ORIGINAL ARTICLE

Biomechanical effect of ankle ligament injury in AO 44B2.1 lateral malleolus fractures after lateral plate fixation: A finite element analysis

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Background: Distal fibula fractures at the ankle level are common and are usually accompanied by ligament injuries. This study aims to evaluate the effects of ankle ligament ruptures on ankle
joints, fracture instability, and plate stress after distal fibula fracture fixed with plate created by finite element analysis (FEA) modeling and loading applied to ligament rupture models that may accompany this fracture.

**Methods:** A finite element model consisting of 3-D (3D) fibula, tibia, foot bones, and ankle ligaments was designed to investigate the effects of ligament injuries accompanying plate-detected Arbeitsgemeinschaft für Osteosynthesefragen (AO 44B2.1)-type fractures on fracture detection, fixation material, and ankle joints. Then, the results were evaluated by modeling ligament rupture in 6 different ways.

**Results:** In the modeling where the deltoid and the talofibular ligament are broken together, instability is the highest in the ankle (7.31 mm) and fracture line (0.15 mm). In our study, the rupture of the tibiofibular anterior and posterior ligaments associated with syndesmosis caused less instability in the fracture and ankle than the single rupture models of both the deltoid and the talofibular ligament.

**Conclusions:** In the finite element modeling of AO 44B2.1-type fractures detected with plate, the importance and potential effects of often overlooked ankle ligaments are pointed out shown. It is important to keep in mind that when treating ankle injuries, the ankle should be treated as a whole, with both bone and soft tissue. In some cases, the fracture may represent the visible tip of the iceberg.
The rapidly increasing financial burden resulting from the fractures in the workforce, as well as the loss of productive capacity caused by fractures, has made it an essential part of society to tackle this increasing public health issue and to make the necessary efforts to carry out fracture repair research (1). Ankle fractures constitute 9% of all fractures. Over the past 30 years, the incidence of ankle fractures has been increasing steadily, and one in 800 people is affected by this injury each year, particularly young, active men and elderly women with osteoporosis (2). Surgical intervention is rarely performed for stable fractures where the ankle joint is intact. Depending on the patient’s additional injuries and functional state prior to the injury, unstable fractures require fixation following closed or open reduction. Although there is an increasing tendency for surgical treatment of unstable fractures today, there are studies on the good long-term outcomes of conservative treatment in the past (3).

Unfortunately, ankle injuries are not always simple injuries, and various complications, such as nonunion, malunion, implant failure, osteoarthritis, and wound problems ranging from one-third to half of the patients in different series, permanent complaints, and recurrent traumas, are encountered (4, 5). The often underlying cause of such problems is ankle instability and fracture detection. In order to achieve optimum stability in ankle and fracture diagnosis, ligament injuries must be carefully evaluated rather than only the bones being fixed (6).

Distal fibula fractures at the ankle level are common, usually accompanied by ligament injuries, and are among the ankle fractures (7).
There are different approaches to distal fibular fractures in the literature. There is no complete consensus on the treatment procedures since the surgeon must consider many factors (8).

In the literature, Weber and AO classified distal fibula fractures located at the ankle level as type B. Type B fractures may damage the connective structures, especially in deltoid and syndesmosis (9, 10).

In this study, should the ruptured ligaments accompanying the distal fibula fracture located at the joint level be repaired? Can fracture and joint instability develop if ligament repair is not performed? And does instability due to ligament tears represent a risk factor for osteoarthritis, nonunion, and implant failure? We have been searching for answers to questions like these. To address this question in our study, we sought to provide a different perspective using finite element analysis (FEA).

There is no consensus on whether deltoid and syndesmosis ligament ruptures should be repaired in stable ankle fractures (11, 12). However, it is emphasized in some publications that the anterior talofibular ligament (ATFL) lesions, which are not used in classifications, usually associated with inversion injuries, also accompany distal fibular fractures (13, 14). However, there are few articles on joint-level fractures and ATFL lesions of the distal fibula (15, 16). Additionally, no study has evaluated ATFL lesions and other possible ligament ruptures in distal fibula fractures.
The finite element method (FEA) is a method that enables the material models selected for bone, ligament, and implant in orthopedics and traumatology practice to be verified with boundary and loading conditions and to reach results with material properties. FEA helps with successful fixation, anatomical restoration of fractures, and evaluation of ligament structures (17).

This study aimed to evaluate ankle joint instability, fracture detection instability, and stress forces on the plate by using distal fibula fracture (AO 44B2.1) and rupture modeling of the ligaments created by finite element analysis (FEA).

Methods

This finite element analysis study was conducted at Yozgat Bozok University Faculty of Mechanical Engineering between July 2022 and September 2022. In this study, a model consisting of 3-D (3D) fibula, tibia, foot bones, and ankle ligaments was designed and used to investigate the effects of ligament injuries accompanying AO 44B2.1-type fractures on fracture detection, fixation material, and ankle joints.

In this model, fracture type AO 44-B2.1 (Weber B) was created according to the Arbeitsgemeinschaft für Osteosynthesefragen [AO] classification, which can simulate real fractures on the distal fibula using Space claim software.

In distal fibula fractures, AO/OTA, published in 2018, presented a simple and easy-to-understand classification system. It is divided into three infra-syndesmosis, trans-syndesmosis,
and supra-s Syndesmosis, according to the location of the fracture in the fibula. The location of the fracture in the distal fibula at the ankle level is called 44b. They used injuries in the deltoid and syndesmosis as a reference when dividing 44 B-type fractures into subgroups. According to this classification, a fibula fracture showing an ankle-level location, including deltoid and syndesmosis injury, is defined as 44B2.1 (10).

The solid models created were converted into finite element models using Ansys Workbench software. The plate used to join the fibula (AO44B2.1)-type fracture consists of titanium alloy material. Linear elastic isotropic material models were applied for plates, bones, and ligaments. The material parameters used for plate, bone, and ligaments are presented in Tables 1 (18) and 2 (19).

Finite element models are fixed so that they cannot be moved or rotated in any way from the lower limit of the model. Loadings were applied to the upper limit of the model on the tibia, a force of 600-N downward in the vertical direction, and a moment of 12,497-N mm in the lateral malleolus (distal part of the fibula) region (19, 20). The limiting conditions and loads are shown in Figure 1. To simulate the actual condition of the fibula and tibia in the tissue, movement from the upper part of the model in certain directions was prevented. The elements used for the connection are fixed on the fibula in a way that corresponds to the real conditions. The coefficient of friction was assumed to be 0.2, considering the fracture interface as frictional contact.
To obtain the best result in the finite element analysis, mesh optimization was performed and the best mesh density was determined. With the best mesh density, the finite element models of 3D models were also statically analyzed under the uploads given using the Ansys Workbench 2020R2 Finite Elements software.

Then, in the distal fibula fracture modeling (Figure 2), which was detected with platescrew under loading, the deltoid, anterior tibiofibular, posterior tibiofibular, and anterior talofibular ligaments possibly associated with the fracture were torn in different ways. Two criteria were selected to present the results of the numerical analysis (SEA-Finite Element Analysis). One is the von Mises stress on the metal component of the fixing methods. The von Mises stretch determines where a particular material will be damaged. Another criterion is the displacement and rotation of the fracture space and ankle joint. The displacement and rotation measured after putting the effect of the physical load are defined as the movement between the parts.

Results

After plate detection of the distal fibula AO B2.1 fractures, loadings were applied in single and multiple rupture models of the deltoid, anterior tibiofibular, posterior tibiofibular, and anterior talofibular ligaments. The displacement of the ankle joint (Figure 3) (Table 3), fracture line (Figure 4) (Table 4) after loading, and the distribution of the stress force on the fixation material plate (Figure 5) were shown using finite element modeling.
In the AO 44B2.1 fracture modeling detected with plate, the effect of the ligaments on ankle stability in the case of rupture is given in Figure 3. The tearing of the deltoid alone created a total mobility of 2.2168 mm, while the single tears of the talofibular anterior created 1.0205 mm ankle instability. In our finite element study, the fact that the tibiofibular anterior and posterior regions associated with syndesmosis are broken creates less foot instability than the single rupture models of both the deltoid and the talofibular ligament. The highest ankle instability (2.3176 mm) was observed in the model, where the deltoid and talofibular ligament ruptured together (Figure 3).

In the AO 44B2.1 fracture modeling detected with plate, when the effect of ligament ruptures on fracture stability was evaluated, the rupture of the deltoid alone created 0.0929 mm instability, while the single rupture of the talofibular anterior created 0.1221 mm fracture instability. In our study, the rupture of the tibiofibular anterior and posterior ligaments associated with syndesmosis created less fracture instability than the single rupture models of both the deltoid and the talofibular ligament. In multiple ligament tear modeling, it was observed that the highest fracture instability (0.1521) occurred in the modeling where the deltoid and talofibular ligament were ruptured together (Figure 4) (Table 4).

When the effect of ligament ruptures on the plate, which is the fixation material, was evaluated in the modeling of the distal fibula fracture detected with plate, the deltoid rupture alone created a stress of 85.753 MPa, while the single ruptures of the talofibular anterior created a stress force of 82.443 MPa. The rupture of the tibiofibular anterior and posterior
areas associated with syndesmosis created less plate stress force than the single rupture models of both the deltoid and the talofibular ligament (Figure 5).

In single-ligament rupture modeling, it was observed that the amount of displacement between fracture fragments was the highest in the modeling (0.1221 mm) in which the talofibular anterior was broken. It was observed that the amount of displacement in the ankle joint was the highest in the modeling (2.2168 mm) in which the deltoid ligament was torn. It was determined that the minimum amount of displacement in both the fracture line and the ankle was in the modeling where the tibiofibular anterior and posterior ligament associated with syndesmosis was ruptured.

Fracture modeling, including tibiofibular anterior and posterior ligament ruptures associated with syndesmosis, was found to be more stable for the fracture line and ankle joint after loading than other single-ligament injuries.

In six different ligament rupture models, after the loading given to stable ankle fracture modeling, the ankle joint and instability in the fracture line were evaluated. It was found that ankle instability was the highest (2.3176 mm) in the modeling where the deltoid and talofibular ligaments were ruptured together.

Discussion

Ankle fractures are a very common orthopedic injury that is routinely treated by surgeons (21). However, in the current literature, there is no clear indication for the repair of the deltoid
ligament in the treatment of ankle fractures (6). It is well-known that conservative and surgical options are available for ankle ligament injuries, according to published literature. In a study, it was supported that deltoid ligaments and posterior syndesmosis play an essential role in the stability of ankle fractures with supination-eversion injuries. If these structures remain intact, conservative treatment is recommended in patients without fracture displacement or with minimal (<2 mm) (22). However, there have been some studies that have indicated that ligament injuries are often overlooked by the conservative approach. According to this study, the medial ligaments of the ankle are injured more frequently than are commonly believed. Tears of the deltoid ligament are sometimes observed in lateral malleolar fractures or himalleolar fractures. It is emphasized that patients with triple arthrodesis or total ankle arthroplasty have a history of chronic deltoid ligament insufficiency (23).

There are a lot of studies in the literature in which the finite element study, which is an in vitro method, is used clinically (24-30). In our study, we tried to show the effect of ligament injuries that may accompany Weber type B fractures on fracture and ankle stability and possible clinical results in vitro. Data from finite element modeling show that the deltoid ligament is the most effective bond to plate stress, which provides ankle stability and distal fibula detection. On the other hand, it was concluded that the ligament with the least effect on ankle stability and plate stress that provides distal fibula fixation were the anterior and posterior tibiofibular ligament associated with syndesmosis. Although these results seem to contradict Weber’s statement, “The height of the fibular lesion is directly connected to the
condition of the syndesmosis, regardless of whether there is a medial ankle injury, and of what type this may be.” Current publications support these findings (23). Ankle instability is associated with ankle osteoarthritis and plate stress in implant failure. In this respect, we explained the relationship between deltoid ligament rupture, osteoarthritis, and implant failure in our study. On the other hand, it is suggested that AO, which is based on the ankle classification made by Weber, may have made the fracture classification more anatomical than prognostic. Perhaps it will show that AO is wrong due to the new studies carried out, as in Weber.

To the best of our knowledge, this is the first study in the literature to emphasize the importance of single and multiple ligament injuries to the deltoid, syndesmosis, and ATFLs, which have been lacking in the literature, as well as to compare and make sense of the available literature. According to our results, deltoid ligament rupture was observed to be the most effective factor for ankle instability among possible ligament ruptures in distal fibula fracture modeling detected by plate. However, deltoid ligament repair is a controversial topic in the literature. While various publications recommend repair (31), some studies emphasize that repair is controversial (32). In our study, we observed that although a stable fracture line and a stable ankle joint were achieved after plate fixation of the distal fibula fracture, instability may develop (2.3176 mm) in the ankle if the deltoid rupture occurs after loading. In this respect, our study supports deltoid ligament repair. Thus, we think that complications such as nonunion,
osteoarthritis, and malunion that may occur after fracture stability and implant failure will decrease.

Another study stated that the integrity of the medial colon (deltoid ligament) is key for ankle stability in isolated lateral malleolar fractures. Most of the isolated trans-syndesmotic fibula fractures (Weber-B, SER, AO 44-B) are stable and can be treated safely without surgery. It is emphasized that surgical fixation can be considered for a fracture to ensure stability, reduce the need for syndesmosis fixation and improve the distribution of contact pressure (33). A study on multiple ligament injuries stated that ankle fractures were common in the lower extremities and that syndesmosis injuries may accompany approximately 20% of them. Even though the deltoid ligament is not really considered a part of the syndesmotic complex, it is well-known that it plays a significant role in ankle stability; therefore, its integrity should always be evaluated whenever a syndesmotic injury is suspected (34).

After the modeled AO44 B2.1 fibula fracture detection, we concluded that anterior talofibular injury is the strongest ligament injury that disrupts fracture reduction in both single and multiple models on the X, Y, and Z axes. According to a small number of recent studies, it is emphasized that anterior talofibular rupture accompanying distal fibular fracture may be more common than previously thought and should be repaired (13,14). In our finite element modeling, we concluded that anterior talofibular ligament rupture accompanying distal fibular fracture at the joint level plays an essential role in fracture and ankle stability.
It is emphasized that interfragmentary movement, especially in the axial direction, negatively affects the healing of the fracture and provides a basis for osteoarthritis after instability in the joint (35). With the modeling, we tried to show the risk of osteoarthritis that may develop after instability according to the movement of the ankle joint on the three axes. After fibula AO 44B2.1 fracture detection, it was concluded that deltoid ligament rupture was the strongest ligament injury that impaired the stability of the ankle joint on the X, Y, and Z axes in both single and multiple models.

In studies of syndesmosis, it has been shown that clinical and radiological outcomes after 4-6 years of follow-up in ankle fractures of the SER IV type (Weber B) do not differ from those of patients with stable syndesmosis (36). In another study, it was stated that related syndesmosis injuries were rare in supination-external rotation ankle fractures and that syndesmotic transfusion with screws had no effect on functional outcome and pain at one-year follow-up compared to with no fixation (13). In a study on Weber B-type ankle fractures, it was emphasized that syndesmotic rupture does not affect the clinical and radiological outcome parameters in the fracture but leads to a significant restriction in dorsiflexion of the ankle joint (37). In our study, we observed that ankle joint stability (0.6559 mm) and fracture stability (0.0511 mm) were impaired after loading in the anterior taliofibular and posterior taliofibular rupture ligament, which we associated with a syndesmosis injury. However, the instability values in the ruptures of these ligaments were observed to be lower than those in the deltoid or anterior talofibular ligament rupture. In the fixation finite element modeling of stable AO 44
B2.1 fracture with plate, it was concluded that the effect of anterior tibiofibular and posterior tibiofibular ligament tear on the ankle and fracture line after loading in the presence of stable syndesmosis was not as much as the rupture models of the deltoid and anterior talofibular ligaments. Moreover, in the finite element study, the rupture model of the tibiofibular anterior and posterior associated with syndesmosis produced less plate stress force than in the single rupture models of both the deltoid and talofibular ligament.

Weber type B fractures look like simple fractures on X-ray. These fractures can cause stiffness and arthritis in the ankle joint (4, 5). Although the current classification is made according to bone structure, syndesmosis, and deltoid ligament (9, 10), we think that ATFL, which is not used in classification, is also important and effective in the development of stiffness and arthritis, which are the clinical consequences of Weber type B fractures. Radiographs are the same in some Weber type B fractures, soft tissue, and connective tissue injuries that cannot be seen on the radiograph and may accompany the fracture can change the clinic of the fracture. In order to achieve optimal stability in ankle and fracture diagnosis, ligament injuries must be carefully evaluated rather than just fixing the bones (6).

In distal fibular fractures defined in various ways, Danis-Weber and Lauge-Hansen classifications are descriptive, but they have not been proven to be prognostic. (38-41). Anterior talofibular ligament lesions have not been identified in these classification systems. However, it is noted that anterior talofibular ligament ruptures are substantial and more common in distal fibula Weber type b fractures (13,14). In ligament rupture modeling of the
anterior talofibular alone, total instability of 1.0205 mm in the ankle and 0.1221 mm in the fracture line is observed after loading. Our study was one of the few studies that revealed that anterior talofibular ligament rupture accompanying distal fibular fractures (AO 44B2.1) might also be important. However, further clinical studies are needed to determine the prognosis of ATFL ruptures accompanying distal fibula fractures.

Conclusions

The fracture (AO 44 B2.1) was fixed with a plate in the finite element modeling. Subsequently, ankle and fracture instability were observed in case of rupture of deltoid ligament or anterior talofibular ligaments. Ligament repair may be required if deltoid and anterior talofibular ligament rupture is considered, even if a stable ankle joint in AO 44 B2.1 fracture is detected with plate. Additionally, the hypothesis should also be supported by clinical studies.

In ankle traumas, it is important to remember that sometimes the fracture is only the tip of the iceberg, and that the ankle should be considered as a whole, including its soft tissues and bones.

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Conflict of Interest: None reported.
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Figure 1. Boundary conditions and load diagram.

A: Static Structural
Static Structural
Time: 10, s

A: Force: 600, N
B: Moment: 12,497 N-mm
C: Displacement
D: Fixed Support

This Original Article is a preprint. It has been reviewed, accepted for publication, and approved by the author but has not been copyedited, proofread, or typeset.
Figure 2. Finite element modeling of the deltoid, anterior talofibular, posterior talofibular, anterior tibiofibular, posterior tibiofibular, and calcaneofibular ligaments in distal fibular fracture detected by plate.
Figure 3. When ligaments or ligaments are ruptured in modeling, post-loading ankle instability values

Ankle displacement (mm)

- deltoid and talofibular anterior ligaments rupture: 2.3176 mm
- deltoid ligament rupture: 2.2168 mm
- deltoid, tibial fibular anterior and posterior ligaments rupture: 2.2673 mm
- talofibular anterior ligament rupture: 1.0205 mm
- tibial fibular anterior posterior ligaments rupture: 0.6559 mm
- ligaments are normal: 0.6571 mm
Figure 4. When the ligaments or ligaments are also ruptured in modeling, the instability values occurring in the fracture line after loading.
Figure 5. Stress distributions in the plate when the ligaments are intact, and the deltotoid and anterior talofibular ligaments are ruptured. Stress values in the plate, which is the fixation material in the fracture line after loading when the ligaments or ligaments are ruptured in modeling.
Table 1. Properties of bone and plate materials [18]

<table>
<thead>
<tr>
<th>Materials</th>
<th>Modulus of elasticity (GPa)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone</td>
<td>16.8</td>
<td>0.3</td>
</tr>
<tr>
<td>Plate</td>
<td>110</td>
<td>0.33</td>
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</table>

Table 2. Material properties of ligaments [19]

<table>
<thead>
<tr>
<th>Ligaments</th>
<th>Modulus of elasticity (MPa)</th>
<th>Poisson’s ratio</th>
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<tr>
<td>Posterior Tibiofibular</td>
<td>260</td>
<td>0.4</td>
</tr>
<tr>
<td>Anterior Tibiofibular</td>
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<td>0.4</td>
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<tr>
<td>Posterior Talofibular</td>
<td>215.5</td>
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<tr>
<td>Anterior Talofibular</td>
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<td>Calcaneofibular</td>
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<td>Tibiocalcaneal</td>
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<tr>
<td>Tibionavicicular</td>
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<tr>
<td>Anterior Tibiotalar</td>
<td>184.5</td>
<td>0.4</td>
</tr>
<tr>
<td>Posterior Tibiotalar</td>
<td>99.5</td>
<td>0.4</td>
</tr>
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</table>
Table 3. In single and multiple ligament rupture modeling, the amount of displacement in the three axes (X-mediolateral direction, Y-anteroposterior, Z-superoinferior) formed in the ankle joint after loading

<table>
<thead>
<tr>
<th>Ankle displacements</th>
<th>X Axis displacement (mm)</th>
<th>Y Axis displacement (mm)</th>
<th>Z Axis displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ligaments are normal</td>
<td>-0.3543</td>
<td>-0.1439</td>
<td>0.1589</td>
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<tr>
<td>Tibiofibular anterior and posterior ligaments rupture</td>
<td>-0.3201</td>
<td>-0.179</td>
<td>0.1568</td>
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<tr>
<td>Talofibular anterior ligament rupture</td>
<td>-0.5845</td>
<td>-0.2757</td>
<td>-0.1603</td>
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<tr>
<td>Deltoid, tibiafibular anterior and posterior ligaments rupture</td>
<td>-0.7148</td>
<td>-0.7696</td>
<td>0.7829</td>
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<tr>
<td>Deltoid ligament rupture</td>
<td>-0.7275</td>
<td>-0.7439</td>
<td>0.7454</td>
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<tr>
<td>Deltoid and talofibular anterior ligaments rupture</td>
<td>-1.121</td>
<td>-0.7652</td>
<td>0.4314</td>
</tr>
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</table>
Table 4. In single and multiple ligament rupture modeling, the displacement amounts in the three axes (X-mediolateral direction, Y-anteroposterior, Z-superoinferior) formed in the fracture line after loading

<table>
<thead>
<tr>
<th>Distal fibula fracture displacements</th>
<th>X Axis displacement (mm)</th>
<th>Y Axis displacement (mm)</th>
<th>Z Axis displacement (mm)</th>
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<tr>
<td>Ligaments are normal</td>
<td>0.0265</td>
<td>0.0128</td>
<td>0.0058</td>
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<tr>
<td>Tibiofibular anterior and posterior ligaments rupture</td>
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<tr>
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<td>0.0329</td>
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<td>Deltoid, tibiofibular anterior and posterior ligaments rupture</td>
<td>0.0626</td>
<td>0.0226</td>
<td>0.0211</td>
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