3	0	
Tricondylar fractures	5	8	
Follow-up time (month)	2.75 ± 0.71	3.13 ± 0.99	0.39

Table 1. Patient's demographics distribution and fracture characteristics. $p < 0.05$ was used as cut off for bold significance.

Postoperative management

Postoperatively, prophylactic antibiotics were administered for 48 h, and low–molecularweight heparin combined with pneumatic foot pumps was applied to prevent lowerlimb deep vein thrombosis and reduce swelling. On postoperative day 2, patients began isometric quadriceps exercises and active ankle dorsiflexion–plantarflexion; on day 3, continuous passive motion (CPM) of the knee was initiated. In cases with concomitant cruciateligament reconstruction, external immobilization was maintained for 4–6 weeks. From weeks 4 to 6, patients were allowed non–weightbearing ambulation with crutch assistance; beginning in week 6, under the guidance of a physical therapist, they transitioned to partial weightbearing—approximately 20% of body weight at week 6, increasing by 5% each week until reaching around 50% by week 12. Full weightbearing ambulation was permitted only after three months postoperatively (or once radiographs confirmed callus formation and satisfactory fracture healing). Followup radiographs were used to assess the medial proximal tibial angle (MPTA) and posterior tibial slope (PTS) to evaluate reduction quality and functional recovery.

Finite element modelling

Tibial plateau fracture model establishment and fracture reduction

A 64-slice CT scanner (GE Healthcare, USA) was used to scan the lower leg, including the knee joint, of eight patients with complex tibial plateau fractures in the FEP (finite element planning) group. The scanning parameters were as follows: slice thickness, 0.8 mm; and bone threshold Hounsfield units (HUs), ranging from 226 to 1794. The acquisition matrix was 512 × 512, with a pixel size of 0.625 mm × 0.625 mm and a field of view of 400 mm × 400 mm. The CT images were stored in DICOM format and imported into the reverse modelling software Mimics 19.0 (Materialise, Belgium). Appropriate grayscale values were selected to distinguish bone from surrounding soft tissue. Through threshold segmentation, erasing, region growing, and editing processes, each fracture fragment was precisely segmented and converted into a three-dimensional model. This model will be used for repositioning analysis and surgical planning. The 'Edit' tools, specifically 'Move' and 'Rotate', were used to precisely adjust the position of each segmented fracture fragment. By moving and rotating the 3D models of the fracture fragments, attempts were made to reposition them close to their normal anatomical positions. After repositioning, the comparison tools within the software were used to evaluate the appropriateness of the fragment positions, check the smoothness of the junctions, and ensure that there were no excessive overlaps or gaps. Adjustments could be made repeatedly until the desired repositioning effect was achieved. Once the repositioning process was completed, the adjusted 3D model could be exported as an STL file for subsequent biomechanical analysis. The bone STL file was then imported into Geomagic Wrap 2017 (Geomagic, USA) for smoothing, meshing, and surface fitting. The finalized skeletal solid model was saved as an IGS file.

Internal fixation model establishment and simulated surgery

The product manual of the tibial plateau anatomical steel plate was created by China Kangli Orthopaedic Device Co., Ltd. The basic shape of the steel plate was designed on an appropriate plane using the 'Sketch' feature of Pro/E 5.0 software (PTC, USA). The outline of the steel plate was drawn on the basis of the position and shape of the tibial fracture. The sketch was transformed into a three-dimensional steel plate model using the Extrude or other Solid functions. The thickness and edges of the steel plate were adjusted to fit the fracture area. The designed steel plate model was positioned in the fracture area to ensure that it fit as closely as possible to the surface of the fracture site. The curvature and angle of the steel plate were adjusted on the basis of its contact with the bone to ensure that it did not interfere with surrounding tissues or cause discomfort. All threads on the locking screws were simplified to cylindrical bodies with a diameter of 5.0 mm, and the length of the screws ranged from 13 to 70 mm. Holes for the fixing screws were designed on the steel plate. The position, size, and distribution of these holes should be determined according to surgical needs and biomechanical principles. The steel plate-screw model was assembled with the tibial model to check if the position of the steel plate and the holes matched expectations. Depending on different plans for the FEP group, both dual-plate fixation models and multiplate fixation modes were set. Boolean operations were performed on the same patient's fracture model and internal fixation device to remove overlapping areas of the fracture, a fracture-internal fixation model was constructed to simulate internal fixation surgery, and the assembly file was saved in Parasolid format (Fig. 2).

Mesh division and material properties

Using Hypermesh 2014 software (Altair, USA), the assembly file containing the fracture internal fixation device was loaded in Parasolid format. After the geometry was cleaned, the assembly model was meshed and discretized using tetrahedral elements. Standard four-node tetrahedral elements (T4) were used for mesh generation. The various parts of the model were exported and saved in INP format to obtain the mesh models of each component.

The components in the INP format were imported into Abaqus 6.14 software (Dassault Company, France), and the material properties were assigned. In this study, the bone and metal components used for internal fixation were simplified as isotropic linear elastic materials[13]. Considering that the segmentation of the fracture blocks in this study involved only cortical bone, the assignment of material properties to the bones was limited to cortical bone. The Young's modulus and Poisson's ratio of cortical bone are 17,000 MPa and 0.33, respectively[14,15]. The steel plate and screws were made of titanium alloy. The Young's modulus and Poisson's ratio of the implants are 110,000 MPa and 0.3, respectively[16].

Load and boundary condition settings

Figure 3 shows the load and constraint conditions of the two fixation modes, where distributed coupling constraints are used to apply the load in this experiment. Two reference points are set at the centre of the medial and lateral tibial plateaus and are coupled with the corresponding articular surfaces of the medial and lateral plateaus. Concentrated force loads of 600 N and 1800 N are applied vertically at the reference points while standing, with the lateral plateau bearing 40% and the medial plateau bearing 60%, to simulate the static forces on the knee joint when standing on both legs and on one leg, respectively[15,17,18]. To prevent tibial motion during analysis, the distal tibia is restricted in all directions[19]. Friction contact conditions are established, with a friction coefficient of 0.46 between the fracture ends, 0.42 between the bone and the implant, and 0.2 between the implants[20].

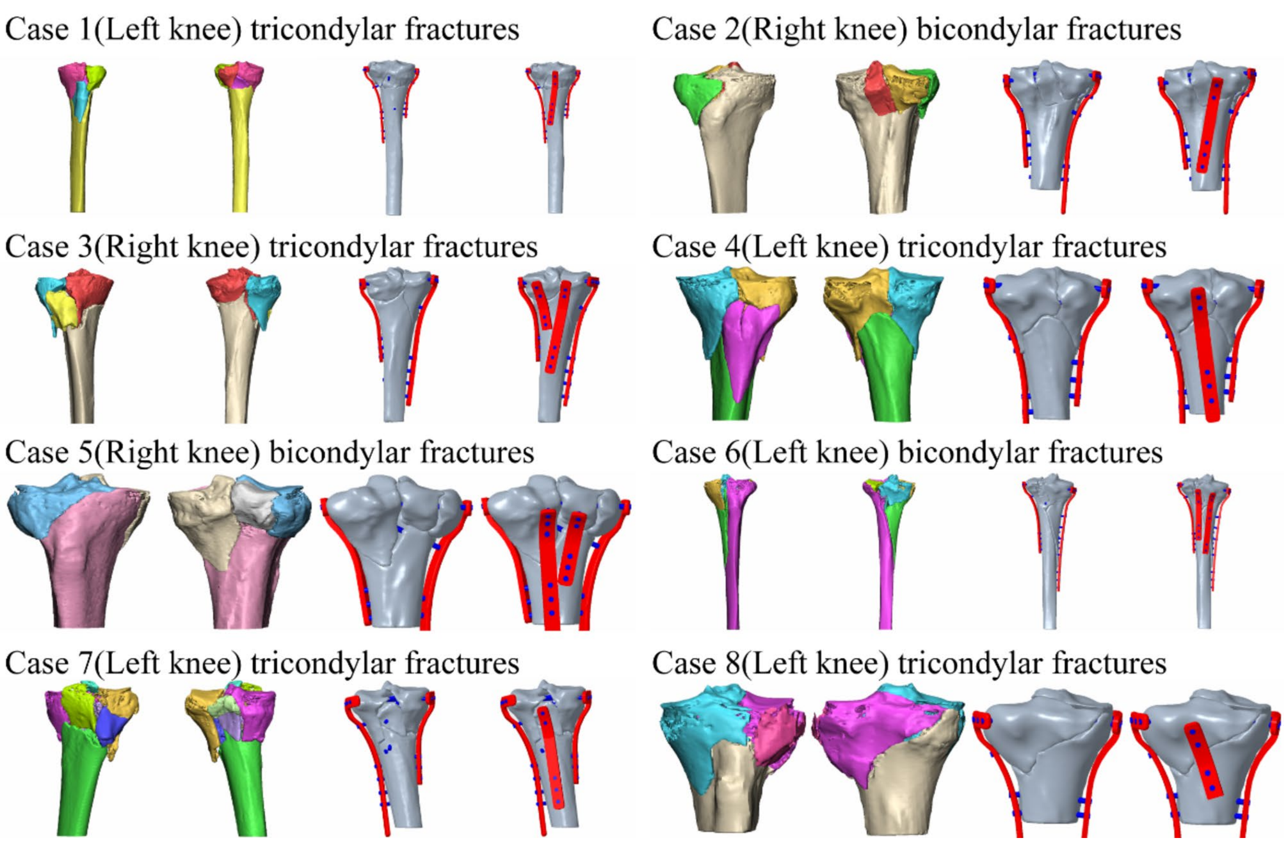

Fig. 2. The fracture configurations, dual-plate, and multi-plate fixation patterns of the finite element planning group's 8 patients.

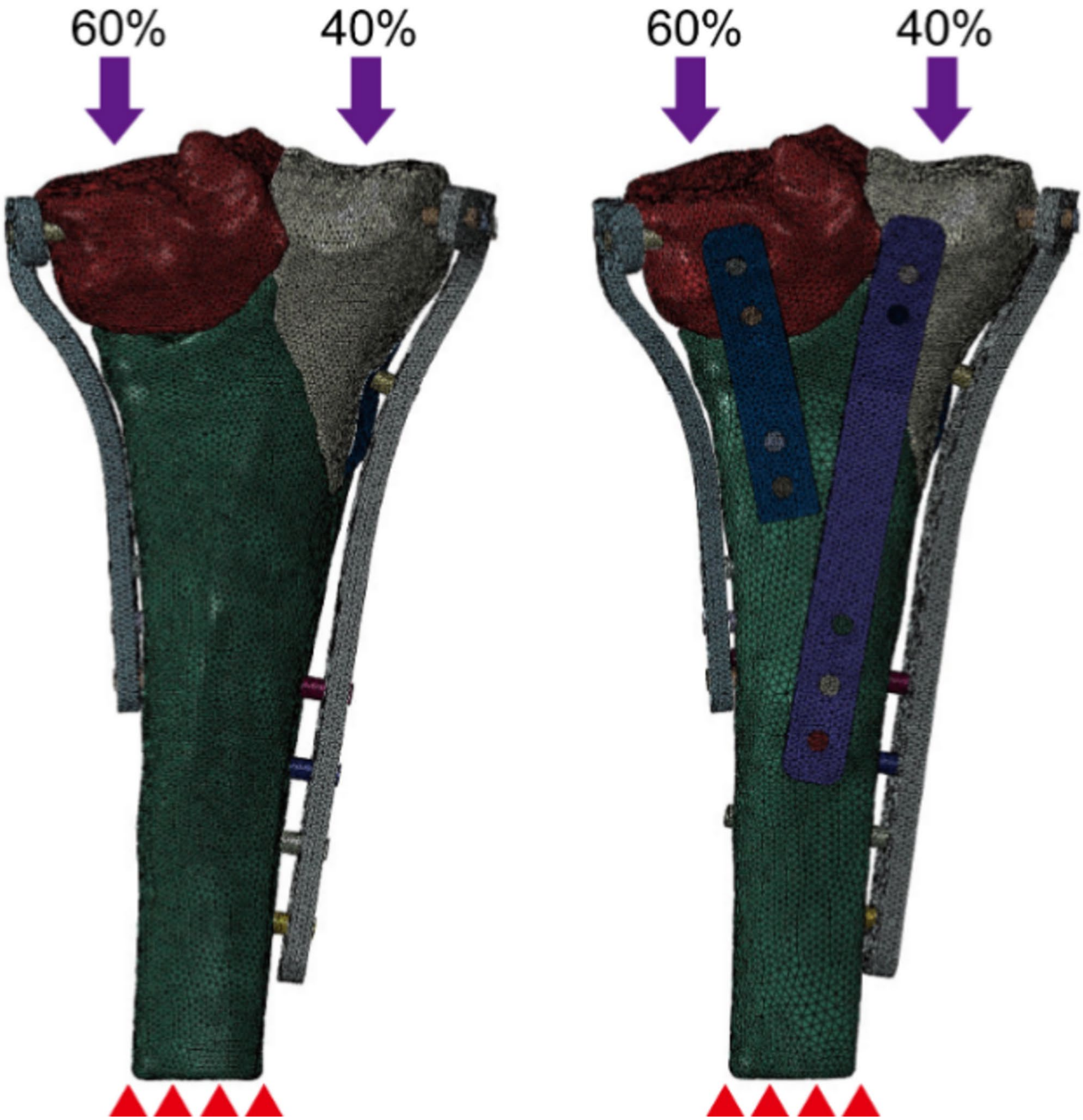

Fig. 3. Boundary conditions and load setting pattern diagram.

Grid sensitivity analysis
A mesh convergence study was conducted to establish the appropriate level of mesh refinement. A complete cortical tibia model was used for mesh convergence analysis. The h-refinement technique was employed, and the finite element model was optimized through convergence analysis. Mesh sensitivity analysis demonstrated the relationship between the von Mises stress and the number of elements (Fig. 4a), as well as the relationship between the displacement magnitude and the number of elements (Fig. 4b), both indicating good convergence of the model[21].

Finite element model validation
In the study by Lu et al.[22] on the novel tibial plateau plate design, the displacement of the bone-implant system under a 750 N load was observed to be 2.08 mm, which is similar to the results from this study, where the tibia-plate model had a maximum displacement value of 1.36 mm under similar loading conditions. The maximum von Mises stress observed in their study (143.26 MPa) is within a similar range to the stress value observed in this study's finite element analysis (147.83 MPa under similar loading conditions), indicating consistent stress patterns and confirming the reliability of the model.

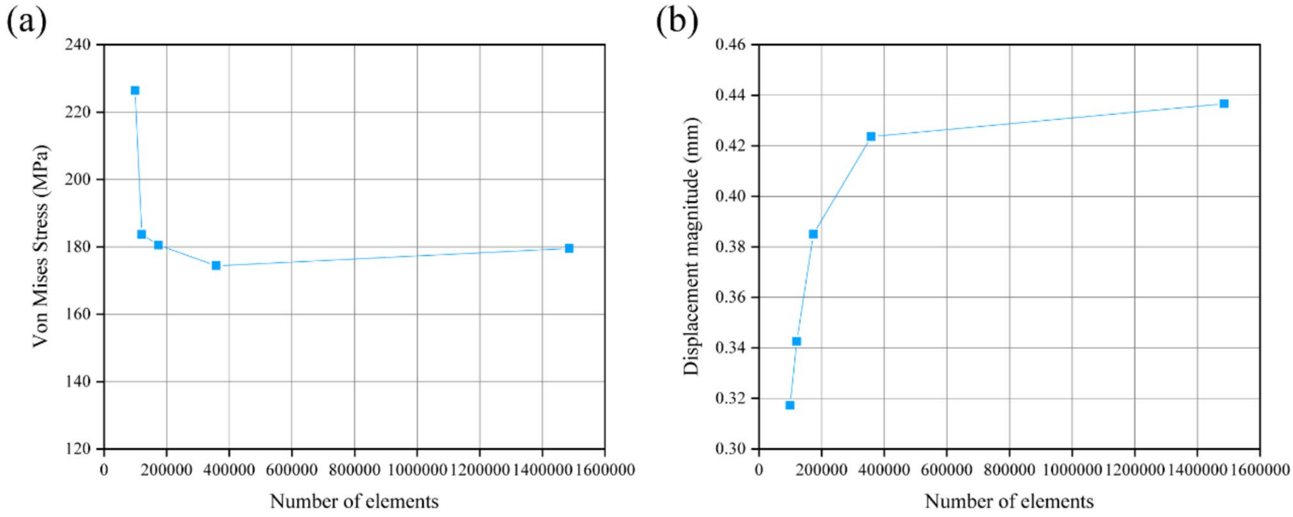

Fig. 4. Mesh sensitivity analysis (**a**) Compare Von Mises stress values and the number of elements and (**b**) Compare the magnitude of displacement and the number of elements.

Cost-effectiveness analysis

Treatment costs were determined by measuring variable direct costs (medical personnel, implants, medications, consultations, disposable supplies, imaging tests, blood tests, and hospital bed charges) and fixed direct costs (equipment and support staff). In this study, we omitted details of other expenses not directly related to internal fixation consumables; instead, we gathered data on the items of interest. We recorded the surgical costs, internal fixation device expenses, and total costs incurred during the hospital stay for different patients.

The cost-effectiveness ratio (CER) and incremental cost-effectiveness ratio (ICER) are theoretically used to analyse the differences between the costs of various treatment methods and the health outcomes obtained[8–10]. Cost-effectiveness analysis has become a valuable tool in the field of public health because it can help decision-makers determine the most effective ways to allocate resources for the prevention, diagnosis, and treatment of diseases. The formulas for calculating CER and ICER are as follows:

$$CER = \frac{Cost}{Indicators\ of\ interest} \tag{1}$$

$$ICER = \frac{Cost(multi\_plate) - Cost(dual\_plate)}{Indicators\ of\ interest(multi\_plate) - Indicators\ of\ interest(dual\_plate)} \tag{2}$$

In this study, the metrics of interest include MSB (Maximum Stress in Bone), MSIFD (Maximum Stress in Internal Fixation Device), and MDBIF (Maximum Displacement in Bone-Internal Fixation).

Statistical analysis

Continuous variables are expressed as the mean ± standard deviation (SD) and were evaluated using the Student's t test. Categorical variables were analysed using the chi-square test. For ordinal data, the Mann–Whitney U test was employed. All the statistical analyses were performed using SPSS 26.0 (SPSS Inc., Chicago, Illinois, USA). A p value < 0.05 indicated statistical significance.

Results

Clinical outcomes of the FEP and trad groups

A total of 16 elderly patients were included, with 8 in the FEP group and 8 in the Trad group. The follow-up period was 2 to 5 months (average 2.94 ± 0.85 months). The analysis results are as follows (see Tables 2 and 3; Fig. 5):

In terms of the perioperative indicators, there were no significant differences between the two groups in terms of intraoperative blood loss, incision length, transparency rate, or length of hospital stay ($p > 0.05$). However, the patients in the FEP group had shorter operation times (170.00 ± 59.52 vs. 240.00 ± 59.04, $p = 0.033$).

In terms of the postoperative follow-up indicators, there were no significant differences between the two groups in terms of the time to full weight-bearing activities after orthopaedic surgery, scores or functional indices at the last follow-up (including Harris score, VAS score, and knee extension-flexion ROM), radiological indices (including MPTA and PTS), or time to fracture healing ($p > 0.05$). Postoperative re-examinations of anteroposterior and lateral X-rays in both groups revealed blurred fracture lines and callus formation, indicating good fracture healing. The only difference was that patients in the Trad group resumed ground activities earlier than those in the FEP group did (12.88 ± 0.99 vs. 14.25 ± 1.49, $p = 0.047$).

Variable	FEP Group	Trad Group	*p* value
Operation time (min)	170.00 ± 59.52	240.00 ± 59.04	0.033
Intraoperative blood loss (ml)	168.75 ± 79.90	237.75 ± 168.27	0.313
Medial incision length (cm)	11.25 ± 4.40	14.00 ± 2.51	0.147
Lateral incision length (cm)	12.38 ± 5.24	12.13 ± 2.48	0.905
Fluoroscopy frequency (times)	6.75 ± 1.58	8.88 ± 2.64	0.071
Hospital Length of Stay (days)	14.38 ± 3.16	21.13 ± 12.10	0.149
Internal fixation cost (¥)	4772.25 ± 217.31	8991.88 ± 2811.25	0.004
Operation cost (¥)	2468.75 ± 353.26	3283.63 ± 1246.98	0.097
All-in cost (¥)	34796.75 ± 9749.19	65405.14 ± 28684.80	0.013

Table 2. Comparison of perioperative data and healthcare costs between the two patient groups. $p < 0.05$ was used as cut off for bold significance.

Variable	FEP Group	Trad Group	*p* value
Time to ambulation after orthopedic surgery (day)	14.25 ± 1.49	12.88 ± 0.99	0.047
Time to full weight-bearing activity after orthopedic surgery (week)	18.25 ± 1.39	18.38 ± 0.92	0.835
Harris score at last follow-up	90.50 ± 2.07	91.50 ± 2.33	0.380
VAS score at last follow-up	1.00 ± 0.76	0.88 ± 0.84	0.758
Knee extension-flexion ROM at last follow-up (°)	102.00 ± 10.64	104.13 ± 11.74	0.710
Quality of fracture reduction			1.000
Excellent	7	7	
Good	1	1	
Poor	0	0	
Postoperative MPTA (°)	87.63 ± 1.06	87.75 ± 1.04	0.815
Postoperative PTS (°)	9.88 ± 0.84	10.13 ± 1.36	0.664
Fracture healing time (week)			0.590
<12	3	2	
12–14	5	6	
>14	0	0	

Table 3. Surgery and postoperative follow-up information of patients. Assessing the reduction quality of articular surface fractures: excellent for anatomical reduction, good for displacement<2 mm, poor for displacement ≥ 2 mm. MPTA: medial proxi-mal tibial angle, PTS: posteriortibial slope. $p < 0.05$ was used as cut off for bold significance.

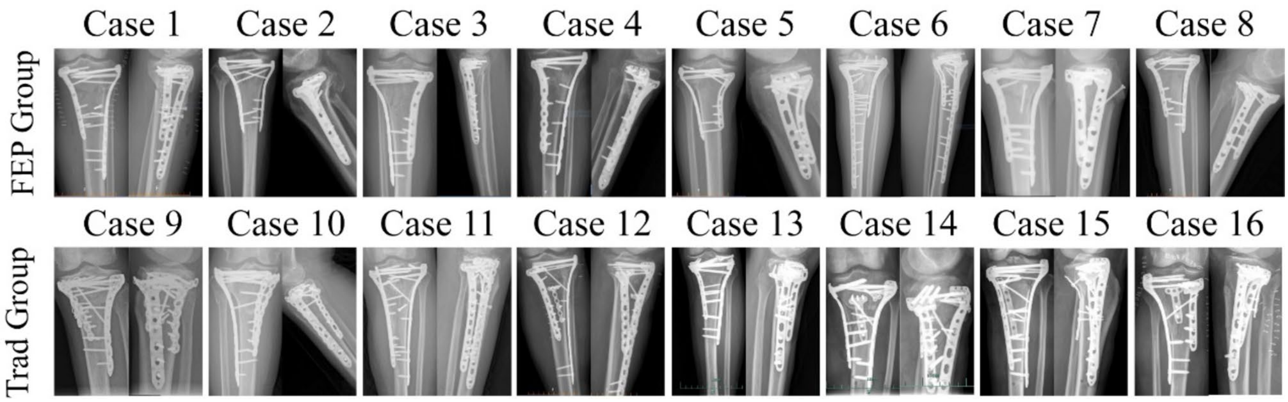

Fig. 5. At the final follow-up X-rays in both groups, imaging showed bony union in all fracture patients, with satisfactory positioning of the internal fixation devices. FEP: Finite element planning, Trad: traditional.

Comparison of the stress distributions and maximum stresses in the double plate and multiple plate fixation modes in the finite element planning group

The stress testing results for the two internal fixation modes are shown in Fig. 6. Stress contour maps were used to assess the bone and internal fixation models of 8 patients with tibial plateau fractures under two different internal fixation modes. These models are divided into four categories: dual-plate fixation mode with bilateral foot stress (600 N) and single-foot stress (1800 N) and multiplate fixation mode with bilateral foot stress (600 N) and single-foot stress (1800 N). The stress contour maps reveal the following results: (1) Impact of fixation mode: The dual-plate fixation mode generally results in greater stress concentrations, especially under single-foot stress conditions. In contrast, the multiplate fixation mode appears to offer a more uniform stress distribution, reducing the risk of stress concentration. (2) Impact of loading conditions: Under the same fixation mode, stress levels under single-foot stress conditions are significantly greater than those under bilateral foot stress conditions. (3) Stress hotspots: The images display potential stress concentration points, particularly near the articular surface and where the fixation meets the bone.

Furthermore, by comparing the differences in maximum stress across different models, it can be seen that under bilateral standing (600 N) conditions, the average maximum stress of bone and internal fixation in the dual-plate mode exceeds that of the multiplate mode by 32.2% and 25.9%, respectively. Under single-foot standing (1800 N) conditions, the average maximum stress of bone and internal fixation in dual-plate mode exceeds that in multiplate mode by 6.3% and 1.7%, respectively (Fig. 8a).

Comparison of the stress distributions and maximum stresses of the double plate and multiple plate fixation modes in the finite element planning group

The displacement test results for the two internal fixation modes are shown in Fig. 7. The arrangement of the displacement contour maps is similar to the aforementioned stress distributions. The displacement contour maps reveal the following results: (1) Impact of the fixation mode: The dual-plate fixation mode fails to effectively limit the displacement at the fracture site in some cases, especially under high loads. This could increase the risk of fracture redisplacement and affect the quality of fracture healing. (2) Impact of the loading conditions: Displacement levels under single-foot stress conditions are significantly greater than those under bilateral foot stress conditions are, indicating that unilateral weight-bearing in daily activities might lead to greater risks of fixation fatigue and failure. (3) Individual differences in bone models: The displacement contour maps indicate significant differences in displacement distribution among cases, which may be due to factors such as the type of fracture, location, and severity, as well as the patient's age, sex, and weight. These factors can influence the biomechanical properties of bones and thus affect the performance of fixation.

Furthermore, by comparing the differences in maximum displacement between the models, it can be noted that under bilateral standing (600 N) conditions, the average maximum displacement of the bone-internal fixation model in dual-plate mode exceeds that in multiplate mode by 10.0%. Under single-foot standing (1800 N) conditions, the average maximum displacement of the bone-internal fixation model in dual-plate mode exceeded that in multiplate mode by 14.1% (Fig. 8b).

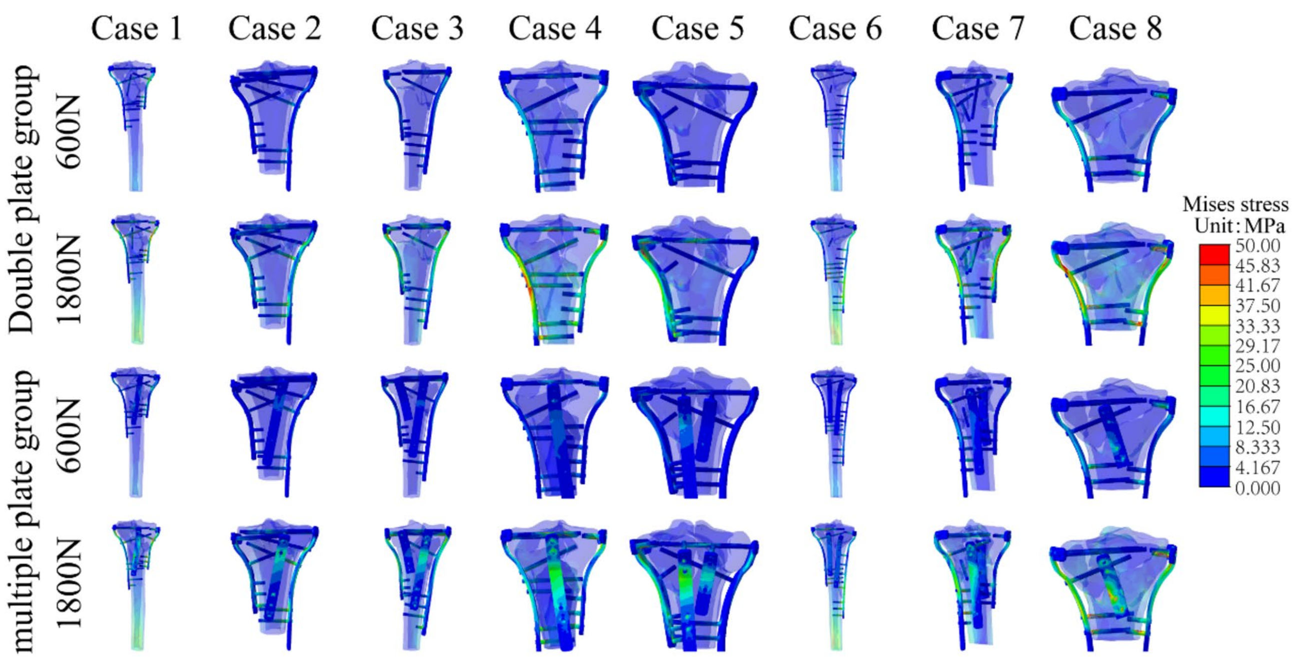

Fig. 6. The stress distribution maps of bone and internal fixation devices under single/double leg standing simulations preoperatively for 8 patients in the finite element planning group, depicting dual-plate and multi-plate fixation patterns. High stress is indicated in red and low stress in blue.

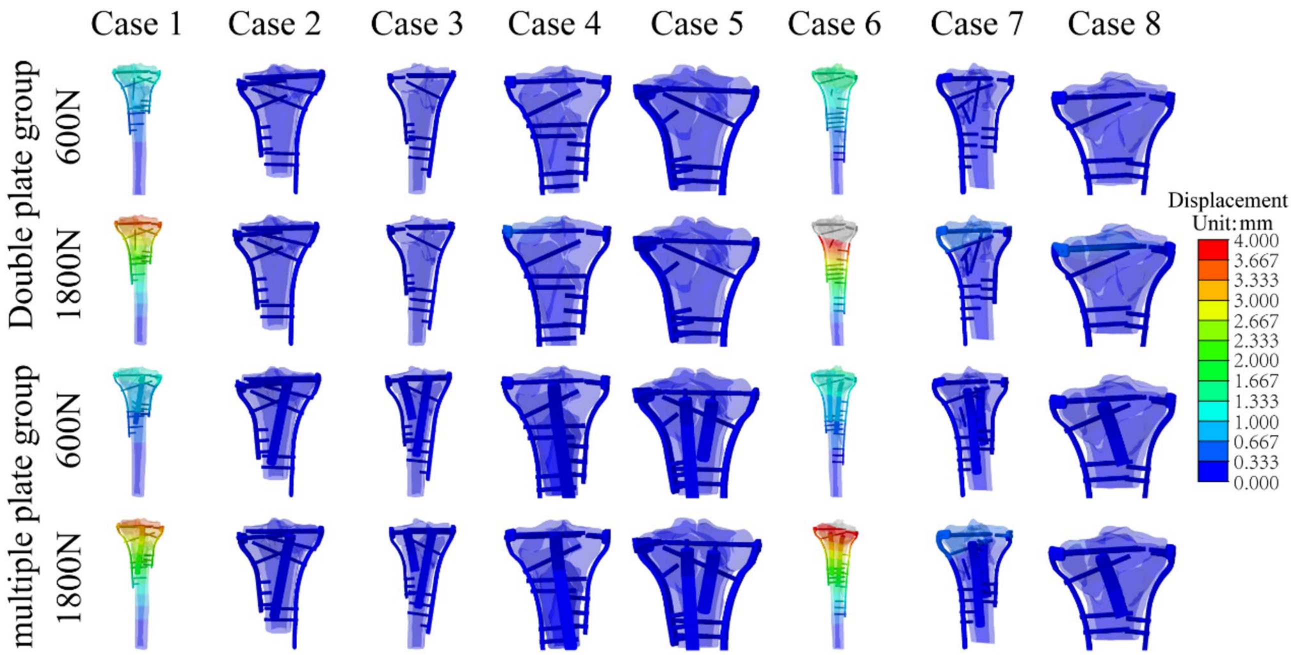

Fig. 7. The displacement distribution maps of bone and internal fixation devices under single/double leg standing simulations preoperatively for 8 patients in the finite element planning group, depicting dual-plate and multi-plate fixation patterns. High displacement is indicated in red and low displacement in blue.

Cost-effectiveness analysis

We compared the costs incurred during hospitalization between the FEP group and the Trad group. We found that there was no significant difference in surgical costs ($p > 0.05$). However, statistically significant differences were observed in the costs of internal fixation (4772.25 ± 217.31 vs. 8991.88 ± 2811.25, $p = 0.004$) and total hospitalization costs (34796.75 ± 9749.19 vs. 65405.14 ± 28684.80, $p = 0.013$), with the Trad group incurring higher expenses than the FEP group did (Table 2).

When we compared the costs of internal fixation between the dual plate and multiplate fixation modes within the FEP group, we still observed results similar to those where the FEP group's consumable costs were higher than those of the traditional group. Figure 8c shows that the costs for the multiplate group, which adopted the same fixation strategy as the traditional group, were 61.9% higher than those of the dual plate group, and this difference was statistically significant.

Cost per minimum (MPa) stress reduction: The cost required to reduce the stress in a structure by one metric, which is used to evaluate the economic benefits of different design solutions in stress reduction. Cost per millimetre displacement reduction: The cost required to reduce the displacement of a structure by one millimetre, which is used to assess the economic efficiency of various techniques in improving structural stability. We also compared the cost-effectiveness metrics of the two fixation modes within the FEP group. The calculations revealed that, under both double-foot standing and single-foot standing conditions, the cost per minimum (MPa) stress reduction for the multiplate mode compared with the double-plate mode was 635.82 yuan and 294.58 yuan, respectively. Focusing solely on internal fixation, the cost per MPa stress reduction was 1209.31 yuan and 1948.54 yuan, respectively. In the complete assembly model, the costs per millimetre displacement reduction were 84,392.50 yuan and 26,372.66 yuan, respectively (Table 4).

Discussion

The aim of this study was to compare the clinical outcomes, biomechanics, and cost-effectiveness between the finite element planning (FEP) and traditional (Trad) procedures in the treatment of complex tibial plateau fractures in middle-aged and elderly patients. The results indicate that the FEP group had a shorter surgical duration, whereas patients in the traditional group were able to mobilize earlier. However, no statistically significant differences in the primary follow-up indicators were observed between the two groups. Although the multiplate fixation mode in the FEP group resulted in more uniform stress distribution and reduced the risk of stress concentration in the biomechanical analysis, this mechanical advantage did not translate into statistical significance. However, the cost-effectiveness analysis revealed that the FEP group had significantly lower internal fixation and total hospitalization costs, suggesting that this method is more cost-effective and less of a burden on patients.

Surgical efficiency and postoperative recovery

The surgical time in the FEP group was significantly shorter than that in the control group, which was attributed to the advantage of preoperative individualized surgical planning through finite element analysis. This method

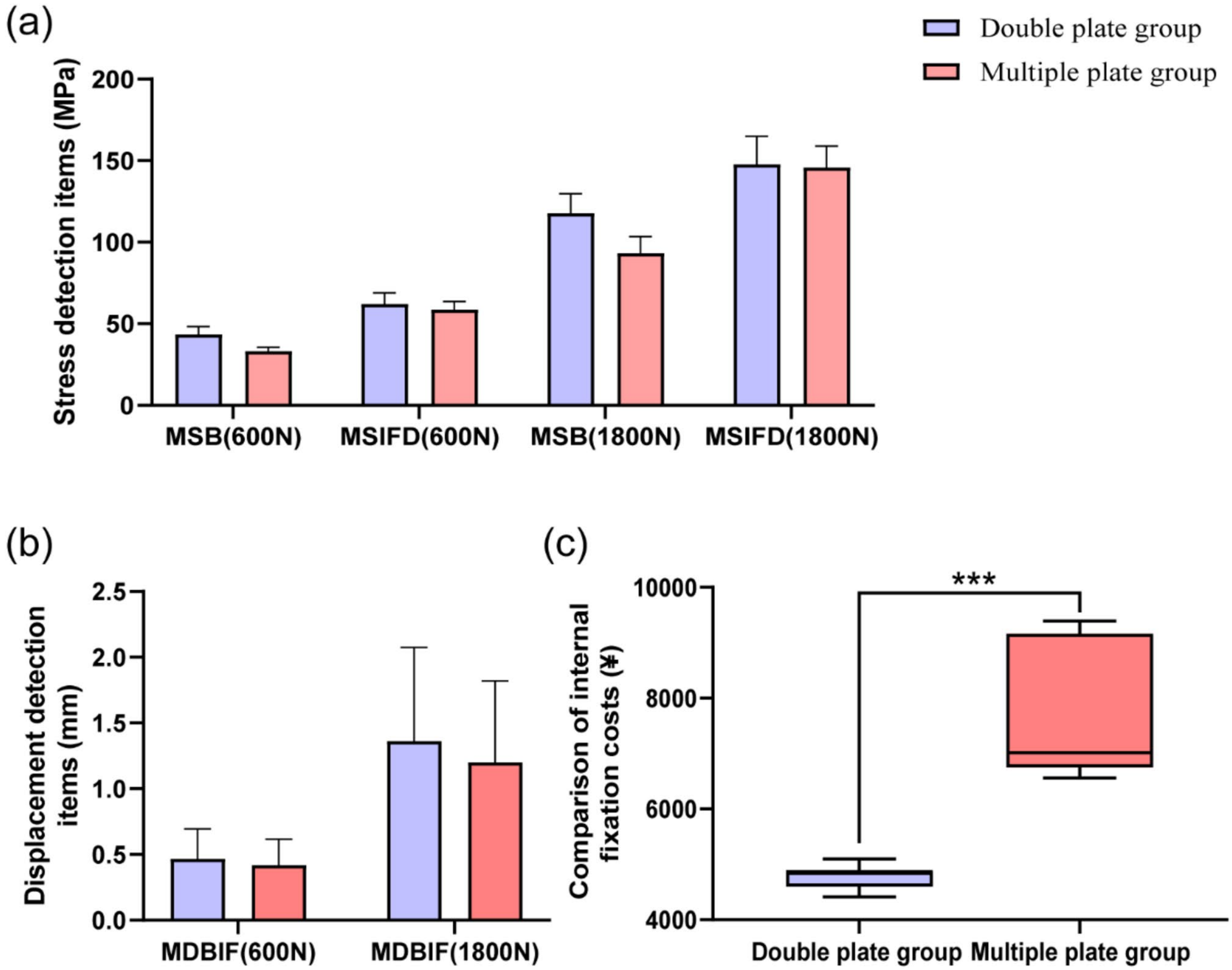

Fig. 8. Comparison of double plate group and multiple plate group in terms of stress, displacement, and economic indicators. MSB: maximum stress in bone, MSIFD: maximum stress in internal fixation device, MDBIF: maximum displacement in bone-internal fixation.

Index	Internal fixation scheme	CER	ICER
MSB (600)	Double plate	119.80 ± 35.72	635.82 ± 470.34
	Multiple plate	282.05 ± 88.60	
MSB (1800)	Double plate	43.85 ± 12.50	294.58 ± 317.64
	Dultiple plate	99.74 ± 25.48	
MSIFD (600)	Double plate	82.88 ± 22.56	1209.31 ± 1279.57
	Multiple plate	158.17 ± 47.98	
MSIFD (1800)	Double plate	34.92 ± 8.97	1948.54 ± 2268.72
	Dultiple plate	63.27 ± 17.46	
MDBIF (600)	Double plate	32360.36 ± 22491.86	84392.50 ± 53808.01
	Multiple plate	59521.80 ± 34877.29	
MDBIF (1800)	Double plate	16686.70 ± 14485.08	26372.66 ± 16815.00
	Dultiple plate	31149.20 ± 23341.06	

Table 4. Comparison of the cost-effectiveness of the two fixed models. CER: cost-effective-ness ratio, ICER: incrementalcost-effectiveness ratio, MSB: Maximum Stress in Bone, MSIFD: Maximum Stress in Internal Fixation Device, MDBIF: Maximum Displacement in Bone-Internal Fixation.

allows surgeons to gain a comprehensive understanding of the fracture morphology and preselect appropriate implants, thus improving surgical efficiency[23]. A shorter surgery time reduces the patient's exposure to anaesthesia, lowering anaesthesia-related risks such as postoperative cognitive dysfunction and complications, which is especially important for elderly patients. Additionally, it reduces the risk of infection during the procedure. Shortening surgery time improves operating room turnover and optimizes medical resource utilization, allowing hospitals to handle more cases and improving overall service efficiency. For surgeons, a shorter surgery time reduces the risk of surgeon fatigue, thereby maintaining operational precision and decision-making quality. From the patient's perspective, a shorter surgery time alleviates anxiety and fear, promotes a positive mindset, and helps accelerate the recovery process while reducing postoperative complications. Although patients in the traditional group were able to begin mobilizing earlier, this difference might be related to individual rehabilitation programs rather than the effect of the surgery itself[24]. Early postoperative mobilization typically depends on various factors, including the patient's physical condition, the quality of rehabilitation training, and adherence to medical advice[13]. In this study, there was no significant difference in early postoperative mobilization between the two groups, indicating that both surgical methods had similar effects on postoperative recovery. However, it is worth noting that the shorter surgical time in the FEP group may reduce the risk of postoperative complications, thereby indirectly facilitating faster recovery. Furthermore, some studies suggest that personalized surgical planning and precise implant selection contribute to improved postoperative functional recovery[14,25]. These findings further support the potential advantage of the FEP group in terms of postoperative recovery.

Biomechanical performance

The FEP group with multiplate fixation presented a more uniform stress distribution and a reduced risk of stress concentration. Specifically, finite element analysis revealed that the stress distribution in the multiplate mode was more even, especially under high-load conditions, such as standing or walking, with peak stress values significantly lower than those in the dual-plate mode. These findings suggest that the multiplate fixation mode is better at distributing stress and reducing the likelihood of local stress concentration, thus lowering the risk of implant loosening or failure. Additionally, the multiplate mode provides better stability for fracture fragments, which is beneficial for fracture healing. In addition to stress distribution, the stability of fracture fragments is also a crucial factor in evaluating biomechanical performance. Research has shown that the multiplate fixation mode has a significant advantage in maintaining fracture fragment stability. Through finite element analysis, researchers found that the multiplate mode maintained better stability of fracture fragments under various loading conditions, particularly in complex three-column or multicolumn fractures, where this advantage was more prominent[26]. In contrast, the dual-plate mode might lead to fragment displacement or instability in certain cases, affecting healing outcomes[14]. Therefore, the multiplate fixation mode demonstrated superior biomechanical performance, offering better postoperative stability and functional recovery conditions for patients. Despite the theoretical advantage of the multiplate fixation mode in terms of stability, no statistically significant differences were observed in actual application. Possible reasons for this may include the following: (1) The complexity of the internal fixation device may lead to prolonged surgical time and increased costs (Table 2). Additionally, the multiplate fixation mode has greater operational complexity, which may increase the difficulty of the surgery and place greater demands on the surgical team's skillset. (2) The patient's recovery process depends not only on the effectiveness of the internal fixation but also on factors such as postoperative rehabilitation training, personal physical condition, and other variables. Therefore, although the multiplate fixation mode theoretically offers certain advantages, its clinical outcomes have not been significantly superior to those of the dual-plate fixation mode in practice. Future studies should further explore the long-term effects of different fixation modes, use larger sample sizes, and investigate how to optimize fixation strategies to achieve the best balance between clinical outcomes and economic benefits[27]. Moreover, with the development of 3D printing technology and personalized medicine, FEP technology has the potential to become the new standard for treating complex fractures[23,28]. Several studies suggest that personalized implant design and precise surgical planning can significantly improve postoperative outcomes and reduce complications[24,29]. Therefore, future research should continue to explore the application of FEP technology in other types of fractures and verify its long-term efficacy and cost-effectiveness through multi-centre randomized controlled trials[30].

Cost-effectiveness analysis

Direct costs

Cost-effectiveness analysis is a crucial component in evaluating medical interventions. This study revealed that the FEP group had significantly lower internal fixation and total hospitalization costs than the traditional group did, particularly in terms of the cost per megapascals of stress reduction and the cost per millimetre of displacement reduction (Table 4). Specifically, for stress reduction under both double-leg standing and single-leg standing conditions, the multiplate mode had costs of 635.82 yuan and 294.58 yuan, respectively, compared with the dual-plate mode. For internal fixation alone, the cost per megapascals of stress reduction was 1209.31 yuan for the multiplate mode and 1948.54 yuan for the dual-plate mode; in the bone-internal fixation condition, the cost per millimetre of displacement reduction was 84392.50 yuan for the multiplate mode and 26372.66 yuan for the dual-plate mode. These data indicate that although the FEP group still incurred material costs, its overall cost-effectiveness was superior, particularly in reducing the economic burden on patients.

Indirect costs

In addition to direct costs, indirect costs are also an essential indicator for assessing the economic efficiency of medical interventions. Research indicates that surgical time and postoperative recovery speed significantly affect indirect costs[8]. The FEP group had lower indirect costs due to shorter surgical times and faster postoperative recovery. For example, a study on distal radius fractures revealed that the use of soft bandages and immediate discharge reduced both hospitalization time and nursing costs[31]. Another study on hip fracture protection devices also revealed that preventive measures could significantly reduce indirect costs[9]. Therefore, the FEP group's advantage in terms of indirect costs is also noteworthy. Although FEP is associated with greater cost-effectiveness in terms of explicit costs, some potential hidden costs should still be considered. The software licensing fees for finite element analysis are a necessary expenditure for preoperative planning. Although this cost was not included in the current study, it could have an impact on the total cost, especially when used over the long term and for analysing multiple cases. The time required for preoperative simulation and planning is also an unavoidable hidden cost. The process of finite element analysis usually takes a considerable amount of time, which may lead to additional workload and time costs, particularly in high-demand clinical settings.

Long-term economic benefits

In this study, although the finite element planning (FEP) group demonstrated significant advantages in terms of short-term economic benefits, some potential long-term economic benefits are still worth considering. Specifically, FEP may influence factors such as implant lifespan and repair rates by optimizing the surgical plan. Although this study did not directly measure the lifespan of the implants, the stress distribution and displacement test results showed that the multiplate fixation mode provided a more uniform stress distribution (Fig. 6), which theoretically should reduce local stress concentrations and thus extend the lifespan of the implants. In contrast, although the dual-plate fixation mode resulted in higher stress concentrations in some cases, its relatively simple structure reduced surgical complexity and time, lowering the risk of early failure due to surgery-related factors. Therefore, both fixation methods may have advantages and disadvantages in terms of implant lifespan, which needs to be further verified through long-term follow-up studies. With respect to the repair rate, i.e., whether patients require secondary surgery to repair or replace the internal fixation device, existing data show that the FEP group had significantly lower overall hospitalization costs than the traditional group did (Table 2), suggesting that optimization of the internal fixation plan by FEP may reduce the need for subsequent repairs due to suboptimal initial surgery. However, these assumptions still need to be confirmed through long-term follow-up data, especially those focused on key indicators such as postoperative complication rates, reoperation rates, and patient satisfaction.

In the long run, FEP not only reduces both direct and indirect costs but also improves patient quality of life and societal productivity[12]. Studies revealed that personalized surgical planning and precise implant selection help reduce the risk of postoperative complications and enhance patients' quality of life[14]. Furthermore, FEP can shorten the hospitalization time and reduce the waste of medical resources, leading to greater social and economic benefits. Therefore, FEP has significant advantages in terms of long-term economic benefits and deserves further promotion and application.

Notably, the concept of the 'marginal effect' in health economics, where under constant conditions, the incremental health output from continued medical investment gradually decreases, can also be described as a phenomenon where the health return per unit of additional expenditure decreases after medical spending on a certain disease reaches a threshold[32]. This phenomenon in our study occurs in the specific context of using multiple plates and screws for complex fracture simulations. Compared with conventional surgical procedures, biomechanical analysis revealed no significant mechanical benefits, yet the extensive use of high-cost consumables significantly increased expenses. Our research can recommend to patients and physicians the use of less expensive treatment options that balance efficacy and cost, selecting the most cost-effective approach. This maximizes the output from effective medical resources, which is greatly beneficial for both patients and macro health insurance policies. In this scenario, patients in the FEP group reduced the use of internal supplies for preoperative limited fixation on the premise of ensuring the safety and reliability of fracture fixation, contributing to reducing the economic burden of patients and medical insurance. It is based on a series of assumptions and simplifications, such as the linear elastic model of material properties, which may deviate from actual biomechanical behaviour. Finally, the cost-effectiveness analysis omitted some indirect costs and nonmedical expenses, which might affect the comprehensive evaluation of the overall economy of treatment strategies. Given these limitations, future studies should expand the sample size, extend the follow-up period, and consider more factors affecting patient recovery to provide a more comprehensive and in-depth evidence base.

Conclusion

This study included a comparative analysis of finite element planning (FEP) versus traditional (Trad) methods in the surgical treatment of complex tibial plateau fractures in middle-aged and elderly patients. Biomechanical analysis revealed that the multiplate fixation mode was superior to the dual-plate mode, although there were no significant differences in clinical outcomes. Cost-effectiveness analysis confirmed significant lower internal fixation and hospitalization costs for the FEP group, demonstrating the economic advantage of FEP. Therefore, FEP, while ensuring treatment efficacy, effectively reduced the economic burden on patients, highlighting its potential and value in the treatment of complex tibial plateau fractures.

Data availability

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

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Author contributions

Z.X. and H.Z. contributed to the research design and implementation, and made in-depth discussions on research hotspots and technical difficulties. Y.W.L. contributed to model development and data acquisition. X.X.

contributed to clinical data collection and data acquisition. S.J.T. and M.Y. analyzed and interpreted the data and drafted the manuscript. All authors approved the final version of the manuscript.

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Declarations

Approval committee or the internal review board (IRB)
Organization name: Zhangjiagang Fifth People's Hospital.

Ethics approval and consent to participate
This research does not involve any content that violates any personal rights of the subjects. The participation in the study was voluntary and written informed consent was obtained from the participants. This study conforms to the provisions of the Declaration of Helsinki and has been reviewed and approved by the Institutional Review Board of Zhangjiagang Fifth People's Hospital (yx11202404008). All protocols are carried out in accordance with relevant guidelines and regulations.

Competing interests
The authors declare no competing interests.

Additional information
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