Original Research

The In Situ Force and Contribution of Each Ligamentous Band of the Deltoid Ligament in Ankle Joint Stability

A Cadaveric Biomechanical Study

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Investigation performed at Sapporo Medical University, Sapporo, Japan

Background: Each band of the deltoid ligament cooperatively contributes to stability of the medial side of the ankle joint. Investigating the function of each band of the deltoid ligament is essential to assess abnormalities and develop treatment options.

Purpose: To evaluate the changes in ankle kinematics when each band of the deltoid ligament is injured and to measure the in situ force of each ligamentous band in intact ankle kinematics.

Study Design: Descriptive laboratory study.

Methods: A total of 8 healthy fresh-frozen cadaveric legs were examined by applying forces through eversion and external rotation of the ankle joint using a 6 degrees of freedom robotic system. The deltoid ligament was separated into 6 discrete bands: tibionavicular ligament, tibiospring ligament, tibiocalcaneal ligament (TCL), anterior tibiotalar ligament, superficial posterior tibiotalar ligament (sPTTL), and deep posterior tibiotalar ligament; the bands were then sequentially transected. A loading test was performed in each model, and the changes in ankle motion and in situ force of each ligamentous band were measured using the robotic system.

Results: When an eversion force was applied to the intact ankle, the in situ force of the sPTTL was 21.6 N in dorsiflexion and that of the TCL was 19.4 N in plantarflexion, both of which were significantly greater than those of the other ligamentous bands. Additionally, the amount of eversion under eversion loading increased significantly by 3.3° with sPTTL resection in dorsiflexion and by 4.2° with TCL resection in plantarflexion.

Conclusion: The TCL and sPTTL play important roles among the ligamentous bands of the deltoid ligament. The sPTTL played a more significant role in ankle dorsiflexion, whereas the TCL played a more significant role in ankle plantarflexion.

Clinical Relevance: The TCL and sPTTL should receive attention in the treatment of deltoid ligamentous injuries.

Keywords: biomechanics; ligament injury; deltoid ligament

The medial collateral ligament of the ankle attaches the medial malleolus to the navicular, calcaneus, and talus and is also referred to as the deltoid ligament.[2,4] The deltoid ligament is divided into superficial and deep layers. The superficial layer consists of the tibionavicular ligament (TNL), tibiospring ligament (TSL), tibiocalcaneal ligament (TCL), and superficial posterior tibiotalar ligament (sPTTL), whereas the deep layer consists of the anterior tibiotalar ligament (ATTL) and deep posterior tibiotalar ligament (dPTTL)[2,4,6,9,16,18] (Figures 1 and 2).

The deltoid ligament contributes to ankle joint stability, particularly during talar abduction.[21] Although some biomechanical studies have investigated deltoid ligament function,[12,25,26,28] these reports had several limitations such as the absence of assessments for specific ligamentous bands, evaluations of only the superficial layer and not the deep layer, or partial evaluations of ligamentous bands.

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None of the previous reports has directly evaluated the function and in situ force of each ligamentous band, particularly in the deep layer of the deltoid ligament.

Previous studies have documented the use of a 6 degrees of freedom (DOF) robotic system for biomechanical research, which allows the precise examination of changes in the kinematics and in situ force of a ligament during a ligamentous injury.[7,13,14,17,22-24] Although this methodology has been applied to the knee and lateral ligaments of the ankle, no reports have described its application to the deltoid ligament. Many recent reports have described surgical repair and augmentation procedures for deltoid ligamentous injuries as well as the classification and treatment of deltoid ligamentous injuries.[5,11,19,27,29] Thus, elucidation of the function of each ligamentous band of the deltoid ligament to effectively assess these abnormalities and develop treatment options is important.

The purpose of the present study was to explore alterations in ankle stability resulting from an injury to each ligamentous band of the deltoid ligament and to measure the in situ force of each ligamentous band in intact ankle kinematics.

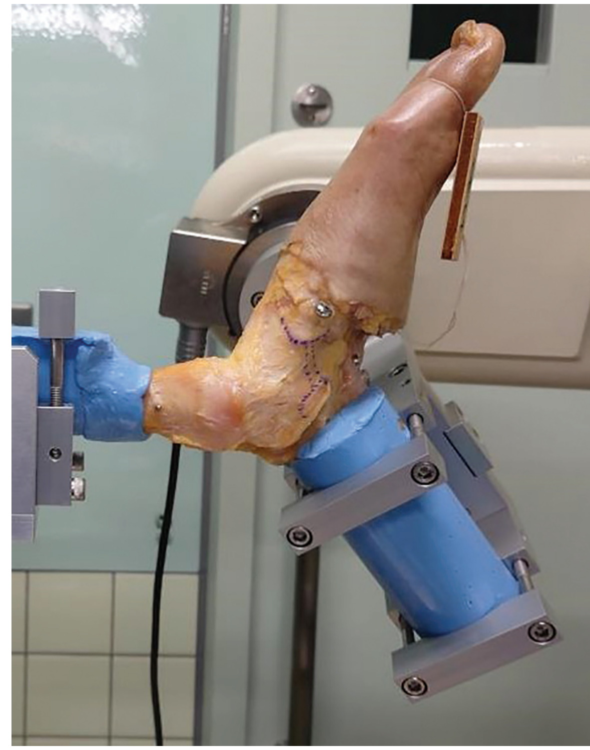

Figure 1. An image of the ankle joint attached to a robotic clamp.

METHODS

Specimen Preparation

This study was approved by our institutional ethics committee. The study specimens comprised 8 fresh-frozen cadaveric legs (6 male and 2 female) donated to the Department of Anatomy at our institution. The mean age at the time of death was 83.9 years (range, 73-96 years). Cadaveric specimens with ankle joint osteoarthritis, a history of fractures, or lower leg surgery were excluded from the study. An assessment was conducted before and after testing to verify the integrity of the specimens. Before testing, plain radiography was performed to confirm the absence of tibiotalar or subtalar osteoarthritis. After testing, a macroscopic assessment was conducted to ensure the absence of degenerative changes in the tibiotalar or talocalcaneal joints.

For testing, each leg was cut 15 cm from the lateral malleolus with no disruption of soft tissue. The specimens were stored at −20°C and thawed overnight at room temperature before use. Soft tissue, including the skin, subcutaneous tissue, muscles, and tendons, was dissected from the proximal end of the specimen to the navicular region. The capsule and ligaments surrounding the ankle joint were kept intact. The distal tibiofibular syndesmosis was fixed with 2 screws (4.5-mm Cortex Screw; DePuy Synthes) and acrylic resin (Ostron II; GC), while the ankle joint complex, which consisted of the tibiotalar and talocalcaneal joints, was placed in a neutral position.[30] The ends of the tibia and the fibula were inserted into cylindrical molds of acrylic resin. Steinmann pins and screws were inserted into the calcaneal tuberosity and advanced into the talar body. The posterior part of the calcaneus was inserted into cylindrical molds of acrylic resin. Additionally, the talocalcaneal joint was fixed using 2 screws (4.5-mm Cortex Screw), and the talonavicular joint was fixed using a screw (4.5-mm Cortex Screw). The lower leg and calcaneal cylinders were then secured to the clamps of the robotic system, as described below.

Robotic System

The specimen was fixed with aluminum clamps and attached to the end effector of the robotic testing system (FRS2015; Technology Service) (Figure 1). This mechanical

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Ethical approval for this study was obtained from the Ethics Committee of Sapporo Medical University. (3-1-64).

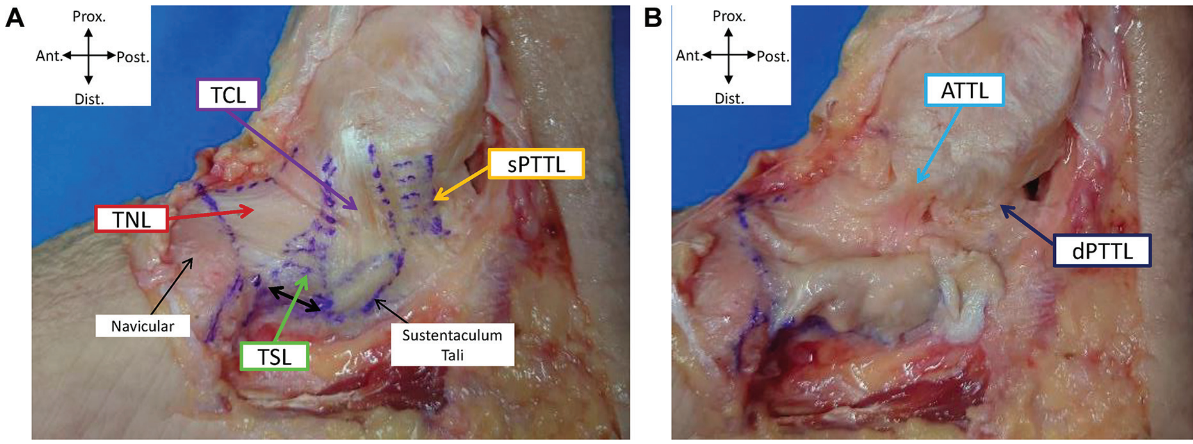

Figure 2. (A) An image depicting each ligamentous band of the superficial layer. (B) An image depicting each ligamentous band of the deep layer. ATTL, anterior tibiotalar ligament; dPTTL, deep posterior tibiotalar ligament; sPTTL, superficial posterior tibiotalar ligament; TCL, tibiocalcaneal ligament; TNL, tibionavicular ligament; TSL, tibiospring ligament.

testing system consists of a 6-DOF manipulator, servomotor controllers, and a control computer.[8] The 6-DOF manipulator is composed of 3 translational actuators (SGMP Series; Yaskawa) and 3 rotational actuators (FHA Series; Harmonic Drive Systems). The manipulator has a positional accuracy of approximately 120 nm when 500 N is applied to the clamp and has a clamp-to-clamp stiffness of >312 N/mm. This system was controlled in real time using an original LabVIEW-based program (Version 12.0.1; National Instruments) for displacement and application of the force/torque to each axis. Bone positions and movements were described relative to the coordinate system reported by Wu et al.[30] The maximum clamp-to-clamp compliance of the robotic system is 3 μm/N (the robotic system has a maximum deformation of 3 μm when a force of 1 N is applied to the clamp), while the force control fluctuations are 10 N in force and 0.4 N·m in moment.[8] The neutral position was set according to the technique described by Wu et al.[30]

Testing Protocol for Intact State

Eversion and external rotation moments were applied to the intact ankle joint complex at 15° of dorsiflexion, in the neutral position (0°), and at 15° and 30° of plantarflexion. A constant axial load of 5 N was maintained throughout testing. During eversion testing, the inversion-eversion DOF was rotated to eversion under displacement control up to 1.7 N·m at a rate of 1 deg/s, whereas the remaining 4 DOFs, except the plantarflexion-dorsiflexion DOF, were set under force control with zero force or moment. Similarly, during external rotation testing, the internal rotation–external rotation DOF was rotated externally under displacement control at the same rate as that during eversion testing. A 2.0-N·m eversion force and a 2.0-N·m external rotation force were applied separately, each repeated 3 times for preconditioning. Subsequently, a 1.7-N·m eversion force and a 1.7-N·m external rotation force were applied (force based), and ankle motion data were recorded (loading test). Thus, we reproduced the recorded intact ankle motion in each model (position based) and measured the 6-DOF force and torque data (replay test).

Transection

After measuring in the intact condition, each ligamentous band was sequentially transected in the following order: TNL, TSL, TCL, ATTL, sPTTL, and finally dPTTL (Figure 2). Loading and replay tests were performed between transection of each ligamentous band.

Each ligamentous band was transected at the distal insertion of the ligament because the proximal insertion was smaller than the distal insertion and was difficult to separate into individual fibers.[1,21] Transection of the TNL was performed by detaching the anterior fiber bundle from the lateral attachment of the navicular region to the attachment of the spring ligament. Transection of the TSL was performed by detaching the anterior fiber bundle from the navicular attachment of the spring ligament to the attachment of the calcaneus. Transection of the TCL was performed by detaching the remaining anterior fiber bundle from the sustentaculum tali. The ATTL, sPTTL, and dPTTL were identified independently, and each ligamentous band was detached at its respective attachment to the calcaneus. The attachment sites for each ligamentous band were identified based on a protocol previously reported by Campbell et al.[4] Loading and replay tests were performed for each condition. However, because the loading test caused ankle dislocation and exceeded the robot's motion limits, only the replay test was conducted after transection of the dPTTL.

Testing Protocol for Transected State

We first performed the replay test for each model. Throughout this procedure, the force and torque exerted by the robotic system were recorded. By subtracting these

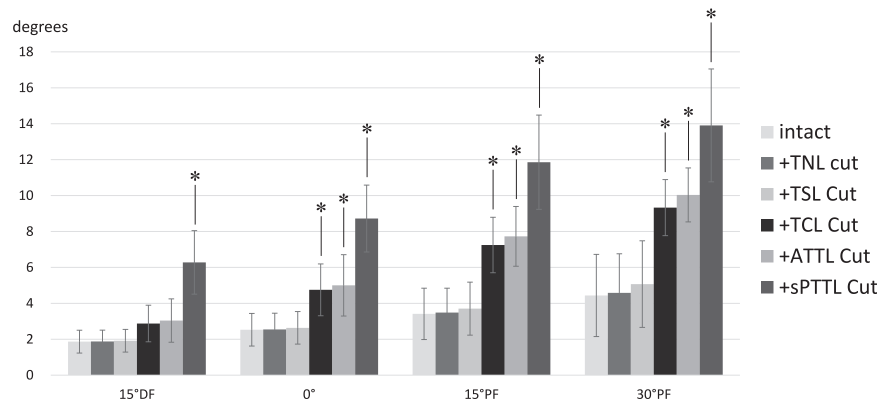

Figure 3. Displacement of the talus observed when an eversion force was applied to each ligament transection model. Error bars represent 1 SD. ATTL, anterior tibiotalar ligament; dPTTL, deep posterior tibiotalar ligament; sPTTL, superficial posterior tibiotalar ligament; TCL, tibiocalcaneal ligament; TNL, tibionavicular ligament; TSL, tibiospring ligament. *Significantly larger than the intact group ($P < .05$).

values from the forces recorded in the previous test, we calculated the in situ force of each ligamentous band.[8] In situ force was defined as the force applied to each ligamentous band during eversion and external rotation loading on the intact ankle. Subsequently, we performed the loading test similar to that performed for the intact model and recorded the motion of the ankle joint. The replay test was first conducted to minimize the damage to soft tissue caused by repeated loading because loads and movements were greater after detachment of the ligamentous band during the loading test. We measured the amount of eversion of the talus relative to the tibia during eversion loading (in degrees) and the amount of external rotation of the talus relative to the tibia during external rotation loading (in degrees) and investigated the changes in each model. All tests were performed in the following order: 0°, 15° of dorsiflexion, 15° of plantarflexion, and 30° of plantarflexion. Manual examinations and radiography analyses were performed after all tests to confirm that each joint fixation remained secure.

Statistical Analysis

All the collected data and sample sizes were analyzed using EZR (Saitama Medical Center, Jichi Medical University), a graphical user interface for R (Version 4.0.3; R Foundation for Statistical Computing). The normality of all outcome data was confirmed using the Shapiro-Wilk test. Ankle displacement and in situ force under each condition were compared using the Bonferroni test. Statistical significance was set at $P < .05$.

RESULTS

Displacement (Loading Test)

When a 1.7-N·m eversion force was applied, displacement of the talus was significantly greater than that of the intact ankle at 15° of dorsiflexion after the sPTTL was transected. Conversely, at 0° to 30° of plantarflexion, displacement was significantly greater than that of the intact ankle after the TCL was transected (Figure 3). Because of the ankle dislocating and exceeding the range of motion of the robot, the loading test after dPTTL transection could not be conducted for both eversion and external rotation.

When a 1.7-N·m external rotation force was applied, displacement of the talus gradually increased with each fiber bundle transection compared with when the eversion force was applied. At 15° of dorsiflexion to 0°, displacement was significantly greater than that of the intact ankle after the sPTTL was transected, whereas no significant changes were observed in comparison with the intact ankle at 15° to 30° of plantarflexion (Figure 4).

In Situ Force (Replay Test)

When a 1.7-N·m eversion force was applied to the intact ankle, the in situ force of the sPTTL was significantly greater than that of the other fiber bundles at 15° of dorsiflexion. In contrast, at 0° to 30° of plantarflexion, the in situ force of the TCL was significantly greater than that of the other fiber bundles (Figure 5).

When a 1.7-N·m external rotation force was applied to the intact ankle, the in situ force of the sPTTL was significantly greater than that of the other fiber bundles at 15° of dorsiflexion. However, at 15° to 30° of plantarflexion, the in situ forces of the TNL and dPTTL were significantly greater than those of the other fiber bundles (Figure 6).

DISCUSSION

The results of our study demonstrate the functional role of each ligamentous band within the deltoid ligament. In particular, the TCL and sPTTL exhibited greater activity than the other ligamentous bands when eversion and external rotation forces were applied, as evidenced by displacement

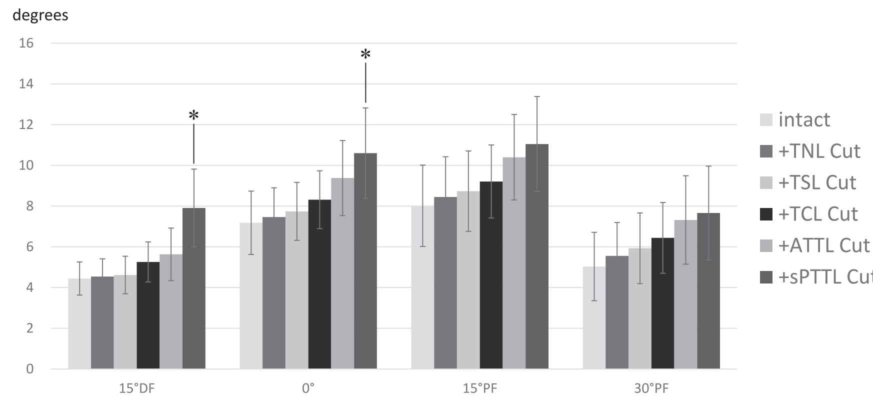

Figure 4. Displacement of the talus observed when an external rotation force was applied to each ligament transection model. Error bars represent 1 SD. ATTL, anterior tibiotalar ligament; dPTTL, deep posterior tibiotalar ligament; sPTTL, superficial posterior tibiotalar ligament; TCL, tibiocalcaneal ligament; TNL, tibionavicular ligament; TSL, tibiospring ligament. *Significantly larger than the intact group ($P < .05$).

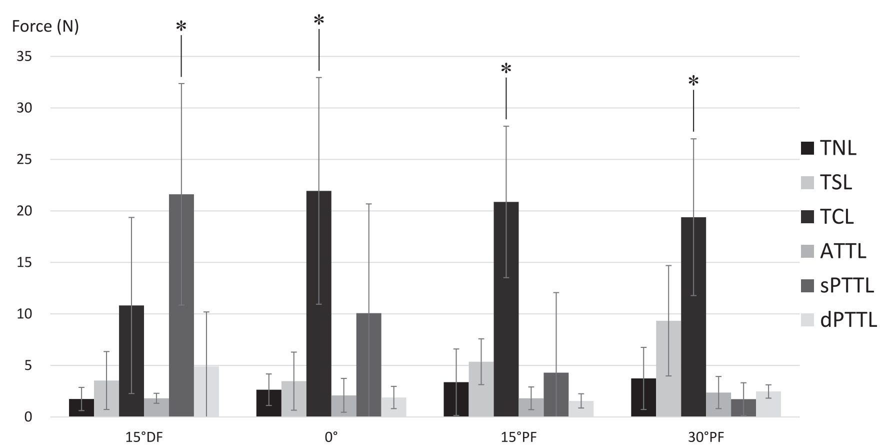

Figure 5. In situ force observed when an eversion force was applied to the intact ankle. Error bars represent 1 SD. ATTL, anterior tibiotalar ligament; dPTTL, deep posterior tibiotalar ligament; sPTTL, superficial posterior tibiotalar ligament; TCL, tibiocalcaneal ligament; TNL, tibionavicular ligament; TSL, tibiospring ligament. *Significantly larger than all other ligamentous bands ($P < .05$).

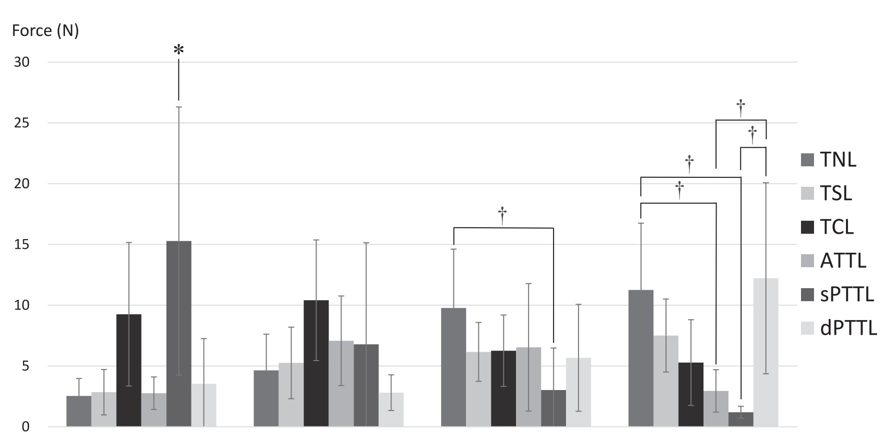

Figure 6. In situ force observed when an external rotation force was applied to the intact ankle. Error bars represent 1 SD. ATTL, anterior tibiotalar ligament; dPTTL, deep posterior tibiotalar ligament; sPTTL, superficial posterior tibiotalar ligament; TCL, tibiocalcaneal ligament; TNL, tibionavicular ligament; TSL, tibiospring ligament. *Significantly larger than all other ligamentous bands ($P < .05$). †Significantly different between 2 ligamentous bands ($P < .05$).

and in situ force measurements. To the best of our knowledge, this study represents the first direct evaluation of the function of all 6 ligamentous bands within the deltoid ligament (except for the kinematics after dPTTL transection), and no similar studies have been conducted to date.

Several reports have described the anatomy of the deltoid ligament.[1,2,6,9,16,18] In the present study, 5 of the ligamentous bands (TNL, TSL, TCL, sPTTL, and dPTTL) were present in all cadaveric specimens and were not deficient. In contrast, while the ATTL showed some variation in characteristics (ranging from fibrous to membranous tissue extending from the deep medial malleolus to the anterior aspect of the talus), soft tissue present in the same region was considered the ATTL. Therefore, the same procedure could be applied for sectioning all specimens.

Several studies have investigated the biomechanics of the deltoid ligament.[12,25,26,28] The strength of this study is that we directly assessed the in situ force of each ligamentous band and the changes in ankle displacement when each ligamentous band was injured. Notably, no other study has evaluated the function of the deep fiber bundles. In this study, we adopted a method to directly evaluate the function of each ligamentous band by transecting the bands at their distal attachments because these attachments were relatively larger than the proximal attachment. However, complete separation of the anterior TNL, TSL, and TCL was not possible, and the presence of some interaction effects cannot be ruled out. Nevertheless, the measured values were consistent with the findings for statistical significance, and we considered the results to be reasonably reliable. Furthermore, the anterior ligamentous bands can be considered to be a single unit: the tibiocalcaneonavicular ligament.[1,6] In clinical practice, an injury to the proximal attachment of the anterior ligamentous bands is often reported, suggesting that these bands are frequently injured simultaneously in such cases.[5,11]

Furthermore, complete transection of the deltoid ligament can easily lead to tibial dislocation. Therefore, in this study, we were unable to measure displacement after transecting the dPTTL. However, the 6-DOF robotic system used in this study can accurately reproduce ankle motion under loading in an intact ankle. This allowed us to investigate the function of the deep deltoid ligament, which was one of the strengths of this study.

The results of the present study showed that the TCL and sPTTL played important roles, particularly when an eversion force was applied to the ankle. We believe that the anatomic location of each ligamentous band contributed to these functional characteristics. The TCL and sPTTL fibers extended vertically when the ankle joint was in midposition. This anatomic feature may have increased the tension of both ligamentous bands during eversion, thereby contributing to ankle joint stability and resulting in a high in situ force in response to the eversion force. The differences in the function of both ligamentous bands could have occurred because the sPTTL, which is located more posteriorly, was tensioned during dorsiflexion, whereas the TCL, which is located more anteriorly, was tensioned during plantarflexion. However, when subjected to an external rotation force, the function of the sPTTL was significant in ankle dorsiflexion, similar to that during eversion. In contrast, in ankle plantarflexion, the difference in the function of each ligamentous band was not as pronounced as that during eversion. On the other hand, despite being the largest and thickest fibrous bundle,[10] the force exerted on the dPTTL was not significant in this study. However, previous reports have suggested that the dPTTL plays an important role under axial loading,[15] indicating that different protocols may yield different results in future studies.

Although many biomechanical studies on the lateral ligaments of the ankle have been performed,[14,22,24] only a few have been conducted on the deltoid ligament. The anatomy of the deltoid ligament is one of the factors limiting biomechanical studies on it. In particular, the lateral ligaments (anterior talofibular, calcaneofibular, and posterior talofibular ligaments) have independent structures for each fiber bundle, whereas the deltoid ligament has a complex structure with continuous fiber bundles. The fact that the deltoid ligament is attached to multiple bones (from the tibia to the navicular, talus, and calcaneus) complicates this study. In this study, we devised a method to investigate the function of each fiber bundle. Although the current method still has room for improvement, this is the first study to investigate the function of each ligamentous band of the deltoid ligament in detail, and further refinement of the method and the advancement of research are needed in the future.

In the past, deltoid ligamentous injuries were often treated nonoperatively; however, recent reports have described the use of surgical treatment such as repair, augmentation, and reconstruction.[3,20,31] The results of the present study are expected to facilitate the determination of surgical indications for injured ligamentous bands and the choice of the placement of reconstruction grafts or augmentation. Furthermore, these findings could contribute not only to surgical treatment but also to the development of nonoperative treatment protocols, such as restricting plantarflexion in cases of a TCL injury or limiting dorsiflexion in cases of an sPTTL injury. The biomechanical differences between surgically treated and naturally healed deltoid ligaments are also not yet fully understood and thus remain an important topic for future research.

Limitations

First, our study involved the excision of soft tissue around the joint, except for the joint capsule and ligaments. Although we believe that this procedure is necessary for the accurate identification and dissection of each ligamentous band in the deltoid ligament, it may have limited the replication of in vivo biomechanics. Second, the tibiofibular, talocalcaneal, and talonavicular joints were fixed in each model. Because of the characteristics of the robotic system used in this study, which measures the change in motion between 2 clamps, the addition of more than 2 joints complicated the identification of the moving joints and the extent of movements. To address this, we fixed the joints affecting the deltoid ligament other than the tibiotalar joint. Moreover, because of the robot's size limitations, the entire lower leg could not be mounted, thus necessitating amputation of the tibia and fixation of the tibiofibular joint. Third, the applied forces were uniaxial in nature and appreciably lower than in vivo forces. The magnitudes of the applied forces were determined on the basis of the results of previous studies.[11,19,21] Fourth, we could not assess ligamentous injury patterns in vivo. We created ligamentous injuries via sharp transection at the distal insertion sites. In contrast, injuries have been reported at proximal attachments,[5,11] especially in the superficial layer; thus, our models may not fully replicate clinical ligamentous injuries. Fifth, because of the nature of the study, reliability analysis could not be performed. Despite these limitations, we conducted the present study as closely to actual clinical conditions as possible. Sixth, we used only a single ligament dissection protocol. In this study, we established the sequence of ligamentous band transection to evaluate the kinematics of deltoid ligamentous injuries from anterior to posterior. However, owing to the limited number of specimens, we were unable to perform a different or randomized sequence of ligamentous band transection. Different insights might be obtained by sequentially transecting each ligamentous band of the deltoid ligament from posterior to anterior or from the deep to superficial layer. Finally, the sample size was small. Despite these limitations, this is the first study to directly evaluate the function of each band of the deltoid ligament. In the future, we aim to expand these findings by investigating the effects on the talocalcaneal and talonavicular joints and aiming for applications in treatment protocols for ligamentous injuries.

CONCLUSION

The TCL and sPTTL play particularly important roles among the ligamentous bands of the deltoid ligament. The sPTTL was important in ankle dorsiflexion, whereas the TCL was particularly important in ankle plantarflexion.

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