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Finite element analysis of locking plate and 1/4 tubular plate for first tarsometatarsal joint fracture-dislocation

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Abstract

Objective: The optimal plate for fixation of tarsometatarsal joint injuries is controversial. The objective of this study was to compare the biomechanical characteristics between a locking plate and 1/4 tubular plate for first tarsometatarsal joint fracture-dislocation.

Method: Finite element analysis was used after establishment of a first tarsometatarsal joint fracture-dislocation model. Two implant simulations using a locking plate and five-hole 1/4 tubular plate were designed to simulate fixation of the fracture-dislocation. The displacement of the first tarsometatarsal articular surface and the stress distribution in the implants were calculated.

Results: A 700-N load was applied to both models. The minimum displacement of the articular surface in the locking plate and 1/4 tubular plate model was 0.6471 mm and 0.3833 mm, respectively. The maximum principal stress in the locking plate and 1/4 tubular plate was 1.212×10^3 MPa and 1.107×10^3 MPa, respectively.

Conclusion: Use of a 1/4 tubular plate is recommended for fixation of first tarsometatarsal joint fracture-dislocation after consideration of other factors such as economical issues.

Keywords

Locking plate, 1/4 tubular plate, tarsometatarsal joint, fracture-dislocation, finite element analysis

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Introduction

The first tarsometatarsal (TMT) joint plays an important role in the foot, and its integrity has important significance in maintenance of the foot arch and load transfer. Therefore, injuries of the first TMT joint should be actively treated to recover the

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alignment of the midfoot and ensure load transfer from the forefoot to the midfoot.[1] A plate might be a good choice for fixation of the first TMT joint, especially for comminuted fractures of the articular surface that cannot be fixed with screws. However, the most suitable type of plate remains controversial. An improper implant may cause changes in the local biomechanical environment of the feet, leading to complications such as implant breakage, loss of reduction, and malunion.[2] Therefore, the biomechanical characteristics of different plates must be evaluated.

Biomechanical research of the irregularly shaped first TMT joint is difficult using corpse specimens.[3] Therefore, a three-dimensional (3D) model of first TMT joint fracture-dislocation was established by finite element analysis (FEA), and fixation was simulated using two kinds of plates: a locking plate (DARCO Modular Forefoot System UPS 2.7 Plate; Wright Medical Group, Memphis, TN, USA) and a five-hole 1/4 tubular plate (Kanghui Medical, Changzhou, China). The aim of this study was to determine the displacement of the articular surface and the stress distribution of each plate and thus provide experimental evidence for the choice of plate when repairing first TMT joint injuries.

Methods

General data

A 35-year-old healthy male Chinese volunteer (height, 170 cm; weight, 70 kg) was recruited. Physical and X-ray examinations of his foot showed no deformities or damage. The volunteer provided written informed consent regarding the potential radiation hazard. The experiment was approved by the Ethics Committee of Ningbo No. 2 Hospital.

Equipment and software

The following equipment and software were used in the present study: (1) a 4D dual-source CT system (Siemens, Erlangen, Germany), (2) Mimics 12.0 (Materialise, Leuven, Belgium), (3) Geomagic Studio (Geomagic, Morrisville, NC, USA), (4) SolidWorks 2010 (Dassault Systèmes, Vélizy-Villacoublay, France), and (5) ANSYS 13.0 (ANSYS Ltd., Canonsburg, PA, USA).

Experimental method

The 4D dual-source CT system was used to scan the volunteer from the lower segment of the leg to the whole foot in the neutral position. The original CT image data were loaded into Mimics 12.0 to obtain a 3D model of the foot. After optimization, the model was loaded into ANSYS 13.0 to obtain a 3D FEA model of the foot with 66,540 nodes and 349,475 units. The materials in the model were simplified as homogeneous elastic materials. The thickness of the cortical bone was set at 2 mm, and the ligaments and plantar fascia were established by a two-node truss unit. The model of the foot was then loaded into SolidWorks 2010 to simulate cutting off the dorsal and plantar ligaments between the medial cuneiform and first metatarsal and performing an osteotomy along the articular surface of the first TMT joint, thus creating a first TMT joint intra-articular fracture model.[4]

The geometric parameters of the plates and screws were loaded into SolidWorks 2010, and two implant models were established according to the experiment. The locking plate was placed on the dorsal side of the first TMT joint, and trans-articular fixation was performed with four locking screws that were respectively fixed to the plate according to the designed directions. The five-hole 1/4 tubular plate was also placed on the dorsal side of the first TMT joint, and trans-articular fixation was performed with four cortical screws perpendicular to the plate with two screws on each side of the joint.

According to the mechanism of TMT joint injury, the ankle was fixed at 30° of plantar flexion. We set the lowest contact point of the tibia and fibula and the head of the first metatarsal with the ground as the constraint point. The load was 700 N in accordance with the body weight. The direction was set from the lower leg perpendicular to the ground, while the reverse direction was set in the head of the first metatarsal. The tensile force caused by the traction of the muscles and ligaments that around the joint could be offset according to the principle of the synthesis and decomposition of the force.[5]

Results

Displacement of articular surface

After application of the 700-N load, both of the plates provided firm fixation of the model without breakage of the plates or destruction of the model. However, the articular surface still showed a tendency toward dorsal dislocation in both models. The maximum displacement in the locking plate fixation model was 6.4710 mm, which appeared in the first metatarsal head. However, the minimum displacement in this model was 0.6471 mm, which appeared in the first TMT articular surface. The maximum displacement in the 1/4 tubular plate fixation model was 4.5990 mm, which appeared in the first metatarsal head. However, the minimum displacement in this model was 0.3833 mm, which appeared in the first TMT articular surface (Figure 1).

Stress distribution in both implants

After application of the 700-N load, a balanced stress distribution was observed in both the locking plate and 1/4 tubular plate models. The maximum stress in the locking plate model was 1.212×10^3 MPa, which was mainly concentrated in the holes of the locking plate and in the locking screws, especially on the side of the first metatarsal, which supported more stress than did the the side of the medial cuneiform. The maximum stress in the 1/4 tubular plate model was 1.107×10^3 MPa, which was also mainly concentrated in the holes of the plate and in the screws on the side of the first metatarsal (Figure 2).

Discussion

FEA is used for biomechanical research because of its special advantage of high-accuracy simulation of complex shapes and material properties.[6,7] In the present study, the original data from the CT scan of the foot was loaded into Mimics 12.0 software to obtain an initial 3D model of the foot. SolidWorks 2010 was then used to cleave the model according to a Myerson classification type B1 injury to obtain a model of first TMT joint fracture-dislocation. ANSYS 13.0 can simulate operations and assign physical properties to implants. After loading, calculations could be carried out to determine the displacement of the articular surface and the stress distribution in the implants. However, FEA also has intrinsic limitations because the mechanical properties of materials are defined as continuous, homogeneous, and isotropic; therefore, this assumption will be slightly different from the real situation of the first TMT joint itself.[8,9]

According to the mechanism of TMT joint injury, the model was axially loaded at 30° of plantar flexion of the ankle. To more accurately reflect the displacement of the articular surface and stress distribution of the implants, the fracture line and articular surface were replaced and bonded by soft material with a modulus of elasticity of 5 MPa and Poisson ratio of 0.40, and the titanium plate and screws were replaced with a material with a modulus of elasticity of 200 GPa and Poisson ratio of 0.28. After loading, the results showed that the

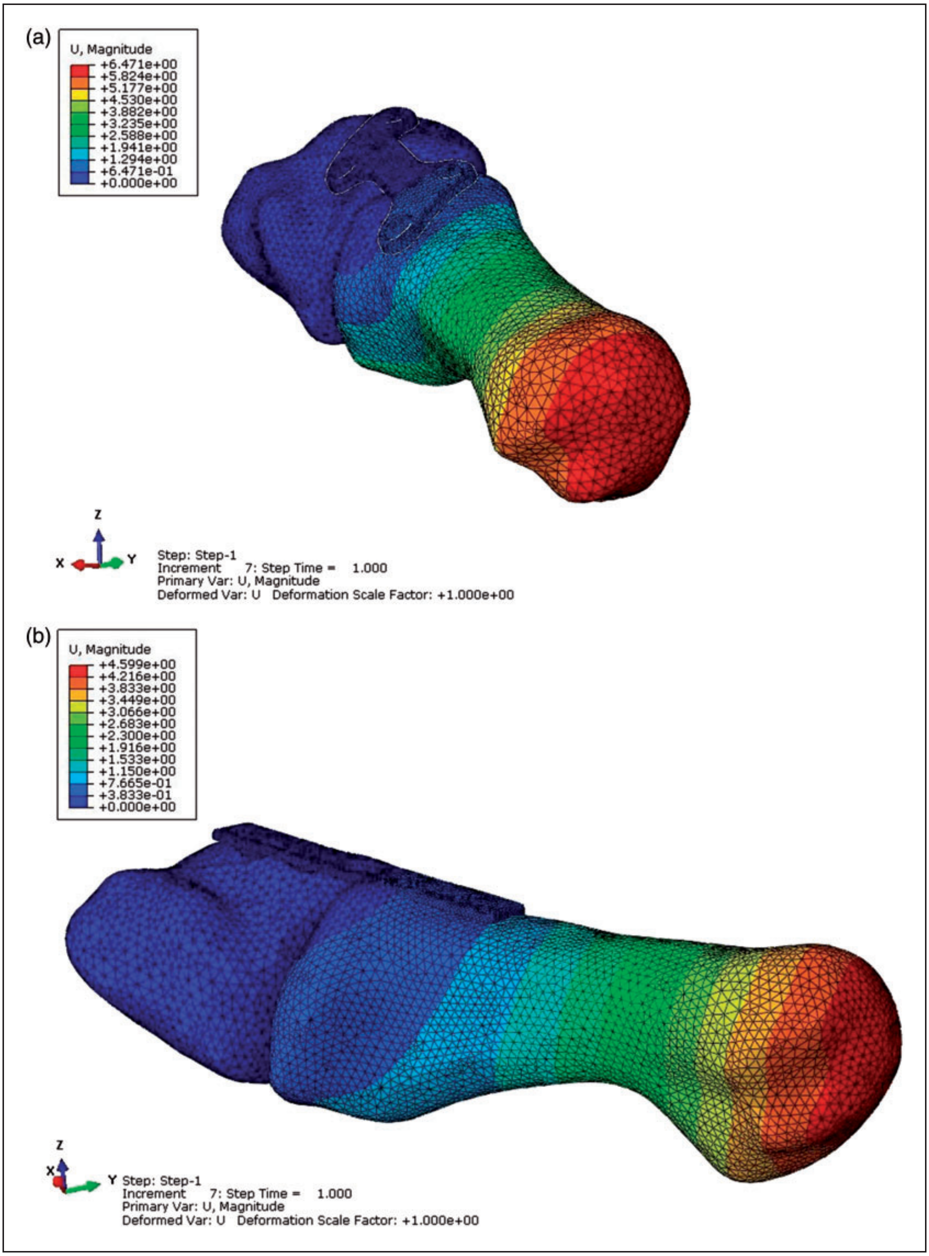

Figure 1. Displacement of the articular surface. (a) The maximum displacement in the locking plate fixation model was 6.4710 mm, which appeared in the first metatarsal head, and the minimum displacement in this model was 0.6471 mm, which appeared on the articular surface of the first tarsometatarsal joint. (b) The maximum displacement in the 1/4 tubular plate fixation model was 4.5990 mm, which appeared in the first metatarsal head, and the minimum displacement in this model was 0.3833 mm, which appeared on the articular surface of the first tarsometatarsal joint.

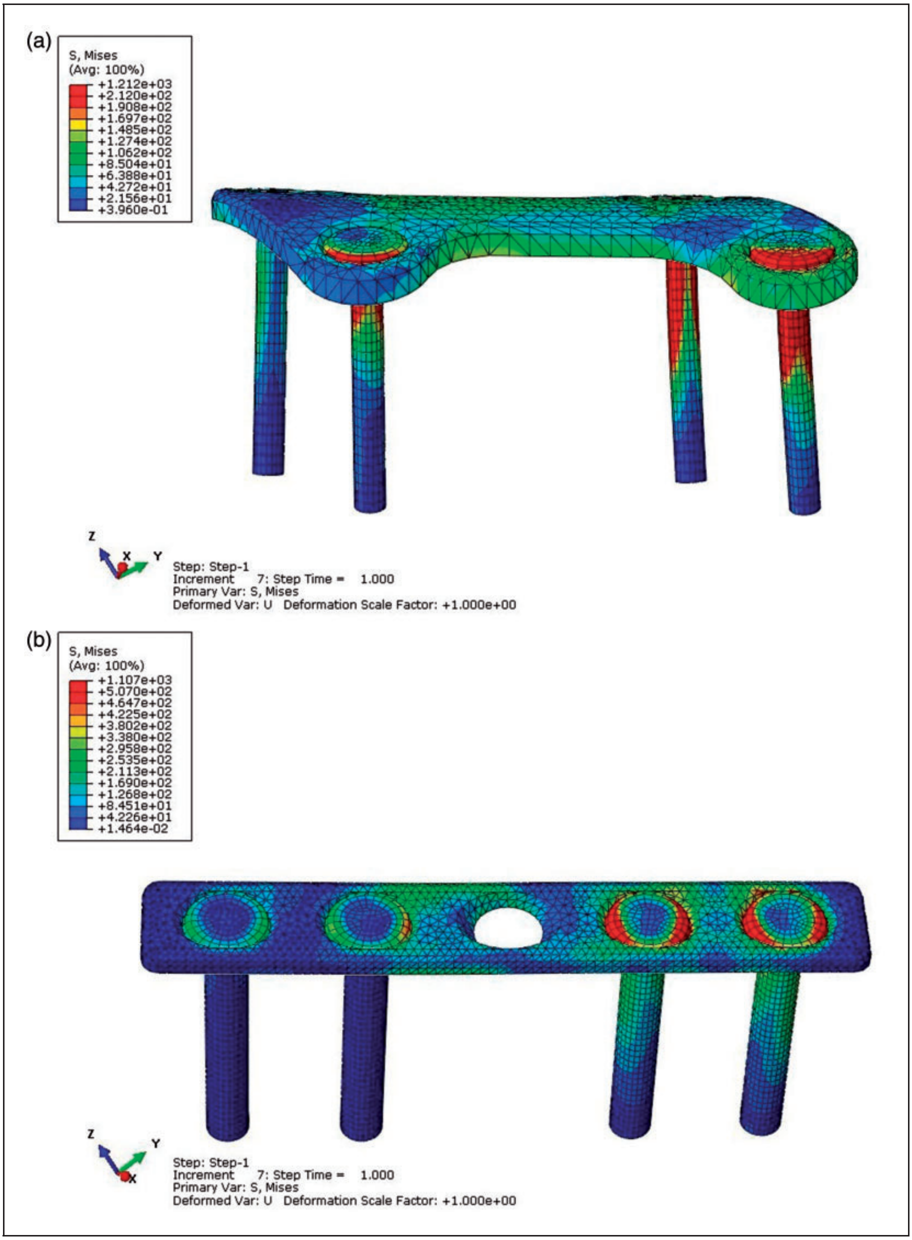

Figure 2. Stress distribution in the implants. (a) The maximum stress in the locking plate was 1.212×10^3 MPa, which was mainly concentrated in the holes of the locking plate and in the locking screws. (b) The maximum stress in the 1/4 tubular plate was 1.107×10^3 MPa, which was also mainly concentrated in the holes of the plate and in the screws on the side of the first metatarsal.

displacement of the articular surface was <2 mm in both models, indicating that both of the implants could provide firm fixation.[10] However, the articular surface still showed a tendency toward dorsal dislocation in both models. In the locking plate fixation model, the minimum displacement of the articular surface was 0.6471 mm, while it was 0.3833 mm in the 1/4 tubular plate fixation model. These results show that the firm fixation provided by either the locking plate or 1/4 tubular plate could restore the normal anatomy and slight mobility of the first TMT joint. According to the FEA results, the maximum displacements were located in the in the head of the first metatarsal bone in both models. Therefore, in patients with a first TMT joint injury, it is advisable to avoid weight bearing on the foot regardless of whether the implants are fixed. Continued weight bearing may cause instability of the first ray, leading to complications such as metatarsalgia, plantar fasciitis, and pressure ulcer formation.[11]

The stress distribution in the implants was balanced in both the locking plate and 1/4 tubular plate models. The implants exhibit a certain stress-shielding effect, which is beneficial for early fracture healing and early functional exercise without weight bearing.[12] In the present study, the maximum stress in the locking plate and 1/4 tubular plate were 1.212×10^3 MPa and 1.107×10^3 MPa, respectively, and mainly concentrated in the holes of the plates and screws, especially on the side of the first metatarsal. Thus, the stress was slightly larger in the locking plate than in the 1/4 tubular plate, and the locking plate could accordingly provide a greater stress-shielding effect. A certain stress-shielding effect may be beneficial to a fracture, but it can become detrimental if the stress-shielding effect is too strong because it may result in implant breakage and fracture nonunion.[13] Therefore, the patient should avoid weight bearing on the foot when an implant is present in the first TMT joint. It is advisable to remove the plate if the patient wants to walk or run after the first TMT joint injury has healed.[14] During removal of the implant, surgeons should pay close attention to the holes of the plates and screws, where the stress is more concentrated.

The main factor affecting the prognosis of TMT joint injury is maintenance of the congruity of the articular surface by implants. Many kinds of implants can be used for fixation of the TMT joint. However, K-wires are considered useless for fixation of the first TMT joint because they cannot provide solid fixation.[15] Staples are more suitable for fixation of TMT joint subluxation.[16] Occasionally, in some cases of comminuted TMT joint fracture-dislocation, the use of cannulated screws will eventually lead to failure of the fixation because the guide pin cannot be drilled though the articular surface. Therefore, a plate might be the most suitable implant in this situation. In the present study, we evaluated both a locking plate and 1/4 tubular plate. The results showed that both of the plates were suitable for fixation of first TMT joint fracture-dislocation. The locking plate used in this study was the DARCO Modular Forefoot System UPS 2.7 Plate, which is mainly used for fusion of the forefoot; however, it can also be used for fixation of forefoot fractures.[17] Compared with the 1/4 tubular plate used in this study, it had no obvious advantages in fixing a fracture-dislocation over a comminuted fracture-dislocation. Furthermore, a locking plate may cost more than a 1/4 tubular plate in many developing countries.[18,19] Therefore, fixation of first TMT joint fracture-dislocation using a 1/4 tubular plate is more suitable than using a locking plate with respect to both biomechanical and economical factors and can be widely used in the clinical setting.

Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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