Research Article

The Journal of Hepatology

3D finite-element analysis is used to compare several internal fixation models in ankle arthrodesis.

Heng De, Jing-bo Hb, Huang-jing jai[1].

***Corresponding author**

Heng De,
Department of Orthopaedic Medicine, Third Afliated Hospital of Inner Mongonia Medical University, China.

Received Date : May 04, 2024
Accepted Date : May 06, 2024
Published Date : June 06, 2024

ABSTRACT

Background : Abstraction The aim of this work is to investigate the biomechanical characteristics of several internal fixators for ankle arthrodesis using three-dimensional finite-element analysis.
Techniques We compared four distinct internal fixations in ankle arthrodesis using finite-element analysis:
Group D had one anterior anatomical plate (Ø3.5 mm) and one posterior-lateral screw (Ø6.5 mm), Group C only had an anterior anatomical plate (Ø3.5 mm), and Group A had three crossed screws (Ø6.5 mm); Group B had two crossed screws (Ø6.5 mm) and an anterior plate (Ø2.7 mm). The displacement of the arthrodesis surface, as well as the stress peak and stress distribution of these models under intorsion, extorsion, and dorsifexion torque, were analyzed and compared for the four types using Ansys 21.0 software. and a vertical load that is neutral.
Outcomes : Arthrodesis surface displacement: Under neutral vertical load and dorsifexion torque, Group A's maximum displacement was more than Group D's, but it was less under intorsion and extorsion torque. The maximal displacement in Group B was less than that of the other three fxation models against dorsifexion, neutral vertical load, intorsion, and extorsion. The maximum displacement in Group C was much higher than that in the other three fixation models when compared to the four loading patterns mentioned above. Stress peak and distribution: the middle portions of the compression screws, plate joints, and bending portions of the plates were where the peak von Mises stress was concentrated, according to the stress distribution of the four models.

conclusion : The fxation model with an anterior and two crossing screws performed better in terms of biomedical benefits than the other three fxation models; as a result, this model may be considered a secure and trustworthy internal fxation method for ankle arthrodesis.

Keywords : Ankle arthrodesis, Biomechanics, Digital orthopedics, Internal fxation, 3D fnite element

INTRODUCTION

Fusion surgery is still crucial in the treatment of end-stage ankle osteoarthritis, even if there is still no clear gold standard. Nowadays, ankle arthrodesis is seen as a favorable option because of its increased rate of healing and broader spectrum of application [1]. Since Austrian surgeon Eduard Alber first proposed ankle arthrodesis in 1879, the procedure has undergone numerous revisions, leading to the development of dozens of surgical methods [2]. The efficacy of ankle arthrodesis is guaranteed by a sufficient a robust and steady fixation and compression, as well as an efficient and strong contact area. It can help realign lower limbs, relieve discomfort, correct abnormalities, and reconstruct plantigrade feet [2, 3]. The choice of internal fixators is crucial for ankle arthrodesis. A variety of fixation techniques are available, such as internal plate fixation, compression screw internal fixation, intramedullary nail fixation, and external support fixation; nevertheless, the non-healing rate remains between 5 and 37% [4]. There is disagreement over the best location and orientation for internal fxators due to their varying biomechanics. Therefore, by conducting ankle arthrodesis with two crossing screws (Ø6.5 mm) and anterior plates (Ø2.7 mm), we were able to obtain adequate efficacy in this trial. Ten In order to better understand the biomechanical properties of various internal fxators and offer a better solution for maximizing the fxation of ankle arthrodesis, we compared this with other widely used internal fxation methods using biomechanical fnite-element analysis. This laid the theoretical groundwork for upcoming clinical research.

MATERIALS AND PROCEDURES

Participants in the study

A healthy adult male volunteer who was 175 cm tall and 65 kg in weight was chosen; he signed an informed permission form and had no prior history of foot and ankle conditions, injuries, or other pertinent conditions. The Inner Mongolia Baogang Hospital Ethics Committee gave its approval to this study.

Method of study

Developing a 3D ankle model in its preliminary stages

We took a 64-slice spiral CT plain scan of the volunteer's right ankle.Using the imported CT imaging data in the DICOM format, we were able to first separate and extract the ankle's bone tissue structure using the Mimics software. Next, we employed segmentation and denoising to produce a precise and lucid initial 3D tumor model. To match the produced tibiotalar model with the real situation, we imported the pertinent fles into the Geomagic 2017 software. We replicated the joint cleaning procedure used for ankle arthrodesis to build a 3D tibial model. Together with the cartilage and subchondral tissue from the astragalar dome, we also excised the distal tibia.

Making four internal fixation types for ankle arthrodesis in three dimensions The interference steps were employed in Solidworks 2017. Software that uses four different internal fixation models to simulate the ankle arthrodesis process. Ultimately, as illustrated in Figs. 1, 2, and Table 1, we performed a fnite-element analysis of the four fxation models. The apparent density of bone [ρ (kg m−3)] was converted to Young's modulus [E (MPa)]. Based on previous studies [5, 6], E=0:2ρ1:52 (for ρ≤476:7) and E=−3842+13ρ (for ρ>476:7) are calculated. It was not allowed for the contact surfaces to slide or separate. The Young's modulus of the screw is 200 GPa.

It was expected that the Poisson's ratio for the screws and bones was 0.3. Screws and bones are examples of frictionless interactions. To increase the precision of the contact normal computation, Kuhn surfaces were applied to all exterior surfaces.

Calculating loads and contact boundary conditions

We fixed the bottom portion of the astragalus and simulated the mechanical changes of ankle joints under dorsifexion, neutral, internal rotation, and external rotation forces, referring to our earlier experimental investigation [7, 8] and the real motion of the ankle joints during walking. Ten, in accordance with our previous research [5, 6, 9], we applied neutral vertical load (2100 N), dorsifexion torque (10 N m), extorsion torque (10 N m), and intorsion torque (10 N m) to the upper surface of the tibia for each model, as shown in Fig. 3. Figs. 4 and 5 show the von Mises stress distribution and displacement cloud atlas of the four different fixation models, respectively.

Indicators of assessment

Our primary assessment focused on the internal fxators' stability and safety. In particular, we evaluated safety by looking at the stress peak and distribution of the plates, screws, and bone, and stability by measuring and evaluating the maximum displacement of the ankle arthrodesis surface. Plastic materials frequently suffer from yield failures, including stain-resistant steel. We applied the fourth strength theory-based von Mises stress as a failure criterion. However, we evaluated the stress condition of screws, bones, and steel plates using von Mises stress.

Outcomes

displacement of the surface of the arthrodesis

Table 2 shows the maximum displacement of the arthrodesis surface under four stressors for each of the four ankle arthrodesis models. When compared to the other three fixation models, the model with two crossing screws and one anterior plate showed the smallest maximum displacement under dorsifexion torsion, extorsion, intorsion, and neutral vertical stress. When compared to the other three fxation models, the maximum displacement against the four loading patterns indicated earlier was notably greater in the fxation model with anterior plates alone. Under neutral vertical load and dorsifexion torque, the maximum displacement in the model with three screws was greater than in the model with anterior plates and posterior-lateral screws. The maximum displacement compared to the fixation model with front plates and posterior-lateral screws, the arthrodesis surface under intorsion and extorsion torque was reduced in the model with three screws.

Stress distribution and stress peak

The stress distribution and stress maxima for the four different fxation models are shown in Tables 3, 4, 5, 6, and 7. When we compared the overall stress peaks of the four models, we discovered that the stress peaks in the models with anterior plates and posterior-lateral screws and the model with two crossed screws and anterior plates had smaller stress peaks with respect to extorsion and intorsion torque than the models with anterior plates and three screws. Regarding the neutral vertical load and dorsifexion torque, the stress peak was smaller in the flexion-strain model with three screws and anterior plates than it was in the flexion-strain model with two crossed screws and anterior plates and the flexion-strain model with anterior plates and posterior-lateral screws. The model with the largest stress peak across all four forces was the fxation model with just anterior plates. The fracture model with two crossing screws and anterior plates, as well as the one with three screws, had the highest risk of fractured screws and plates, as well as stress fracture under vertical load, based on the stress peaks of the bones, plates, and screws in the four models. The models for fixation that used anterior plates alone and those that used anterior plates along with posterior-lateral screws showed the highest risk of stress fracture under intorsion and extorsion stress patterns, as well as fractured screws and plates. The compression screws, plate joints, and plate bending elements are all evidently under significant stress in their center regions, as indicated by the stress maps of all four models.

DISCUSSION

The ankle joint must be in good working order for the human body to support weight and move forward. Ankle arthroplasty and ankle arthrodesis are two surgical techniques used to treat end-stage joint illnesses include post-traumatic ankle arthritis, persistent ankle instability, and paralytic deformity with muscle–tendon imbalance. Research has indicated that the fusion rate and control of complications were better with screw fxation, particularly following the introduction and extensive application of three compression screw fxation [8, 16, 17]. The majority of the capsule is retained after arthroscopic fusion, which may increase the stability of the fusion. However, screw fixation is the sole option available with arthroscopic fusion.Recent advancements in ankle arthrodesis have led to the adoption of several locking plate types and orientations. Biomechanical testing has demonstrated that the anterior plates act as "tension bands," effectively preventing ankle flexion and extension.reducing the ankle arthrodesis surface's micro-motion. They can also significantly raise rotational resistance and help heal broken bones [18–20]. A transparent surgical field can make the process easier and allow for a more thorough exposure of the ankle joint. The third posterior-lateral screw may significantly withstand dorsifexion and rotational forces and boost initial stability, depending on the two crossing screws; nevertheless, its placement can easily damage the peroneal nerve and cause the screws to clash. So et al. [21] evaluated and examined the percentage of articular surface area (SA) loss on the top of the astragalus between the conventional fixation with two screws and that with three screws using image analysis software.

According to the results, the third posterior-lateral screw caused an oval hole because of its modest entry angle and non-perpendicular direction, which led to a 6%–10% loss of the SA in the subtarsal joint. As a result, patients with low bone mass must utilize this screw cautiously. So et al. suggested combining low screw force with locking plates. Since 2020, we have been doing ankle arthrodesis through a small anterior incision utilizing the fxation with two crossed screws (Ø6.5 mm) and anterior plates (Ø2.7 mm), after carefully weighing the advantages and disadvantages of several internal fxation models and access options. The biomechanical characteristics could not be identified, despite the positive therapeutic outcomes.Because of the rapid advancement and widespread use of computer technology, finite-element analysis is a dynamic, widely used, practical, and efficient numerical analytical method that has quickly spread from structural engineering strength analysis to practically all sectors of science and industry. It was first applied to the measurement of bone stresses in orthopedic biomechanics in 1972 [22]. Since then, its application to stress analysis of bones and bone prosthesis, fracture fixation devices, and non-bone tissues has grown. Its purpose is to evaluate the connection between load-bearing function and morphology and to offer a theoretical foundation for clinical practice, thereby optimizing implant design and fxation techniques. For static or dynamic analytical study, finite-element analysis can replicate operating circumstances that are not possible to produce in traditional biomechanical studies.

with the benefits of being quick, inexpensive, repeatable, and having thorough performance testing. It can also supplement traditional biomechanical experiments and offer more thorough, precise, varied, and three-dimensional mechanical data for therapeutic use. The application of the finite-element approach to the research of ankle joint biomechanics has increased recently [23–26]. Ankle arthrodesis has been analyzed using finite-element method. The initial stability of three-screw fixation for ankle arthroscopic anthrosis was the main focus of Wang et al.'s investigation. In comparison to the posteromedial home-run screw, the screw configuration of the latter was proven to be more biomechanically stable and to prevent collisions [27]. Three types of two-screw configuration fixation were used by Zhu et al. to analyze the initial stability and stress distribution of ankle arthroscopic arthrodesis.

For the present being, however, there isn't a finite-element analysis that focuses on the mechanical characteristics of the anterior plate in ankle arthrodesis. Furthermore, to offer trustworthy evidence support for additional clinical research and clinical practice, a cross-sectional assessment of the mechanical characteristics of various ankle arthrodesis internal fixation techniques by finite-element analysis is urgently required.

In this investigation, we gathered and imported into the Mimics software the CT scan imaging data of a volunteer adult male in good health. We used this information to build a crude 3D ankle joint model. Using the Geomagic software, we smoothed and denoised the model to create a strong model. Lastly, we put the data into the Solidworks program to simulate various procedures like ankle arthrodesis and perform assembly and cutting. Using this, we developed the experimental models for finite-element analysis for four different types of ankle arthrodesis. In order to get the final analysis findings, we

The Journal of Hepatology

lastly imported the models into the finite-element analysis program Ansys and adjusted the loading conditions, analysis settings, and characteristics. This study has a high degree of simulation and validity since the 3D finite-element model it built can fully acquire spatial information from different angles and the design of many parameters approximates clinical reality.

The term "microdisplacement of the arthrodesis surface" describes the deformation of the ankle's arthrodesis surface under torsion, extorsion, dorsifexion torsion, and and neutral stresses brought on by walking's stride. The effectiveness and durability of internal fixators for ankle arthrodesis can be determined by the displacement value. According to the study's findings, the displacement of the arthrodesis surface under neutral and dorsifexion torsion in the fixation model with anterior plates alone was significantly smaller than that under extorsion and intorsion. This suggests that anterior plates had a significant advantage against neutral and dorsifexion torsion, but that their resistance to intorsion and extorsion was only moderate. The displacement under neutral load, dorsifexion intorsion, extorsion, and intorsion was significantly less in the fxation model with anterior plates than it was in the model with a 6.5 mm posterior-lateral screw based on anterior plates, particularly under intorsion and extorsion. suggesting that a greater fixation effect may result from the posterior-lateral screw's location. This notion is also supported by the findings of Xie [30] and Cliford [29].

The degree of deformation of the arthrodesis surface under the four forces varied little in the fxation model with three screws, suggesting that this model can offer more evenly distributed resistance to outside forces.

In terms of resistance to intorsion and extorsion, the fusion model with three screws proved to be more advantageous than the fusion model with anterior plates and posterior-lateral screws; the anterior plates demonstrated satisfactory resistance to both neutral stress and dorsifexion intorsion, particularly the latter. In relation to the displacement of the arthrodesis surface, the fixation model utilizing anterior plates and posterior-lateral screws fared better.

The displacement of the arthrodesis surface against neutral stress, dorsifexion intorsion, intorsion, and extorsion was smaller in the fxation model with two crossed screws and anterior plates than in the other three models, according to our analysis of the experimental results, which clearly showed this to be the most stable configuration out of the four models. The majority of forces were centered in the middle regions of the compression screws, plate joints, and plate bending portions, according to the stress distribution and stress peak. This suggests that after ankle arthrodesis, the materials used in these areas should be strengthened and thickened to avoid fractured screws and plates. Regarding resistance to extorsion and intorsion, the fxation model with three screws and the fxation model with two crossed screws and anterior plates outperformed the fxation model with anterior plates and the fxation model with anterior plates and posterior-lateral screws. In terms of resistance to dorsifexion intrusion and neutral (vertical) stress, the fusion model with anterior plates and two crossed screws, as well as the fusion model with anterior plates and posterior-lateral screws, outperformed the fusion model with three screws.

SUMMARY

Out of the four fxation models, the one with two crossing screws and anterior plates had the best biomechanical performance, according to a thorough investigation of the stability and safety of the models. In comparison to the other three fxation models, it exhibited the smallest maximum displacement under extorsion, intorsion, torsion, and neutral vertical load. Out of the four models, the fixation type with two crossing screws and anterior plates had the best safety in terms of dorsifexion and intorsion torque.

The results of this study suggest that basic anterior plate fxation with three screws is best saved for patients with strong bones because it has a minimal compressive effect and is not very safe. When a plate and screws are applied together, the biomechanical effects are better and the fixation strength is higher than when either plate or screw is applied alone. A better option for patients who need more fixation strength is to apply plate screws in combination.

The tiny anterior plate can counteract the Achilles tendon's strength, and by shrinking it, patients' local blood flow and soft tissue damage can be lessened. This offers patients who have poor local soft tissue conditions in the surgical site an alternate surgical choice.

However, there were numerous issues with this study: The study did not take into account the impact of soft tissues, including muscles and ligaments, on ankle joints. Additionally, the majority of patients receiving ankle arthrodesis are middle-aged and older individuals suffering from osteoporosis, and their bone problems are directly linked to the loosening of screws. Our investigation is restricted to the software's use, and more biomechanical studies are required to confirm the results.

REFERENCES

1. Ahmad J, Raikin SM. Ankle arthrodesis: the simple and the complex. Foot Ankle Clin. 2008;13:381–400.

2. Woo BJ, Lai MC, Ng S, et al. Clinical outcomes comparing arthroscopic vs open ankle arthrodesis. Foot Ankle Surg. 2020;26:530–4.

3. McGuire MR, Kyle RF, Gustilo RB, et al. Comparative analysis of ankle arthroplasty versus ankle arthrodesis. Clin Orthop Relat Res. 1988;226:174–81.

4. Zwipp H, Rammelt S, Endres T, et al. High union rates and function scores at midterm followup with ankle arthrodesis using a four screw technique. Clin Orthop Relat Res. 2010;468:958–68.

5. Alonso-Vázquez A, Lauge-Pedersen H, Lidgren L, et al. Initial stability of ankle arthrodesis with three-screw fxation. A fnite element analysis. Clin Biomech (Bristol, Avon). 2004;19:751–9.

6. Yang CW, Li Q, Sun W, Zhang ZY, Cai ZD. Three dimensional fnite element analysis of multiple cannulated screws fxation for adduction femoral neck fracture. Chinese Journal of Orthopedics. 2009;17(14):1077–80.

7. Lu CH, Yu B, Chen HQ, Lin QR. Establishment of a three-dimensional fnite element model and stress analysis of the talus during normal gait. J South Med Univ. 2010;30(10):2273–6.

8. Xie XM, Li LF, Zhao XC, Li Q, Liu HS, Bu JP, Zhang TY. Clinical study on the biomechanical efect of middle and upper fbular fracture on ankle joint. Chinese Journal of Orthopedics. 2009;17(14):1081–3.

9. Thordarson DB, Markolf K, Cracchiolo A. Stability of an ankle arthrodesis fxed by cancellous-bone screws compared with that fxed by an external fxator. A biomechanical study. J Bone Joint Surg Am. 1992;74:1050–5.

10. Ferguson Z, Anugraha A, Janghir N, et al. Ankle arthrodesis: a long term review of the literature. J Orthop. 2019;16:430–3.

11. Li W, Li Y, Zhou YX, Jiang Y, Ji SJ, Li JL, Zhao HY. Analysis of the efect of total ankle replacement on ankle osteoarthritis. Chin J Trauma. 2011;27:1012–6.

12. Giannini S, Buda R, Faldini C, Vannini F, Romagnoli M, Grandi G, Bevoni R. The treatment of severe posttraumatic arthritis of the ankle joint. J Bone Joint Surg Am. 2007;89:15–28.

13. Karl-Heinz K, Hans-Jorg T, Fusszentrum W. Ankle arthrodesis with an anterior approach. Tech Foot Ankle Surg. 2007;4:243–8.

14. Betz MM, Benninger EE, Favre PP, Wieser KK, Vich MM, Espinosa N. Primary stability and stifness in ankle arthrodes-crossed screws versus anterior plating. Foot Ankle Surg. 2013;19:168–72.

15. Berend ME, Glisson RR, Nunley JA. A biomechanical comparison of intramedullary nail and crossed lag screw fxation for tibiotalocalcaneal arthrodesis. Foot Ankle Int. 1997;18:639–43.

16. Easley ME, Montijo HE, Wilson JB, Fitch RD, Nunley JA 2nd. Revision tibio-talar arthrodesis. J Bone Joint Surg Am. 2008;90:1212–23.

17. Holt ES, Hansen ST, Mayo KA, et al. Ankle arthrodesis using internal screw fxation. Clin Orthop Relat Res. 1991;268:21–8.

18. Tarkin Ivan S, Mormino Matthew A, Clare Michael P, et al. Anterior plate supplementation increases ankle arthrodesis construct rigidity. Foot Ankle Int. 2007;28:219–23.

19. Imsdahl Sheri I, Stender Christina J, Cook Brian K, et al. Anteroposterior translational malalignment of ankle arthrodesis alters foot biomechanics in cadaveric gait simulation. J Orthop Res. 2020;38:450–8.

20. Kusnezov N, Dunn JC, Koehler LR, et al. Anatomically contoured anterior plating for isolated tibiotalar arthrodesis: a systematic review. Foot Ankle Spec. 2017;10:352–8.

21. So E, Brandão RA, Bull PE. A comparison of talar surface area occupied by 2- versus 3-screw fxation for ankle arthrodesis. Foot Ankle Spec. 2020;13:50–3.

22. Huiskes R, Chao EY. A survey of fnite element analysis in orthopedic biomechanics: the frst decade. J Biomech. 1983;16:385–409.

23. Morales-Orcajo E, Souza TR, Bayod J, et al. Non-linear fnite element model to assess the efect of tendon forces on the foot-ankle complex. Med Eng Phys. 2017;49:71–8.

24. Tsai A, Coats B, Kleinman PK. Biomechanics of the classic metaphyseal lesion: fnite element analysis. Pediatr Radiol. 2017;47:1622–30.

25. Xie Q, Wang ZH, Liu WY, Gao YF, Xue XX. Mechanical stability after plating ankle arthrodesis based on three-dimensional fnite element analysis. Chin J Tissue Eng

Res. 2018;22(3):392–7.

26. Hejazi S, Rouhi G, Rasmussen J. The efects of gastrocnemius-soleus muscle forces on ankle biomechanics during triple arthrodesis. Comput Methods Biomech Biomed Engin. 2017;20:130–41.

27. Wang S, Yu J, Ma X, Zhao D, Geng X, Huang J, Wang X. Finite element analysis of the initial stability of arthroscopic ankle arthrodesis with threescrew fxation: posteromedial versus posterolateral home-run screw. J Orthop Surg Res. 2020;15(1):252.

28. Zhu M, Yuan CS, Jin ZM, Wang YJ, Shi YX, Yang ZJ, Tang K. Initial stability and stress distribution of ankle arthroscopic arthrodesis with three kinds of 2-screw confguration fxation: a fnite element analysis. J Orthop Surg Res. 2018;13(1):263.

29. Cliford C, Berg S, McCann K, et al. A biomechanical comparison of internal fxation techniques for ankle arthrodesis. J Foot Ankle Surg. 2015;54:188–91.

30. Xie Q. Ankle fusion by plating through an anterior approach followed by posterolateral approach: a three-dimensional fnite element analysis. Res Tissue Eng China. 2017;21(35):5697–702.