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Journal of ISAKOS

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Original Research

Optimal assessment for anterior talofibular ligament injury utilizing stress ultrasound entails internal rotation during plantarflexion

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ARTICLE INFO

Keywords:

Stress ultrasound
Anterior talofibular ligament
Chronic ankle instability
Diagnosis
Biomechanics
6 degree-of-freedom robot

ABSTRACT

Objectives: An optimal load and ankle position for stress ultrasound of the injured anterior talofibular ligament (ATFL) are unknown. The objectives of this study were to compare stress ultrasound and ankle kinematics from a 6 degree-of-freedom (6-DOF) robotic testing system as a reference standard for the evaluation of injured ATFL and suggest cut-off values for ultrasound diagnosis.

Methods: Ten fresh-frozen human cadaveric ankles were used. Loads and ankle positions examined by the 6-DOF robotic testing system were: 40 N anterior load, 1.7 Nm inversion, and 1.7 Nm internal rotation torques at 30° plantarflexion, 15° plantarflexion, and 0° plantarflexion. Bony translations were measured by ultrasound and a robotic testing system under the above conditions. After measuring the intact ankle, ATFL was transected at its fibular attachment under arthroscopy. Correlations between ultrasound and robotic testing systems were calculated with Pearson correlation coefficients. Paired t-tests were performed for comparison of ultrasound measurements of translation between intact and transected ATFL and unloaded and loaded conditions in transected ATFL.

Results: Good agreement between ultrasound measurement and that of the robotic testing system was found only in internal rotation at 30° plantarflexion (ICC = 0.77; 95% confidence interval 0.27–0.94). At 30° plantarflexion, significant differences in ultrasound measurements of translation between intact and transected ATFL ($p < 0.01$) were found in response to 1.7 Nm internal rotation torque and nonstress and stress with internal rotation ($p < 0.01$) with mean differences of 2.4 mm and 1.9 mm, respectively.

Conclusion: Based on the data of this study, moderate internal rotation and plantarflexion are optimal to evaluate the effects of ATFL injury when clinicians utilize stress ultrasound in patients.

Level of evidence: III.

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<https://doi.org/10.1016/j.jisako.2024.02.001>

Received 10 October 2023; Received in revised form 11 December 2023; Accepted 4 February 2024

Available online xxx

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What are new findings?

- With 1.7 Nm internal rotation (approximately the torque required to flip most smartphones) at 30-degree plantarflexion, the angular displacement measured by the robot is most closely correlated with the linear displacement measured by stress ultrasound in the anterior talofibular ligament-deficient ankle.
- In the anterior talofibular ligament-deficient ankle, 1.7 Nm internal rotation at 30-degree plantarflexion resulted in a 1.9 mm increase in the fibula-talus distance when compared to anterior talofibular ligament-deficient ankles under no stress.
- Anterior talofibular ligament deficiency resulted in a 2.4-mm increase in fibular-talus distance under 1.7 Nm internal rotation at 30-degree of plantarflexion when compared to intact ankles under the same stress.

INTRODUCTION

Ankle sprains are among the most common sports-related injuries, comprising up to 30% of sports injuries [1,2]. The anterior talofibular ligament (ATFL) and calcaneofibular ligament are the most frequently injured ligaments. Tearing, stretching, and recurring sprains of these ligaments can result in chronic ankle instability (CAI) [3]. It has been reported that 28%–74% of individuals with a previous history of ankle sprains suffer from some type of residual and chronic symptoms, recurrent ankle sprains, and/or perceived instability [4,5].

To diagnose CAI, manual stress tests such as the anterior drawer test, talar tilt test, and stress radiography are commonly performed. However, the anterior drawer and talar tilt are subjective tests in nature, and stress radiography for the identification of mechanical ankle laxity has been shown to be unreliable [6,7]. Musculoskeletal ultrasound represents a readily available and cost-effective imaging modality that has gained popularity in sports medicine as a diagnostic tool. Advances in ultrasound technology and techniques have considerably increased its diagnostic usefulness in CAI [8]. Recent studies reported that stress ultrasound, in which the change in ATFL length is measured with ultrasound under a certain stress, can detect CAI secondary to ATFL injuries [9–15].

However, an optimal loading condition and ankle position in stress ultrasound are still controversial. In early studies, anterior drawer stress was applied to the ankle to evaluate instability due to ATFL deficiency [10,11]. An internal rotation torque was used for stress ultrasound exams in some studies [12,13], while an inversion stress yielded the highest measurement reliability in the other study [14]. Moreover, stress ultrasound was performed in various ankle positions, such as neutral position, 10–20 degrees of plantarflexion, and maximal plantarflexion [9–15].

These clinical investigations encompassed a spectrum of instances involving lateral ankle instability, comprising partial tears of the ATFL, complete ATFL tears, and ATFL tears concurrent with calcaneofibular ligament insufficiency. Furthermore, the variability in applied force, torque, and ankle positioning during manual examination was inevitable. A meticulously controlled laboratory investigation employing cadavers alongside a 6 degree-of-freedom (6-DOF) robotic system enables us to (1) fabricate an isolated and complete ATFL injury model and (2) administer force consistently within a fixed ankle position. Hence, the accurate quantification of instability resulting from an isolated ATFL tear via stress ultrasonography becomes feasible.”

The objective of the current study was to determine the most optimal method of stress ultrasound for evaluating injured ATFL using the 6-DOF robotic testing system as a reference standard, which has been validated to provide accurate and objective data to measure the laxity of the ankle joint [16–18]. We hypothesized that the internal rotation torque in a plantarflexed ankle position could detect ankle instability due to ATFL injury with stress ultrasound, and ultrasound measurement of ankle instability performed under this condition is highly correlated with the kinematic data from the robotic testing system.

MATERIALS AND METHODS*Sample Size and Specimens*

The required minimum number of samples was estimated to be 11 for the detection of 0.75 intraclass correlation coefficients (ICC) between the stress US and 6-DOF robotic testing systems with 0.05 of the alpha level and 0.2 of the type II error rate. Sample size was calculated with G*Power v 3.1.9.2; Heinrich Heine Universität Dusseldorf [19].

Fifteen fresh-frozen cadaveric ankles were used in this study, which received ethics committee approval. The specimens were stored at -20°C and thawed overnight at room temperature. Specimens were screened for any osteoarthritic changes and abnormal bony morphology by radiography. Two specimens with os subfibrale and osteolytic changes in the fibula and talus were excluded. Two samples with a thin ATFL (less than 1 mm) and one with a partial ATFL tear were also excluded after ultrasound examination of the ATFL. The integrity of the calcaneofibular ligament was confirmed by ultrasound and arthroscopy. Finally, 10 fresh-frozen human cadaveric ankles (100% male) were included in the current study with the mean age of 57 years (range, 28–74 years) at the time of death.

Preparation of Cadaver

The lower leg was cut to 25 cm in length from the distal end of the medial malleolus, and the soft tissues, including skin, subcutaneous tissues, and muscles up to 5 cm above the medial malleolus, were carefully removed to expose the tibia and fibula. The soft tissues 4 cm from the tip of the calcaneus were also removed, and the soft tissues 3 cm from the tip of the fibula were left intact to preserve the ATFL and calcaneofibular ligament. The proximal tibio-fibula syndesmosis was fixed with two screws of 4.5-mm-diameter. After the potting of the tibial side in an epoxy compound (Bondo, 3M, St. Paul, MN), three 4.5 mm diameter wood screws were inserted into the calcaneus. Finally, the calcaneus and attached screws were potted in a cylindrical mold (Fig. 1A).

6 Degree-of-freedom Robotic Testing System

The ankle was mounted onto a 6-DOF robotic testing system (MJT model FRS2010). The position and orientation repeatability of the robotic testing system are less than ± 0.015 mm and $\pm 0.01^{\circ}$, respectively. The tibia clamp was rigidly fixed to the lower plate of the robotic testing system, and the calcaneal clamp was attached to the upper end plate of the robotic manipulator through a universal force/moment sensor (UFS; ATI Delta IP60 model SI-660-60), which is utilized to provide feedback to the controller (Fig. 1B). The measurement uncertainty of the UFS is approximately 1% of full scale. The system was controlled by a LABVIEW program (Technology Services Inc.) designed for ankle biomechanical testing and was operated in hybrid velocity-impedance control.

The tips of the lateral and medial malleoli were marked to follow the definition of the ankle joint coordinate system in accordance with International Biomechanics Society (ISB) [20]. The neutral configuration of the ankle joint was defined according to the technique by the ISB on three

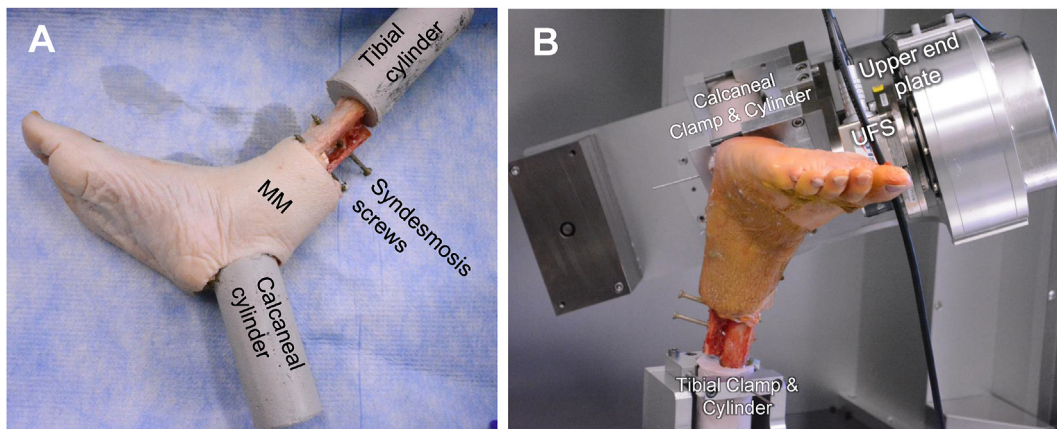


Fig. 1. Ankle specimen and 6-degree-of-freedom robotic testing system. (A) The skin and soft tissues were removed up to 5 cm above the MM and 4 cm from the tip of the calcaneus. Proximal tibio-fibula syndesmosis was secured with two screws. Both tibial and calcaneal ends were potted in cylindrical molds. (B) The tibial clamp and cylinder were secured to the lower plate. The calcaneal clamp and cylinder were attached to the upper end plate with a UFS. MM, medial malleolus; UFS, universal force/moment sensor.

planes: neutral plantar flexion/dorsiflexion (PF-DF) on the sagittal plane of the ankle, neutral inversion/eversion (IV-EV) on the frontal plane, and neutral internal rotation/external rotation (IR-ER) on the transverse plane. Neutral PF-DF was defined as 0 between the long axis of the plantar aspect of the foot and the line perpendicular to the long axis of the tibia projected on the sagittal plane of the ankle. Neutral IV-EV was defined as 0 between the short axis of the plantar aspect of the foot and the line perpendicular to the long axis of the tibia projected on the frontal plane of the ankle. Neutral IR-ER was defined as 0 between the frontal plane of the tibia and the line perpendicular to the long axis of the second metatarsal [20].

Three external loads were applied to each specimen: 40 N anterior-posterior load, 1.7 Nm IV-EV torque, and 1.7 Nm IR-ER torque. 40N anterior-posterior load is similar to the force required to open and close most doors without making a sound. 1.7 Nm IV-EV and IR-ER torques approximate the torque required to flip most mobile phones. A 5 N axial load was applied to maintain contact with the talocrural and subtalar joints during the application of the loads. During the anterior-posterior load, motion along the anterior-posterior axis was under displacement control. The proximal-distal and medial-lateral axes were under force control and allowed unconstrained motion to minimize forces and moments along each respective axis. PF-DF, IV-EV, and IR-ER were constrained under position control. During IV-EV and IR-ER torques, the respective IV-EV and IR-ER axes were rotated under displacement control. The remaining 4-DOFs (anterior-posterior, medial-lateral, proximal-distal, and IV-EV or IR-ER) were

under force control except for PF-DF, which was constrained under position control.

The maximum anterior translation (mm) in response to 40 N anterior load, inversion (degree) in response to 1.7 Nm inversion torque, and internal rotation (degree) in response to 1.7 Nm internal rotation torque from the passive path were measured at 3 ankle positions: 30° PF, 15° PF, and 0° PF. The passive path positions were defined as the positions of the ankle joint from 30° PF to 0° PF when the forces and moments were minimized. 20 N anterior-posterior load, 0.85 Nm IV-EV torque, and 0.85 Nm IR-ER rotation torque 5 times were applied as preconditioning to avoid creep effects before each recording.

Stress Ultrasound Evaluation

Stress ultrasound evaluation of the ATFL was performed using the Logiq 8 US machine with a linear transducer of 12 MHz (GE Healthcare Ultrasound Ltd.) before and during each loading. The transducer was placed over the ATFL, identifying both the fibular and talar bony attachments, which were located at the anteroinferior part of the fibula and at the lateral talar body. A long-axis view of the ATFL with a fibrillar pattern was captured. The distance (cm) between the fibular and talar bony peaks of the ATFL attachments was recorded as ATFL length (Fig. 2) [14]. These bony peaks were identified during the external loads to ensure that the fibular and talar attachments of the ATFL were consistently selected at a similar location across images. A digital caliper on the ultrasound machine allowing measurements to two decimals was used for measurements.

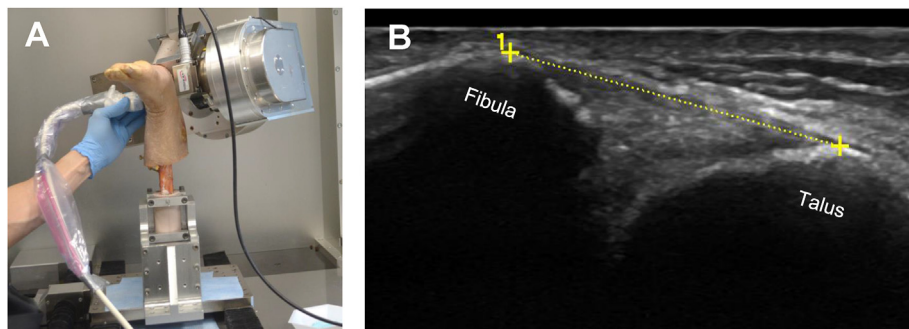


Fig. 2. Ultrasound measurement of ATFL length. (A) Ultrasound transducer was applied between the distal fibula and talus to visualize a long axis of ATFL. (B) Ultrasound images of fibular and talar bony peaks and the long axis of ATFL with a fibrillar pattern. Distance between two bony peaks (yellow +) was measured as ATFL length with a digital caliper (yellow dashed line).

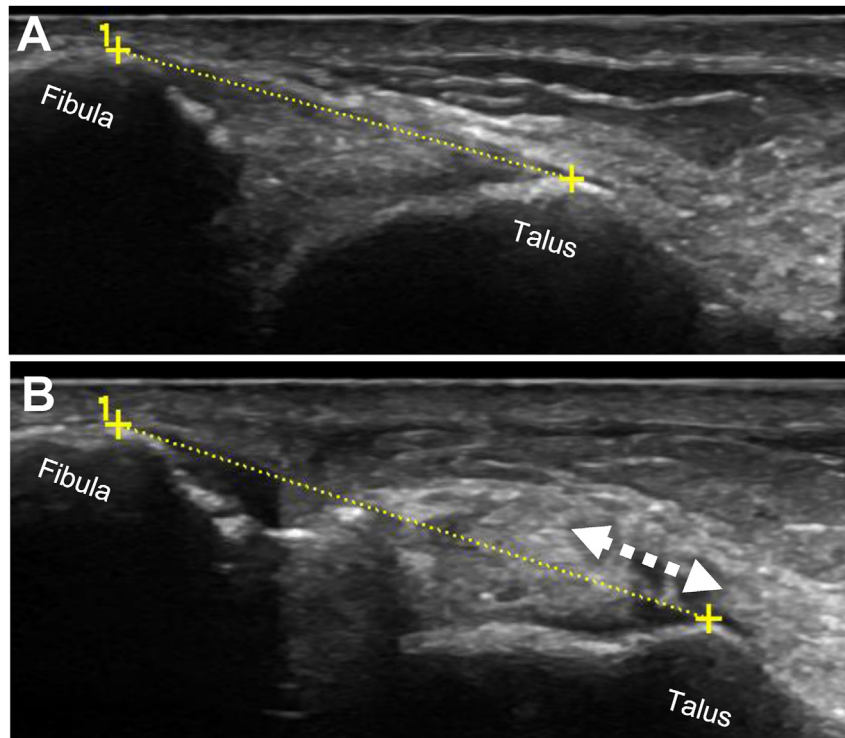


Fig. 3. Ultrasound measurement of bony translation in response to an external load. (A) ATFL length (yellow dashed line) before the load. (B) ATFL length (yellow dashed line) during the load. The distance of bony translation (white arrows) was measured by subtracting ATFL length before the load from ATFL length during the load.

After the ATFL distance was measured at 0° PF without loads, measurements were repeated under 3 loading conditions: 40 N anterior load, 1.7 Nm inversion torque, and 1.7 Nm internal rotation torque. The bony translation was calculated by subtracting the ATFL length before the load from that during the load (Fig. 3). The same measurement and calculation protocol were repeated at 15° PF and 30° PF.

Arthroscopic Dissection of the Anterior Talofibular Ligament

Under arthroscopic guidance, the ATFL was sharply transected with scissors and shaver at the attachment on the fibula using standard anterolateral and anteromedial portals to create an ATFL-transected model [15]. Arthroscopic and ultrasound visualization ensured complete section of ATFL and integrity of calcaneofibular ligament (CFL). The same testing protocol as the intact ankle was repeated on the ATFL-transected ankle (Fig. 4).

Statistical Analysis

The primary outcome of this study was the correlations between the bony translations measured by the stress ultrasound and joint motion from the robotic testing system for the three loading conditions and three ankle positions. Intraclass correlation coefficients (ICC) between the stress ultrasound and joint kinematics were calculated with the Pearson correlation coefficient and analyzed using Koo and Li's guidelines. Measurements of agreement were below 0.5, poor agreement; 0.50–0.75, moderate agreement; 0.75–0.90, good agreement; and above 0.90, excellent agreement [21].

The secondary outcomes were to determine cut-off values for diagnosing transected ATFL using stress ultrasound. Paired t-tests were performed for comparison of translation between the intact and transected ATFL and the unloaded and loaded conditions in transected ATFL. All statistical analyses were performed using EZR v 2.13.0; Saitama Medical Center, Jichi Medical University [22].

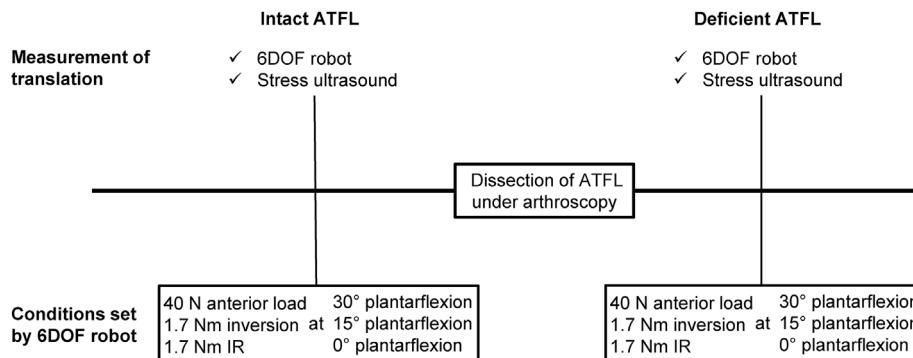


Fig. 4. Flow chart of the experiment. Bony translation of the ATFL was measured before and after dissection of the ATFL by 6 DOF robot and stress ultrasound under a 40 N anterior load, 1.7 Nm inversion, and 1.7 Nm IR at 30° plantarflexion, 15° plantarflexion, and 0° plantarflexion. ATFL, anterior talofibular ligament; DOF, degree of freedom; IR, internal rotation.

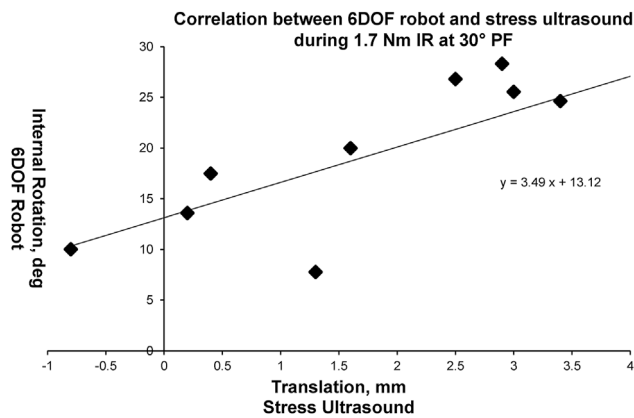


Fig. 5. Correlation of bony translation measured by 6 degree-of-freedom (6DOF) robot and stress ultrasound in response to 1.7-Nm IR torque at 30° PF. Internal rotation was expressed in degree (deg) from the robotic testing system and millimeter (mm) displacement by stress ultrasound, respectively. Good agreement was detected between two measurements. IR, internal rotation; PF, plantarflexion.

Reliability of Ultrasound Evaluation

To evaluate the reliability of stress ultrasound, two experienced orthopedic surgeons (SH and TO) performed measurements of the ATFL length in 10 different conditions of ATFL-transsected ankles. The ICC was calculated using the Pearson correlation coefficient and interpreted with Koo and Li's guidelines [21].

RESULTS

Good agreement between bony translation measured by stress ultrasound and the robotic testing system was found only for the 1.7 Nm internal rotation torque at 30° PF in the transected ATFL (Fig. 5). No statistically significant agreement in other loading conditions at any ankle positions was found (Table 1).

Between intact and transected ATFL, a significant difference was found in response to a 1.7 Nm internal rotation torque at 30° PF ($p < 0.01$). The effect size was medium, with a Cohen's d of 0.69. The mean difference was 2.4 ± 1.8 mm (range, -0.8 to 4.6) (Fig. 6A). A significant difference was also found in response to a 1.7 Nm internal rotation torque at 30° PF between stressed and unstressed conditions in the transected ATFL ($p < 0.01$). The effect size was medium, with a Cohen's d of 0.55. The mean difference was 1.9 ± 1.6 mm (range, -0.8 to 4.1) (Fig. 6B).

Excellent agreement of the stress ultrasound exam of the transected ATFL between two examiners was found (ICC = 0.96; 95% confidence interval, 0.85–0.99; $p < 0.001$).

Table 1

ICC, 95% CI and P-values between bony translation measured by stress ultrasound and 6 degree-of-freedom robotic testing system in transected ATFL with Pearson correlation and coefficient.

| Load | Ankle position | ICC | 95% CI | P-value |
|------------------------------------|----------------|-------|---------------|------------|
| Internal rotation torque of 1.7 Nm | 30° PF | 0.77 | 0.27–0.94 | $P < 0.01$ |
| | 15° PF | -0.25 | -0.76 to 0.45 | 0.48 |
| | 0° PF | -0.25 | -0.78 to 0.5 | 0.52 |
| Inversion torque of 1.7 Nm | 30° PF | 0.35 | -0.36 to 0.8 | 0.33 |
| | 15° PF | -0.02 | -0.64 to 0.62 | 0.96 |
| | 0° PF | 0.12 | -0.54 to 0.76 | 0.62 |
| Anterior load of 40 N | 30° PF | 0.39 | -0.32 to 0.82 | 0.27 |
| | 15° PF | -0.31 | -0.79 to 0.34 | 0.38 |
| | 0° PF | -0.05 | -0.69 to 0.64 | 0.91 |

ATFL, Anterior Talofibular Ligament; PF, Plantarflexion; ICC, intraclass correlation coefficients; CI, confidence interval.

ICC: Below 0.5, poor agreement; 0.50–0.75, moderate agreement; 0.75–0.90, good agreement; and above 0.90, excellent agreement.

DISCUSSION

The most significant findings in this study were that (1) bony translation measured by stress US exam of the ATFL transected ankle was significantly correlated with the motion data of the robotic testing system only in response to a 1.7 Nm internal rotation torque at 30° PF, and (2) significant differences were found between the intact and transected ATFL and between loaded and unloaded conditions for the 1.7 Nm internal rotation torque at 30° PF using stress ultrasound with the mean difference of 2.4 mm and 1.9 mm, respectively. These differences can be diagnostic criteria of the stress ultrasound for a complete ATFL tear. 1.7 Nm of internal rotation approximates the torque required to flip most mobile phones.

No consensus among previous studies on the stress ultrasound evaluation of lateral ligament injuries exists regarding loading conditions and ankle positions. Some studies employed anterior drawer stress at 0° PF [10], and others used internal rotation stress at 10–20° plantarflexed position [8,12]. In the current study, the most optimal load and ankle position for a stress ultrasound exam of an injured ATFL was internal rotation torque at 30° PF, and two possible explanations exist for this finding.

First, to delineate the long axis of ATFL during the stress ultrasound, the transducer was placed on the transverse plane (or the plane that has the best proximity to the transverse plane), similar to previous studies [23,24]. Internal rotation torque and bony translation also occurred on the same transverse plane. The direction of ATFL and its translation in response to the internal rotation torque were parallel to the transducer. Therefore, the bony translation of the ATFL was most accurately measured by the internal rotation torque with stress ultrasound in this study. Anterior load and inversion torque, both of which were applied on the sagittal and coronal planes, respectively, were not sensitive enough to detect the bony translation of the transected ATFL, which occurred on the transverse plane.

Secondly, the stability of the ankle depends on the contour of the talar articular surface. The lateral border of the talar body is oblique and directed postero-medially, and the talar surface is narrowed posteriorly [25]. According to a biomechanical study, lateral tibiotalar pressure gradually increased as the ankle moved from 30 degrees of plantarflexion to 5 degrees of dorsiflexion [26]. Therefore, the 30° plantarflexed position led to the most unstable lateral ankle and allowed for quantifying ankle instability due to the transected ATFL with stress ultrasound most accurately.

Variations in cut-off values for diagnosing lateral ligament injury with ultrasound exist from previous studies. Previously, in comparison with healthy individuals, a 3.7 mm difference was suggested as a diagnostic criterion of ankle instability [10]. 7.1 mm of displacement of ATFL compared with resting condition and 5.1 mm difference in comparison with uninjured side of ankles [8] were reported to be the cut-off values. In addition, a 1.26 mm translation under stress was regarded as a cut-off value for injured ATFL [14]. These variations could be due to the

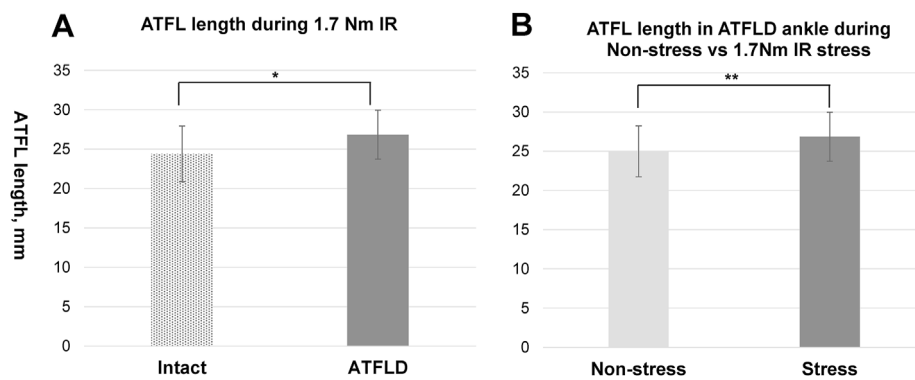


Fig. 6. Mean ATFL length was measured with ultrasound at 30° plantarflexion. (A) Significant difference between intact and ATFLD ankle (* $p < 0.01$) in response to 1.7-Nm IR torque was found. Mean difference was 2.4 ± 1.8 mm. (B) Comparison of ATFL length in the ATFLD ankle during nonstress versus stress with a 1.7-Nm IR load showed a significant difference (** $p < 0.01$). Mean difference was 1.9 ± 1.6 mm. ATFL, anterior talofibular ligament; ATFLD, ATFL-deficient; IR, internal rotation.

inclusion of a wide variety of ATFL injuries. ATFL injury was classified into 3 categories: partial ATFL (Grade 1) tear, complete ATFL tear (Grade 2), and ATFL and calcaneofibular ligament tear (Grade 3) [27]. In clinical studies, diagnostic cut-off values might depend on the severity of the ATFL injury of the patient populations of each study. On the contrary, the current study used cadavers and created a complete ATFL transection without damaging the calcaneofibular ligament. The subject of this study had less variation than previous clinical studies. The cut-off values for diagnosing transected ATFL with stress ultrasound were 2.4 mm in comparison with the intact ankle and 1.9 mm compared with the unloaded condition in this study. According to a systematic review of cadaveric studies, a 2.3 mm increase in anterior laxity after the ATFL was dissected was found in 9 cadaveric studies [28], which was comparable to the result of the current study of 2.4 mm translation.

There are some limitations to this study. First, the mean age of cadavers was 57 years old, and this age group does not match the peak age of ATFL injuries. Second, in an actual clinical situation, a partial ATFL injury or concomitant calcaneofibular ligament injury can occur during an ankle sprain. These types of lateral ligament injuries were not evaluated in this study. The intra-observer reliability of the stress ultrasound exam was not evaluated in this study. Finally, the actual sample size of this study ($N = 10$) was smaller than an a priori sample size calculation ($N = 11$), and the study might have been underpowered.

CONCLUSION

Internal rotation torque at 30° plantarflexion was the most optimal load and ankle position to evaluate increased translation of the ATFL-deficient ankle when clinicians utilize stress ultrasound in patients. There were significant differences between the intact and transected ATFL and between loaded and unloaded conditions in internal rotation at 30° plantarflexion, with the mean differences of 2.4 mm and 1.9 mm, respectively. These differences can be used as cut-off values to detect lateral ankle instability due to ATFL injuries with stress ultrasound.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors thank Dr. Hiroki Matsui for helping with the biostatistical analysis of the manuscript.

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