# Original Article Finite element analysis of the stress concentration in pronation-abduction ankle joint injuries

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**Abstract:** Purpose: This study aims to investigate the stress concentration features of pronation-abduction injuries in the Lauge-Hansen classification scheme. Method: A finite element model of the ankle joint was constructed that included ligaments and skeletal structures. Ansys (Version 14.0, ANSYS Inc, PA, USA) was used to model a full constraint on the distal end of the tibiofibula while applying a vertical 300-N force on three points along the lateral side of the foot, simulating the pronation position of the ankle joint, a common type of injury. Results: During the simulated loading process, the maximum value of equivalent stress occurred in sequence at the fibular attachment point of the anterior lower tibiofibular ligament, the anterior lower tibiofibular ligament, and the posterior lower tibiofibular ligament. The maximum value of normal contact stress was first located at the articular facet of the medial malleolus between the astragalus and the malleolus medialis contact surface, and then at the posterior margin of the fibula at the contact surface between the astragalus and the lateral malleolus. Conclusions: Based on the validation of the injury mechanism, the existence of a IV degree injury was revealed.

Keywords: Ankle, Lauge-hansen classification, pronation-abduction ankle injury, finite element analysis, stress concentration

#### Introduction

The Lauge-Hansen classification is a commonly used system of ankle injury classification [1]. It is widely used in clinical applications because it classifies injuries based on the position of the ankle during the injury, as well as the magnitude and direction of the force. In pronationabduction ankle injuries, the injury is classified according to degree of seriousness: first degree (i.e., injury of the interior deltoid ligament or malleolus medialis); second degree (i.e., injury of the tibiofibular syndesmosis structure and/or avulsion facture of the posterior malleolus); or third degree (i.e., fibular facture above the ankle joint and/or dislocation of talus). Finite element (FE) software can simulate the injury process, but there is still no research concerning the biomechanics of pronation-abduction ankle joint injuries based on FE models. This paper aims to simulate the injury process of pronation-abduction movements by establishing an FE model of the ankle joint. Furthermore, the biomechanical mechanism is also validated

based on stress analysis, thus providing a basis for improvement of clinical treatments plans.

#### Model establishment

Acquisition of ankle computed tomography image

A healthy 50-year-old woman was the main participant in this study. Her right ankle was placed in a neutral, non-load-bearing position. A Brightspeed Spiral computed tomography (CT) scanner was used (resolution ratio of  $512 \times 512$ ; GE, General Electric Company 64 multislice spiral CT USA) was used. A total of 299 image layers were acquired from the heel to the proximal, of the tibia, with a layer thickness of 1 mm and an interval of 1 mm. The data were saved in Dicom format.

#### Establishment of FE model

MIMICS software (version 14.12; Materialise, Leuven, Belgium) was used to process the CT

the line element			
Construction	Element	Young's	Poisson's
element	type	modulus (MPa)	ratio
Compact bone	Solid (solid187)	14000 [7]	0.3
Cancellous bone	Solid (solid187)	350 [7]	0.3
Ligament	Shell (shell181)	260 [11]	0.49 [12]

 
 Table 1. Element type and material parameters of the elements in the finite element (FE) model



Figure 1. Finite element (FE) model.

images of the ankle and foot. The tibia, astragalus, and fibula were reconstructed and integrated with other skeletal features like the calcaneus, tarsal navicular bone, interior and lateral cuneiform bones, and the cuboid and intermediate cuneiform bones. We added eight ligaments to the model, including three interior deltoid ligaments (tibionavicular ligament, tibiocalcaneal ligament, and tibiotalar ligament), three lateral collateral ligaments (anterior talofibular ligament, posterior talofibular ligament, and calcaneofibular ligament), and two distal tibiofibular anterior and posterior ligaments (anterior lower tibiofibular and posterior lower tibiofibular ligaments). The membranes between the tibiofibulas were generated at the same time. Based on our references, the anatomical features and material parameters of each tissue are listed in Table 1 [2-8]. The bones and ligaments were modelled as isotropic homogeneous linear elastic elements. Different material parameters were assigned to the bones, while the ligaments were set to have different thicknesses. Face-to-face slide contact conditions were set between the astragalus, fibula, and tibia, with the friction coefficient set as 0.1. Bond contact was introduced between the ligaments and bones, as well as between the calcaneus and astragalus. Ansys 14.0 was used to conduct stress analysis on this model. An FE model containing 131,504 nodes and 77,376 elements was produced for the stress analysis, and it included the major ligaments and bones of the ankle joint, as shown in Figure 1.

# Model verification

After verification of the model, 500 N and 100 N of pressure were applied to the upper surfaces of the tibia and fibula, respectively. The distal posterior surface of the calcaneus, the tuberosity of the fifth metatarsal, and the distal surface

of the first metatarsal were completely constrained. The results of a normal human body weight loading simulation were compared with the experimental results provided by Anderson [9], as shown in **Figures 2** and **3**. The maximum contact stress was close to the result of Ankle 2 in Anderson's [10] experiment, indicating that the model constructed in this study agrees well with Anderson's results (**Table 2**).

# Load and constraint

According to the Lauge-Hanson classification and the experimental conditions, the proximal surfaces of the tibia and fibula were completely constrained. A 300-N load was applied vertically on three points along the outside of the planta pedis, simulating the pronation position of the ankle joint and applying abduction injury movement to the astragalus (**Figure 4**).



**Figure 2.** Stress distribution in the specimen and FE model of the facies articularis inferior tibiae of two ankle joints, provided by Anderson.



Figure 3. Stress distribution in the facies articularis inferior tibiae based on the FE model.

#### Simulation of the pronation-abduction injury

Ansys 12.0 was used for statistical analysis, with the obtained von Mises stress distribu-

tion diagram. A 10-Nm abduction movement was applied to the model to simulate a pronation-abduction first degree injury. The maximum equivalent stress was located at the fibular ligament attachment point in front of the distal tibiofibula. The maximum contact surface stress was located at the internal malleolar facet of the tibia between the astragalus and malleolus medialis (Figure 5A and 5B). This distribution agreed with the stress concentration features of first degree pronation-abduction injuries. Afterward, contact between the interior deltoid ligament, the astragalus, and the malleolus medialis was removed according to the first degree injury; this finished the first degree injury simulation. A 10-Nm abduction movement was applied to the model again to simulate further injury. The maximum equivalent stress occurred on the upper side of the anterior lower tibiofibular ligament, while the maximum contact surface stress appeared at the lateral malleolus (Figure 5C and 5D). These matched the features of second degree injuries. Then, according to the stress concentration features, the anterior lower tibiofibular ligament was removed, and an approximated transverse osteotomy was conducted on the fibula at the tibiofibular syndesmosis area (Figures 6 and 7). A 10-Nm abduction movement was gradually applied over three stages, at increments of approximately 3.3 Nm during

each stage, simulating further injury. The maximum equivalent stress was located at the distal tibiofibular posterior ligament, while the maximum contact surface stress appeared at

	Anderson experiment				
	A	nkle 1	Ankle 2		- This study
	Tekscan	FE simulation	Tekscan	FE simulation	-
Maximum contact stress (MPa)	3.69	3.74	2.92	2.74	2.52

**Table 2.** Comparison between the results of the contact stress distribution in the facies articularis inferior tibiae obtained from Anderson's experiment and this study



Figure 4. Loading diagram of the simulated moment.

the posterior margin of the fibula at the contact surface between the astragalus and the lateral malleolus. In addition, the maximum equivalent stress increased as the load increased, (**Table 3**; **Figures 8** and **9**). This matched the stress concentration feature of third degree injuries.

#### Discussion

# Simplification of the FE model of the ankle joint

To date, no FE models have been constructed to simulate and analyze Lauge-Hansen pronation-abduction ankle injuries. In this study, an FE model with complete structures of the tibia, fibula, astragalus, and related ligaments was constructed. Because we mainly focused on the distribution and variation of stress in the tibia, fibula, and astragalus, the model of calcaneus and surrounding foot bones were simplified. According to Huiskes et al. [11], both the cortical bones and the cancellous bones can be considered linear and isotropic materials under static loading conditions.

# Advantages of using shell elements to simulate the addition of ankle joint ligaments

Significant deviations exist among the material parameters reported by various studies on ankle and foot ligaments [12-15]. Most of the studies used the bar element to establish their models [16-18]. Liu Qinghua et al. [19] used a spring element, while Shin J et al. [20] adopted a beam element. In our study,

we modeled the ligaments using shell elements. The SHELL181 element is suitable for the analysis of shell structures with a certain thickness. It is a four-node element, with six degrees of freedom for each node (displacement freedom degrees in X, Y, Z directions, and rotational freedom degrees around X, Y, Z axes). It can be used to analyze large rotational linear or nonlinear deformations. The shell element can bear compression and tension, as well as bending movements. Hence, it can favorably simulate thin-walled structures and is closer to actual human body ligaments than a bar element, which is why we used it to model the eight major ligaments of the ankle joint.

The numerical results of this study were compared with those of Anderson's experimental study. It was found that the contact surface pressure was almost the same in both scenari-



**Figure 5.** A. Stress diagram of the ligament attachment point at the front tibiofibular syndesmosis where the maximum equivalent stress exists. B. Stress diagram of the malleolus medialis where the maximum contact surface stress appears. C. Stress diagram of the upper side of the anterior lower tibiofibular ligament, where the maximum equivalent stress is located. D. Stress diagram of the lateral malleolus, which has the maximum contact surface stress.

os, indicating our model was valid and is applicable to mechanical analysis on pronationabduction ankle joint injuries.

# Discovery of the pronation-abduction fourth degree injury

In this study, stress concentration sites were found to occur in the anterior lower tibiofibular ligament after the first degree injury. The equivalent stress in the anterior lower tibiofibular ligament reached the maximum value at the second degree injury. However, stress concentration occurred in the posterior lower tibiofibular ligament only when the abduction force continued after the third degree fibula fracture, which is different from the description of the second degree injury in the Lauge-Hansen classification. According to our study, anterior lower tibiofibular ligament fractures occur in the second degree injury while no stress concentration or facture exists in the posterior lower tibiofibular ligament. After the third degree fibula fracture, a stress concentration fracture occurs in the posterior lower tibiofibular ligament only when abduction force continues. Therefore, it is reasonable that fourth degree injuries may occur after pronation-abduction third degree injuries and could result in the fracture of the anterior lower tibiofibular ligament or the avulsion fracture of the posterior malleolus.

Even though the shell elements used in this study possess mechanical properties more similar to actual ligaments than other elements, they are still unable to simulate the ligament



Figure 6. Ortho position image of the osteotomy.



Figure 7. Lateral position image of the osteotomy.

structure perfectly using FE technology. A more accurate FE simulation will likely be developed as technology improves.

#### Conclusion

A 3D FE model of the ankle joint with major skeletal structures and related ligaments was constructed in this study. The simulated first degree pronation-abduction ankle joint injury matched the Lauge-Hansen classification description. However, an anterior lower tibiofibular ligament fracture occurred in second degree injuries, while the posterior lower tibiofibular ligament did not fracture. In third degree injuries, the high-position fracture of the fibula could occur only with fracture of the anterior lower tibiofibular ligament, while the posterior lower tibiofibular ligament was impossible to harm. Only with continuous application of violent abduction after the third degree facture of the fibula did the posterior lower tibiofibular ligament show signs of stress concentration before fracturing. Therefore, we concluded that fourth degree injuries can occur after pronation-abduction third degree injuries and lead to fracture of the posterior lower tibiofibular ligament, or even avulsion fracture of the posterior malleolus. The Lauge-Hansen classification is difficult to understand and control clinically. The simulation in this study allowed for better visual understanding and analysis of this classification. The method proposed can contribute to further study of the biomechanics of other ankle joint injuries belonging to the Lauge-Hansen classification, and help to investigate the shift regularity of bone fractures in ankle joint

injuries in depth. Thus, a more reliable biomechanical basis for the restoration and fixation of ankle joint injuries is provided. The outcome of this study has validated the need for it and provided biomechanical references to understand damage mechanisms and improve treatment plans. It also provides new ideas for further study on ankle joint injury mechanisms. In the meantime, our FE model can be used to simu-

# Analysis of the stress in ankle joint injuries

Injury degree	Abduction load applied	Value and position of the maximum equivalent stress/MPa	Value and position of the maximum contact surface stress/MPa
First degree	0-10 Nm	The tibia attachment site of the anterior lower tibiofibular ligament (359.9 $\ensuremath{MPa}\xspace)$	Interior articular surface of the malleolus medialis at the contact surface between the astragalus and malleolus medialis (52.7 MPa)
Second degree	0-10 Nm	Upper side of the anterior lower tibiofibular ligament (326.3 MPa)	Posterior margin of the fibula at the contact surface between the astragalus and lateral malleolus (49.5 MPa) $$
Third degree	One-third of the full load	Posterior tibiofibular ligament (45.7 MPa)	Posterior margin of the fibula at the contact surface between the astragalus and lateral malleolus (4.9 MPa)
	Two-thirds of the full load	Posterior tibiofibular ligament (70.2 MPa)	Posterior margin of the fibula at the contact surface between the astragalus and lateral malleolus (5.2 MPa)
	Full load	Posterior tibiofibular ligament (94.0 MPa)	Posterior margin of the fibula at the contact surface between the astragalus and lateral malleolus (5.4 MPa)

<b>Table 3.</b> Distribution of stress and pressure in the pronation-abduction
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# Analysis of the stress in ankle joint injuries



Figure 8. Stress distribution in the posterior talofibular ligament after the abduction load was applied. A. Applying one-third of the full load; B. Applying two-thirds of the full load; C. Applying the full load.





late other injury mechanisms of the ankle joint, and to review, validate, and investigate the occurrence of ankle diseases. However, taking the complexity of the ankle joint injury into consideration, the construction of FE models for Lauge-Hanse pronation-abduction ankle joint injury still requires further investigation.

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# Disclosure of conflict of interest

None.

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