Original Article

Three-dimensional finite element analysis of ankle arthrodesis

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Abstract: Background: Ankle arthrodesis is the gold standard and most commonly used method for the treatment of post-traumatic ankle arthritis. Aims: This study is to investigate the biomechanical safety and stability of four ankle fusion models through three-dimensional finite element analysis. Methods: Four ankle fusion models were established, including anterior plate ankle fusion model, lateral plate ankle fusion model, anterior plate plus posterolateral screw ankle fusion model and lateral plate plus posterolateral screw ankle fusion model. The four movement modes of the ankle internal rotation, external rotation, dorsiflexion and neutral mode were respectively simulated. The maximum displacement of the fusion surface and the stress of four movement modes were measured and analyzed. Results: The anterior plate plus posterolateral screw ankle fusion model had significantly decreased maximum surface displacement at all four movement modes than the anterior plate ankle fusion model (P<0.05). The maximum surface displacement of the lateral plate plus posterolateral screw plate ankle fusion model was significantly reduced at all four movement modes than that of the lateral plate ankle fusion model (P<0.05). Similarly, the stress peak of bone, plate and screw in the anterior/lateral plate plus posterolateral screw ankle fusion model was significantly reduced than that in the anterior/lateral plate ankle fusion model at the internal rotation state, the external rotation state and the dorsiflexion state, respectively (P<0.05). There was no significant difference at the neural state. Conclusion: The anterior/lateral plate plus posterolateral screw ankle fusion models have better fusion safety and higher fusion stability.

Keywords: Ankle arthritis, ankle arthrodesis, ankle fusion, three-dimensional finite element, plate, biomechanical

Introduction

Post-traumatic ankle arthritis often causes ankle pain and dysfunction if left untreated [1, 2]. Surgery, including ankle arthrodesis and ankle arthroplasty, is the main therapeutic method for post-traumatic ankle arthritis [1, 3]. And, ankle arthrodesis is the gold standard and most commonly used method [4-6]. There are more than 40 types of ankle arthrodesis [7-12]. The internal fixation is the preferred choice for most patients [13]. However, the healing of ankle fusion is hard to achieve and is still the biggest problem for ankle arthrodesis. It is reported that the three screw fixation has achieved good fusion rates. For example, Holt et al. [14] found that the best fixation was achieved when the first screw was placed from the posterior malleolus into the neck. Ogilvie et al. [15] argued that one lateral screw should be first placed to achieve good fixation during three screw fixation. Thus, the posterior screw and the lateral screw are of great importance for three screw fixation.

Plate ankle fusion is another widely used method for ankle fusion and has shown good clinical efficacy [16]. At present, the type of steel plate used mainly includes the anterior steel plate, the lateral steel plate and the posterior steel plate. Kakarala et al. [17] suggested that cross screw fixation plus the anterior contoured plate could produce stable internal fixation for ankle arthrodesis. However, there is no report on the biomechanical analysis of this combined ankle fusion method.

In the present study, we investigated the biomechanical properties of four different ankle fusion models by three-dimensional finite ele-
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Our findings may provide a better solution for the optimization of ankle arthrodesis and lay a theoretical foundation for further clinical research.

Materials and methods

Subject

One male volunteer was enrolled in this study. This volunteer was healthy, with age of 30. Ankle trauma and other related medical history were ruled out. This volunteer had been informed about the details of the experiment. Prior written and informed consent were obtained from this volunteer and the study was approved by the ethics review board of Affiliated Hospital of Chengde Medical College.

CT scanning

CT scanning was performed with Philip Tomoscans R7000 64 SCT. The right ankle joint was scanned. Data were saved and exported in DICOM format.

Establishment of plate ankle fusion model and plate plus posterolateral screw ankle fusion model

The model establishment was performed as previously described [18, 19]. Briefly, the anterior and the lateral plate ankle fusion models were established by fixing the plates on the anterior (Figure 1A) and the lateral sides (Figure 1B) by screws, respectively. Then, a posterolateral screw was placed from the distal end of the posterolateral tibia to the talus neck and talus head direction. The screw went
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Table 1. The finite element model statistics

<table>
<thead>
<tr>
<th>Finite element model</th>
<th>Total number of elements</th>
<th>Total number of nodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>The anterior plate ankle fusion model</td>
<td>170163</td>
<td>279042</td>
</tr>
<tr>
<td>The lateral plate ankle fusion model</td>
<td>171184</td>
<td>279041</td>
</tr>
<tr>
<td>The anterior plate plus posterolateral screw ankle fusion model</td>
<td>178042</td>
<td>279041</td>
</tr>
<tr>
<td>The lateral plate plus posterolateral screw ankle fusion model</td>
<td>179063</td>
<td>279041</td>
</tr>
</tbody>
</table>

Table 2. Material properties of bone, plate and screw

<table>
<thead>
<tr>
<th>Material</th>
<th>Elastic modulus (MPa)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone</td>
<td>7300</td>
<td>0.3</td>
</tr>
<tr>
<td>Plate and screw</td>
<td>200000</td>
<td>0.3</td>
</tr>
</tbody>
</table>

through the longest diameter of talus [20]. Thus, the model of anterior plate with posterolateral screw ankle fusion (Figure 1C) and the model of lateral plate with posterolateral screw ankle fusion (Figure 1D) were established.

Assignment of elements and material properties

The modified second-order tetrahedral element (C3D10M) in the baqus/standard was used for bones. The reduced hexahedral element C3D8R was used for plates and screws. The specific grid statistics of the finite element model are shown in Table 1. The bone structure was defined as an isotropic linear elastic material. The material properties of bone, plate and screws were determined by reference to the prior literature [21] and are shown in Table 2.

Contact boundary conditions and loads

In this study, the geometric model of the screw was simplified. Therefore, in order to simulate the pressing effect of the threaded part, the contact surface between the thread and the talus, and that between the upper of the screw and the tibia were set as tie constraints. Other contact parts were set as hard contact. The friction coefficient was set as 0.15. The friction coefficient between tibia and talus surface was set as 0.7. The remaining contact parts that had small effects on the results were defined as frictionless hard contact [22]. According to the actual activities of walking state, the four movement modes of the ankle internal rotation, external rotation, dorsiflexion and neutral mode were respectively simulated [23] (Table 3).

Evaluation index

The fusion stability and safety of the four models in this study were evaluated. The fusion stability was evaluated by the maximum displacement of the fusion surface. The fusion safety was assessed by the stress peak and stress distribution of bone, plate and screw.

Statistical analysis

Data was processed using SPSS 18.0 statistical software. Paired t-test was used to analyze the differences between two groups. P<0.05 was considered statistically significant.

Results

The maximum surface displacement

To determine the fusion stability of the four fusion models, the maximum surface displacement at four different movement modes was evaluated. As shown in Table 4, The maximum surface displacement of the anterior plate plus posterolateral screw ankle fusion model was decreased than that of the anterior plate ankle fusion model, with significant differences at all four movement modes (P<0.05). Similarly, compared with the lateral plate ankle fusion model, the maximum surface displacement of the lateral plate plus posterolateral screw plate ankle fusion model was significantly reduced at all four movement modes (P<0.05). This result indicates that the fusion stability of the anterior/lateral plate plus posterolateral screw ankle fusion model is higher than that of the anterior/lateral plate ankle fusion model, respectively.

The stress peak and stress distribution of bone, plate and screw

To analyze the fusion safety of four fusion models, the stress peak and stress distribution of
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Table 3. The load parameters of four different movement modes

<table>
<thead>
<tr>
<th>Load amplitude (NM)</th>
<th>Internal rotation (Torque)</th>
<th>External rotation (Torque)</th>
<th>Dorsiflexion (Bending moment)</th>
<th>Neural mode (Vertical)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>2100</td>
</tr>
</tbody>
</table>

Table 4. The maximum surface displacement of four different movement modes in four fusion models

<table>
<thead>
<tr>
<th>The maximum surface displacement (mm)</th>
<th>Internal rotation (Torque)</th>
<th>External rotation (Torque)</th>
<th>Dorsiflexion (Bending moment)</th>
<th>Neural mode (Vertical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>The anterior plate ankle fusion model</td>
<td>1.6</td>
<td>0.33</td>
<td>2.07</td>
<td>0.37</td>
</tr>
<tr>
<td>The anterior plate plus posterolateral screw ankle fusion model</td>
<td>0.18*</td>
<td>0.16*</td>
<td>0.17*</td>
<td>0.38*</td>
</tr>
<tr>
<td>The lateral plate ankle fusion model</td>
<td>0.24</td>
<td>1.4</td>
<td>0.45</td>
<td>0.48</td>
</tr>
<tr>
<td>The lateral plus posterolateral screw plate ankle fusion model</td>
<td>0.16*</td>
<td>0.16*</td>
<td>0.23*</td>
<td>0.49*</td>
</tr>
</tbody>
</table>

Note: The anterior plate ankle fusion model VS The anterior plate plus posterolateral screw ankle fusion model, *P<0.05. The lateral plate ankle fusion model VS The lateral plus posterolateral screw plate ankle fusion model, #P<0.05.

Figure 2. The stress distribution of the anterior plate ankle fusion model at the internal rotation state, the external rotation state, the dorsiflexion state, and the neutral state. A. The stress distribution of the bone at four movement modes. B. The stress distribution of the plate at four movement modes. C. The stress distribution of the screw at four movement modes.
bone, plate and screw were assessed. The stress distribution of bone, plate and screw in the anterior plate ankle fusion model was shown in Figure 2, that in the anterior plate plus posterolateral screw ankle fusion model was shown in Figure 3, that in the lateral plate ankle fusion model was shown in Figure 4, and that in the lateral plate plus posterolateral screw ankle fusion model was shown in Figure 5.

The stress peak of bone, plate and screw in the anterior plate ankle fusion model and the anterior plate plus posterolateral screw ankle fusion model was listed in Table 5. The stress peak of bone, plate and screw in the anterior plate plus posterolateral screw ankle fusion model was significantly decreased at the internal rotation state, the external rotation state and the dorsiflexion state (P<0.05), but not at the neutral state. Similarly, as shown in Table 6, the stress

Figure 3. The stress distribution of the anterior plate plus posterolateral screw ankle fusion model at the internal rotation state, the external rotation state, the dorsiflexion state, and the neutral state. A. The stress distribution of the bone at four movement modes. B. The stress distribution of the plate at four movement modes. C. The stress distribution of the screw at four movement modes.
peak of bone, plate and screw in the lateral plate plus posterolateral screw ankle fusion model was significantly reduced than that in the lateral plate ankle fusion model at the internal rotation state, the external rotation state and the dorsiflexion state, respectively (P<0.05). No significant difference was found at the neutral state. Together, these results suggest that the anterior/lateral plate plus posterolateral screw ankle fusion models have better fusion safety.

**Figure 4.** The stress distribution of the lateral plate ankle fusion model at the internal rotation state, the external rotation state, the dorsiflexion state, and the neutral state. A. The stress distribution of the bone at four movement modes. B. The stress distribution of the plate at four movement modes. C. The stress distribution of the screw at four movement modes.

**Discussion**

The finite element analysis technique was first used in the field of orthopedic surgery in 1972 [24] and has been widely used in the field of orthopedics since. SpyrouLA established a three-dimensional finite element model of the normal ankle joint, which also included the distal tibia [25]. The finite element model has stable mechanical properties and can be used repeatedly to simulate the complex anatomical
structures and material properties [26-28]. It can also simulate various working conditions that cannot be achieved by traditional biomechanical experiments [28]. In this study, the three-dimensional finite element model of normal human ankle joint was successfully established by collecting the CT image data of normal human ankle joint. The ankle joint fusion operation was simulated on this model. Four different ankle fusion models were successfully established, with good fusion stability and safety.

The internal fixation and the fusion surface are two key factors of the ankle fusion, and are also two artificial controllable factors during the fusion process [29]. The use of screws and intramedullary nails is to increase the fixation strength and pressure of the fusion surface as much as possible [30]. In recent years, with the development of steel plate technology, steel plate fixation is used in ankle fusion [31, 32]. In the clinical practice, we observe that the fixation effect of steel plate is better, with good stability. The joint stiffness of patients can be

Figure 5. The stress distribution of the lateral plate plus posterolateral screw ankle fusion model at the internal rotation state, the external rotation state, the dorsiflexion state, and the neutral state. A. The stress distribution of the bone at four movement modes. B. The stress distribution of the plate at four movement modes. C. The stress distribution of the screw at four movement modes.
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The external force may induce deformation in the ankle joint surface and the degree of the deformation will affect the effect of ankle fusion [32]. It is reported that plate plus screw fixation can significantly increase fusion strength [34, 35]. In the present study, the internal rotation, external rotation, dorsiflexion and neutral movement modes were used to simulate the external forces. The maximum surface displacement of the anterior/lateral plate plus posterolateral screw ankle fusion model was significantly decreased. Consistent with previous reports [34, 35], our results indicate that by combining plate and screws, the strength and stability of the ankle joint fusion is greatly enhanced. Meanwhile, the stress peak of the anterior/lateral plate plus posterolateral screw ankle fusion model was significantly reduced. This suggests that the risks of broken nails, broken plate and even stress fractures may be effectively reduced and the safety of fixation may be greatly improved.

This study has some limitations. First, the fibula and surrounding soft tissue were removed in our models and their effects on the ankle movement were omitted. Second, the screws and steel plate were simplified. Third, the effects of bone conditions on screw fixation were ignored. Thus, there is still a certain degree of difference between the finite element model and the real situation of the ankle joint. Further study is warranted to more realistically simulate the real situation of the ankle joint.

In conclusion, our findings demonstrate that the anterior/lateral plate plus posterolateral screw ankle fusion model is effective and feasible in treatment of post-traumatic ankle arthritis.

Disclosure of conflict of interest
None.

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