

Original Article

Comparative biomechanical evaluation of fixation methods in posterior pilon fractures: a finite element analysis

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Abstract: *Background and aim:* The clinical management of posterior pilon fractures (PPF) remains a controversy with various surgical fixation techniques induced as the screws or tubular plate. The comparison of stability of fixation methods for PPFs, could help to determine clinical treatment. Therefore, the displacement and stress of fragment fixed via screws, T-plate and tubular plate were studied by finite element analysis method. *Materials and methods:* A three-dimensional finite element model of normal ankle was established based on the anatomical data from an healthy male volunteer. The PPF model with single fragment were built by cutting the posterior tibial lip parallel to the bimalleolar axis, while the three fixations of screws, T-plate or tubular plate were established and applied on the unstable model. The PPF model with double fragments was cut in sagittal plane based on the PPF model with double fragments, followed by the simulated four fixation methods (two screws or tubular plate fixed to each fragment) applied on the model. The peak displacement and stress on bone or fixation system were identified under the loads of neutrality, external rotation and plantar flexion. *Results:* For PPF with single fragment, the T-plate system was proved to be superior to screw or tubular plate system in terms of the highest displacement of fracture under neutral loading or external rotation loading. For PPF with double fragments, two tubular plates provide the minimum of fracture displacement under neutral loading or external rotation loading. All fixations performed similarly under the plantar flexion loading while the highest stress on implants or bone around fixations was similar. *Conclusions:* T-plate can be superior to screws and tubular plate in fracture stability for single segment of PPF. Two tubular plates could be most stable in fixing double segments in PPF, while the medial plating could behave more stable than lateral plating.

Keywords: Posterior pilon fracture, screw, T-plate, tubular plate, finite element analysis

Background

Posterior pilon fractures (PPFs) are challenging fractures encountered in orthopedic trauma practice [1, 2]. In 2000, Hansen firstly described the fracture pattern occurred through a combined rotational and axial loading mechanism as "posterior pilon" [3]. In 2001, Karachalios recognized a trimalleolar fracture with a posteromedial and posterolateral fragment involving the posterior malleolus [4]. In 2004, Weber described this unique subtype of trimalleolar fracture with distinct features unlike the well-

known posterolateral fragment [5]. In 2006, Haraguchi categorized the medial-extension fracture line pattern parallel to the bimalleolar axis [6]. In 2013, Klammer recommended fixation with screws or plates and proposed a classification system of PPFs [2]. Nowadays, it is generally agreed that PPF fragment is large, comminuted, as well as the involving articular surface. The estimated incidence of PPFs was 19% of posterior malleolar fractures and 8% of malleolar fractures [5, 6]. PPFs could lead to incongruity of articular surface thus posttraumatic arthritis with unsatisfied function out-

comes [7]. In addition, the operative indications and suitable treatment methods evolved from screws to plates still remained a controversy and represent a major challenge [8].

Various treating methods have been introduced for the treatment of PPFs. The conservative treatment has been fallen into disuse cause the possible situation of PPF that small fragment assessed on lateral X-ray but the most or nearly all of the medial malleoli involved [9]. Multi fixation methods were described: external fixation combined with limited internal fixation [10]; the fixing method of about three cancellous lag screws fixed into each fragment of PPFs was firstly described [4]; the using of tubular plate along the posterior tibia longitudinally to buttress PPFs through posteromedial, posterolateral, or combined approaches gains in popularity recently [1, 2]; the T-size plate to buttress the posterior fragments was also described [11]. Despite all the surgical fixation methods applied, the restoration and sustained stability of a normal anatomic morphology is widely accepted as the key element for a good functional outcome [12]. However, several factors as the soft tissue condition and complication should be taken into account importantly before management. Perhaps the fracture stability under various fixing could also be an important aspect in choosing fixation. Thus, there is an ongoing need to compare the stability of PPFs under various fixation methods, maybe contributing to the problem of treatment.

The clinical trial is costly and time consuming, while biomechanical experiment has the shortage of specimens. However, the method of finite element analysis is a computational technique that could identify the displacement and stress of physical model under various conditions accurately [13]. Considering the lack of studies on comparison of stability under multi fixations of PPFs, the finite element method was utilized in this study. Based on the clinical practice, two screws, T-plate or tubular plate were applied on the single fragment of PPF model; two screws or tubular plate fixed to each fragment of PPF model with double fragments. Our study compared screwing and the buttress-plating as the 1/4-tubular plate and T-plate in fixing PPFs with a single or double fragments,

thus providing a theoretical reference on the fixation choices of PPFs.

Materials and methods

Finite element model of the ankle reconstruction

To create geometrically a normal finite element model of ankle, three-dimensional (3D) reconstruction of CT images of the foot was utilized. CT scanning was performed on the right foot in the neutral unloaded position of a healthy male volunteer (the second author of this study, 24 years age, weight 70 kg, height 178 cm and bone lesion was excluded by X-ray examination). The male volunteer accepted this participation of experimental procedures, and signed the informed consent. This study was approved by ethics committee of Nanfang hospital and performed in accordance with the Declaration of Helsinki. The Lightspeed 64-slice spiral CT (produced in GE company, USA) was performed on the ankle of the volunteer, and cross-sectional CT images taken with 0.625 mm intervals were saved as Dicom files.

A static model of ankle was built by using the established methods with several techniques available in software [14]. The CT images of ankle obtained were imported to the Mimics 10.0 (developed by Materialise NV company) to depict bone surface and 3D structure of each bone. The highly detailed boundary surfaces were fit to each bone automatically according to various ranges of grayscale by using thresholding segmentation and region growing tools, manually modified according to the anatomic shape of bone. In this experimental process, the cortical bone and cancellous bone were also distinguished and drawn. After it was paved and smoothed by in the geomagic 2010 software (developed by Geomagic Inc.), the geometric model structure was primarily established. Then, the separate solid objects representing the bones were assembled within SolidWorks to form a three-bone ankle complex including the tibia, fibula and talus. The coordinate axes of the model were marked and aligned: the X-axis pointed medially, the Y-axis pointed posteriorly and the Z-axis pointed upward. Finally, the three-dimensional finite element model of IGES files was created in the ANSYS 10.0 (from ANSYS company) after grid divided. The established 3D finite element

ankle model was composed of approximately 94135 elements and 25,048 nodes.

To simulate the connections status of ligament, several linear, tension-only springs were applied on the ankle model. Based on the geometries of ligament, the springs set as the direct connecting of the attachment areas to simulate connected ligament. A total of 7 ligaments such as deltoin ligament (anterior tibiotalar part and posterior tibiotalar part), anterior tibiofibular, posterior tibiofibular, anterior talofibular ligament, posterior talofibular ligament and transverse tibiofibular ligament were stimulated by springs [15]. While the contact areas were determined by the data acquired in anatomical database or published articles [16]. Initial ligament lengths were taken as the distance between insertion sites in the neutral position. The preloading of ligaments was stimulated as implemented by a reduction in zero-load length of 2% [17], which was introduced by Liacouras and Wayne, which was applied to represent the basic tension of each ligament.

Material properties

Properties of the cortical and cancellous bone structures were idealized and assumed to be isotropic, homogeneous, and linearly elastic due to the lack of precise organic information. The Young's modulus of materials were 17000 MPa (for cortical bone) and 700 MPa (for cancellous bone), and Poisson's ratios were 0.3 (for cortical bone) and 0.2 (for cancellous bone). The Young's modulus and Poisson's ratio of cartilage with a 1.0 mm thickness are 12 and 0.42. These parameters were measured and used by some finite element analysis [18, 19]. The articular surfaces were marked according to the anatomic character of ankle, of which the interactions were considered as smooth and frictionless to simulate the lubricating nature of cartilage.

Stiffness values of various ligaments, which represent the different processed mechanical properties of tensile springs were defined by some previous literature and utilized in finite element analysis. The data of stiffness value measured by several researches [20, 21] were applied to the tibiofibular syndesmosis ligaments and medial and lateral collateral ligaments of the ankle in this finite element analysis. Combined with the three-dimensional

anatomical positions on the bone surfaces and these values referred to the articles, the model of ligaments were established.

Validation of three-dimensional model

After following the previous finite element analysis methods as drawing boundary conditions and material properties, the finite element models of ankle joints were created. To validate these models, neutral mechanical load of weight was applied to the normal static models. Then, the calculated results of contact peak pressure and area in articular surface were compared with the results in the literature focusing on the real condition of ankle joint in neutral position during weighting. The talus was fixed in space, while the tibial and fibula were fixed to be allowed moving only in the Z direction. According to that both tibial and fibula bear weighting (5/6 for tibial and 1/6 for fibula of the whole weighting), the neutral load (350N, the weight of volunteer on one foot) was nearly 290N on proximal tibial and 60N on proximal fibula [22, 23]. The good agreement between finite analysis-computed and experimentally measured results in contact area and press in ankle was confirmed. It is needed to compare our results with the results in other articles, though there exerts some differences among the results in the literature because of the diverse methods used and individual shape.

Fractures with fixations models construction

PPF is reported as the transverse fracture of posterior tibial lip involved the medial malleolus with a fracture line parallel to the bimalleolar axis. Haraguchi has detected this fracture pattern and this pattern was used by Rassch [6], who cut the tibial calculated as a percentage of the maximum anteroposterior dimension in the cross-sectional view of the ankle at the level of the maximum anteroposterior dimension. According to this method, the 30% size of PPF model was built in this finite element analysis study [6], which the fracture line exits to the medial malleoli through the posterior colliculus. The lines that divided the maximum anteroposterior dimension as the above percentages were marked. The fragment heights were also selected as 35 mm [24, 25], the mean height of pilon fracture studied from the largest apex of fragment to the articular surface on sagittal reconstruction views. The single fragment

Finite element analysis of fixed posterior pilon fractures

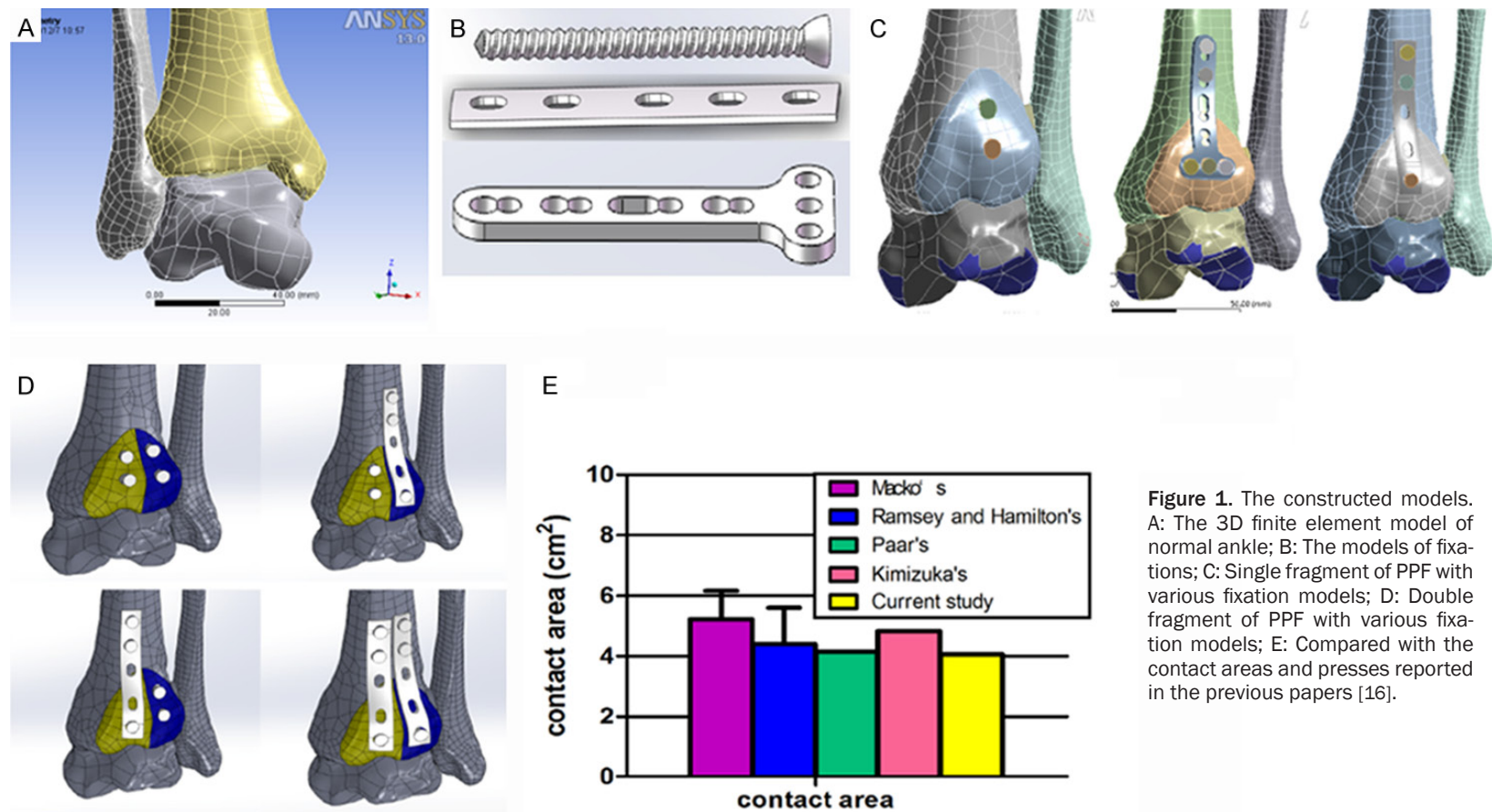


Figure 1. The constructed models. A: The 3D finite element model of normal ankle; B: The models of fixations; C: Single fragment of PPF with various fixation models; D: Double fragment of PPF with various fixation models; E: Compared with the contact areas and presses reported in the previous papers [16].

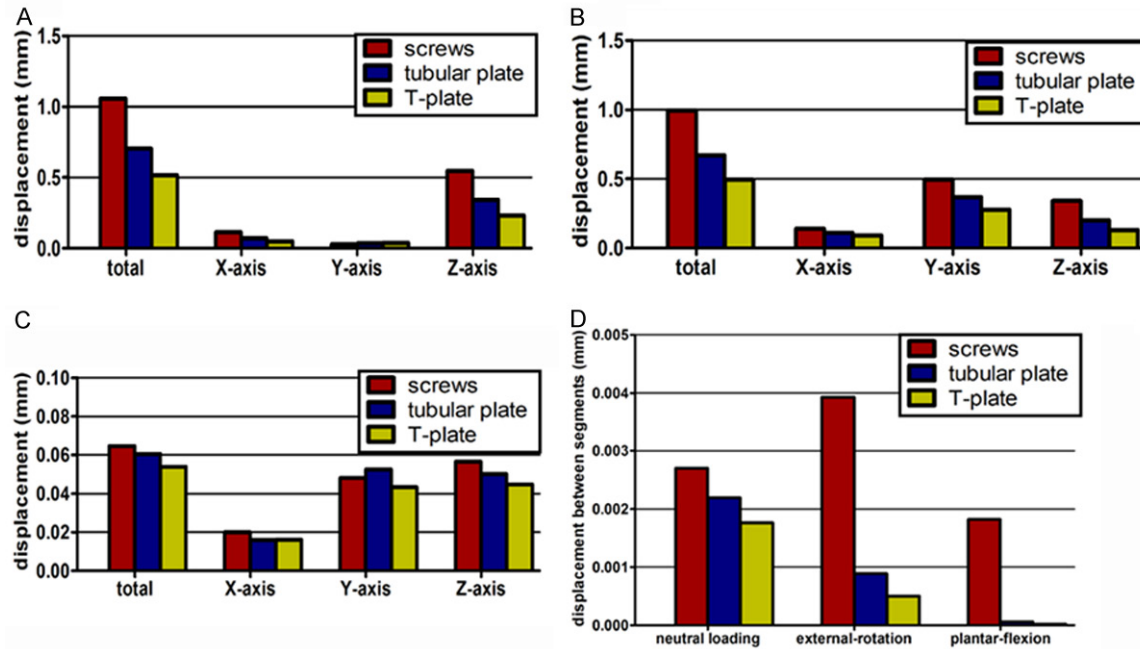


Figure 2. The max displacement in single fragment of PPF with various fixations. A: The peak displacement of fragments in the neutral ankle; B: The peak displacement of fragments in the external rotation of ankle; C: The peak displacement of fragments in the plantar flexion of ankle; D: The peak relative displacement between fragments.

could be cut along the middle line of fragment, thus making PFFs models with either single fragment or double segments.

With the design tools in SolidWorks software (SolidWorks corporation) and the fixation data currently available in clinical treatment, the screws and plates were constructed. Based on the data of Synthes plates designing (Synthes Inc), the tubular plate of 6 holes, the T-plate of 3 holes, cortical bone screw and cancellous bone screw in the diameter of 3.5 mm were transferred to the three-dimensional models. The titanium plates and screws were created, of which the Young's modulus and Poisson's ratios used in this analysis were 106000 MPa and 0.33, which was acquire from the materials database of SolidWorks.

When applied to the fracture, the plates were modeled to fit the irregular bone surface and then fixed on to the models. A small space was left between the plate and bone to represent the clinical situation. According to the clinical principles and surgery methods reported in the literature [26], three fixation methods (two screws, one tubular plate, one T-plate) were applied respectively to PPF model with single fragment. While the four fixation methods (four

screws, two tubular plates, medial screws with lateral tubular plate and medial tubular plate with lateral screws) were simulated to fix double segments in PPF model. Depending on the fixation system, all screws were inserted and connected fully along the plate and bone surfaces except the screws near to the fracture line or the ledge of fragment. The screws were fixed parallel to the opposite side of cortical bone, which were located to divide the fragment on the lateral radiographs into three equal parts. When placing screws distally in plating processes, the screws were angulated approximately 20 degree cephalad to fix the fragments, which was in consideration to prevent penetration of tibial plafond.

Analysis under mechanical loads

To simulate the fragment displacement and press in this study, the mainly three loads of neutral loading, plantar flexion and external rotation were loaded to observe the stability and press distribution of fragments. Complete fractures were set with a friction coefficient of 0.2 between fragments and tibial which was referred to the literature [27]. The neutral load which was nearly 290N on proximal tibial and 60N on proximal fibula with the low surface of talus fixed in space, was used to stimulate the

Finite element analysis of fixed posterior pilon fractures

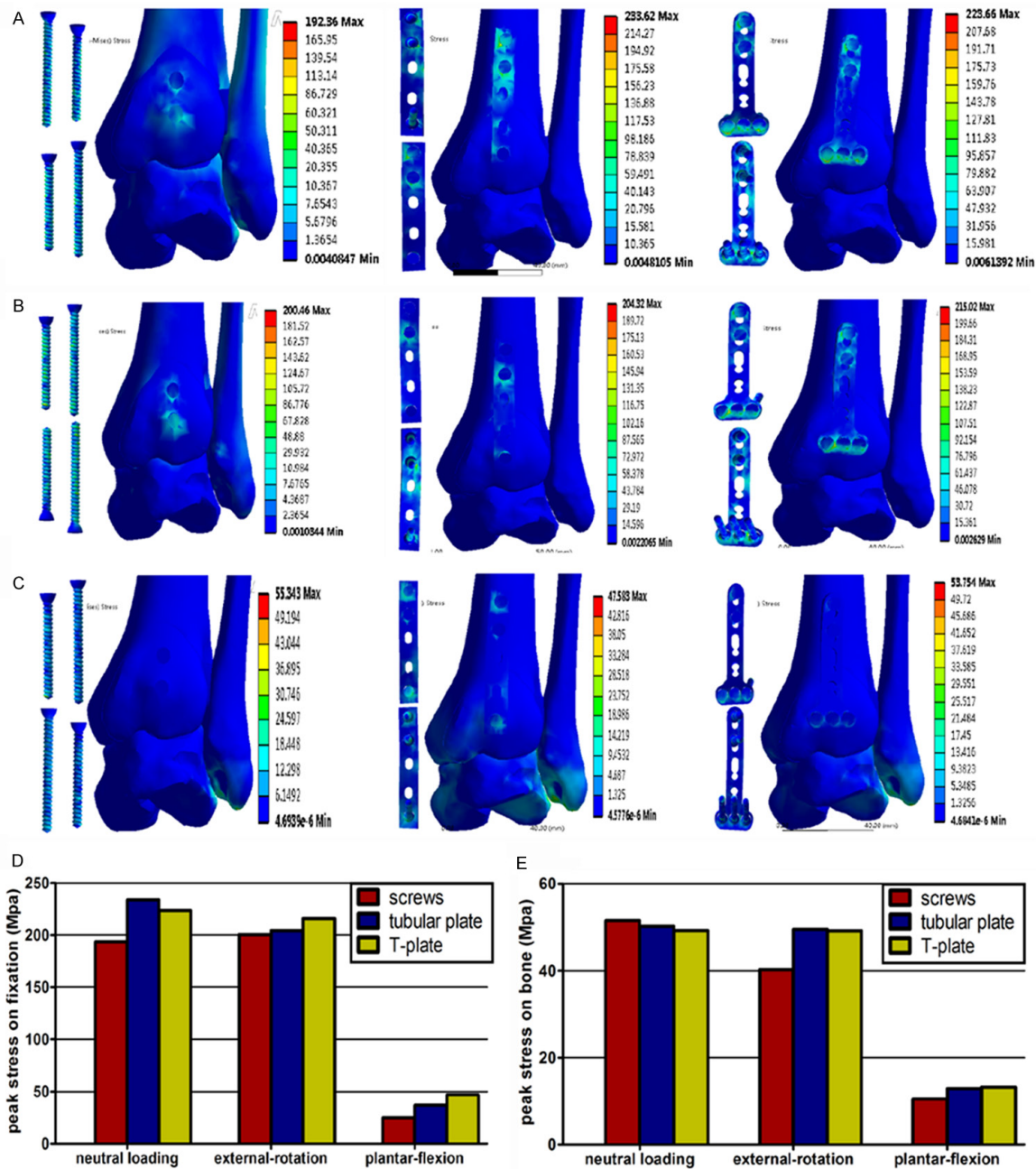


Figure 3. The stress state of bone and fixation in single fragments of PPF with various fixations. A: The stress distribution of model in the neutral ankle; B: The stress distribution of model in the external rotation of ankle; C: The stress distribution of model in the plantar flexion of ankle; D: The peak stress on fixation compared in various models; E: The peak stress on bone compared in various models.

neutral weighting of ankle in the two-foot standing condition. Plantar flexing of ankle was similarly stimulated by a 600N force angulated approximately 15 degree dorsad applied to the low surface of talus. To stimulate the ankle affected by the rotation force, with the longitudinal axis of the tibia set as the rotation axis, a 100N-cm of clockwise torsional force was applied at the proximal tibia to make a slightly

twisting effect of tibial. The direct results of Von Mises stress and displacement distributed in the bone, fragment and fixations were obtained. To look for the most stable fixation method, the effects of three fixations types in PPF were bio-mechanically compared in finite element analysis, including the displacement of fragment and the Von Mises stress distributed in the bone or fixation were compared. Under the force condi-

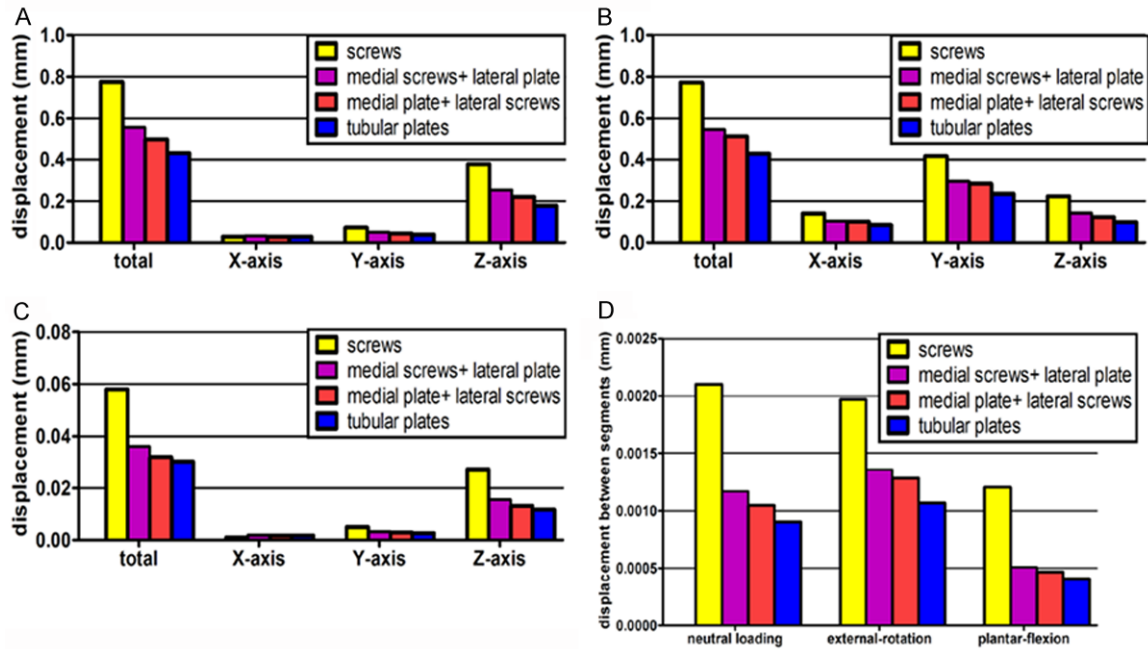


Figure 4. The max displacement in double fragments of PPF with various fixations. A: The peak displacement of fragments in the neutral ankle; B: The peak displacement of fragments in the external rotation of ankle; C: The peak displacement of fragments in the plantar flexion of ankle; D: The peak relative displacement between fragments.

tion, the displacement of fragment was detected and then the displacement projected on X, Y or Z axis was measured to show the directions of displacement. The referred relative displacement is the calculated by the highest balance between the two sides of fracture line which represent the displacement of fragment relative to bone.

Results

Model validation

The established 3D finite element ankle model and fixations were constructed (**Figure 1A** and **1B**) and applied to PPF models (**Figure 1C** and **1D**). In the part of validation of three-dimensional ankle model, our results revealed that the contact area was 405 mm²; the peak contact force was 4.5 MPa, while the main force concentrated in the anterior and lateral surface of ankle surface. Compared with the contact areas and presses reported in the previous papers [16] (**Figure 1E**), our results located in the range of results in literatures and the force distribution was approximately consistent with the results in cadaver ankles, indicating the ankle model was considered reliable. The neu-

tral loading was applied to simulate the single-foot standing position, as the results considered proper compared above. After applying the force of plantar flexion or external rotation, the motion of ankle joint was similar to the plantar-flexion or external-rotation condition of ankle in reality.

The advantage of T-plating method on stability reflected by the max displacement of fragment was revealed in the comparisons under three loading conditions. Under neutral loading, the max displacement in T-plate group was obviously lower compared with the tubular plate group or screws group (0.514 mm compared with 0.705 mm or 1.058 mm, **Figure 2A**), the displacement difference in Z-axis contributed to this difference mostly. While under loading of external rotation, the max displacement in T-plate group was also significantly lower compared with the tubular plate group or screws group (0.493 mm compared with 0.672 mm or 0.997 mm, **Figure 2B**), the displacement difference in Y-axis and Z-axis contributed to this difference equally. The displacement difference under plantar-flexion loading depicted the trend as well, but the value was tide and displacement difference in all axes was similar (**Figure**

Finite element analysis of fixed posterior pilon fractures

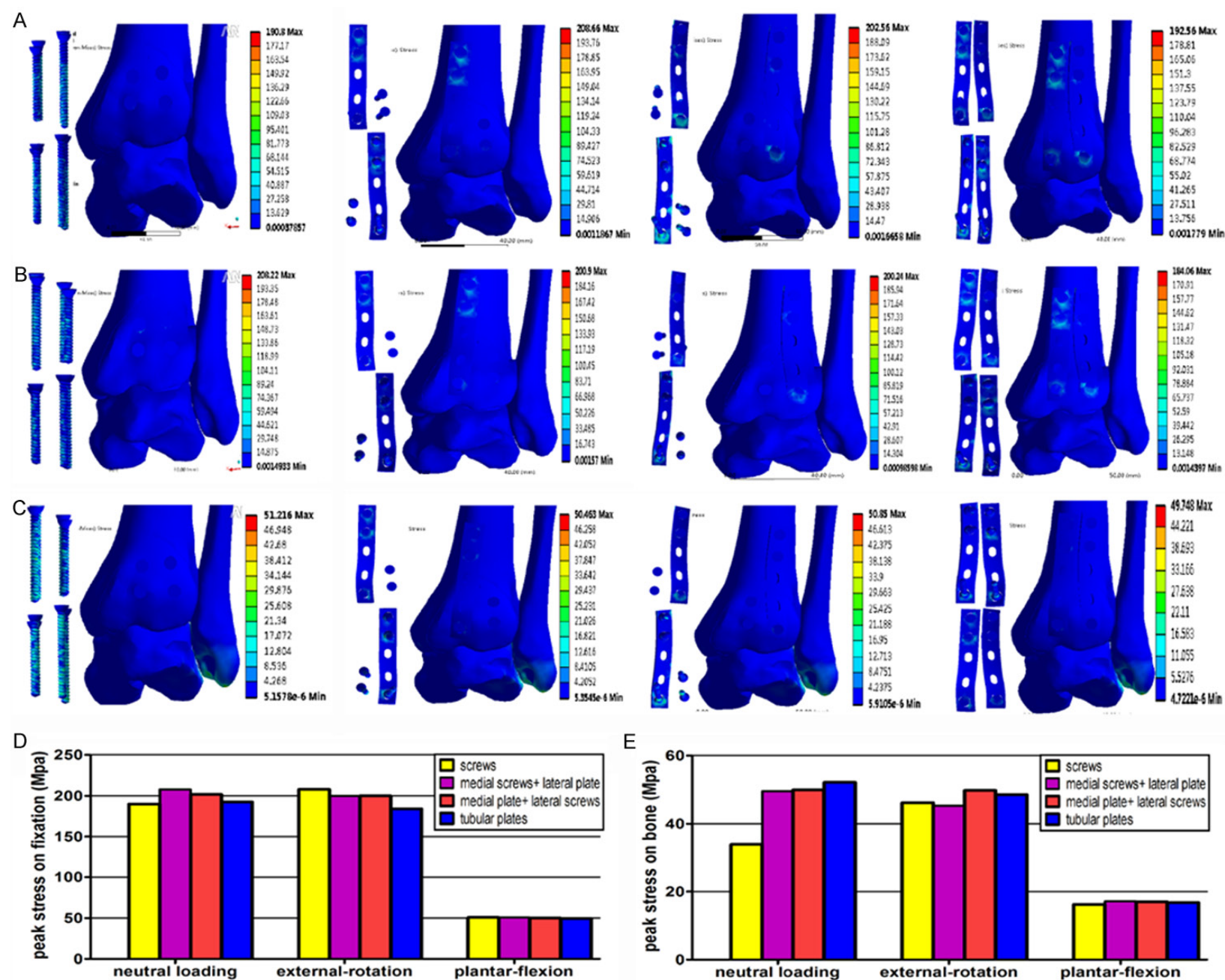


Figure 5. The stress state of bone and fixation in double fragments of PPF with various fixations. A: The stress distribution of model in the neutral ankle; B: The stress distribution of model in the external rotation of ankle; C: The stress distribution of model in the plantar flexion of ankle; D: The peak stress on fixation compared in various models; E: The peak stress on bone compared in various models.

2C). When referring to the relative displacement between fracture segments, the lowest displacement was observed in T-plate group compared with tubular-plating group or screwing group (**Figure 2D**).

The stress distribution on plants could demonstrate the stress concentration in various groups under various conditions (**Figure 3A-C**). In the screwing group during neutrality, plantar flexion or external rotation of ankle, the stress was all distributed uniformly on the arbor. When tubular plate was applied, the relative high stress value was detected around the top of plate (first and second hole) under neutral loading, also observed on the area of lowest screw and plate part. However, under the external-rotation condition, the area around the second hole and bottom of plate showed a high stress concentration. In addition, this distribution character was focused on the area around first hole and the bottom with the condition under plantar flexion loading. The peak stress seems to be highest on T-plate in external or plantar-flexion position and tubular plating in neutral position, while it is lowest on screw fixation condition (**Figure 3D**).

The advantage of plating method compared with screwing was significantly obvious for fixing two fragments in double PPF fragments. With the models under loading of neutral compressing, external rotation and plantar flexion, the max displacement all decreased with the number of plates increased. In addition, the medial plating with lateral screwing method showed a better stability than the lateral plating with medial screwing method (**Figure 4A-C**). These trends were also illustrated by the results of relative displacement analysis. The four screws used for fixation showed the relatively poor stability while the peak displacement could be reduced (decreased more than 36.5% at least) once the plating was adopted. The comparison trend of displacement values at three axis were similar to the loading trends in the single fragment of PPF models.

The stress distribution characters of four fixing methods under various conditions were demonstrated (**Figure 5A-C**). The results in the

three conditions revealed that the place of the plate affected the distribution of stress on fixation system: when the plate applied on the medial side of posterior distal tibial, the top first and second hole as well as the lowest hole bear obvious stress; when the single plate applied on the lateral side of fracture, the plate part around top second hole and the lowest hole bear obvious stress. These values of peak stress on bone tissue or fixation system was close within the four fixing method groups in plantar-flexion position.

Based on the results obtained from finite element analysis as images showing various force distribution conditions and numbers indicating even tiny displacements, we only tried to clarify the force variation between groups. Then the displacement value was not repeatable due to individual anatomy [13]. Thus the statistic software was not applied.

Discussion

Currently, one of the most controversial topics regarding the managing of PPFs was the using of screws and plates methods. To improve the unsatisfied outcomes of PPFs, the comparison of fixing effect of various fixation systems could contribute to the controversy of clinical treatment. Apart from the soft tissue problem that could affect the fixation choose largely, the stability of fixed fracture could reflect the fixing effect of multi fixations. In this finite element analysis of the current study [13], the main comparison focused on the two aspects: a, the peak displacement of fragment (total displacement or displacement in the axis); b, the peak stress and stress distribution on the fixation systems or bone tissue around, thus indicating the most stable and efficient fixation for PPF with single or double fragments. Our results indicated the most stable method could be the T-plate for the single fragment PPF model and the double plating method for the two segments PPF model, which could help guide the management choice in clinical practice.

Combined with the definition of PPF that the fragment typically involved the entire posterior lip as well as the posterior colliculus, the PPF

models were established following the typical appearance of PPF drawn by Weber [5] and the similar model used in biomechanical research by Rassch [6]. Based on the description and categorizing by Haraguchi [6], PPF belonged to the sub-type of medial-extension fracture pattern that involved the fracture of posterior colliculus, the fracture line of which was parallel to the bimalleolar axis according to the definitions. The accuracy of 3D model construction method was justified reasonable [14], while the result reflecting the displacement and stress close to reality was widely applied in the current studies. Finite element analysis serves as a valuable supplement to help guide treatment by simulating the hardly obtained bone reacting and investigating the stress distribution status in any surface of model. Using this relatively accurate method, the effectiveness of various fixation methods was evaluated experimentally.

PPF with single fragment was always revealed as the posterior malleolar fracture in the previous literature [9, 28]. The proper treatment of PPF also ranged from screws only to plating method as posterior malleolar fracture: cancellous lag screws fixation method was firstly described [4]; the using of tubular plate to buttress PPFs through posteromedial, posterolateral, or combined approaches was widely speared recently [1, 4]; the T-size plate to buttress the posterior fragments was also described [11, 29]. These above treatment choose researches were all based on the retrospective study or summary of experience with an evidence of level II. Our study revealed that fixation method of plates, especially T-plate, was experimentally superior stable than screws. The plating methods, tubular plate or T-plate used, reduced the displacement in the neutral, external rotating and plantar flexion ankle approximately decreased the half of displacement in the neutral ankle. The advantage of plating was widely considered as the prevention of superior migration of the posterior fragment under neutral loading [30], which was consistent with our results. The anteroposterior screws or dorsal antiglide plate fixation made different quality of the reduction of the posterior tibial malleolus (anatomic reduction in 27% patients in screwing group and 83% patients in the plating group) [31], which could account for the more stable holding of plating than screw-

ing. Although the stable behavior of plate was better than screws, the special fixation method was determined by the actual conditions of fracture and soft tissue, for instance the small fragment with compressive articular surface that screws were suitable in some cases [32].

The suppressing effect of either tubular plate or T-plate was produced by screwing above the apex of fragment [26, 33], thus preventing fragment migration upward. The posterolateral or posteromedial approach was available for the using of tubular plate fixing the lateral or medial side of fracture [30, 34]. The T-size plate was not so widely used for PPF but its biomechanical stability was observed obviously better than two screws [29]. Our analysis results showed the better suppressing behavior of T-plate than tubular plate, while the better stress distribution was also revealed. Due to the three screws in the T-plate fixed to the fragment thus providing more holding strength than one screw in the tubular plate, the fragment moved more slightly in each axis. The more screws of T-plate made more well-distributed stress due to the number of holding units. Currently, the tubular plate was more widely used perhaps because of the convenient shaping easily to be fit to the bone surface, the relatively limited exposure that approach provided [32]. However, some complex or comminuted segments of PPFs made tubular plate hard to apply.

Our results showed that the more plates applied, the more stable condition acquired. The stress distribution character that concentrated on the part above and below the proximal fracture edge indicating the exerted actual preventing moving upward effect. In clinical practice, the fracture segment size and the exposure that approach provided largely affected the clinical treatment choosing.

The position of plate in fixing two fragments of PPF affects the fracture stability in our study, suggesting the plate placed in the medial side produce more suppressing effect than the lateral side. That could be reasonable due to the critical role of medial structure in ankle stability that the deep structure of deltoid ligament attached to the posterior. Colliculus of medial malleolus, as well as the articular surface of media structure bearing more weighting than lateral structure [35]. Thus, the three points on the posteromedial main fragment were pro-

posed to be considered to be fixed as the lateral edge, proximal edge and posterior colliculus [5]. Medial applied plating caused more stress distributed area than the lateral plating, indicating its suppressing function and well distributed character. The posteromedial approach provided the proper but always relatively limited exposure to apply the method [30]. Therefore, the medial plating was feasible taken the fracture patterns into account.

The limits of technology in both equipment and software both affected our results. It is inevitable that any finite element model was distinguished with the real situation or cadaver model. All these simulated models were only approximately resemble the actual condition, while the deviation could affect the experimental accuracy. In addition, the properties could be affected over time by occurring of bone reconstruction. However, the more accurate were needed to simulated, but the results of fixations comparing could be reliable under the relatively accurate and same condition, thus depicting the actual trend of displacement and stress distribution.

T-plate can be superior to screws and tubular plate in fracture stability for single segment of PPF. In addition, the two tubular plates could be most stable in fixing double segments in PPF, while the medial plating could behave more stable than lateral plating.

Disclosure of conflict of interest

None.

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