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Effects of Lateral Ligament Sectioning on the Stability of the Ankle and Subtalar Joint

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ABSTRACT: Patients with subtalar joint instability are often diagnosed with ankle instability. Only after a prolonged period of time in which a patient does not improve after treatment for ankle instability is subtalar joint instability considered. To develop a clinically relevant method to diagnose subtalar joint instability, the kinematics of the simulated unstable subtalar joint were examined. A 6 degree-of-freedom positioning and loading device was developed. Plantarflexion/dorsiflexion, inversion/eversion, and internal/external rotation were applied individually or as coupled motions along with an anterior/posterior drawer. Kinematic data were collected from sensors attached to the calcaneus, talus, and tibia by keeping all the ligaments intact, and by serially sectioning anterior talofibular ligament (ATFL), calcaneofibular ligament (CFL), cervical ligament, and talocalceneal interosseous ligament. Kinematic results were reported using Euler angles. The ATFL and CFL contributed talocrural instability, similar to previous studies. The interosseous ligament was the greatest contributor to subtalar joint stability. The hindfoot motion (calcaneus relative to tibia) showed significant increases in motion when the ankle and/or subtalar joint was made to be unstable. Therefore, it is difficult to diagnose subtalar joint instability on physical examination alone. © 2011 Orthopaedic Research Society. Published by Wiley Periodicals, Inc. J Orthop Res 29:1459–1464, 2011

Keywords: subtalar; instability; kinematics; hindfoot; biomechanics

Most patients have subtalar joint instability for years before treatment because subtalar joint instability is usually inferred after treatment for ankle instability has failed. Subtalar instability was clinically identified to occur with a frequency of 10–25% in patients with chronic lateral functional hindfoot instability,[1] and ligaments stabilizing the subtalar joint may be damaged in 50–70% of patients with acute lateral ankle sprains.[2] Because the end result of untreated chronic subtalar joint instability is pain, dysfunction, deformity, and potentially degenerative arthritis,[3] early diagnosis of this instability is necessary.

One reason why subtalar joint instability is diagnosed late is because it is difficult to distinguish between ankle instability and subtalar joint instability on a physical exam.[4,5] A clinician may observe acute lateral ankle swelling and increased inversion to the hindfoot, and increased external rotation or the medial translation of the calcaneus may be noted.[3] However, these symptoms are similar to symptoms in ankle instability.[6] Stress radiography has been used to investigate subtalar joint instability.[7–12] However, subtalar joint motion is complex and occurs in three planes, so stress radiographic techniques may be insufficient to diagnose subtalar joint instability because the output depends on the direction from which the radiograph was taken. MRI is expensive, time consuming, and difficult to interpret (i.e., a partial or full rupture of the interosseous ligament may be present; however, that does not confirm instability). A clinically relevant technique to diagnose subtalar joint instability would lead to improved diagnosis, treatment, and subsequent recovery. The first step toward developing a clinically useful technique to diagnose subtalar joint instability is to understand the contributions of selected ligaments to hindfoot stability.

The exact injury mechanism for subtalar joint instability remains unknown.[1] It is widely accepted that most subtalar ligamentous injuries occur in combination with injuries of the lateral ligament of the ankle during a severe inversion sprain,[1,13] but it is also believed that subtalar joint instability can occur as an isolated event,[3] with inversion of the subtalar joint with the ankle locked in a dorsiflexed position.[3,8] Therefore, various combinations of disrupted ligaments may cause subtalar joint instability. The calcaneofibular ligament (CFL) is a major contributor to subtalar joint stability.[6,10,14,15] If the foot is plantarflexed while the inversion sprain occurs, the anterior talofibular ligament (ATFL) is usually torn. Conversely, if the foot is dorsiflexed, the ATFL usually remains intact.[10] Anatomic studies suggest that the stabilizers for the subtalar joint include the CFL, the inferior extensor retinaculum, the lateral talocalcaneal ligament, the cervical ligament, and the interosseous talocalcaneal ligament.[10] Another proposed injury mechanism is sequential tearing of the ATFL (if the foot is plantarflexed), CFL, talonavicular ligament and joint capsule, lateral talocalcaneal ligament, cervical ligament, deltoid ligament, and interosseous talocalcaneal ligament.[10] In this study, we chose to follow the injury mechanism suggested by anatomic support of the subtalar joint, as this mechanism has not been completely investigated in the literature.

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The need also exists for understanding how the 3D kinematics of the subtalar joint are affected by ligament sectioning. The subtalar joint provides the axis for inversion–eversion of the ankle joint complex, but a comprehensive study of the kinematics of the ankle and subtalar joints with the ATFL, CFL, cervical ligament, and extensor retinaculum and interosseous talocalcaneal ligament serially sectioned while moving the hindfoot in AP drawer, plantarflexion/dorsiflexion, inversion/eversion, internal/external rotation, supination/pronation, and inversion/eversion while the ankle is locked in dorsiflexion has not been completed.

Therefore, our purposes were to create a cadaver model of the aforementioned injury mechanism of subtalar joint instability and to investigate the effects of this mechanism on subtalar joint instability on the 3D kinematics of the ankle and subtalar joints under multiple loading conditions. We hypothesized that subtalar joint instability would be detected when inversion/eversion, pronation/supination, and inversion/eversion in combination with ankle dorsiflexion was applied after the CFL was sectioned and after the interosseous talocalcaneal ligament was sectioned.

METHODS

Eight fresh-frozen cadaveric lower extremities cut at the mid-shank were obtained; five were left legs and three were right legs (mean age $= 74.3 \pm 6.7$ years, six females, one male, and one unknown sex). Two pairs of limbs came from the same cadaver. X-rays were obtained to ensure that the specimens did not have coalitions, severe arthritis, or an injury that would affect our results. The specimens were thawed in a refrigerator for 24 h before testing. An incision on the lateral side of the ankle was used to expose the ligaments. The surgeon also examined the hindfoot to confirm that no instability or other pathology existed that was not observed in the X-ray. The study was approved by the Institutional Review Board at Naval Medical Center Portsmouth.

Each specimen was placed into a custom non-metallic 6 degree-of-freedom positioning and loading device (Fig. 1). The tibia was fixed using two clamps, and stainless steel k-wires were used to secure the bone. The calcaneus was fixed to the device using titanium bone screws. This method allowed us to apply the desired motion without skin motion artifact that would occur if no bone pins were used. Kinematic data were collected using Polhemus LIBERTY™ (Polhemus, Inc., Colchester, VT), and The MotionMonitor software (Innovative Sports Training, Chicago, IL) was used to collect and process the data. Custom-made sensor holders, machined from delrin, were mounted to the tibia, talus, and calcaneus using titanium bone screws, to eliminate the potential for electromagnetic interference when kinematic data were collected. Line levels were attached to the positioning and loading device (Fig. 1) and were used as guides to help the surgeon assure that the foot returned to neutral after each trial.

Hindfoot instability was created by serially sectioning the ATFL, CFL, cervical ligament in conjunction with the inferior extensor retinaculum and interosseous talocalcaneal ligament.[10] Because the lateral talocalcaneal ligament is usually not present or is integrated with the ATFL and CFL, it was not sectioned as an individual structure.[15] For each condition, two trials of data were collected throughout the range of motion in plantarflexion/dorsiflexion, inversion/eversion, internal/external rotation, supination/pronation, AP drawer, and inversion/eversion while the ankle was held in dorsiflexion. Supination was the combination of plantarflexion, inversion, and internal rotation, while pronation was the combination of dorsiflexion, eversion, and external rotation. The same foot and ankle surgeon performed all manipulations. Additionally, the motion of the footplate was monitored to ensure that a similar motion was being applied during each trial.

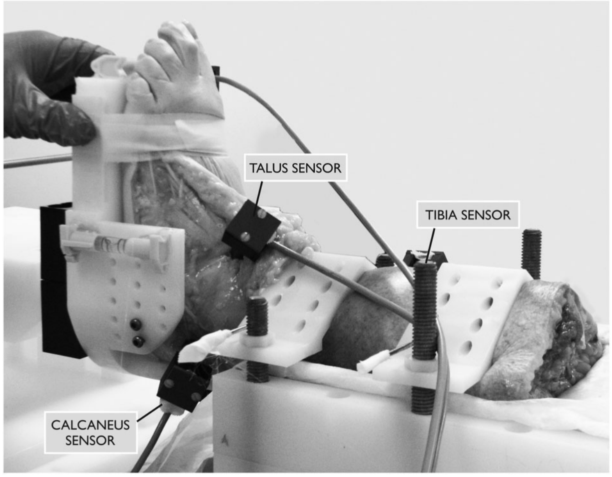

Figure 1. Experimental set up including the 6 degree-of-freedom positioning device, and a limb with electromagnetic sensors attached to the tibia, talus, and calcaneus.

Euler angle data were exported from the software for all conditions, except for AP drawer where the change in magnitude of the relative position of the bones was analyzed. A custom program written in Matlab (The Mathworks, Natick, MA) was used to plot the data, allowed for manual truncation of the data to be one cycle long, calculation of the maximum and minimum range of motion for each trial and input of all data into a table for ease of analysis. Hindfoot motion was reported as the motion of the calcaneus relative to the tibia, motion of the ankle was the talus relative to the tibia, and subtalar joint motion was the calcaneus relative to the talus. The data were exported from The Motion Monitor using an X–Y'–Z'' Euler rotation sequence for the subtalar joint[16] and a Y–X'–Z'' Euler sequence for the ankle and hindfoot motions for all rotation motions.[17,18] Positive X-axis was pointing towards the toe, Y-axis perpendicular to that tibial axis in horizontal plane, and positive Z-axis was pointing towards the knee. Inversion/eversion occurred about the X-axis, plantaflexion/dorsiflexion about the Y-axis, and internal/external rotation about the Z-axis.

A within-subjects repeated measure ANOVA with a Bonferoni correction was used to analyze the difference in joint motion when each ligament was sectioned using SPSS (SPSS, Inc., Chicago, IL). A method developed by Bland and Atman[19,20] was used to calculate the coefficient of repeatability between two data sets, which was used to determine if the results exceeded experimental error. Specifically, the difference in the data between trial 1 and trial 2 were calculated. The 95% confidence interval (the coefficient of repeatability) was then defined as the mean difference ±1.96 standard deviations.

RESULTS

The coefficient of repeatability was ±4.4° at the subtalar joint (Fig. 2), ±5° at the ankle, and ±5.5° at the hindfoot. The coefficients of repeatability for translation at the ankle, subtalar joint, and hindfoot were ±4.2, ±11.3, and ±8 mm, respectively. Any changes that were $<3^\circ$ for rotation and 3 mm for translation were considered clinically insignificant. When the difference between two conditions (e.g., intact and ATFL cut) exceeded clinical significance, but not the coefficient of repeatability, the difference was considered within the limits of experimental error.

The means and standard deviations of all motions of interest are presented in Tables 1–3. During the application of inversion–eversion load, an increment of 13.45° ($p = 0.004$) occurred between the conditions of cervical ligament sectioned to interosseous ligament sectioned at the subtalar joint (Fig. 3). For the ankle, a significant increase in joint motion was measured after sectioning the ATFL (4.28°, $p = 0.004$) and CFL (8.56°, $p = 0.007$). There were significant increases in joint motion measured at the hindfoot after sectioning ATFL (4.88°, $p = 0.017$), CFL (9.1°, $p = 0.008$), and interosseous (11.85°, $p = 0.031$) ligaments.

When internal–external rotation motion was applied, clinically significant changes in joint motion were not measured at the subtalar joint during internal rotation. A significant increase in internal rotation was measured at the ankle (8.8°, $p = 0.0003$) after sectioning the ATFL, and a similar pattern was measured at the hindfoot when the ATFL was sectioned (6.87°, $p = 0.0003$). Although significant increments were measured after sectioning the CFL at the subtalar joint (1.78°, $p = 0.05$) and after sectioning the interosseous ligament at the hindfoot (3.81°, $p = 0.036$) during external rotation, those measurements were within experimental error.

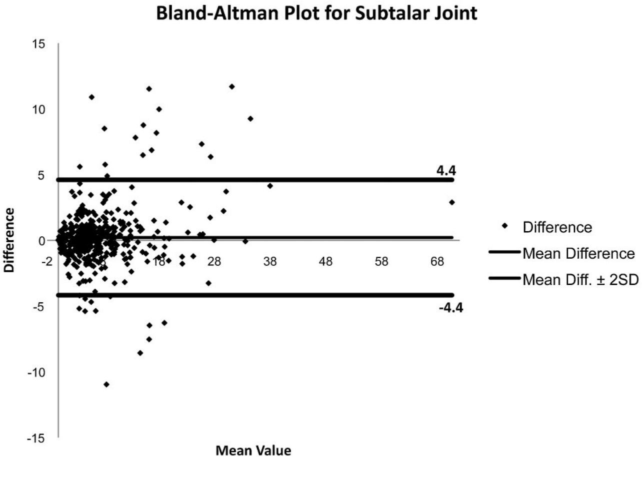

Figure 2. Bland–Altman plot for subtalar joint rotations.

When the supination–pronation motion was applied, inversion–eversion and internal–external rotation motions from the Euler angle output were analyzed. At the subtalar joint, a significant increase in inversion motion (9.45°, $p = 0.012$) was found after interosseous ligament was sectioned. At the hindfoot, a significant increase in inversion was measured after the interosseous ligament (5.55°, $p = 0.004$) was sectioned. A significant increase in internal rotation at the subtalar joint (5.58°, $p = 0.047$) was observed after the interosseous ligament was sectioned during supination–pronation. There were significant increases in internal rotation at the ankle when the ATFL (8.21°, $p = 0.001$), CFL (4.0°, $p = 0.046$), and interosseous ligament (5.26°, $p = 0.01$) were sectioned. At the hindfoot, significant increases were also measured after the ATFL (5.26°, $p = 0.008$), CFL (3.86°, $p = 0.039$), cervical ligament (6.72°, $p = 0.007$), and interosseous ligament (9.15°, $p = 0.003$) were sectioned. However, no significant increases in any of the joints were noticed during external rotation.

When the ankle was held in a dorsiflexed position and inversion–eversion was applied, no significant change was measured at the ankle or subtalar joints between any two successive conditions of ligament sectioning. At the hindfoot, a significant increase (6.64°, $p = 0.039$) in inversion was measured after the CFL was sectioned.

During the application of AP drawer, a significant increase in anterior translation (4.53 mm, $p = 0.027$) was measured at the ankle when the ATFL was sectioned. Also, a significant increase in translation at the subtalar joint was measured between the conditions when the ATFL was sectioned and the interosseous ligament was sectioned (7.3 mm, $p = 0.008$). Both of these findings were within the limits of experimental error.

DISCUSSION

We examined the effects of the serially sectioned anterior talofibular, calcaneofibular, cervical and interosseous talocalcaneal ligaments on the kinematics of the ankle, subtalar joint, and hindfoot (i.e., motion of the calcaneus relative to the tibia). These ligaments were chosen because they provide anatomic stability to the subtalar joint and therefore provide one proposed injury mechanism that may lead to subtalar joint instability. Further, this injury mechanism has not been comprehensively evaluated in a kinematics study of the subtalar joint.

The interosseous ligament is believed to be the most significant ligament in stabilizing the subtalar joint.[8,12,21,22] The joint became unstable when it was sectioned in isolation[22] and was also found to be unstable in a previous study in which the CFL, cervical ligament, and interosseous talocalcaneal ligament were sectioned, while maintaining the extensor retinaculum in both the frontal and coronal planes.[23] Also, the surgical reconstruction of the interosseous

Table 1. Mean ± Standard Deviation of Maximum Motion of the Subtalar Joint With Ligaments Serially Sectioned

Motion	Intact	ATFL	CFL	Cervical	Interosseous
Inversion (°)	5.7 ± 2.8	7.2 ± 1.8	6.8 ± 2.0	7.0 ± 2.0	20.4 ± 9.5[a]
Int rot (°)	8.1 ± 6.1	6.8 ± 4.1	6.0 ± 4.6	7.8 ± 4.7	10.4 ± 7.1
Ext rot (°)	5.3 ± 4.2	6.1 ± 3.7	7.9 ± 4.3[a]	7.7 ± 4.4	7.8 ± 3.8
Sup/inv component (°)	7.3 ± 3.3	6.0 ± 2.1	5.6 ± 2.0	8.4 ± 7.4	17.8 ± 9.5[a]
Sup int rot component (°)	15.6 ± 7.1	12.9 ± 6.6	12.8 ± 6.0	13.1 ± 5.9	18.7 ± 11.3[a]
DF + inv (°)	5.3 ± 2.0	5.8 ± 2.2	6.2 ± 2.7	5.7 ± 2.7	20.6 ± 21.3
Ant drawer (°)	9.2 ± 6.2	8.1 ± 4.3	13.2 ± 7.4	12.7 ± 7.6	15.4 ± 9.6[a]

[a] Significant difference from a previous condition.

ligament has shown that this ligament plays a significant role in stabilizing the subtalar joint.[21] Even though our study examined the effect of the interosseous ligament with the ATFL, CFL, and cervical ligament sectioned before the interosseous ligament was sectioned, clinically significant increases in subtalar joint motion were observed when inversion–eversion and supination–pronation was applied to hindfoot, thus supporting the theory that the interosseous ligament is a major support structure for the joint.

Another proposed subtalar joint support structure is the CFL,[7,10] which significantly contributed to stability in one in vitro study when inversion/eversion (mean increase of 1.2°) and internal/external rotation (mean increase of 1.2°) were applied.[14] In our study, a significant increase (1.78°, $p = 0.008$) was noticed when external rotation was applied while the CFL was sectioned. While this finding should not be considered clinically significant in either study, it suggests that the role of the CFL in subtalar joint stability should be further investigated.

A clicking sound has been observed during anterior drawer in some patients with subtalar joint instability[12]; however, no study has quantified a change in subtalar joint kinematics during anterior drawer when an unstable subtalar joint was simulated. One problem with studying anterior drawer is that its magnitude is highly variable from subject to subject,[24] which may be one reason why differences are not detected. This study found a significant increase in anterior drawer motion at the subtalar joint between the conditions where the ATFL was sectioned and the interosseous talocalcaneal ligament were sectioned (8.13–15.43 mm). This suggests that subtalar joint instability may be detectable with the anterior drawer test. Before this study, it was believed that anterior translation occurs exclusively at the ankle,[25] but our findings suggest that detecting instability by applying anterior drawer should be investigated further.

Previous studies[13,26] and clinical knowledge showed that the ATFL and CFL have a significant role in stabilizing the ankle. This was supported by our findings during the application of anterior translation and internal rotation after the ATFL was sectioned and inversion–eversion after the CFL was sectioned. Most studies examined hindfoot kinematics during anterior drawer to identify ATFL insufficiencies[10,25,26] and inversion to identify CFL insufficiencies.[9,25,27,28] But internal rotation at the ankle increased significantly (8.8°) after ATFL sectioning. Also, when supination was applied, a significant (8.21°) increase in internal rotation was also observed. These findings suggest that when the ATFL is sectioned, rotational instability in the transverse plane is present along with instability in anterior translation.

The hindfoot motion increment for the inversion–eversion stress was significant after sectioning the ATFL, CFL, and interosseous ligament. When examining the ankle joint data, instability was seen when the ATFL and CFL were sectioned as in the case of inversion, internal rotation, and supination–pronation. When examining the subtalar joint data, instability was observed when the interosseous ligament was sectioned as in the case of inversion, internal rotation, and inversion and internal rotation during supination–pronation. These results confirm that

Table 2. Mean ± Standard Deviation of Maximum Motion of the Ankle Joint With Ligaments Serially Sectioned

Motion	Intact	ATFL	CFL	Cervical	Interosseous
Inversion (°)	6.9 ± 5.1	11.2 ± 5.0[a]	19.7 ± 6.3[a]	21.4 ± 8.8	20.0 ± 16.0
Int rot (°)	6.1 ± 3.5	14.9 ± 5.0[a]	17.4 ± 4.0[a]	18.7 ± 4.1	18.4 ± 5.5
Ext rot (°)	13.8 ± 2.6	13.4 ± 3.6	13.9 ± 3.1	16.0 ± 5.6	16.4 ± 10.3
Sup/inv component (°)	6.2 ± 4.9	9.1 ± 5.8	12.5 ± 6.0	15.3 ± 8.2	13.7 ± 12.6
Sup int rot component (°)	14.8 ± 10.1[a]	23.0 ± 9.3[a]	27.0 ± 8.7	29.1 ± 9.1	34.4 ± 11.6[a]
DF + inv (°)	3.9 ± 2.9	4.2 ± 2.8	10.1 ± 8.5	14.6 ± 14.8	17.3 ± 20.4
Ant drawer (mm)	8.5 ± 4.1	13 ± 4.8[a]	14.5 ± 5.7	16.4 ± 6.4	18.2 ± 7.6

[a] Significant difference from a previous condition.

Table 3. Mean ± Standard Deviation of Maximum Motion of the Hindfoot (i.e., Calcaneus Relative to the Tibia) With Ligaments Serially Sectioned

Motion	Intact	ATFL	CFL	Cervical	Interosseous
Inversion (°)	12.3 ± 5.6	17.2 ± 4.3[a]	26.3 ± 6.1[a]	28.4 ± 8.3	40.3 ± 16.7[a]
Int rot (°)	14.1 ± 3.5	20.9 ± 5.2[a]	21.8 ± 6.1	24.8 ± 7.6	26.3 ± 7.8
Ext rot (°)	19.2 ± 4.9	19.5 ± 5.3	22.2 ± 6.4	24.3 ± 5.8	28.1 ± 7.2[a]
Sup/inv component (°)	10.8 ± 4.1	12.4 ± 3.6	16.9 ± 4.7	19.1 ± 6.5	24.6 ± 8.5[a]
Sup int rot component (°)	30.6 ± 3.5	35.8 ± 5.2[a]	39.7 ± 6.2[a]	46.4 ± 8.6[a]	55.6 ± 12.1[a]
DF + inv (°)	8.6 ± 3.5	9.9 ± 3.3	16.6 ± 9.4[a]	22.9 ± 15.2	35.2 ± 26.7
Ant drawer (mm)	13.4 ± 9.3	15.6 ± 7.1	20.9 ± 9.6	21.2 ± 7.6	20.5 ± 9.5

[a] Significant difference from a previous condition.

when instability is present at either joint (or both), the instability will be seen when the motion of the calcaneus is measured relative to the tibia. Furthermore, none of the other applied motions could detect subtalar joint instability in isolation, including when the ankle was dorsiflexed and inversion/eversion was applied. Because the dorsiflexion motion locked the ankle, we hypothesized that this motion may reflect subtalar joint instability. However, this did not occur, confirming previous observations that the physical exam cannot detect subtalar joint instability.

Our study had limitations that should be addressed in future studies. Due to financial constraints, we were unable to instrument the positioning and loading device to ensure that the same load was applied during every trial. To compensate, the hindfoot was always moved to its maximum range of motion, the same person always manipulated the hindfoot, and the footplate motion was tracked to ensure that a similar or greater range of motion was applied to the foot plate as each ligament was cut. In a future study, a 6 degree-of-freedom load cell should be incorporated into the positioning and loading device to ensure for more repeatable and reliable data collection. Errors due to the selection of the Euler rotations were present. In a future study, investigation of the rotation about and translation along a helical axis will be investigated as a possible option of describing the motion of the hindfoot. The digitizing of the foot using the method of centroids in The MotionMonitor™ was unable to demonstrate AP translation at the subtalar joint. Since a motion along only one geometric axis cannot be assigned for the AP translation, a more accurate digitizing protocol could simulate the translation motions of the bones in hindfoot.

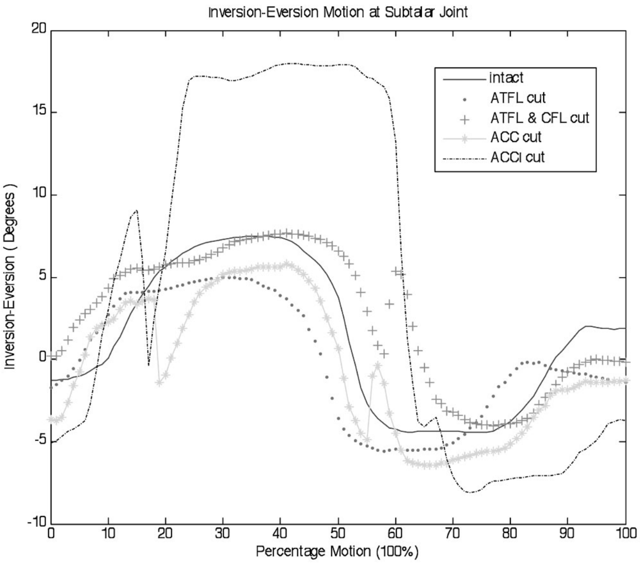

Figure 3. Representative curve of the inversion/eversion kinematics at the subtalar joint for all conditions collected.

In conclusion, our purpose was to improve understanding of the role of four ligaments on the kinematics of the ankle and subtalar joints. The novel contributions in this study were that: (1) the injury mechanism considered serial sectioning of the major anatomic support structures of the joint; (2) the effects of six passive motions (plantarflexion/dorsiflexion, inversion/eversion, internal/external rotation, pronation/supination, inversion/eversion while the foot was dorsiflexed, and AP drawer) were investigated; and (3) the effects of the simulated injuries and the applied passive motions were studied at the ankle (talus relative to the tibia), subtalar joint (calcaneus relative to the talus), and hindfoot (calcaneus relative to the tibia). The ATFL and CFL contributed to ankle instability, similar to previous studies. The ATFL also contributed to ankle stability during internal rotation, which has been rarely documented. We confirmed that the interosseous ligament was the major ligament contributing to subtalar joint instability. Data also suggested that the role of the CFL in subtalar joint stability should be investigated further along with translation of the subtalar joint during anterior drawer when the interosseous ligament is sectioned.

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Department of the Navy, Department of Defense, or the United States Government. Research data derived from *Development of a Method to Quantify Subtalar Joint Instability*, an approved Naval Medical Center, Portsmouth protocol. One author is a military service member. This work was prepared as part of his official duties. Title 17 U.S.C. 105 provides that "Copyright protection under this title is not available for any work of the United States Government." Title 17 U.S.C. 101 defines a United States Government work as a work prepared by a military service member or employee of the United States Government as part of that person's official duties.

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