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Use of three-dimensional finite element models of the lateral ankle ligaments to evaluate three surgical techniques

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Abstract

Objective: To compare three surgical techniques for lateral ankle ligament reconstruction using finite element (FE) models.

Methods: A three-dimensional FE model of the left foot of a healthy volunteer and lateral collateral ligament injury models were developed. Three tendons [one-half of the autologous peroneus longus tendon (PLT), one-half of the peroneus brevis tendon (PBT), and an allogeneic tendon] were used for lateral collateral ligament reconstruction. The ankle varus stress and anterior drawer tests were performed to compare the three surgical techniques.

Results: The ankle varus stress test showed that the equivalent stresses of the anterior talofibular ligament (ATFL) (84.00 MPa) and calcaneofibular ligament (CFL) (27.01 MPa) were lower in allogeneic tendon reconstruction than in the other two techniques but similar to those of normal individuals (138.48 and 25.90 MPa, respectively). The anterior drawer test showed that the equivalent stresses of the ATFL and CFL in autologous PLT reconstruction (31.31 and 28.60 MPa, respectively) and PBT reconstruction (31.47 and 29.07 MPa, respectively) were lower than those in allogeneic tendon reconstruction (57.32 and 52.20 MPa, respectively).

Conclusions: The allogeneic tendon reconstruction outcome was similar to normal individuals. Allogeneic tendon reconstruction may be superior for lateral ankle ligament reconstruction without considering its complications.

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Introduction

Ankle sprain is one of the most common injuries sustained during sport activities.[1] Ankle sprains constitute an estimated 7% to 10% of all admissions to hospital emergency departments.[2] Most ankle sprains involve the lateral ankle ligaments, which mainly comprise the anterior talofibular ligament (ATFL), calcaneofibular ligament (CFL), and posterior talofibular ligament.[3] Sprain of the foot is the most common mechanism of injury to the ankle ligaments.[4] It can cause direct damage to the ATFL because the ATFL is the most important ligament for maintenance of ankle joint stability.[5] Complete rupture of the ATFL often accompanies injury to the CFL and posterior talofibular ligament.[6]

Many surgical procedures for repair of the ATFL and CFL and restoration of lateral ankle stability have been described, including those involving the application of autograft or allograft tendons.[7–9] In 1966, Broström[10] developed a technique for direct repair of the lateral ankle ligaments by shortening the torn ends of the ATFL and CFL. Gould et al.[3] and Karlsson et al.[11] subsequently modified the Broström procedure by mobilization and reattachment of the lateral portion of the extensor retinaculum to the fibula after imbrication of the ATFL and CFL. Unfortunately, the direct repair procedure is not always possible because of the shortage and poor quality of autologous ligaments.[10] Although autografts and allografts have been applied to reconstruct the ATFL and CFL,[12–14] the internal stress states within the bony structures and soft tissues among the different reconstruction techniques cannot be well managed by traditional measures. Development of three-dimensional finite element (FE) analysis has provided scholars with a novel approach to solve this problem. FE analysis can serve as a complementary tool for quantitative evaluation of the biomechanical performance of the ankle–foot complex.[15] FE analysis can precisely control the motions, loading, and structural alterations in parametric analysis of the joint.[16] FE analysis has been used for surgical assessment and preoperative planning in many different applications.[17,18]

In the present study, a three-dimensional FE model of the foot and ankle of a healthy male volunteer was constructed. Based on this normal model, lateral collateral ligament injury models were developed. The lateral collateral ligaments were then reconstructed by three surgical techniques: reconstruction of one-half of the peroneus longus tendon (PLT), reconstruction of one-half of the peroneus brevis tendon (PBT), and allogeneic tendon reconstruction. The ankle introversion and anterior drawer tests were also performed. The objective of this study was to compare the three surgical techniques using three-dimensional FE models.

Methods

All procedures were approved by the ethics committee of the Third Affiliated Hospital of Xinjiang Medical University, and the healthy volunteer whose computed tomography (CT) images were used provided written informed consent to participate in this research project.

Data collection

The geometry of the FE model was obtained from three-dimensional reconstruction of dual-source CT images of the left foot of a healthy male volunteer (age, 30 years; height, 168 cm; weight, 65 kg). The two-dimensional CT images were taken at intervals of 0.625 mm, a slice thickness of 0.625 mm, and a plane resolution of 512×512, and the imaging data were stored in Digital Imaging and Communications in Medicine (DICOM) format.

FE models of normal ankle and ligamentous injury

The imaging data in DICOM format were imported into MIMICS 17.0 software (Materialise, Leuven, Belgium), and a skeleton mask was constructed based on the default thresholds (minimum, 362; maximum, 1555). The 3-dimensional model of the ankle including 14 bony segments (tibia, fibula, talus, calcaneus, cuboid, navicular bone, 3 cuneiforms, and 5 metatarsals) and articular cartilages was then constructed using the command for 3-dimensional calculation in MIMICS. The preliminary three-dimensional model of the ankle was stored in stereolithography (STL) format. The boundary surfaces of the 14 bony segments and articular cartilages were processed with removal of noise and smoothing using Geomagic Studio 2013 (Raindrop Geomagic Inc., Morrisville, NC, USA), obtaining a non-uniform rational basis spline (NURBS) model (Figure 1). The ligaments, including the ATFL, CFL, posterior talofibular ligament, PLT, PBT, and deltoid ligament, were then modeled. Briefly, for construction of the ligaments,

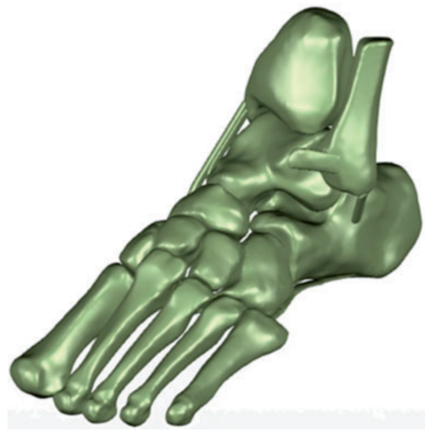

Figure 1. Non-uniform rational basis spline models of the normal ankle

an oval section with a major axis of 5 mm and minor axis of 3 mm was constructed, and the constructed model was then swept through the curve on the enthesis of the ligament. For construction of the PLT and PBT, a circle section with a diameter of 3 mm was constructed, and the constructed model was then swept through the curve on the enthesis of the ligament. The width, thickness, and position of the ligaments, PLT, and PBT were determined according to the anatomy. These NURBS models were stored in initial graphics exchange specification (IGES) format.

The lateral collateral ligament injury models were designed using Unigraphics NX 8.5 (Siemens PLM Software, Plano, TX, USA) based on the established normal ankle model. Three types of lateral collateral ligament injuries were designed: ATFL removal, CFL removal, and both ATFL and CFL removal.

Reconstruction of lateral collateral ligament

Reconstruction of the lateral collateral ligament was carried out using Unigraphics NX 8.5. Three surgical techniques were used to reconstruct the lateral collateral ligament: autologous reconstruction of half of the PLT, autologous reconstruction of half of the PBT, and allogeneic tendon reconstruction.

The surgical technique is described as follows. First, half of the PLT, ATFL, and CFL were removed, and half the thickness of the PLT was resected. The attachment points of the ATFL and CFL on fibula were punched. The resected PLT was then passed through the fibula and attached to the attachment points of the ATFL and CFL (Figure 2(a)). The attachment points of the ATFL and CFL were determined according to the patient's anatomy. The surgical techniques of using half of the PBT (Figure 2(b)) and the allogeneic tendon (Figure 2(c)) were similar to the surgical technique of using the PLT. The mesh generation (tetrahedron elements with four nodes) and FE analysis were performed using ANSYS workbench 15 software (ANSYS Inc., Canonsburg, PA, USA).

Material properties

In the present study, material properties were obtained from data available in the current literature. Skeletons and cartilages were idealized to linear, perfectly elastic, and isotropic materials. The Young's modulus and Poisson ratio for the skeleton were 7300 MPa and 0.3, respectively,[19] and those for the cartilage were 1 MPa and 0.4, respectively.[15] The relationship between the skeleton and ligament was assumed to be bonded. The ligaments were assumed to be nonlinear hyperelastic,[16] and their constitutive relation followed the neo-Hookean model.[20] The formula was as follows:

$$\psi = \frac{1}{2D}\ln(J)^2 + C_1\left(\bar{I}_1 - 3\right) + F_2(\lambda) \tag{1}$$

where C_1 represents the neo-Hookean constant and $\frac{1}{D}$ represents the bulk modulus. The neo-Hookean constant and reciprocal of the bulk modulus for the ligaments were 1.44 and 0.00126, respectively.[21]

Stress loading

In the present study, the ankle varus stress test (Figure 3) and anterior drawer test (Figure 4) were performed to evaluate the effects of the three surgical techniques. In detail, the tibiotalar joint was inverted 15° by adopting the moment of the couple in the inside and outside of the talus and a horizontal force at the bottom of the cuboid. The equivalent stresses of the ATFL, CFL, PLT, and PBT, as well as the internal rotation angle, anteversion angle, and varus angle of the talus, were then detected. The equivalent stresses of the ATFL, CFL, PLT, and PBT were detected under 5-mm anterior translation of the talus. The duration of each test was 1 s. The same loading style was applied for all models.

Statistical analysis

SPSS 19.0 (IBM Corp., Armonk, NY, USA) was used for the statistical analysis in the current study. Different variables were compared between the two groups by independent-sample t-tests. Differences were considered significant when $P<0.05$.

Results

Mesh generation

Based on the ANSYS workbench 15.0 software, 4 models with different elements and nodes (tetrahedron elements with 10 nodes) were constructed. The normal ankle model consisted of 703,371 elements and 447,043 nodes, the one-half PLT reconstruction model consisted of 701,001 elements and 445,469 nodes, the one-half PBT reconstruction model consisted of 701,173 elements and 445,628 nodes, and the allogeneic tendon reconstruction model

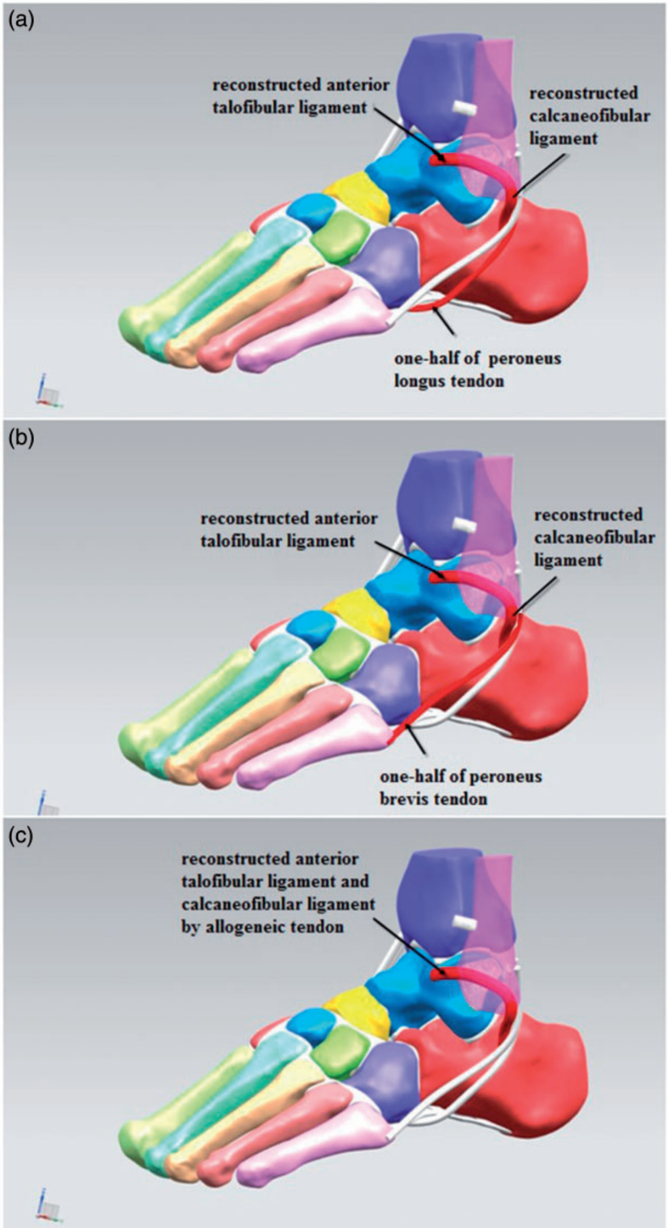

Figure 2. Reconstruction of the anterior talofibular ligament and calcaneofibular ligament using (a) one-half of the autologous peroneus longus tendon, (b) one-half of the peroneus brevis tendon, and (c) an allogeneic tendon

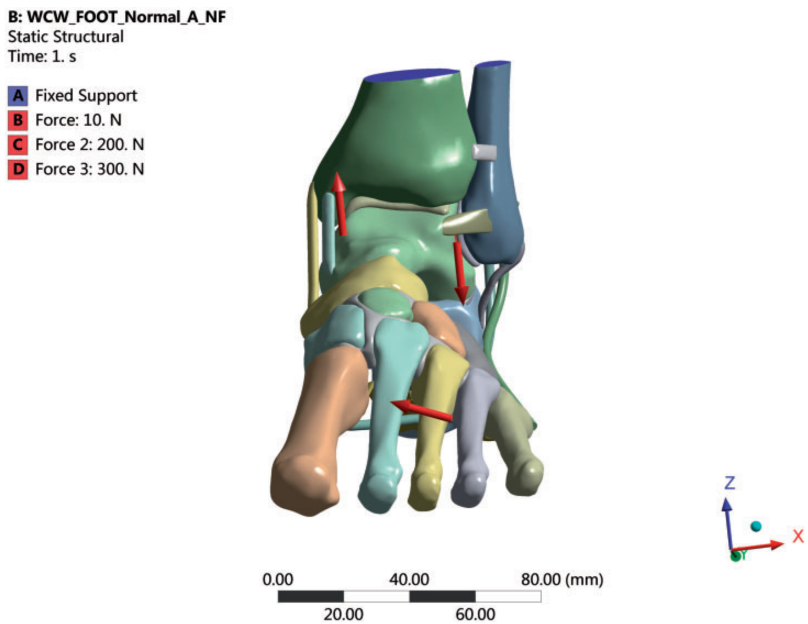

Figure 3. Loading style of the ankle varus stress test

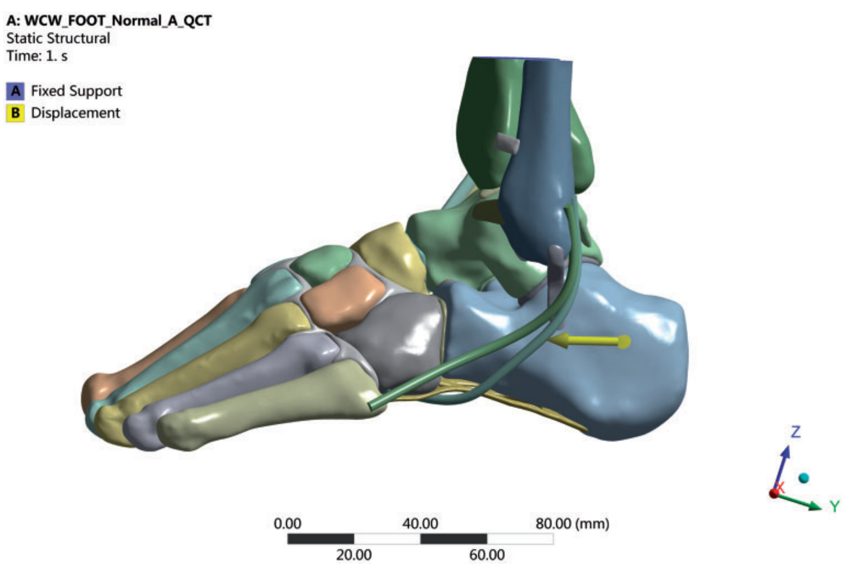

Figure 4. Loading style of the anterior drawer test

Table 1. Equivalent stresses of the lateral ankle ligaments in the ankle varus stress test

Group	Equivalent stress of ATFL (MPa)	Equivalent stress of CFL (MPa)	Equivalent stress of PLT (MPa)	Equivalent stress of PBT (MPa)
Normal	138.48	25.90	3.44	2.40
One-half PLT reconstruction	119.05	33.25	8.90	4.96
One-half PBT reconstruction	118.82	32.64	8.10	2.94
Allogeneic tendon reconstruction	84.00	27.01	3.95	2.45

ATFL: anterior talofibular ligament; CFL: calcaneofibular ligament; PLT: peroneus longus tendon; PBT: peroneus brevis tendon.

Table 2. Internal rotation angle, anteversion angle, and varus angle of talus in ankle varus stress test

Group	Internal rotation angle	Anteversion angle	Varus angle
Normal	10.09°	3.20°	15.03°
One-half PLT reconstruction	15.82°	5.69°	19.32°
One-half PBT reconstruction	15.78°	5.67°	19.27°
Allogeneic tendon reconstruction	11.51°	3.87°	15.78°

PLT: peroneus longus tendon; PBT: peroneus brevis tendon.

consisted of 705,347 elements and 448,129 nodes.

Ankle varus stress test

The equivalent stresses of the ATFL, CFL, PLT, and PBT are shown in Table 1. The maximum equivalent stresses of the ATFL were 119.05 and 118.82 MPa in the autologous PLT reconstruction group and PBT reconstruction group, respectively. These stresses were significantly higher ($P<0.05$) than that in the allogeneic tendon reconstruction group (84.00 MPa) but significantly lower ($P<0.05$) than that in the normal individual group (138.48 MPa). The maximum equivalent stresses of the CFL were 33.24 and 32.64 MPa in the PLT reconstruction group and PBT reconstruction group, respectively. These stresses were significantly higher ($P<0.05$) than that in the normal individual group (25.90 MPa) and allogeneic tendon reconstruction group (27.01 MPa). The maximum equivalent stresses of the PLT and PBT in the autologous tendon reconstruction group were also significantly higher ($P<0.05$) than that in the allogeneic tendon reconstruction group. In addition, the three angles of the talus in the allogeneic tendon reconstruction group were less than those in the other two groups, while they were similar to those in the normal individual group (Table 2).

Equivalent stress in anterior drawer test

The anterior drawer test showed that the maximum equivalent stresses of the ATFL in the autologous one-half PLT reconstruction group and one-half PBT reconstruction group were 31.31 and 31.47 MPa, respectively, both of which were less than that in allogeneic tendon reconstruction group (57.32 MPa). Similarly, the maximum equivalent stress of the CFL in the allogeneic tendon reconstruction group (52.20 MPa) was greater than that in the other two groups (one-half PLT reconstruction group, 28.60 MPa; one-half PBT

Table 3. Equivalent stresses of lateral ankle ligaments in anterior drawer test

Group	Equivalent stress of ATFL (MPa)	Equivalent stress of CFL (MPa)	Equivalent stress of PLT (MPa)	Equivalent stress of PBT (MPa)
Normal	61.67	69.83	20.63	26.75
One-half PLT reconstruction	31.31	28.60	16.05	40.94
One-half PBT reconstruction	31.47	29.07	23.13	32.89
Allogeneic tendon reconstruction	57.32	52.20	21.71	38.03

ATFL: anterior talofibular ligament; CFL: calcaneofibular ligament; PLT: peroneus longus tendon; PBT: peroneus brevis tendon.

reconstruction group, 29.07 MPa). The equivalent stresses of the ATFL, CFL, PLT, and PBT for the normal individual were 66.67, 69.83, 20.63, and 26.75 MPa, respectively (Table 3).

Discussion

Lateral ankle sprains account for about 85% of all ankle sprains.[22] After ankle sprains, the symptoms of pain, joint stiffness, and instability may persist for the long term,[23] highlighting the importance of effective treatment for this condition.[24] In the present study, FE ankle models of a healthy volunteer and lateral ankle sprains were constructed. The FE method has been proven to be a successful comparative tool in the field of orthopedic biomechanics.[25] The results of the present study showed that allogeneic tendon reconstruction, autologous reconstruction of one-half of the PLT, and reconstruction of one-half of the PBT had similar surgical outcomes that differed from the outcome of allogeneic tendon reconstruction.

Many surgical techniques have been applied to the repair of lateral ankle instability,[26] including the direct repair techniques described by Broström,[10] Gould et al.[3] and Karlsson et al.[11] Advantages of these procedures include a simple surgical approach, utilization of the local host anatomy, and fewer complications such as recurrent ankle instability and subtalar joint stiffness. However, these procedures may also decrease the range of subtalar and talocrural motion and increase the risk of adjacent cutaneous nerve injury.[10] In 1969, Chrisman and Snook[27] created a transverse drill hole in the fibula and reconstructed the torn lateral ligaments with one half of the PBT. The Chrisman–Snook procedure closely approximates the ATFL and CFL anatomically and is now commonly performed for chronic lateral ankle instability. In the present study, the FE models of one-half PLT reconstruction and one-half PBT reconstruction were created based on the Chrisman–Snook operation. The varus stress test and anterior drawer test showed that the equivalent stresses of the ATFL and CFL were similar in the two surgical techniques, indicating that the two surgical techniques had similar action effects on lateral collateral ligament injury.

In addition to autografts, allografts have also been used for anatomical ligament reconstruction.[28] Allograft tissue reconstruction can shorten the operative time, reduce postoperative pain, and lower the incidence of postoperative arthrofibrosis compared with autograft transplantation.[29,30] However, allografts have the potential for disease transmission and limited availability.[29] In the present study, the equivalent stresses of the lateral ankle ligaments were measured under allogeneic tendon reconstruction. The ankle varus stress test showed that the equivalent stresses of the ATFL and CFL and three angles of the talus in the allograft were less than those in the autograft. However, the equivalent stress of the CFL and three angles of the talus in the allograft were similar to those in normal individuals. These results suggest that allografts may be a better choice for anatomical ligament reconstruction with respect to the stress distribution. However, the exact mechanisms require further investigation.

The anterior drawer test is used in routine clinical practice to determine the integrity of the lateral ankle ligaments.[31] Many studies have demonstrated the value of the anterior drawer test for evaluating the integrity of the ATFL.[32,33] In the present study, the results of the anterior drawer test showed that the equivalent stresses of the ATFL and CFL in the allogeneic tendon reconstruction group were in closer proximity to that in normal individuals than in the other two groups. The results further indicated the value of allografts in lateral ankle ligament reconstruction. These findings are similar to those in previous reports. Caprio et al.[30] reported that 11 patients undergoing ligament reconstruction using allografts showed an improvement in their average American Orthopaedic Foot & Ankle Society scores from 29.6 to 55.4 points at an average follow-up of 14.1 months. Hua et al.[34] recently used semitendinosus allografts for reconstruction of the lateral ankle ligaments and also achieved a satisfactory result. All of this evidence confirms the satisfactory therapeutic effect of allografts for lateral ankle ligament injury.

Vázquez et al.[35] used the FE method to assess the initial stability of ankle arthrodesis with internal fixation and compare the initial stability of two popular joint preparation techniques. Their study suggested that the FE method was an effective qualitative tool for assessing the initial stability of ankle arthrodesis. Alonso-Vázquez et al.[36] also performed FE analyses to compare the initial stability at the fusion site of ankle arthrodesis with three-screw fixation and predicted higher initial stability than that obtained with two-screw fixation. In the present study, we also performed FE analysis to compare the effect of three surgical techniques on ligament reconstruction. However, our study had several limitations. First, no animal or clinical experiments were performed to verify our results, which may be different *in vivo*. Moreover, for ethical reasons, only one volunteer was included in this study, and there was a lack of comparison. Third, the radiological data applied in the current study was acquired by CT scans, which has low soft tissue resolution and subjects the patient to unnecessary radiation exposure. Therefore, more *in vivo* studies with larger samples and the application of magnetic resonance imaging are needed to confirm our findings.

Conclusion

In conclusion, the FE models indicated that allogeneic tendon reconstruction is in closer proximity to normal individuals in terms of equivalent stresses of the lateral ankle ligaments and the internal rotation angle, anteversion angle, and varus angle of the talus. Thus, allogeneic tendon reconstruction may be superior for lateral ankle sprains. However, the proprioception, rejection reaction, and persistence time of allografts remain to be studied.

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Declaration of conflicting interest

The authors declare that there is no conflict of interest.

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