Int J Clin Exp Med 2017;10(8):11749-11758
www.ijcem.com /ISSN:1940-5901/IJCEM0056441

Original Article

Three-dimensional finite element analysis of ankle arthrodesis

Qiang Xie[1], Wenyi Liu[2], Zhihui Wang[3], Yunfeng Gao[1], Xinxin Xue[1]

[1]*Department of Hand and Foot Surgery, Affiliated Hospital of Chengde Medical College, Chengde, P. R. China; Departments of* [2]*Social Sciences,* [3]*Joint Surgery, Chengde Medical College, Chengde, P. R. China*

Received April 28, 2017; Accepted July 6, 2017; Epub August 15, 2017; Published August 30, 2017

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-

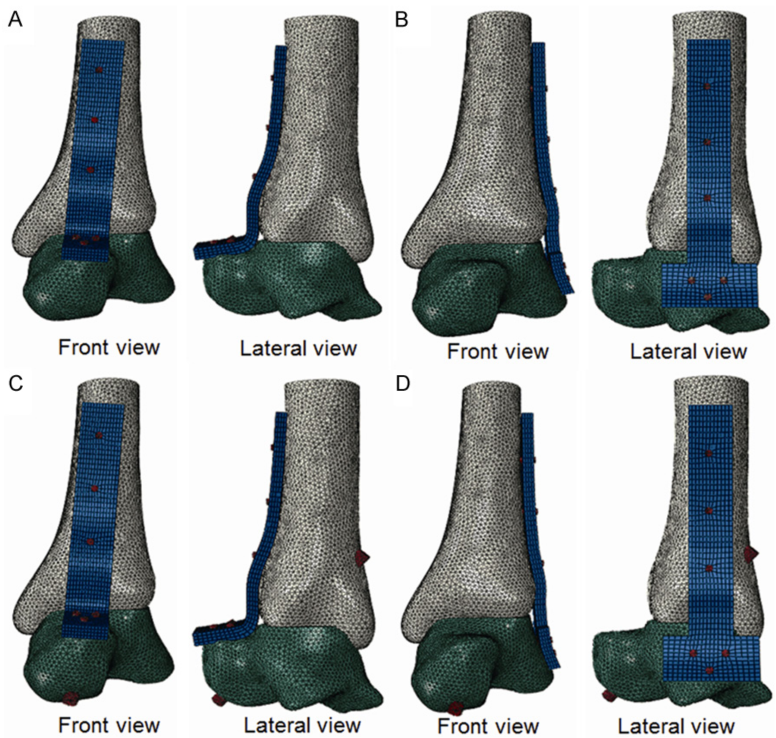

Figure 1. The plate ankle fusion model and plate plus posterolateral screw ankle fusion model. A. The front and lateral views of the anterior plate ankle fusion model. B. The front and lateral views of the lateral plate ankle fusion model. C. The front and lateral views of the anterior plate plus posterolateral screw ankle fusion model. D. The front and lateral views of the lateral plus posterolateral screw plate ankle fusion model.

ment analysis. 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 the three-dimensional finite element model of normal ankle joint

The Mimics 17.0 software (Materialise Co., Belgium) was used to read the DICOM format image data and establish the initial three-dimensional structure of ankle joint. The data were exported as STL grid file. The STL grid file was then imported into Ansa software (BETA, Greece), and geometrically reconstructed and cleaned. The parameters such as the grid, the material, the contact, the constraint, and the load were adjusted to obtain the INP data. The INP data was submitted to the Abaqus 2016 finite element analysis software (Dassault SIMULIA, France) to get the ODB file, which was finally treated with Abaqus/Viewer (Abaqus6.9, Dassault SIMULIA, France) to obtain the three-dimensional geometric model of the ankle joint. In addition, using the solid modeling function of the Abaqus 2016 finite element analysis software, the screws were simplified. The threads were ignored and the screw trucks were replaced with 6.5 mm diameter cylinders. The length of the screws was adjusted according to the actual situation. The ankle fusion plate (Xiamen Dabo Yingjing Medical Devices Co., Ltd., Xiamen, China) was also simplified and reconstructed with this software.

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

Table 1. The finite element model statistics

Finite element model	Total number of elements	Total number of nodes
The anterior plate ankle fusion model	170163	279042
The lateral plate ankle fusion model	171184	279041
The anterior plate plus posterolateral screw ankle fusion model	178042	279041
The lateral plus posterolateral screw plate ankle fusion model	179063	279041

Table 2. Material properties of bone, plate and screw

Material	Elastic modulus (MPa)	Poisson's ratio
Bone	7300	0.3
Plate and screw	200000	0.3

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

Table 3. The load parameters of four different movement modes

	Internal rotation (Torque)	External rotation (Torque)	Dorsiflexion (Bending moment)	Neural mode (Vertical)
Load amplitude (NM)	10	10	10	2100

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

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

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.

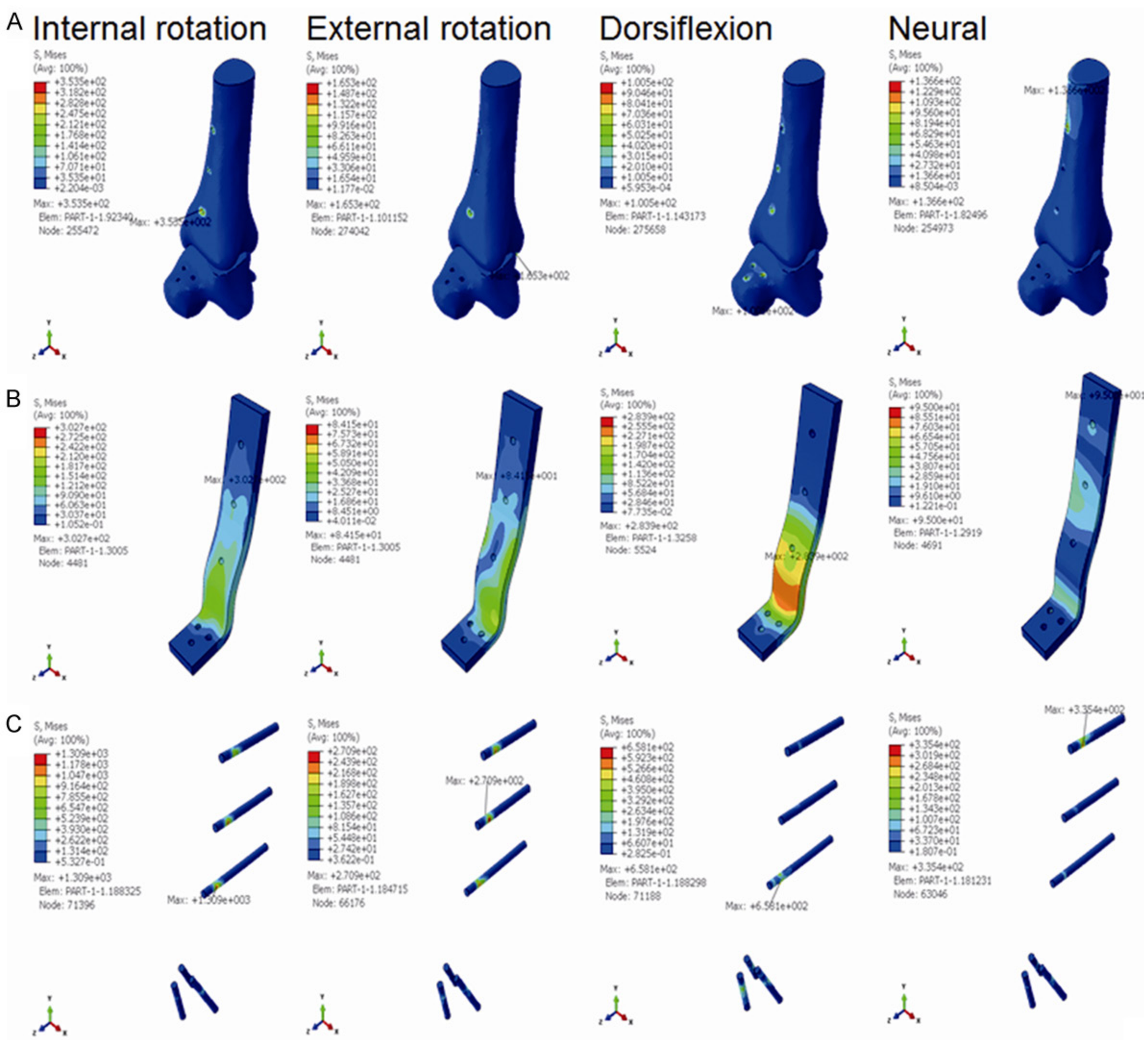

Figure 2. The stress distribution of the anterior plate ankle fusion model at the internal rotation state, the external rotation state, the dorsiflexion state, and the neutral state. A. The stress distribution of the bone at four movement modes. B. The stress distribution of the plate at four movement modes. C. The stress distribution of the screw at four movement modes.

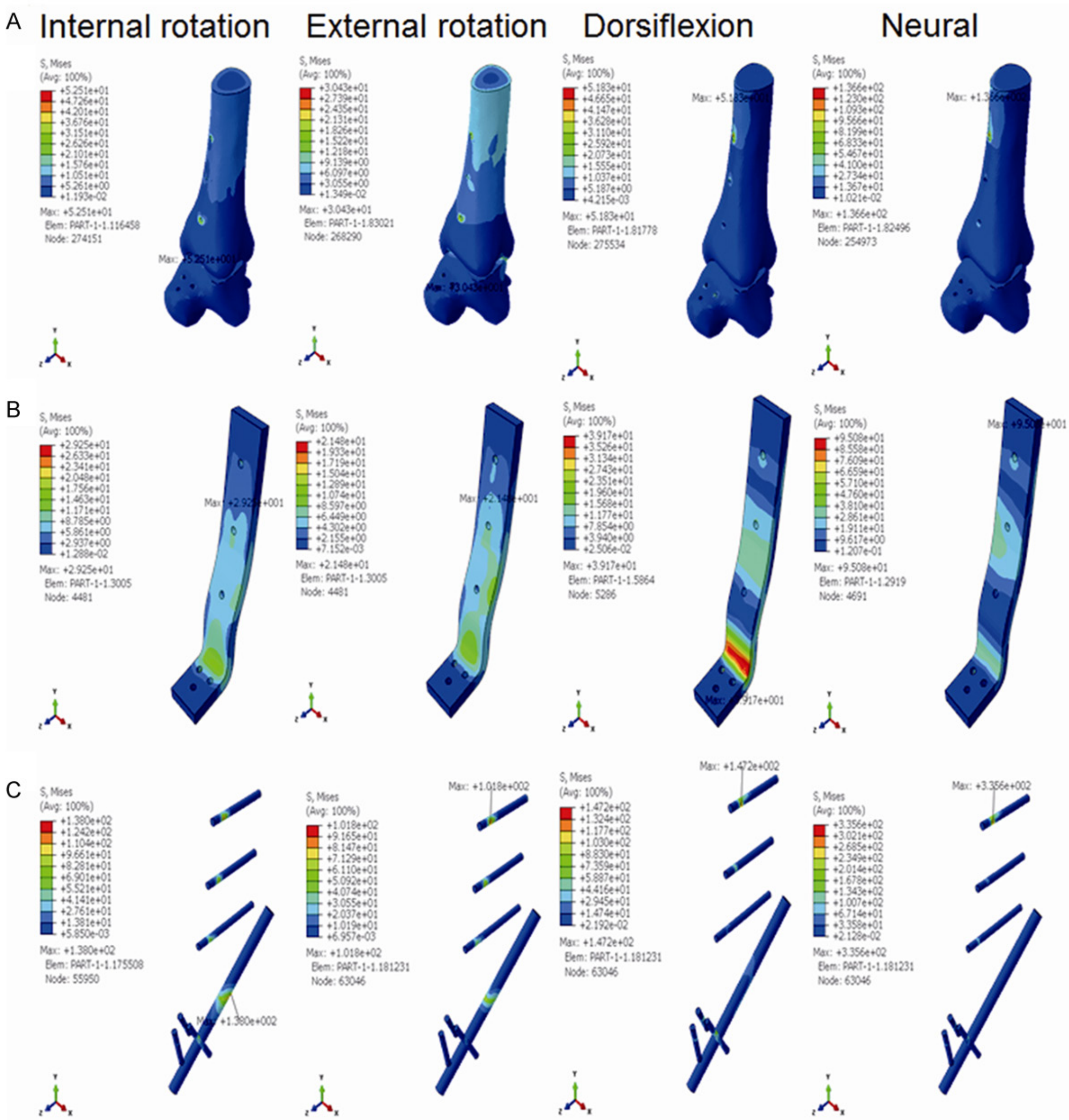

Figure 3. The stress distribution of the anterior plate plus posterolateral screw ankle fusion model at the internal rotation state, the external rotation state, the dorsiflexion state, and the neutral state. A. The stress distribution of the bone at four movement modes. B. The stress distribution of the plate at four movement modes. C. The stress distribution of the screw at four movement modes.

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 neural state. Similarly, as shown in **Table 6**, the stress

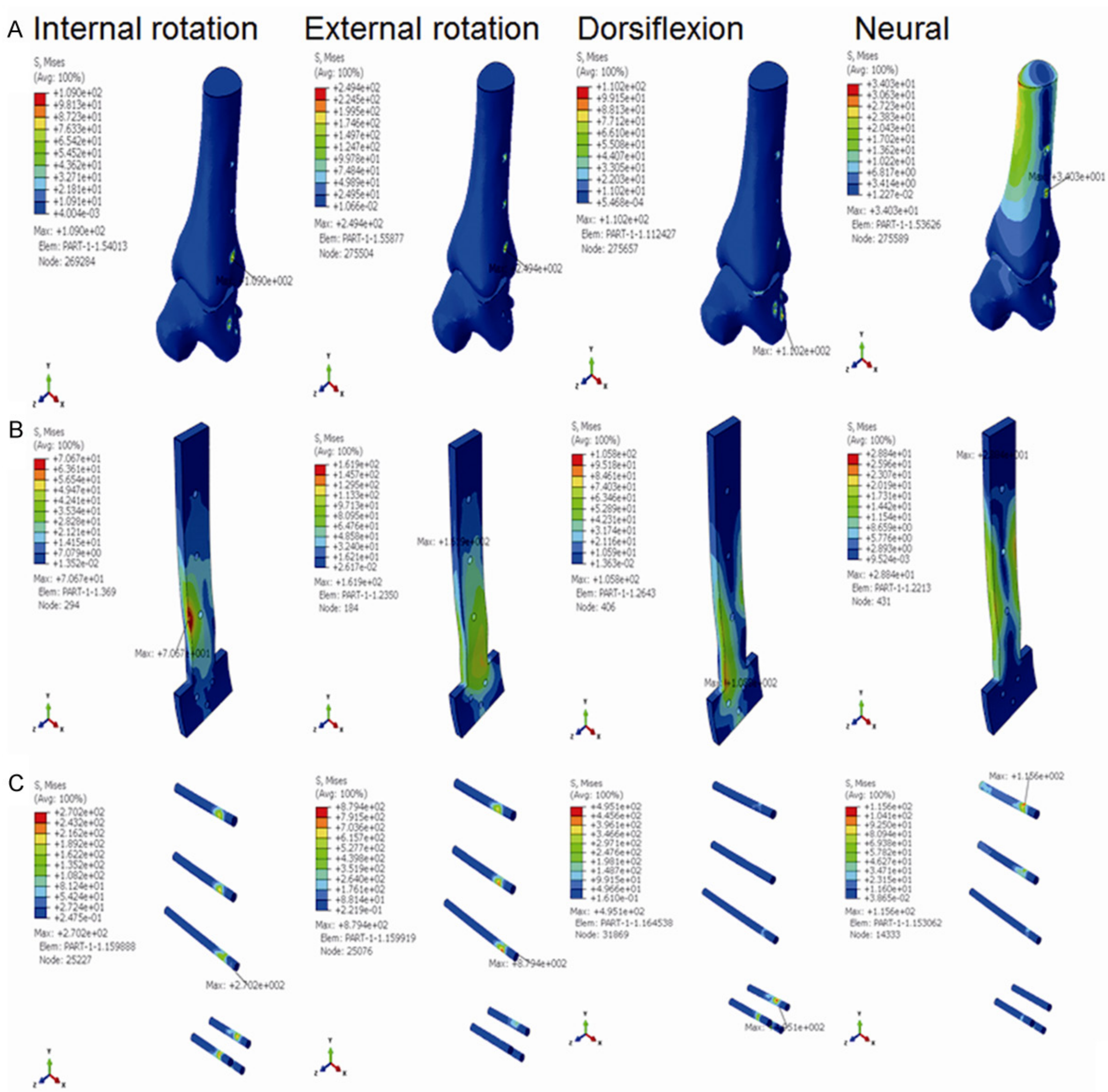

Figure 4. The stress distribution of the lateral plate ankle fusion model at the internal rotation state, the external rotation state, the dorsiflexion state, and the neutral state. A. The stress distribution of the bone at four movement modes. B. The stress distribution of the plate at four movement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

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 neural state. Together, these results suggest that the anterior/lateral plate plus posterolateral screw ankle fusion models have better fusion safety.

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

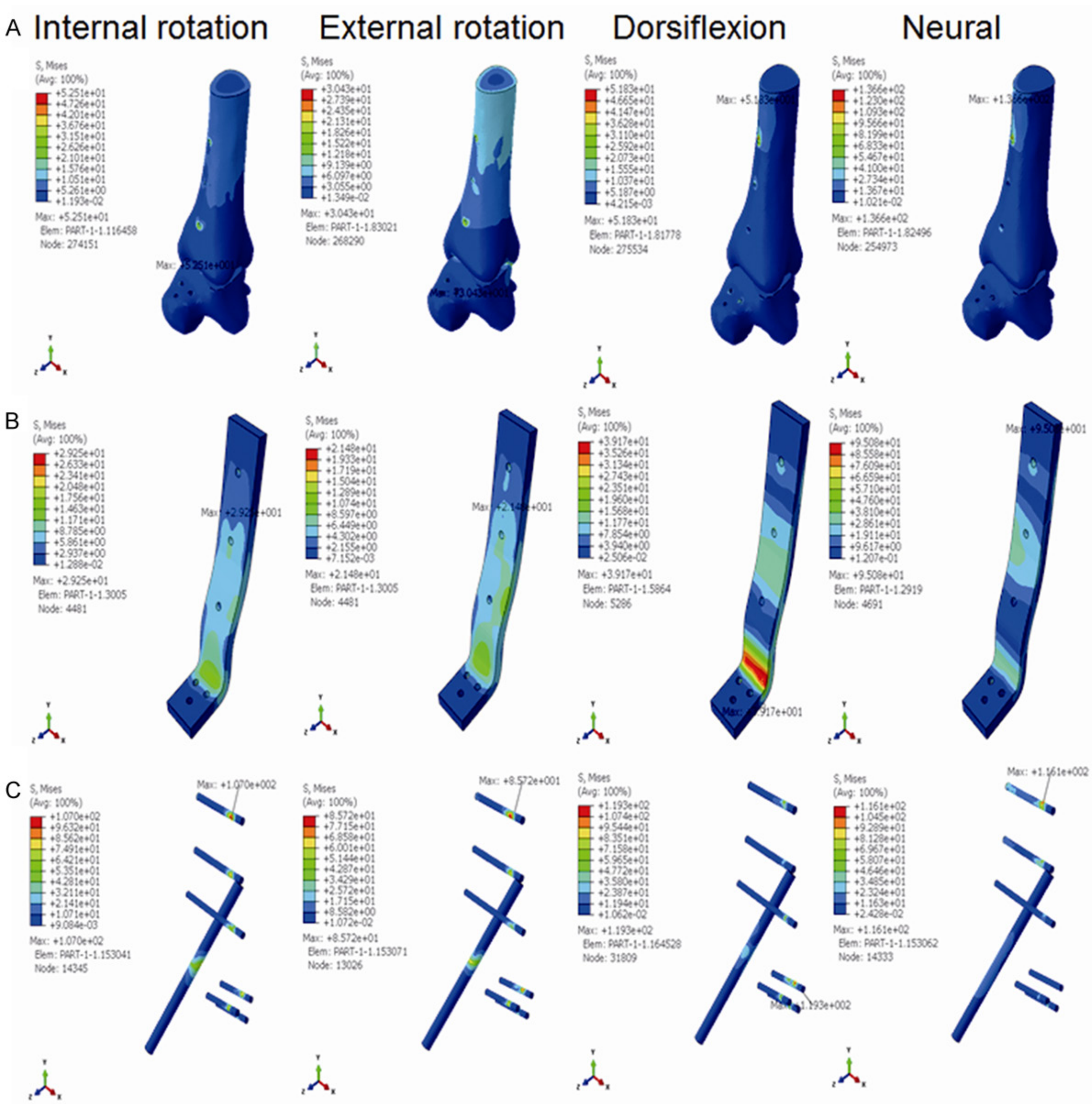

Figure 5. The stress distribution of the lateral plate plus posterolateral screw ankle fusion model at the internal rotation state, the external rotation state, the dorsiflexion state, and the neutral state. A. The stress distribution of the bone at four movement modes. B. The stress distribution of the plate at four movement modes. C. The stress distribution of the screw at four movement modes.

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

Table 5. The stress peak of the anterior plate fusion model and the anterior plate plus posterolateral screw ankle fusion model

	Stress peak (MPa)	Internal rotation (Torque)	External rotation (Torque)	Dorsiflexion (Bending moment)	Neural mode (Vertical)
The anterior plate fusion model	Bone	353.5	165.3	101	136.6
	Plate	302.7	84.2	284.9	95
	Screw	1309	270.9	685.1	335.4
The anterior plate plus posterolateral screw ankle fusion model	Bone	52.5*	30.4*	51.8*	136.6
	Plate	29.3*	21.5*	39.2*	95
	Screw	138*	101.8*	147.2*	335.4

Note: Stress peak of bone, plate, screw in the anterior plate ankle fusion model VS that in the anterior plate plus posterolateral screw ankle fusion model, respectively, *$P<0.05$.

Table 6. The stress peak of the lateral plate fusion model and the lateral plate plus posterolateral screw ankle fusion model

	Stress peak (MPa)	Internal rotation (Torque)	External rotation (Torque)	Dorsiflexion (Bending moment)	Neural mode (Vertical)
The lateral plate fusion model	Bone	109	249.4	110.2	34
	Plate	70.7	161.9	105.8	28.8
	Screw	270.2	879.4	495.1	115.6
The lateral plate plus posterolateral screw ankle fusion model	Bone	43.4*	30.9*	36.5*	34.1
	Plate	24.8*	16.1*	29*	29.1
	Screw	107*	85.7*	129.3*	116.1

Note: Stress peak of bone, plate, screw in the lateral plate ankle fusion model VS that in the lateral plate plus posterolateral screw ankle fusion model, respectively, *$P<0.05$.

decreased by plate fixation [33]. 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.

Address correspondence to: Qiang Xie, Department of Hand and Foot Surgery, Affiliated Hospital of Chengde Medical College, Xinya Villa, Shidongzigou Road, Shuangqiao District, Chengde 067000, P. R. China. Tel: +86-15732453648; E-mail: 554398-579@qq.com

References

[1] Weatherall JM, Mroczek K, McLaurin T, Ding B and Tejwani N. Post-traumatic ankle arthritis. Bull Hosp Jt Dis (2013) 2013; 71: 104-112.

[2] Castagnini F, Pellegrini C, Perazzo L, Vannini F and Buda R. Joint sparing treatments in early ankle osteoarthritis: current procedures and future perspectives. J Exp Orthop 2016; 3: 3.
[3] Popelka S, Sosna A, Vavrik P, Jahoda D, Bartak V and Landor I. [Eleven-year experience with total ankle arthroplasty]. Acta Chir Orthop Traumatol Cech 2016; 83: 74-83.
[4] Nihal A, Gellman RE, Embil JM and Trepman E. Ankle arthrodesis. Foot Ankle Surg 2008; 14: 1-10.
[5] Abidi NA, Gruen GS and Conti SF. Ankle arthrodesis: indications and techniques. J Am Acad Orthop Surg 2000; 8: 200-209.
[6] Haddad SL, Coetzee JC, Estok R, Fahrbach K, Banel D and Nalysnyk L. Intermediate and long-term outcomes of total ankle arthroplasty and ankle arthrodesis. A systematic review of the literature. J Bone Joint Surg Am 2007; 89: 1899-1905.
[7] Colman AB and Pomeroy GC. Transfibular ankle arthrodesis with rigid internal fixation: an assessment of outcome. Foot Ankle Int 2007; 28: 303-307.
[8] Nickisch F, Avilucea FR, Beals T and Saltzman C. Open posterior approach for tibiotalar arthrodesis. Foot Ankle Clin 2011; 16: 103-114.
[9] Torudom Y. The results of ankle arthrodesis with screws for end stage ankle arthrosis. J Med Assoc Thai 2010; 93 Suppl 2: S50-54.
[10] Clare MP and Sanders RW. The anatomic compression arthrodesis technique with anterior plate augmentation for ankle arthrodesis. Foot Ankle Clin 2011; 16: 91-101.
[11] Yasui Y, Takao M, Miyamoto W, Innami K, Komatsu F, Narita N and Matsushita T. Technique tip: open ankle athrodesis using locking compression plate combined with anterior sliding bone graft. Foot Ankle Int 2010; 31: 1125-1128.
[12] Gessmann J, Ozokyay L, Fehmer T, Muhr G and Seybold D. [Arthrodesis of the infected ankle joint: results with the Ilizarov external fixator]. Z Orthop Unfall 2011; 149: 212-218.
[13] Latt LD, Glisson RR, Adams SB Jr, Schuh R, Narron JA and Easley ME. Biomechanical comparison of external fixation and compression screws for transverse tarsal joint arthrodesis. Foot Ankle Int 2015; 36: 1235-1242.
[14] Holt ES, Hansen ST, Mayo KA and Sangeorzan BJ. Ankle arthrodesis using internal screw fixation. Clin Orthop Relat Res 1991; 21-28.
[15] Ogilvie-Harris DJ, Fitsialos D and Hedman TP. Arthrodesis of the ankle. A comparison of two versus three screw fixation in a crossed configuration. Clin Orthop Relat Res 1994; 195-199.
[16] Mitchell PM, Douleh DG and Thomson AB. Comparison of ankle fusion rates with and without anterior plate augmentation. Foot Ankle Int 2017; 38: 419-423.
[17] Kakarala G and Rajan DT. Comparative study of ankle arthrodesis using cross screw fixation versus anterior contoured plate plus cross screw fixation. Acta Orthop Belg 2006; 72: 716-721.
[18] Gui ZS, Xu XF and Li HY. Comparison of headless compression screw and interlocking compression plate fixation in ankle fusion. Zhong Guo Zu Zhi Gong Cheng Yan Jiu 2016; 20: 4623-4629.
[19] Xiong LP and Zhang SM. Technique and short-term results of ankle arthrodesis using anterior plating. Orthopedic Journal of China 2010; 18: 2055.
[20] Schuberth JM, Ruch JA and Hansen ST Jr. The tripod fixation technique for ankle arthrodesis. J Foot Ankle Surg 2009; 48: 93-96.
[21] Lu CH, Yu B, Chen HQ and Lin QR. Establishment and stress analysis of three-dimensional finite element model of talus in normal gait Nan Fang Yi Ke Da Xue Xue Bao 2011; 2273-2276.
[22] Clifford C, Berg S, McCann K and Hutchinson B. A biomechanical comparison of internal fixation techniques for ankle arthrodesis. J Foot Ankle Surg 2015; 54: 188-191.
[23] Yasui Y, Hannon CP, Seow D and Kennedy JG. Ankle arthrodesis: a systematic approach and review of the literature. World J Orthop 2016; 7: 700-708.
[24] Huiskes R and Chao EY. A survey of finite element analysis in orthopedic biomechanics: the first decade. J Biomech 1983; 16: 385-409.
[25] Spyrou LA and Aravas N. Muscle-driven finite element simulation of human foot movements. Comput Methods Biomech Biomed Engin 2012; 15: 925-934.
[26] Vazquez AA, Lauge-Pedersen H, Lidgren L and Taylor M. Finite element analysis of the initial stability of ankle arthrodesis with internal fixation: flat cut versus intact joint contours. Clin Biomech (Bristol, Avon) 2003; 18: 244-253.
[27] de Leeuw PA, Hendrickx RP, van Dijk CN, Stufkens SS and Kerkhoffs GM. Midterm results of posterior arthroscopic ankle fusion. Knee Surg Sports Traumatol Arthrosc 2016; 24: 1326-1331.
[28] Wang Y, Li Z, Wong DW and Zhang M. Effects of ankle arthrodesis on biomechanical performance of the entire foot. PLoS One 2015; 10: e0134340.
[29] Rabinovich RV, Haleem AM and Rozbruch SR. Complex ankle arthrodesis: review of the literature. World J Orthop 2015; 6: 602-613.
[30] Zhang C, Shi Z and Mei G. Locking plate versus retrograde intramedullary nail fixation for tibio-

talocalcaneal arthrodesis: a retrospective analysis. Indian J Orthop 2015; 49: 227-232.

[31] Zwipp H. Arthrodesis of the ankle. Acta Chir Orthop Traumatol Cech 2017; 84: 13-23.

[32] Slater GL, Sayres SC and O'Malley MJ. Anterior ankle arthrodesis. World J Orthop 2014; 5: 1-5.

[33] Chen ZB, Hong GX and Wang FB. Upper limb function assessment table. Zhong Guo Xiu Fu Chong Jian Wai Ke Za Zhi 2004; 18: 520-521.

[34] Ahmad J, Pour AE and Raikin SM. The modified use of a proximal humeral locking plate for tibiotalocalcaneal arthrodesis. Foot Ankle Int 2007; 28: 977-983.

[35] Mueckley TM, Eichorn S, von Oldenburg G, Speitling A, DiCicco JD 3rd, Hofmann GO and Buhren V. Biomechanical evaluation of primary stiffness of tibiotalar arthrodesis with an intramedullary compression nail and four other fixation devices. Foot Ankle Int 2006; 27: 814-820.