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Comparative analysis of internal fixation modalities for PER type IV ankle fractures: a finite element study

Wangsheng Wu[1,2†], Huajuan Wang[2†], Wei Liu[1†], Bingsheng Liu[2], Yang Liu[1] and Chengwei Wang[1*]

Abstract

Background There are many options for the surgical treatment of pronation external rotation (PER) type IV ankle fractures, including the use of fibular plates and screws, the aim of this study was to investigate the biomechanical stability and safety of different internal fixation methods for PER type IV ankle fractures via finite element analysis.

Methods A three-dimensional finite element model of the ankle joint and the whole foot of a healthy 26-years-old adult male was established and validated based on computed tomography images of his lower limb, and a computer-aided design was used to produce a PER type IV ankle fracture and plate and screw model. Four different internal fixation modes were simulated, including a (all ankle fixation—utilizing a fibular plate and screws for comprehensive stabilization of the ankle), b (inferior tibiofibular joint fixation + all ankle fixation), c (inferior tibiofibular joint fixation + unfixed anterior ankle), and d (inferior tibiofibular joint fixation + unfixed anterior and posterior ankles). The results of the four different fixation methods were compared via finite element analysis, and the von Mises stresses. The displacements of the four different fixation methods were analyzed as the output indices.

Results There were no significant differences between the results of using fibular plates and screws and the displacement of fracture breaks among the four internal fixation modalities. The von Mises stress in the tibiotalar joint, median ankle, posterior ankle, and anterior ankle was minimized in the working condition of d, d, b, and d respectively. The von Mises stress in the fibular plate and screws was minimized in the working condition of a. The von Mises stress in the distal fibula was minimized in the working condition of a. However, the stress was mainly concentrated at the attachment point of the inferior tibiofibular anterior ligament, and in the working condition with inferior tibiofibular joint fixation, the stress was significantly concentrated in the inferior tibiofibular joint screw in all the fibular plates and screws.

Conclusions The results of this study demonstrate the feasibility of using finite element analysis to compare the biomechanical stability and safety of four configurations of fibular plates and screws for treating PER type IV ankle fractures. All four modalities provided comparable biomechanical stability and safety, showing no significant differences. However, the current limitations of the finite element analysis methodology preclude specific clinical inferences. Further refinement of the methodology in future studies is necessary to enable reliable clinical applications.

Keywords Ankle fracture, Finite element analysis, Biomechanics, Internal fixation

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Introduction

Rotational ankle fractures are usually classified using the Lauge-Hansen classification system [1], which is based on the ankle position and the direction of force applied in cadaveric models and is usually divided into four categories: supination external rotation (SER), supination adduction (SA), pronation external rotation (PER), and pronation abduction (PA). Among these four types, PER-type ankle fractures are relatively uncommon, but ankle injuries are more severe, accounting for 14–22% of ankle fractures [2–4].

It is widely accepted that ankle PER type IV ankle fractures require a surgical incision, anatomical reduction, and strong fixation [4]. However, there is some controversy over the choice of surgical approach, including whether anterior and posterior ankle fractures need to be treated and whether inferior tibiofibular union needs to be achieved [5, 6]. The traditional treatment for PER type IV ankle fracture involves incisional reduction and the application of a fibular plate and screws for both medial and lateral ankle fractures, followed by Cotton's test to evaluate the stability of the inferior tibiofibular syndesmosis. If the test result is positive, inferior tibiofibular syndesmosis screws are used; however, most scholars believe that distal tibiofibular syndesmosis does not require fixation when the fibula fracture line is within 5 cm of the ankle joint [6, 7]. Previously, reports have disagreed on the management of posterolateral or anterolateral tibial bone blocks. The traditional indications for fixation of posterior ankle blocks were posterior ankle fractures involving > 20% of the ankle joint surface and displacement of the posterior ankle block leading to ankle instability [8]. Whereas, according to the results of a recent study by Quan et al. [9] the bone block of posterior ankle fractures, irrespective of their size, should be internally fixed. Similarly, previous studies have concluded that surgical management with screw fixation is recommended for more than 2 mm of displacement or more than 1 mm of translation [10]. However, it has also been suggested that internal fixation be performed regardless of the size of the fracture mass, and a new technique has been developed to fix any size of anterior ankle fracture mass [11]. Although evidence suggests that the initial biomechanical status of the fracture end is a key factor in the formation of the bone crust and that a reasonable fixation method can provide good stability and safety for the fracture end, none of the above studies have explored the choice of internal fixation from a biomechanical perspective [12]. Therefore, choosing a more biomechanically advantageous surgical approach for the treatment of PER type IV ankle fractures is important for improving clinical prognosis.

There are few studies related to the biomechanical stability and safety of different internal fixation modalities for treating PER type IV ankle fractures, and there are few relevant clinical reports. However, mechanical experiments on relevant cadaveric specimens, despite allowing biomechanical tests to be performed in humans, have relative limitations. For example, it is difficult to perform single-sample repetitive experiments with the goal of controlling bias. Each application of an internal fixation modality and mechanical loading test affects the results of the next application of an internal fixation modality, and it is difficult to maintain the consistency of the sample. In recent years, with the popularity and application of the finite element analysis method in foot and ankle surgery, finite element analysis has become a practical tool for biomechanical experiments. Compared with cadaveric experiments, finite element analysis can control a single model variable, allowing different working conditions represented by each different immobilization modality to be accomplished with the same base model, which provides better control of the experimental bias. The body's internal stresses are difficult to measure experimentally. These stresses, however, can be well predicted by the finite element method and are not subject to the same ethical considerations. Additionally, finite element analysis can provide a wider range of conditions for testing [13, 14] and is more suitable for the study of the application of different internal fixation modalities in the same model [12]. Therefore, in this study, we developed and validated a three-dimensional finite element model of the ankle joint and the whole foot based on computed tomography images of the lower extremity of a 26-years-old healthy adult male, modeled a PER type IV ankle fracture and plates and screws using computer-aided design, and simulated four different methods using a fibular plate and screws along with other fixation devices to investigate the biomechanical stability and safety of these modalities for treating PER type IV ankle fractures.

Materials and methods

Geometry design

To reconstruct a three-dimensional model of a normal foot and ankle, we performed a foot and ankle scan of a 26-years-old healthy adult male volunteer (weight 60 kg, height 1.7 m, no history of foot trauma, tumors, or anatomical abnormalities on clinical examination). This study was conducted in accordance with the principles of the Declaration of Helsinki, and the volunteers provided written consent to participate in our study. The volunteer's foot and ankle were kept in a neutral position during the CT scan (voltage of 120 kV, current intensity of 240 mA, scanning layer thickness of 0.600 mm). The

CT data acquired from the scan were saved in DICOM format. The foot and ankle data were imported into Mimics21.0 (Materialise, Belgium) software in DICOM format, and 3D surface geometry reconstruction of the bones, including the tibia, fibula, and foot and ankle, was performed by threshold segmentation, region growing, and manual erasure. The STL files of the above bones were imported into the reverse engineering software Geomagic Wrap2021 (Geomagic Company, USA). Corrections were made in Geomagic Wrap for the presence of pegs, corners, and small holes, before fitting to the NURBS surfaces. The model was imported into Solid-Works2022 software (Dassault, France) in STP format, and the plate and screw models were established to simulate PER type IV ankle fracture, with the broken end of the fibula fracture 7 cm above the tibial dome, the area of the posterior ankle fracture accounting for 14% of the tibial talonavicular joint, the inner ankle fracture set to be a full cut angle of 30° horizontally, and the area of the anterior ankle fracture accounting for 5%. The parameters of the plate model were set to 88 mm in length, 8.5 mm in width, and 1.4 mm in thickness. There were three types of screws, lower tibiofibular joint fixation screw parameters were set to 3.4 mm in diameter and 52 mm in length, fracture fixation screw parameters were set to 3.4 mm in diameter and 37 mm in length, and the plate fixation screw technique was set to 3.4 mm in diameter and 10 mm in length. The models were sequentially assembled into four different internal fixation schemes, including a (all ankle fixation—utilizing a fibular plate and screws for comprehensive stabilization of the ankle), b (inferior tibiofibular joint fixation + all ankle fixation), c (inferior tibiofibular joint fixation + unfixed anterior ankle), and d (inferior tibiofibular joint fixation + unfixed anterior and posterior ankles) (Fig. 1). All models were imported into Hyperworks 2019 software (Altair, USA) in IGES format, frictionless face-to-face contact was used to represent the relative articular motion between layers of articular cartilage for frictionless sliding between the bones, and the ligaments were modeled using rod units that can only be stretched and not compressed based on anatomical information on the Digital Anatomy Platform and the Human Atlas. These ligaments were manually positioned and added to the model based on relevant anatomical landmarks.

The assignment of material properties

In this study, we used HyperMesh software to mesh the bones, cartilage, and soft tissues using tetrahedral grid cells with mesh sizes of 1 mm for cortical bone, 1 mm for cancellous bone, and 2 mm for peripheral soft tissues. Convergence tests were performed on the discretization of the finite element model until the calculated stress deviation was less than 5% (see Fig. 2), and the final model consisted of 509245 nodes and 2834755 elements. All bones, cartilages, ligaments, and base plates were assumed to be linearly elastic materials with continuity, full elasticity, homogeneity, and isotropy, and the base plate material was modeled as a rigid horizontal plate with a large Young's modulus to simulate the ground. The material properties were obtained from the literature [15–17] (Table 1 lists the material properties of each element).
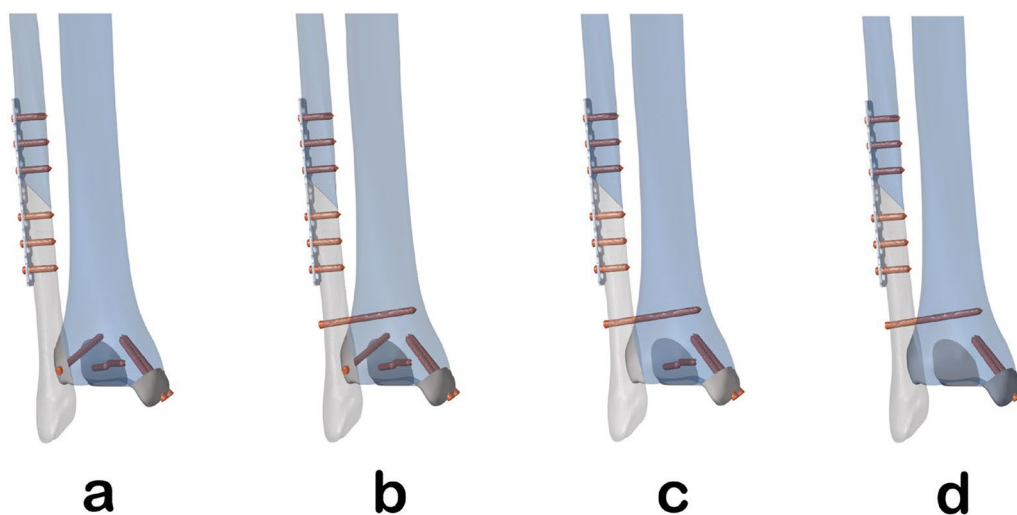

Fig. 1 Model of four different internal fixation modalities for the treatment of PER type IV ankle fractures. **a** All ankle fixation. **b** Inferior tibiofibular joint fixation + all ankle fixation. **c** Inferior tibiofibular joint fixation + unfixed anterior ankle. **d** Inferior tibiofibular joint fixation + unfixed anterior and posterior ankles
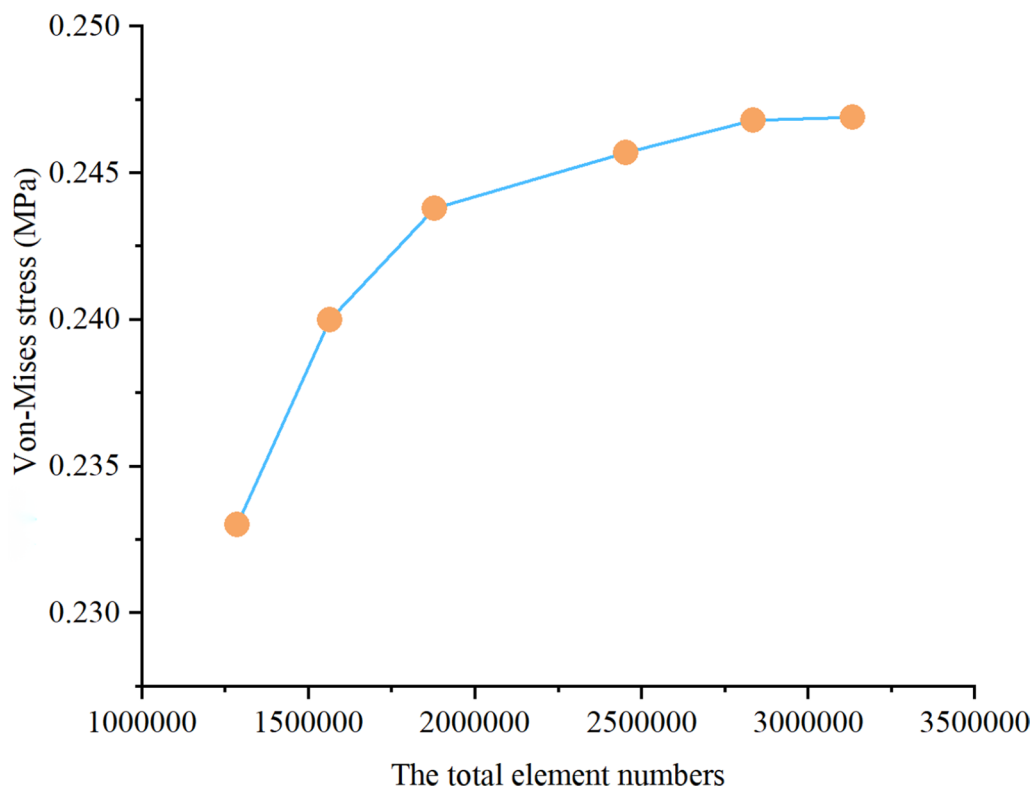
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Fig. 2 Convergence test results in terms of the von Mises stress

Table 1 Material properties used for various components of the model

Components	Young's modulus (MPa)	Poisson's ratio	Element type
Ground	17,000	0.1	8-node linear brick
Soft tissue	1.15	0.49	4-node tetrahedron
Ligaments	260	0	2-node linear 3-D truss
Cartilage	1	0.4	8-node linear brick
Cortical bone	7300	0.3	4-node linear tetrahedron
Cancellous bone	100	0.3	4-node linear tetrahedron

Definition of boundary conditions and loading

The coefficient of friction of the plantar contact with the rigid ground was set to 0.6. The subject weighed 60 kg, and in the standing phase, the right foot carried half of the body weight (300 N), and a load of 300 N was applied vertically upward through the rigid ground to simulate the plantar reaction force in balanced standing, with the tibia, fibula, and the upper surface of the soft tissues completely fixed in the constraints. In balanced stance, the Achilles tendon force is approximately 50% of the force applied to the foot [18], so a further vertical upward force of 150 N was applied to the Achilles tendon (Fig. 3a).

Validation

The boundary settings, load settings, and size of the finite element model vary from study to study, and in comparison with the model, the focus is on the comparison of stress distribution trends. The plantar stress distribution in this experimental model is in high agreement with the trend and magnitude of the plantar stress distribution in the finite element study by Tao [15] (Fig. 3b); thus, the foot and ankle model can be considered valid. The model can be used for finite element analysis and biomechanical studies of the foot and ankle joints.

Results

The stress distributions, von Mises stresses, and displacements of the fibular plates, screws, and fracture break were observed for the four different fixation methods.

Von Mises stress distribution

Differences in von Mises stress were observed among the four modalities (Fig. 4), with the stresses in the tibial talonavicular joints all concentrated mainly in the anterior
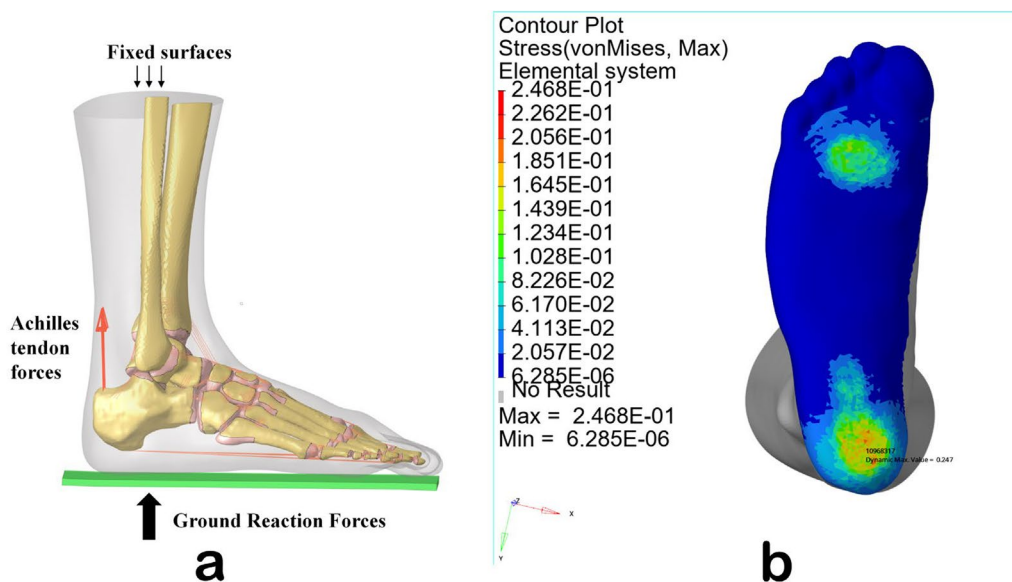
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Fig. 3 Overall model of the foot and ankle. **a** Applying boundary conditions and loading to the models. **b** Validation of model validity by plantar stress distribution

aspect of the medial ankle; the b-mode had the largest von Mises stress of 11.35 MPa, while the d-mode had the smallest von Mises stress of 8.2 MPa. The von Mises stress s of the remaining two fixation methods were 11.19 MPa and 10.99 MPa, which were larger than those of the d method. Since the a-mode did not have inferior tibiofibular joint fixation, the von Mises stress of the a-mode was the smallest, which was mainly distributed on the anterior side of the midplate at 4.558 MPa. The von Mises stresses of the remaining three fixation modes appeared at the inferior tibiofibular joint fixation screw, but the difference in the von Mises stresses of the three fixation modes was smaller. The von Mises stress in the medial ankle was the lowest at 7.267 MPa for d-mode fixation. The difference between the four fixation modes for the von Mises stress in the posterior ankle was smaller. The difference between the four fixation modalities for the von Mises stress in the anterior ankle was similarly small (see Table 2). Since there was no lower tibiofibular union fixation in the a-mode, the von Mises stress in the distal fibula was the smallest, at 5.733 MPa, which was mainly distributed in the attachment point of the lower tibiofibular anterior ligament in the distal fibula, and the smallest fixation in the remaining three fixation modes was in the d-mode, which was mainly distributed in the junction with the lower tibiofibular screws (see Fig. 4).

Model displacement

The displacement gap of the fibular plates and screw, as well as the displacement gap of the fracture break, was insignificant in all models for the four different fixation modalities (see Table 3, Figs. 5).

Discussion

Since most studies agree that immobilization of the inner and outer ankle is necessary for stabilizing the ankle joint [19, 20], in this study, based on the validation of the finite element model, a finite element model of four different internal fixation modalities for the treatment of PER IV ankle fracture was established, including a (all ankle fixation), b (inferior tibiofibular joint fixation + all ankle fixation), c (inferior tibiofibular joint fixation + unfixed anterior ankle), and d (inferior tibiofibular joint fixation + unfixed anterior and posterior ankles), to investigate the biomechanical stability and safety of different internal fixation modalities for treating PER IV ankle fractures.

In regard to whether fixation of the inferior tibiofibular union is necessary, where the 'inferior tibiofibular coalition' refers to the distal tibiofibular joint and its associated syndesmotic ligaments, a review by van et al. [6] suggested that patients with combined ruptures of the anterior tibiofibular ligament, deltoid ligament, and posterior tibiofibular ligament should be treated with inferior tibiofibular union screws or when there is intraoperative doubt about the structural integrity of the inferior tibiofibular union ligament. The results of a retrospective study by Wu et al. [21] showed that immobilizing the inferior tibiofibular coalition did not significantly influence the functional prognosis of patients. According to our results, the stress of von Mises in the
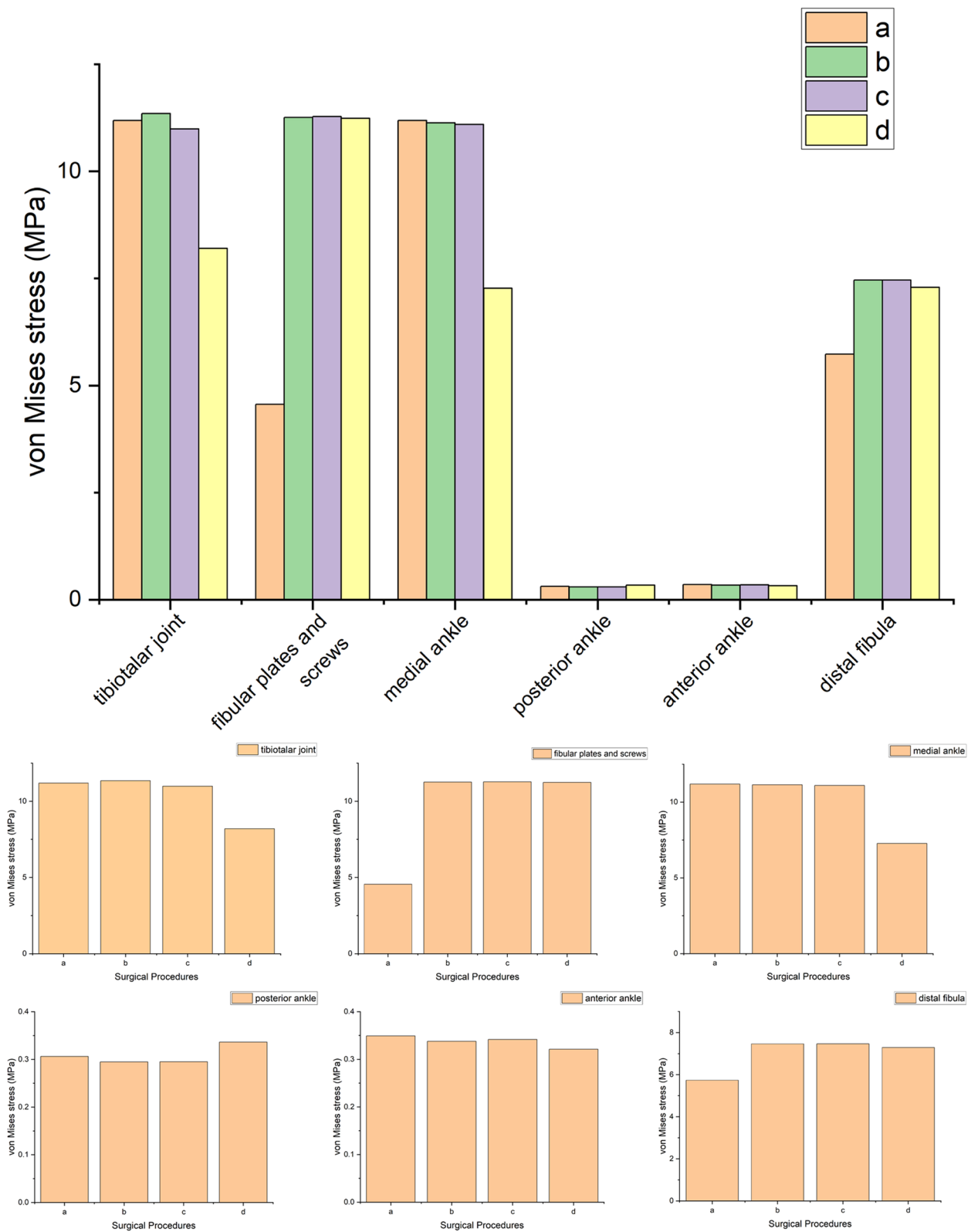
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Fig. 4 Comparison of von Mises stresses in fibular plates, screws, and fracture breaks with four different fixation methods. **a** All ankle fixation. **b** Inferior tibiofibular joint fixation + all ankle fixation. **c** Inferior tibiofibular joint fixation + unfixed anterior ankle. **d** Inferior tibiofibular joint fixation + unfixed anterior and posterior ankles

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Table 2 Comparison of von Mises stresses in fibular plates, screws, and fracture breaks with four different fixation methods (MPa)

Configuration	Group a	Group b	Group c	Group d
Tibiotalar joint	11.19	11.35	10.99	8.2
Fibular plates and screws	4.556	11.256	11.278	11.238
Medial ankle	11.19	11.135	11.099	7.267
Posterior ankle	0.3062	0.2947	0.295	0.3363
Anterior ankle	0.349	0.3378	0.3417	0.3213
Distal fibula	5.733	7.46	7.464	7.29

Table 3 Comparison of the magnitude of displacement of fibular plates, screws, and fracture breaks under four different fixation modalities (mm)

Configuration	Group a	Group b	Group c	Group d
Fibular plates and screws	0.3088	0.3141	0.3129	0.3115
Medial ankle	0.3078	0.3129	0.3118	0.3103
Posterior ankle	0.2064	0.2082	0.2084	0.2069
Anterior ankle	0.2388	0.2418	0.2416	0.2394
Distal fibula	0.2445	0.2474	0.2478	0.2454

medial ankle was the lowest in the d-mode, while that in the other three fixation modes was greater. These results indicated that this fixation mode had a better prognosis for the PER IV ankle joint. The "a" fixation mode did not involve inferior tibiofibular coalition fixation, which was different from the other three modes in that the inferior tibiofibular coalition screws took over the physiological function of the inferior tibiofibular anterior ligament. Therefore, the use of inferior tibiofibular joint screw fixation will assist healing of the inferior tibiofibular joint ligament and the inferior tibiofibular anterior ligament, thus improving the clinical efficacy and prognosis. However, it is worth noting that the lower tibiofibular joint screw still has a high von Mises stress. The results of recent clinical studies have shown that lower tibiofibular joint screw fixation may inhibit the ankle's normal motion and may break after weight-bearing for a period of time, which may sometimes cause tibiofibular subtalar joint pain [22] and may require a second surgery to remove the screws [23]; therefore, we also recommend removing the lower tibiofibular screws before weight-bearing walking on the ground to avoid the risk of nail breakage.

In the present study, the tibial talonavicular joint von Mises stresses for the four different internal fixation modalities were concentrated anteriorly in the medial ankle at the broken end of the medial ankle fracture. This suggests that the inner ankle is more prone to delayed fracture healing or non-union and traumatic
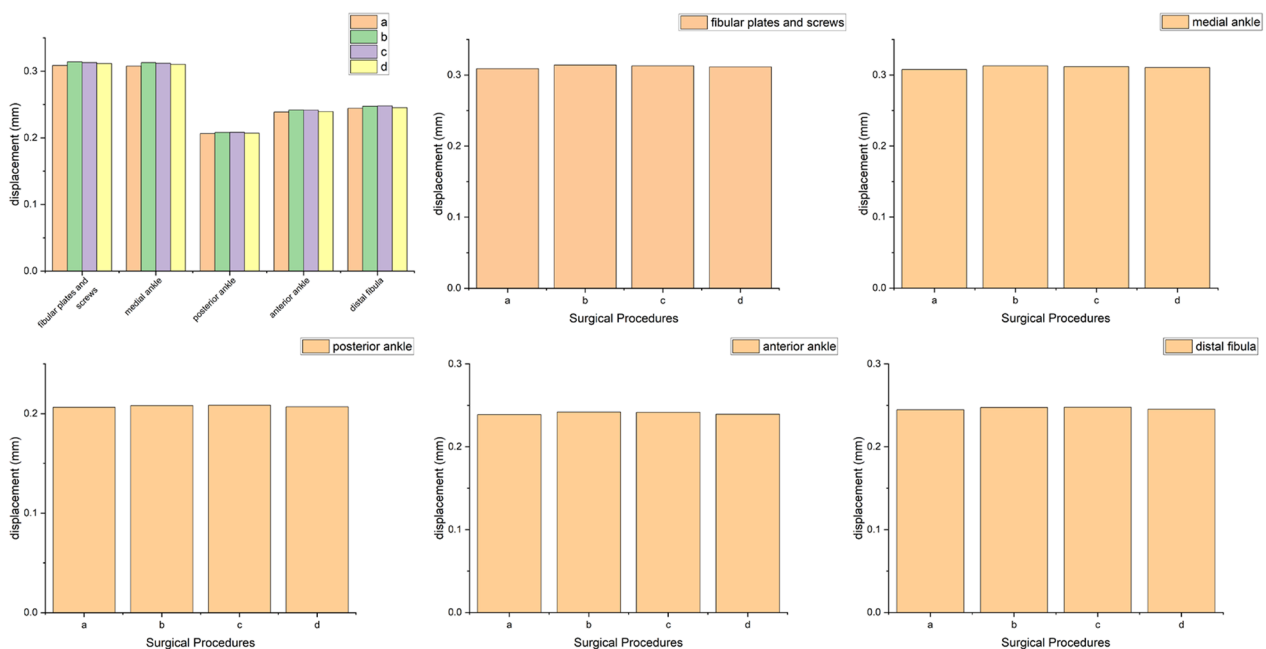

Fig. 5 Comparison of the magnitude of displacement of fibular plates, screws, and fracture breaks under four different fixation modalities. **a** All ankle fixation. **b** Inferior tibiofibular joint fixation + all ankle fixation. **c** Inferior tibiofibular joint fixation + unfixed anterior ankle. **d** Inferior tibiofibular joint fixation + unfixed anterior and posterior ankles

arthritis relative to other locations of the ankle joint. In contrast, the results of a recent study [24] similarly concluded that fractures of the inner ankle are more prone to delayed healing, which is more in line with the results of the present study, but the reason for this is explained by the significant reduction in blood perfusion of the saphenous artery at the fracture site of the inner ankle. Therefore, the concentration of stress in the inner ankle should receive special attention.

In a previous study Gardner et al. [22] generated a model of PER type IV ankle fracture on ten fresh frozen cadaveric lower extremity specimens and randomly assigned five cases to posterior ankle fixation and the remaining five cases to lower tibiofibular union fixation, and completing biomechanical experiments by testing the external rotation stability. They concluded that the fixation of posterior ankle fracture provides better union ligament stability, and that when fibular fracture and posterior lateral ankle fracture occur after reduction and fixation, the lower tibiofibular joint ligament can be sufficiently restored. No further lower tibiofibular joint fixation is needed, whereas most [25–27] scholars believe that internal fixation and stabilization of the posterior ankle are required only when the posterior ankle fracture involves more than 25% of the tibial talonavicular joint. However, the results of this study are more inclined to support the latter, and these four different internal fixation modalities had less effect on the von Mises stresses in the anterior and posterior ankles, which suggests that whether to immobilize the anterior and posterior ankles has little effect on the clinical prognosis when choosing the internal fixation modality. From the perspective of model displacement, there was no significant difference between the displacement of the fibular plates and screws and the fracture break, indicating that all four internal fixation modalities could effectively maintain the stability of the fracture break.

This study has several limitations. First, when modeling the fracture, the fracture line was simplified, and real fracture lines are irregular. However, the foot and ankle joint model met the experimental requirements and was validated. Second, only a single subtype of PER type IV ankle fracture was analyzed by finite element analysis (FEA) in this study, and no other subtypes were considered. Additionally, further refinement of the methodology is needed to reach a point where clinical inferences can be reliably made. Future studies could validate the model and evaluate it using cadaveric biomechanics, studying changes in mechanical behavior from the perspective of combining theory and practice. This approach would help promote the clinical development of internal fixation surgery for ankle fractures.

Conclusion

The results of this study demonstrate the feasibility of using finite element analysis to compare the biomechanical stability and safety of four fixation modalities for PER type IV ankle fractures. All four modalities provided comparable biomechanical stability and safety, showing no significant differences. However, the current limitations of the finite element analysis methodology preclude specific clinical inferences. Further refinement of the methodology in future studies is necessary to enable reliable clinical applications.

Appendix

Glossary

Finite element analysis (FEA)	A numerical method that divides structures or systems into smaller interconnected elements to analyze their behavior under different loads
von Mises stress	A stress measure used in FEA to assess the likelihood of material failure, considering both normal and shear stresses
Biomechanics	The study of how forces and loads affect the structure and function of biological systems, such as bones and joints
Loading Conditions	The external forces or loads applied to a structure during analysis, such as tension, compression, bending, or torsion
Material properties	Characteristics of a material, such as stiffness, strength, and density, which influence its response to applied loads
Boundary conditions	Constraints or forces imposed on the boundaries of a model or system during FEA to define interactions with the environment
Mesh	A discretized representation of a structure or system in FEA, composed of interconnected elements and nodes
Convergence test	A procedure in FEA to determine solution accuracy and reliability, ensuring stable and consistent results
Node	A point in the FEA mesh where elements connect, used for calculating displacement and stress
Mesh element	Individual component of the FEA mesh, such as triangles or quadrilaterals, used for analysis
Continuity	Property of a structure or material without gaps or discontinuities, important for accurate stress and displacement calculations

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Perfect elasticity	Idealized material behavior without permanent deformation or energy dissipation when loads are removed
Homogeneity	Property of a material where properties are uniform throughout, simplifying FEA analysis
Isotropy	Property of a material with consistent mechanical properties in all directions
Linear elasticity	Material behavior where stress is linearly proportional to strain within the elastic range, simplifying FEA analysis
Young's modulus	Measure of a material's stiffness or resistance to deformation under stress
Rigidity	Ability of a material or structure to resist deformation
Poisson's ratio	Measure of lateral contraction when a material is stretched in one direction
Friction coefficient	Dimensionless value representing resistance to sliding between two surfaces in contact
Validation	Process of comparing FEA results with experimental data or analytical solutions to ensure accuracy and reliability
Stress	Internal force or load per unit area within a material
Displacement	Change in position or movement of a point within a structure due to applied loads or deformations

Abbreviations
PER   Pronation external rotation
SER   Supination external rotation
SA   Supination adduction
PA   Pronation abduction

Author contributions
WCW had full access to all the data in the study and took responsibility for the integrity of the data and the accuracy of data analysis. WWS, WHJ, and LW contributed to conducting the experiment and writing the manuscript. LBS contributed to the study design, LY collected experimental data. All authors read and approved the final version of the manuscript.

Availability of data and materials
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
All experimental protocols were approved by the Ethics Committee of The Affiliated Tumor Hospital of Xinjiang Medical University. The study was conducted according to the principles of the Declaration of Helsinki, and participants gave written informed consent to participate in our research.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

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