RESEARCH ARTICLE / *Araştırma Makalesi*

Biomechanical Investigation Of The Effects Of Various Treatment Options On The Talus In Supination External Rotation Type 4 Ankle Injuries With Ruptured Deltoid Ligament: Finite Element Analysis

Deltoid Bağ Rüptürü Olan Tip 4 Supinasyon Dış Rotasyon Ayak Bileği Yaralanmalarında Çeşitli Tedavi Seçeneklerinin Talus Üzerine Etkisinin Biyomekanik Olarak İncelenmesi: Sonlu Elemanlar Analizi

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Geliş Tarihi / Received : **19.12.2022** Kabul Tarihi / Accepted: **30.12.2022** Çevrimiçi / Online: **16.03.2023**

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Cite this article/Atıf
Güvercin Y., Yaylacı M., Biomechanical investigation of the effects of various treatment options on the talus in supination external rotation type 4 ankle injuries with ruptured deltoid ligament: finite element analysis, Sakarya Med J 2023 ;13(1):62-69 DOI: 10.31832/smj.1220996

Abstract

Introduction	The purpose of this study is the biomechanical investigation of the rotation, stress, and deformation caused in the talus, under a specific load, by various fixation methods in the ankle, which has supination external rotation type 4 injury with deltoid rupture (SER type 4 DR).
Materials and Methods	The ankle of a healthy individual was analyzed with the help of a package program based on the finite element method (FEM). Then, the SER type 4 DR injury model was created. Next, the lateral malleolar plate was fixed with a screw, and different repair models for ankle fit were created. In the analysis section, forces obtained from the literature were applied to the healthy and repaired models. As a result of the analyses, mechanical values that occurred in the talus were obtained.
Results	As a result of this study, mechanical changes in the talus, which were caused by, deltoid ligament repair, suture button syndesmosis fixation, syndesmosis fixation with transfixation screw, suture button fixation + deltoid ligament repair and transfixation screw + deltoid ligament repair in the SER type 4 DR injury model with deltoid ligament rupture, were evaluated.
Conclusion	This study showed that the application of syndesmosis screw together with deltoid ligament repair in the treatment of SER type 4 DR ankle injuries with rupture of the deltoid ligament made regression, displacement, and talus rotations on the talus almost normal. In addition, syndesmosis fixation screw applications give better results than syndesmosis fixation suture button applications.
Keywords	Biomechanics, finite element method, talus, syndesmosis fixation

Öz

Amaç	*Bu çalışmanın amacı deltoid yırtığı olan supinasyon dış rotasyon tip 4 yaralanmalı ayak bileğinde belirli bir yük altında talusta meydana gelen rotasyon, gerilme ve deformasyonun çeşitli fiksasyon yöntemleri ile biyomekanik olarak incelenmesidir.*
Yöntem ve Gereçler	*Sağlıklı bir bireyin ayak bileği sonlu elemanlar yöntemine dayalı bir paket program yardımıyla incelendi. Ardından deltoid ligament yırtığı olan supinasyon dış rotasyon tip 4 yaralanma modeli oluşturuldu. Lateral malleol plak vida ile sabitlendi ve ayak bileği uyumu için farklı onarım modelleri oluşturuldu. Analiz bölümünde literatürden elde edilen kuvvetler sağlıklı ve tamir edilmiş modellere uygulandı. Yapılan analizler sonucunda talusda oluşan mekanik değerler elde edildi.*
Bulgular	*Bu çalışma sonucunda, deltoid yırtığı olan supinasyon dış rotasyon tip 4 yaralanma modelinde deltoid bağ tamiri, sütür button syndesmosis fiksasyonu, transfiksasyon vidası ile syndesmosis fiksasyonu, sütür buton fiksasyonu+deltoid bağ tamiri ve transfiksasyon vidası+deltoid bağ tamiri ile talusta meydana gelen mekanik değişiklikler değerlendirildi*
Sonuç	*Bu çalışma, deltoid yırtığı olan supinasyon dış rotasyon tip 4 yaralanma tedavisinde deltoid bağ onarımı ile birlikte syndesmosis vidası uygulamasının talus üzerindeki gerilme, yer değiştirme ve rotasyonların normale yaklaştığını gösterdi. Ayrıca syndesmosis tespit vidası uygulamaları, syndesmosis sütür button uygulamalarına göre daha iyi sonuç vermektedir.*
Anahtar Kelimeler	*biyomekanik, sonlu elemanlar yöntemi, talus, syndesmosis fiksasyon*

INTRODUCTION

Ankle fractures constitute 10 % of the fractures, and 40% of these require surgery.[1] Three different classifying systems are used for malleolar fractures; Lauge-Hansen, Dannis Weber, and American Orthopedic Association classifying systems. While Danis- Weber classification is made concerning the height of relation of fibula fracture with syndesmosis, the Lauge-Hansen classification is made concerning the fracture occurrence mechanism. In this classification, malleolar fractures are divided into 4/four subgroups; pronation- external rotation, supination-external rotation (SER), supination-adduction, and pronation-abduction.[2] Among these subgroups, SER injury is commonly encountered. In recent years, SER injuries have been divided into 4/four subgroups, and the most commonly encountered was reported as SER type 4 injuries.[3-4] The components of SER type 4 ankle injury are: anterior inferior tibiofibular ligament (AITFL) rupture, posterior inferior tibiofibular ligament (PITFL) rupture, oblique lateral malleolar fracture in the syndesmosis level, medial malleolar fracture and deltoid ligament rupture. Deltoid ligament rupture can be overlooked if no medial malleolar fracture is present, and this can lead to chronic ankle instability. This can result in a talus osteochondral defect (OCD) and may cause ankle osteoarthritis. Some authors report that, after ankle trauma, the possibility of developing OCD in the talus is 50%.[5] It is not clear where OCD will develop in the talar dome. While some authors report that OCD may develop in the talar dome lateral, some report that it can develop in the medial.[5-6] Deltoid ligament is the main stabilizer in the medial ankle. The deltoid ligament has shallow and deep layers. While the shallow layer resists the plantar flexion and external rotation of the talus relative to the tibia, the deep layer is more important for stabilization. The main function of the deep layer is to prevent the valgus positioning and posterior and lateral movement of the talus.[7-9] While subjective findings such as swelling in the medial ankle, sensitivity, and ecchymosis point to a deltoid ligament injury, a definitive diagnosis is made with stress radiographies. The most solid finding for diagnosis is medial clear space being 5 mm or more.[10] Treatment protocol for ankle fractures with deltoid ligament injury is still a controversial. The main reason for this uncertainty is that it is not decided whether the deltoid ligament should be repaired or not. While in some old papers, it is asserted that deltoid ligament repair is not necessary,[11-12], in current literature, the tendency is towards deltoid ligament repair.[8,13] Some authors claim that, compared to deltoid ligament repair, the use of a transfixation screw will result in a higher syndesmotic malreduction ratio, thus, abnormal talus motion.[14] No biomechanical study has been found in the literature that analyzes the effect of the deltoid ligament repair in a SER type 4 ankle fracture with a deltoid ligament injury and syndesmotic fixation treatment methods on talus.

Lately, in the biomechanical evaluation of musculoskeletal disorders in orthopedics, and in the development of implants, finite element method (FEM) is used. The advantage of this method is that it is cheaper and more practical than experimental studies. Another important advantage is that it analyzes the mechanical values in detail.[15-17]

In this study, the stress, deformation and rotation values caused in the talus by supination external rotation type 4 injury with deltoid rupture (SER type 4 DR) were investigated. In addition, respectively, deltoid ligament repair, suture button syndesmosis fixation, syndesmosis fixation with transfixation screw, suture button fixation+deltoid ligament repair, and transfixation screw+deltoid ligament repair models were created in the SER type 4 DR injury model. To our knowledge, no detailed study analyzes this phenomenon in this detail. The results of the study give information about the appropriate values that can be used in the application.

MATERIALS and METHODS

The images of the examined model were provided from computer tomography (CT) scans of the right foot ankle of a normal male in the unloaded state. The male was 30 years old, 178 cm in height, and 80 kg in weight. The solid model was obtained from the previously licensed work.[15] The data, consisting of images in DICOM form, were then imported into the Mimics Innovation Suite 24.0 program to create the geometry of the bones (tibia, fibula, talus, calcaneus, cuboid, navicular, cuneiform, metatarsal, and phalange) in the ankle.[18]

Model parts imported from Mimics were composed using Materialise 3-Matic 16.0 to form solid geometries for each bone. The talocrural joint is balanced by modeled ligaments, taking into account their geometric properties. Ligaments; anterior inferior tibiofibular ligament (AITFL), posterior inferior tibiofibular ligament (PITFL), anterior talofibular ligament (ATAFL), posterior talofibular ligament (PTAFL), deltoid ligament (DL), calcaneofibular ligament (CFL) were created (Fig. 1).[19]

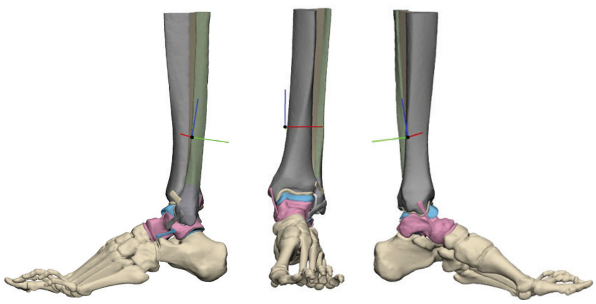

***Figure 1:** Solid model.*

The composed bones, ligaments, and cartilage were transferred to the ANSYS package program based on the finite element method.20 The geometry mesh size was chosen to be the same size. After performing a mesh sensitivity analysis, the mesh size was set to 3 mm (Fig. 2). 1 mm thickness on the surfaces of the tibia, fibula, and talus was set to the cortex of bone, and the inner part was trabecular bone. The thickness of the cartilage was about 1.0 mm.21 The finite element mesh of the model is created of 3D tetrahedron elements.

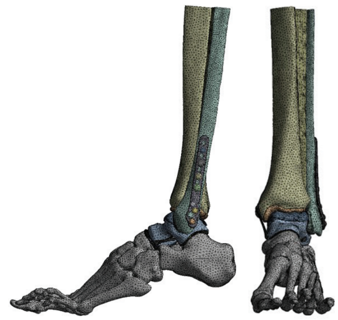

***Figure 2:** Mesh structure of the model.*

Human bone is contained two different types of bone cortical and trabecular. Cortical bone is more rigid than trabecular bone due to cellular density. All elements are modeled as linear elastic, homogeneous and isotropic structures.[22] Ligaments are contained parallel collagen fibers, and articular cartilage is a biphasic material. The material properties used for the model were obtained from the literature (Table 1).[23-31] There are 731928 elements and 1154127 nodes in the finite element model of the created ankle.

Table 1: The material properties of the models.

Material Type		Elasticity Modulus (MPa)	Poisson's Ratio
Calcaneobular		17000	0.49
Talobular		17000	0.49
Cartiladge		10	0.30
Trabecular		530,9	0,30
Cortical		12100	0.30
Interosseous		260	0.40
Titanium (Ti6Al4V)		113800	0.34
UHPWE-Suture button		928.5	0.35
	ATFL	16.55	0.49
	PTFL	18.44	0.49
Ligaments	ATAFL	15	0.49
	PTAFL	15	0.49
	DL	7	0.49
	CFL	11	0.49

2352 N vertical, 235 N horizontal forces, and 2.7 Nm clockwise moment were applied to the upper part of the tibia (Fig. 3).[32-33]

In order to realize the purpose of this study, analysis was carried out in seven different models. These models; screw for syndesmosis fixation (deltoid ligament repaired), suture button for syndesmosis fixation (deltoid ligament repaired), deltoid ligament repaired, screw for syndesmosis fixation (deltoid ligament unrepaired), suture button for syndesmosis fixation (deltoid ligament unrepaired), no syndesmosis fixation (deltoid ligament unrepaired) (Figs. 4-5)

anteroposterior view lateral view

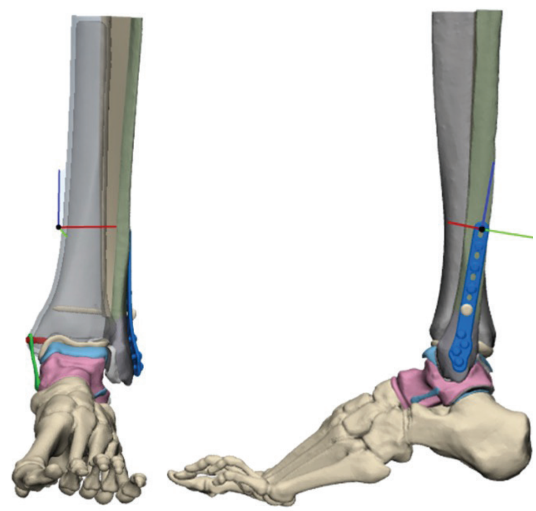

Figure 4: *Screw for syndesmosis fixation+deltoid repaired.*

anteroposterior view lateral view

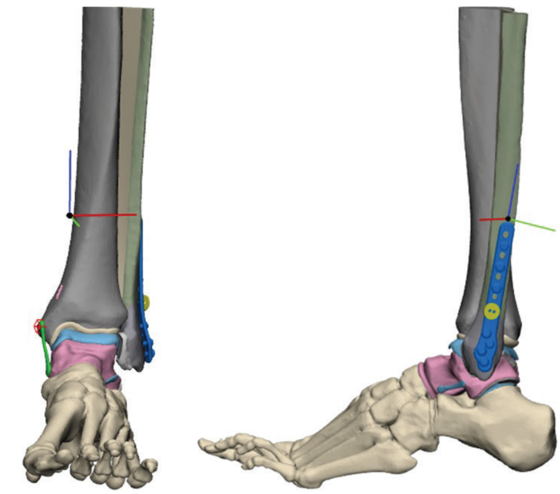

Figure 5: *Suture button for syndesmosis fixation+deltoid repaired.*

After defining all the data required for the element types, material properties, boundary conditions, and loadings, static structural analyzes were performed, and the results are given below.

RESULTS

In this study, different simulations were performed to analyze the seven models. As a result, the rotation, stresses, and deformation obtained for the talus under various geometrical conditions were obtained. The obtained values are presented in the figures.

The stress distribution for different models is given as an example (Fig. 6). These models are defined as; intact, screw for syndesmosis fixation (deltoid ligament repaired) (SSF+DLR), suture button for syndesmosis fixation (deltoid ligament repaired) (SBSF+DLR), deltoid ligament repaired (DLR), screw for syndesmosis fixation (deltoid ligament unrepaired) (SSF), suture button for syndesmosis fixation (deltoid ligament unrepaired) (SBSF), no syndesmosis fixation (deltoid ligament unrepaired) (No SF+No DLR).

The numerical values of the analysis results obtained from different applications are shown graphically in Figure 7-9. The rotation, maximum stress, and deformation values obtained in the talus of seven models (intact, SSF+DLR, SBSF+DLR, DLR, SSF, SBSF, No SF+No DLR are given in the figures. The rotation, changes in the talus are given in Figure 7. From the figure, it can be seen that the difference in rotation obtained from the intact and No SF+No DLR model are great. As seen in the figure, lower rotation values were obtained when the syndesmosis fixation screw application was compared with the suture button. Another result is that deltoid ligament repair reduces rotation values. The deformation values obtained in the talus of seven models are given in Figure 8. The results revealed that model No SF+No DLR has the highest stress values, and model SSF+DLR has the lowest deformation values. Different results were obtained for the different models. Another considerable result seen in the figure is that the values for the syndesmosis fixation suture button are higher than the values for the syndesmosis fixation screw. The maximum stresses in the talus for different models obtained from the analysis are shown in Figure 9. The figure disclosed that model SF has the highest maximum stress, and model SSF+DLR has the maximum stress. Different results were obtained for the geometrical conditions in seven models. As can be clearly seen from the figures, the results closest to the intact model were obtained as follows, SSF+DLR, SBSF+DLR, DLR, SSF, SBSF, and No SF+No DLR, respectively.

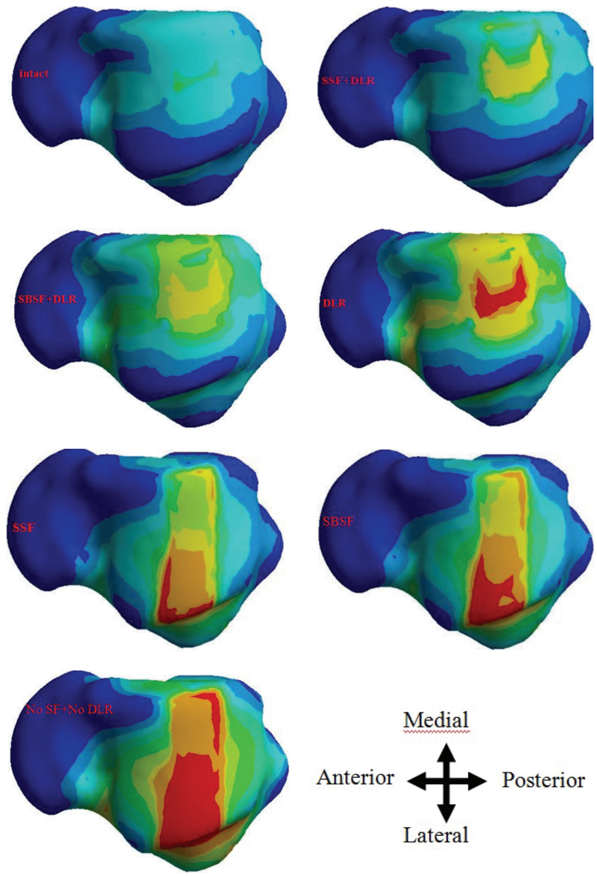

Figure 6: *Stress distribution in the talus for models.*

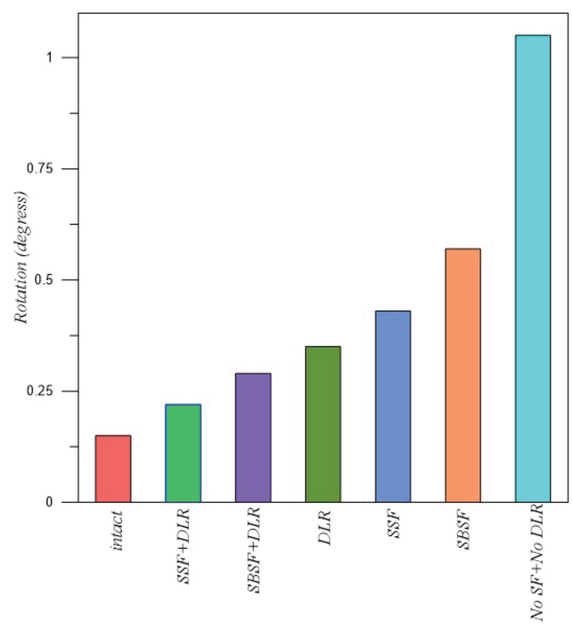

Figure 7: *Rotation in the talus for models.*

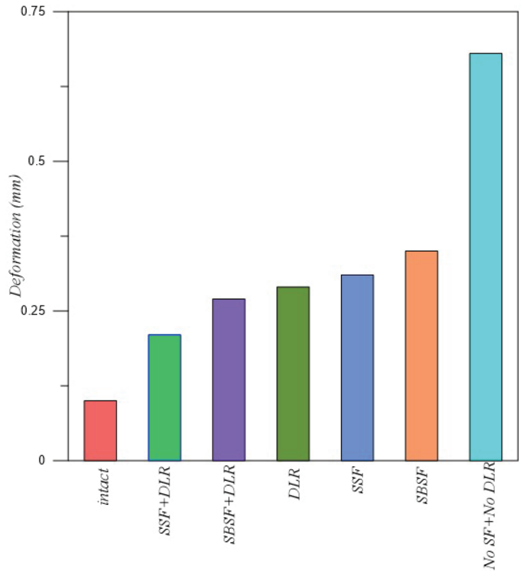

Figure 8: *Deformation in the talus for models.*

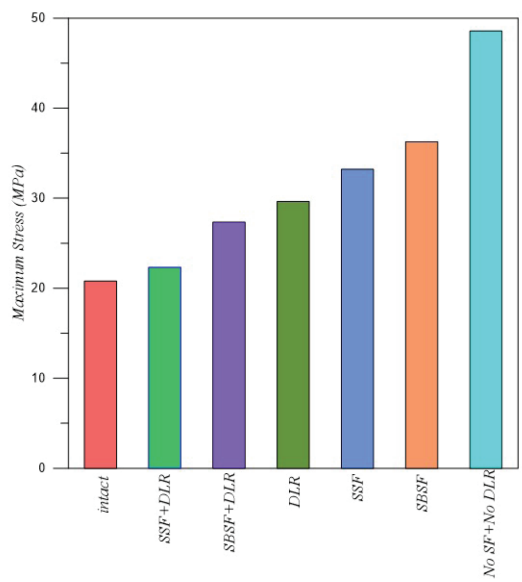

Figure 9: *Maximum stress in the talus for models.*

DISCUSSION

The aim of this study is to investigate the rotation, stress, and displacement that take place in the talus in a model with SER type 4 DR injury of the ankle with a deltoid ligament rupture. The secondary aim of the study is to obtain the values of the stress and displacement in the talus and investigate the relationship with traumatic osteochondral defects. When the data was analyzed, it was seen that the model closest to the healthy ankle was the one in which deltoid ligament repair was used with a transfixation screw. After ankle injuries where medial clear space has been opened, usually, a syndesmosis screw is used. In a study that compares deltoid ligament repair and transfixation screw, authors reported that functional results were similar. They reported that deltoid ligament repair could be an appropriate treatment strategy, and the transfixation screw should be removed.[34] Another biomechanical study reports that the combined usage of a transfixation screw with deltoid repair brought talus rotation and translation levels nearly to normal levels.[35] Butler et al., in their biomechanical study, published the results of deltoid ligament repair in the SER type 4 DR fracture model. They saw an increase in internal and external rotation in the talus under load when the deltoid ligament was not repaired (when open reduction+internal fixation was applied to the lateral malleolar), and they reported that there was no biomechanical difference between deltoid ligament repair and the healthy model.[36] In this study, while only deltoid ligament repair gave satisfactory results in SER type 4 DR injury, the use of deltoid ligament repair together with transfixation screw was found to reduce strain and displacement on the talus almost to the values of the intact model. Also, in this study, the suture button and transfixation screw, which is commonly used in fixing the syndesmosis in SER type 4 DR injury repair where clinical deltoid ligament rupture is present. While the transfixation screw limits the external rotation of the talus, the stress and displacement in the talus are significantly higher in both treatment methods. As a result, when the rotation, stress, and displacement values are analyzed, the transfixation screw is more appropriate than the suture button application.

In recent years, the suture button fixation method has become popular in syndesmosis instabilities. However, in a biomechanical study investigating the effect on talus movements, the authors reported that the suture button method provides less stability in spite of deltoid ligament repair and transfixation screw.[35] As the result of this study, suture button fixation in syndesmosis fixation, without deltoid ligament repair, has significantly increased the stress and displacement on the talus. This situation will probably be considered as the factor leading to osteochondral defect or osteoarthritis in the future.

Publications which report that talus osteochondral defect can occur secondarily to the ankle injury have been popular in recent years. However, no papers have been found in the literature that analyses the relation with deltoid ligament rupture. Martijn et al., in their compilation study, found that post-trauma osteochondral defect occurrence is 45%, and they reported that the most defect occurred in talus anteromedial. They reported that the rate of OCD occurrence was higher in SER injuries compared to other types of injuries.[5] In another study, the authors report that even though OCD incidences were much higher in SER injuries, the majority of the injuries took place in the lateral talar dome.[6] A study that supports this study was published in 2020. In this study, it has been reported that the majority of post-traumatic OCD took place in the lateral dome.[37] When the treatment options in this study were analyzed, it was seen that, both in syndesmosis fixation with transfixation screw and syndesmosis fixation with suture button, stress and displacement increased more in the talar dome middle section and less in the medial section. There was no significant difference in other treatment methods.

CONCLUSION

This study evaluated the talus biomechanically following treatment options for SER type 4 DR ankle injuries with rupture of the deltoid ligament. The results obtained from the study are briefly summarized below:

- The best results were obtained with the application of the syndesmosis screw with deltoid ligament repair.
- Models with deltoid ligament repair gave better results.
- By examining the mechanical values created by various treatment methods on the talus gives us an idea about the possible location of osteochondral defects that may occur after treatment.
- Syndesmosis fixation screws give better results than fixation suture button applications.

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