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Screw fixation of the syndesmosis alters joint contact characteristics in an axially loaded cadaveric model

Jessica E. Goetz[a,b,*], Chamnanni Rungprai[a,1], M. James Rudert[a,2], Lucian C. Warth[a,3], Phinit Phisitkul[a,4]

[a] Department of Orthopaedics and Rehabilitation, University of Iowa, 200 Hawkins Drive, Iowa City, IA 52242, USA
[b] Department of Biomedical Engineering, University of Iowa, 5601 Seamans Center, Iowa City, IA 52242, USA

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ABSTRACT

Background: The purpose of this study was to quantify the effects of rigid syndesmotic fixation on functional talar position and cartilage contact mechanics.
Methods: Twelve below-knee cadaveric specimens with an intact distal syndesmosis were mechanically loaded in four flexion positions (20° plantar flexion, 10° plantar flexion, neutral, 10° dorsiflexion) with zero, one, or two 3.5-mm syndesmotic screws. Rigid clusters of reflective markers were used to track bony movement and ankle-specific pressure sensors were used to measure talar dome and medial/lateral gutter contact mechanics.
Results: Screw fixation caused negligible anterior and inferior shifts of the talus within the mortise. Relative to no fixation, mean peak contact pressure decreased by 6%–32% on the talar dome and increased 2.4- to 6.6-fold in the medial and lateral gutters, respectively, depending on ankle position and number of screws.
Conclusions: Two-way ANOVA indicated syndesmotic screw fixation significantly increased contact pressure in the medial/lateral gutters and decreased talar dome contact pressure while minimally altering talar position.

1. Introduction

The distal tibiofibular syndesmosis is an important soft tissue complex which provides flexible stability to the ankle mortise. Unfortunately, syndesmotic injuries are common, having been reported in up to 18% of ankle sprains and up to 23% of ankle fractures [1]. Injury to the syndesmotic ligaments often results in fibular diastasis and associated abnormal talar kinematics and loading [2], which in turn can increase joint contact stress [3] and lead to eventual post-traumatic osteoarthritis.

Anatomic reduction of the syndesmosis is an important predictor of functional outcome after rotational ankle fracture [4–6]. While anatomic reduction and stabilization of distal tibiofibular syndesmosis is the goal of surgical treatment, there is no concensus regarding the optimal fixation technique. There are an increasing number of hardware options available for performing syndesmotic fixation, though syndesmotic screws remain the most commonly used devices [7]. Screw configurations ranging from a single 3.5 mm-diameter tricortical screw to multiple 4.5 mm-diameter 4-cortex screws are used at surgeon discretion to rigidly fix the syndesmosis, and both biomechanical and clinical studies have shown similar results with all of these configurations [7–9]. However, studies have shown that patients who maintained rigid syndesmotic fixation had inferior postoperative function compared to those with loosened, broken, or removed screws [10,11], suggesting that no matter the hardware used, syndesmosis fixation is detrimental to ankle joint function.

A number of studies have investigated the effects of a variety of syndesmotic screw configurations on talar and fibular kinematics. Results from those studies are somewhat conflicting, with many

* Corresponding author at: Orthopaedic Biomechanics Lab, 2181 Westlawn Building, Iowa City, IA 52242-1100, USA.
E-mail addresses: jessica-goetz@uiowa.edu (J.E. Goetz), chamnanni@yahoo.com (C. Rungprai), jim-rudert@uiowa.edu (M. J. Rudert), lwarth@iuhealth.org (L.C. Warth), phinit.phisitkul@waldenu.edu (P. Phisitkul).
1 Permanent address: 315 Department of Orthopaedics, Phramongkutklao Hospital and College of Medicine, Ratchawithi Rd., Thoung Phayathai, Ratchathewi Bangkok, Thailand, 10400.
2 Permanent address: Orthopaedic Biomechanics Lab, 2181 Westlawn Building, Iowa City, IA 52242-1100, USA.
3 Permanent address: 1801 N. Senate Blvd., Suite 535, Indianapolis, IN 46202, USA.
4 Permanent address: Tri-State Specialists, LLP, 2 Pierce St. Suite 300, Sioux City, IA 51104, USA.

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reports of abnormal bony motion with screw fixation [12–14], but relatively minimal loss of overall ankle function [15–17]. Those studies of ankle kinematics omit study of other biomechanical abnormalities relevant to long-term joint health such as contact pressure. Among the first to address direct biomechanical effects of syndesmosis fixation was a recent study by LaMothe et al. in which decreases in joint contact area after fixation of a disrupted syndesmosis were independent of the method of syndesmosis reduction and fixation [18]. As that analysis omitted a direct investigation of contact mechanics in the medial and lateral gutters, those authors were forced to hypothesize several scenarios explaining the loss of load passing through the in ankles with a repaired syndesmosis

The purpose of this work was to determine the effects of standard syndesmotic screw fixation on contact pressure at several locations within the ankle joint. Our hypothesis was that increasing syndesmotic rigidity with screw fixation would alter both talar dome and medial/lateral gutter contact stresses while minimally modifying talar positioning within the ankle mortise. To directly measure these biomechanical changes, a cadaveric study was performed in which the fibula was left intact, simulating a best-case fracture reduction scenario and isolating the effects of syndesmotic fixation on the ankle biomechanics. Screws were inserted without overtightening in order to investigate changes in joint mechanics resulting from acceptable clinical practice.

2. Materials and methods

2.1. Specimen preparation

Twelve below-knee cadaveric specimens without radiographic abnormality or prior surgery were obtained from a private body donation program (Anatomic Gifts Registry, Hanover MD, US). Institutional Board Review was not required. Mean donor age was 51.1 $\pm$4.78 (range 43–59) years old.

Specimens were cut 30 cm proximal to the ankle joint while preserving the integrity of the interosseous membrane. The proximal-most tibia/fibula, calcaneus, and toes/metatarsal heads were potted in polymethylmethacrylate (PMMA) bone cement blocks. Immediately prior to testing, the overlying soft tissue spanning from 8 cm above to 8 cm below the ankle joint was removed, leaving the anterior talofibular, calcaneal fibular ligament, posterior talofibular ligament, syndesmosis, and Achilles tendon intact. To standardize screw spacing, a 5-hole, 1/3 tubular plate was attached to the lateral side of the fibula with the third hole positioned 2 cm above the joint line. Holes for two 3.5 mm syndesmotic fixation screws were oriented parallel to the joint line and 30° anteriorly along the intermalleolar axis. Holes were drilled free-hand by a fellowship trained foot and ankle surgeon (CR) and tapped through four cortices prior to mounting the specimen for loading.

A calibrated piezoresistive pressure sensor with a resolution of 144 sensor elements/cm^2 (Model 5033, Tekscan Inc, Boston, MA, US) was inserted into the ankle joint between the distal tibia and the talar dome [19–22] in six specimens. In the remaining six specimens, sensors were bisected lengthwise and sealed with tape to create two independent sensing regions (72 sensor elements/cm^2) which were then calibrated prior to insertion into the medial and lateral gutters. A new sensor was used for each specimen, and calibration was performed using a series of 10 progressively larger loads applied by a materials testing machine (MTS 810; MTS Systems Corp., Eden Prairie, MN, US) through a flat platen lined with layers of tape to mimic the compliance of the cartilage [23,24]. A power law curve fit was used to generate calibration curves relating contact pressure to sensor signal intensity. The non-sensing regions of the Tekscan® sensor were fastened to the talus using two 3-mm diameter screws and washers (Fig. 1) to prevent movement during testing. Finally, three rigid, multi-prong clusters of four, 7-mm diameter retroreflective markers each, were screwed directly into the cortical bone of the anterior talus, the distal fibula, and the tibia. Motion of these reflective markers was tracked during experimental loading using a 4-camera motion capture system (Oqus 3+, Qualisys, Gothenburg, Sweden) with a resolution of 1.3 MP (1280 × 1024) and a calibrated accuracy of better than 0.3 mm.

2.2. Experimental testing & data acquisition

Specimens were mounted in a custom-built ankle loading device mounted in an MTS Bionix® (MTS Systems Corp., Eden Prairie, MN, US) [19–22]. This device permits free inversion/eversion of the foot, free internal/external tibial rotation, and free antero/posterior and medial/lateral tibial translation. The Achilles tendon was tensioned with 45 N via hanging weight to simulate gastrosoleus tension (Fig. 2). Contact pressure and bone position data were captured at a rate of 60 frames per second for a period of 30 s. Beginning approximately 5 s into that 30 s acquisition time, a ramp load of 600 N [25] was applied over 15 s and held constant for the remainder of the 30-s data capture. Each specimen was thus tested in 20° plantarflexion, 10° plantarflexion, neutral, and 10° dorsiflexion without any syndesmotic fixation in order to establish each specimen's baseline talus position/orientation and joint contact stress.

A single 3.5 mm diameter screw was then inserted 30 mm above the joint line while the specimen was unloaded and positioned in 20° plantarflexion [15], simulating a consistent intraoperative resting ankle position. The screw was tightened to

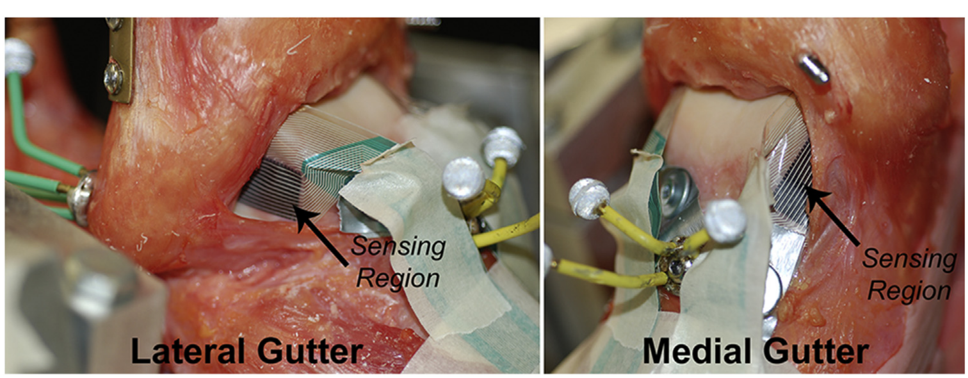

Fig. 1. Photographs illustrating the position of the bisected Tekscan® sensor in the medial and lateral gutters for simultaneous pressure measurements. The screws and washers used to secure the sensor to the non-articulating region of the talus are visible on the medial gutter view. The masking tape on the sensor was used to prevent reflection off the plastic sensor from interfering with the tracking of reflective markers.

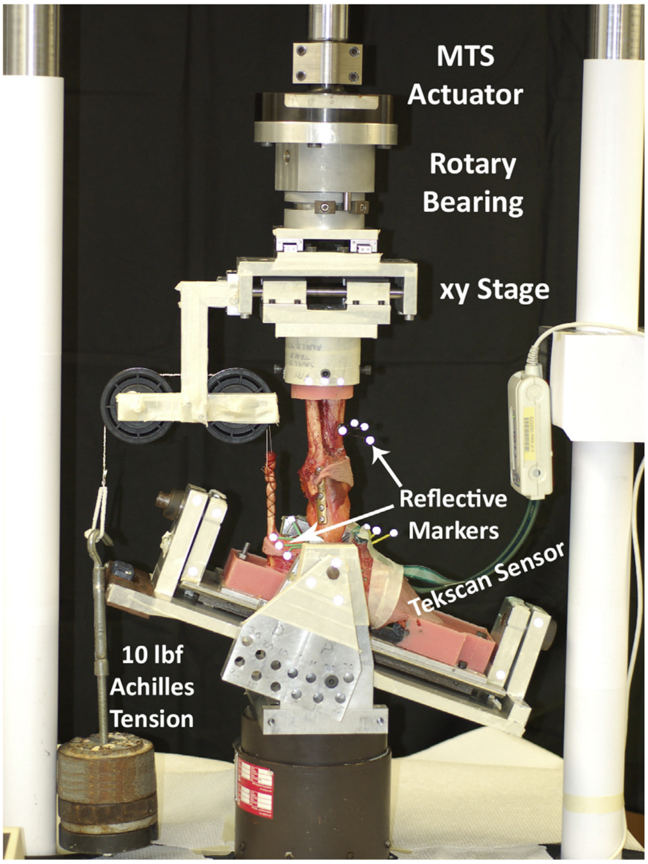

Fig. 2. Experimental testing setup illustrated by a specimen positioned in the MTS Bionix® for testing at 20° plantarflexion. The pulley system and hanging weights provided tension in the Achilles tendon, and the rotary bearing and x–y stage allowed for natural motion of the tibia under load. The reflective markers were placed in locations that were visible over the range of 20° plantarflexion to 10° dorsiflexion and which did not interfere with the Tekscan® sensor. All reflective surfaces were masked to prevent interference with the motion capture measurements.

"two-fingers-tight" [12] by a foot and ankle-trained orthopaedic surgeon using a torque screwdriver to record the resultant torque. The specimen was then loaded as described above in all four ankle flexion angles. Finally, a second 3.5-mm diameter screw was inserted 20 mm above the joint line, again with the specimen unloaded and positioned in 20° plantarflexion, and the loading sequences was repeated.

Additional reflective markers were then adhered to the lateral malleolus, proximal fibula, medial malleolus, proximal tibial shaft, medial talar dome/neck junction, and lateral talar dome/neck junction, and three additional motion capture trials were acquired. These bony landmarks were used to establish an anatomic coordinate system [26] in which to define talar translations and rotations.

2.3. Data analysis

Motion capture data from each specimen's loading experiment in neutral flexion without screws were exported to MATLAB® (The Mathworks, Natick, MA, US) and reoriented into a specimen-specific anatomic coordinate system. The origin was the midpoint between the distal tips of the medial and lateral malleoli [26]. The medial/lateral-axis was oriented along the medial/lateral direction of the vector connecting the malleoli when viewed in an axial plane. This was crossed with a line defined from the origin to the midpoint between the proximal tibial/fibular markers to obtain an anterior/posterior-axis. A final cross product between the medial/lateral (M/L) and anterior/posterior (A/P) axes yielded the superior/inferior axis, oriented vertically along the shaft of the leg [26]. Data from a specimen's experimental flexion position/hardware configuration were transformed into that specimen's anatomic coordinate system using an iterative closest point algorithm to match the experimental tibial marker cluster to the position of those markers when the specimen was oriented in the anatomic coordinate system.

Talar displacement resulting from the addition of each syndesmotic screw was calculated as the difference in talus location with screw fixation at each flexion position, relative to the location of the talus at the corresponding flexion position when no fixation was present. Three instantaneous finite centers of rotation (CoR) [27] of the talus in the sagittal plane (a 2D measure) were also calculated: between 20° and 10° of ankle plantarflexion; between 10° of ankle plantarflexion and neutral ankle flexion; and between neutral ankle flexion and 10° of ankle dorsiflexion. This simplified 2D measure represented the effective axis about which the talus was rotating at different instants within the full range of ankle flexion. A calculated CoR closer to the origin of the ankle coordinate system indicated more rotational movement of the talus, whereas a more remote CoR location was indicative of overall movement with a larger component of talar translation within the mortise or a levering out type of rotation. Differences from the baseline, no fixation CoRs indicated abnormal talar mechanical behavior.

Wilcoxon matched pairs signed-rank tests were used to evaluate differences in talus position and rotation axes resulting from one versus two syndesmotic screws. A Bonferroni correction was used to account for the multiple comparisons, mandating $P \leq 0.0125$ for statistical significance in the talar translation comparison and $P \leq 0.017$ for the CoR comparison. A Pearson correlation coefficient was calculated between the talar translations and the measured screw insertion torque to evaluate any relationship between screw tightening and talar displacement.

Contact stress data were calculated from the raw Tekscan® sensor output and the sensor calibration information. Because overall sensor output decreased over the course of testing a single specimen, sensors were re-calibrated at the completion of testing and raw output was linearly scaled up based upon that particular sensor's loss of signal and the number of the test being analyzed. Peak contact pressure, mean contact pressure, contact patch area, and center of pressure were calculated for the talar dome and the medial/lateral gutters. Changes in stress, contact area, and location of the center of pressure were evaluated using repeated measures 2-way analysis of variance (ANOVA) with significance set at $P \leq 0.05$.

3. Results

3.1. Talus position results

The presence of syndesmotic screw fixation caused negligible translations of the talus in the anterior direction relative to the no-fixation conditions (Fig. 3). While the overall trend was for slight anterior translation of the talus with syndesmotic screw fixation, there was a high degree of variability between specimens (Fig. 3 and Supplemental Table S-1). Translations in 3 of 12 (25%) cadaveric specimens were directed posteriorly, and 2 (16.7%) specimens demonstrated translations less than 0.1 mm in any ankle position as a result of syndesmotic fixation.

Mean talar translations in the superior/inferior direction were extremely small (<0.2 mm) in all ankle positions when a single syndesmotic screw was used. Addition of a second syndesmotic screw increased the small, inferiorly directed translations present

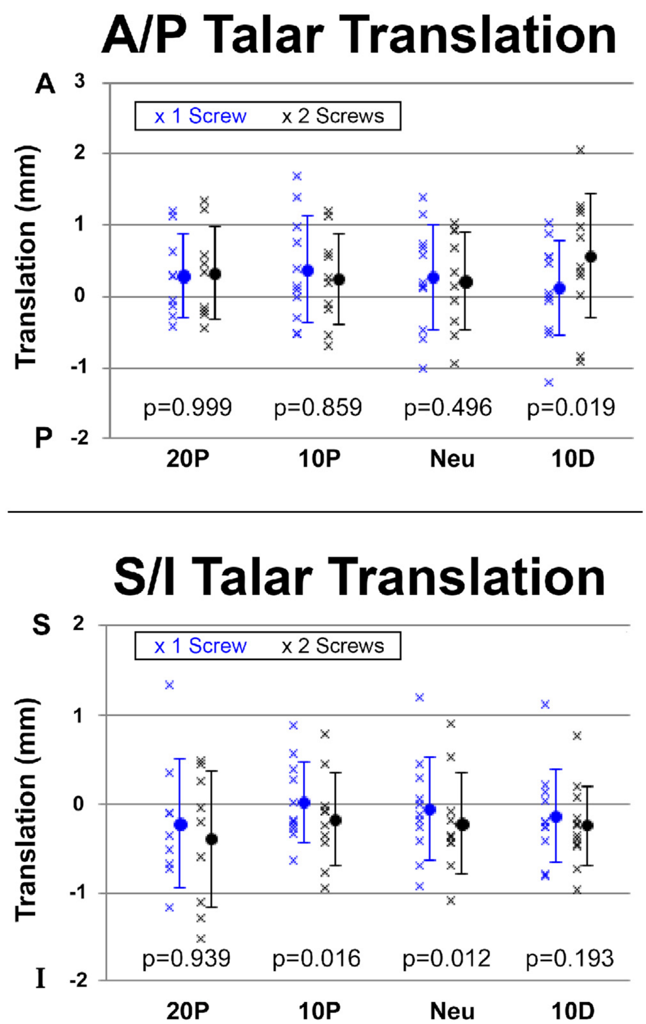

Fig. 3. Individual specimen talar translations (small x's) relative to baseline conditions without syndesmotic fixation. Dots indicate the mean of all specimens, and error bars indicate group standard deviations. *P* values relate to significance of the differences between syndesmotic fixation with one or two screws. With the Bonferroni correction mandating $P \leq 0.0125$ for statistical significance, only the inferior talar translation with the foot in neutral flexion was significantly greater in the presence of two syndesmotic screws.

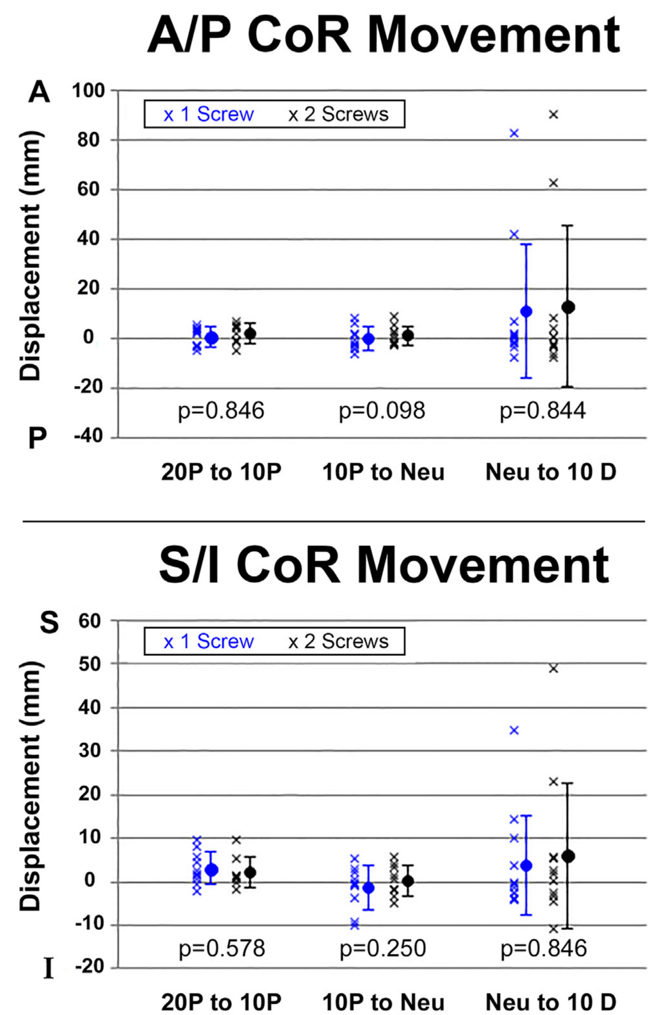

Fig. 4. Movement of the center of rotation (CoR) relative to baseline conditions without syndesmotic fixation for each individual specimen (small x's). Dots indicate the mean of all specimens, and error bars indicate group standard deviations. *P* values relate to significance of the differences between one and two syndesmotic screws. There was no significant difference between one and two syndesmotic screws in terms of movement of the talar CoR. Presence of any screw fixation moved the talar CoR anteriorly and superiorly, particularly during dorsiflexion (Neu to 10D).

with one screw (Fig. 3), although with the Bonferroni correction, this increase was only statistically significant for neutral ankle flexion ($P = 0.012$). As with A/P talar translation, 3 of 12 (25%) specimens (different than those discussed for AP movement) had talar translation opposite the trend (i.e. moved superiorly) with the addition of syndesmotic fixation.

During movement from 20° to 10° of ankle plantarflexion, a single syndesmotic screw caused a mean shift in the 2D talar CoR of 0.90 ± 3.84 mm anteriorly and 3.13 ± 3.74 mm superiorly. Presence of a second syndesmotic screw translated the 2D talar CoR a similar 2.27 ± 4.11 mm anteriorly and 2.24 ± 3.58 mm superiorly relative to baseline. Changes in talar CoR during dorsiflexion (neutral ankle to 10° ankle dorsiflexion) were larger, with a single syndesmotic screw causing a mean shift of the 2D talar CoR 11.10 ± 27.03 mm anteriorly and 3.99 ± 11.91 mm superiorly. A second screw caused a mean shift in the 2D talar CoR 13.25 ± 32.14 mm anteriorly and 5.94 ± 16.58 mm superiorly. The dramatic changes in the mean and standard deviations of CoR during ankle dorsiflexion were the result of including two specimens with CoRs that were calculated well outside the mortise, rather than from an overall increase in CoR for all specimens investigated (Fig. 4 and Supplemental Table S-2).

The magnitude of the torque used to achieve “two-fingers-tight” during syndesmotic screw tightening (average 8.5 ± 6.9 Nm; range 1.6–27.4 Nm) did not correlate with talar translations in the superior/inferior or the anterior/posterior directions (R^2 range 0.024–0.463). Placement of the Tekscan® sensor in the gutters versus over the talar dome similarly did not relate to talar movements in any given direction.

3.2. Contact pressure results

Two-way ANOVA indicated a significant ($P < 0.001$) relationship between syndesmosis fixation and talar dome contact area. In 20° plantarflexion there was little change in talar dome contact area, but in positions between 10° plantarflexion and 10° dorsiflexion the contact area on the talar dome decreased by 9% to 13% with a single syndesmotic screw and by 20%–27% with two syndesmotic screws (Fig. 5). The mean center of pressure moved less than 1 mm in any direction with syndesmotic fixation (mean 0.38 ± 1.68 mm). There was a significant relationship between syndesmotic fixation and lateral gutter contact area ($P < 0.001$), but a non-significant

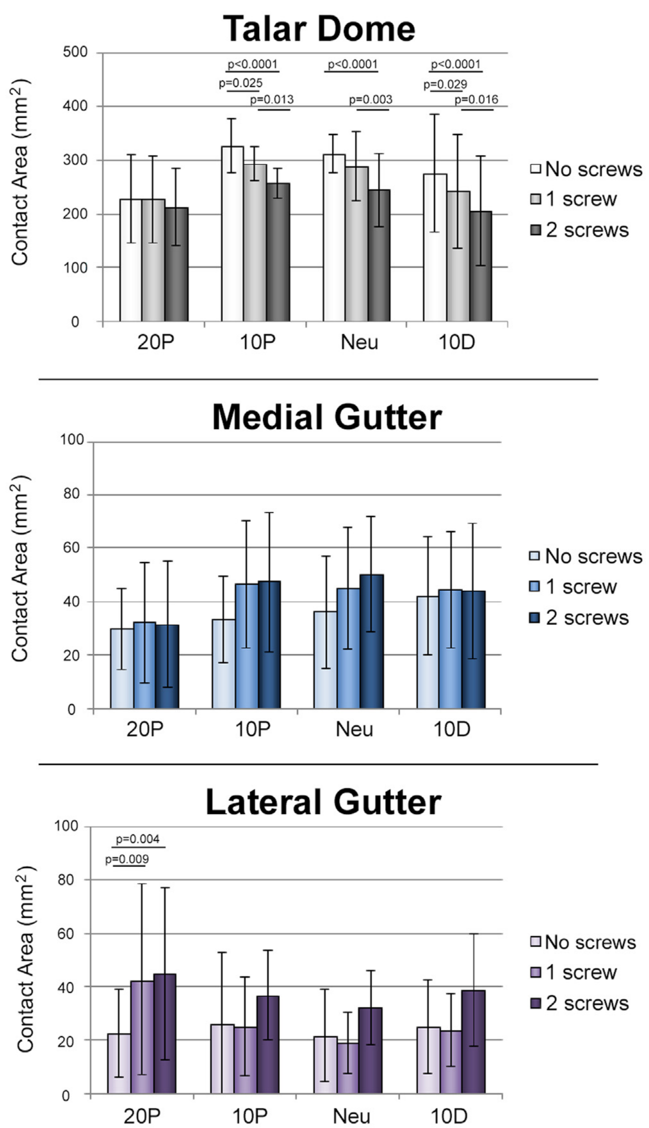

Fig. 5. Contact area measured using Tekscan® sensors inserted in the talar dome or simultaneously in the medial and lateral gutters (n = 6 for each group). Shaded bars represent mean values and error bars are standard deviations. Statistically significant pairwise comparisons are indicated with *P* values.

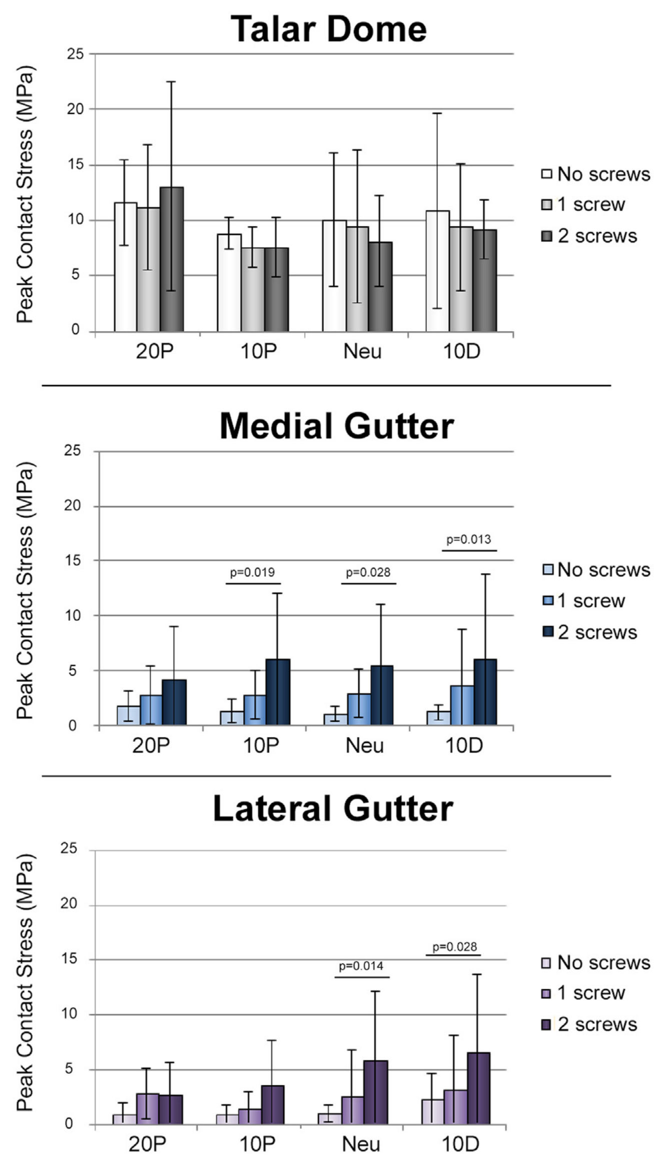

Fig. 6. Peak contact stress measured using Tekscan® sensors inserted in the talar dome or simultaneously in the medial and lateral gutters (n = 6 for each group). Shaded bars represent mean values and error bars are standard deviations. Statistically significant pairwise comparisons are indicated with *P* values.

increase medial gutter contact area with increasing fixation ($P = 0.094$).

Addition of a single syndesmotic screw caused an ankle position dependent decrease of 7% to 13% in mean talar dome contact pressure compared to the no-fixation conditions. Presence of two syndesmotic screws caused a nearly identical decrease of 8%–14% of the normal mean talar dome contact pressure. Two-way ANOVA indicated these slight decreases in peak contact pressure in the talar dome with increasing syndesmotic fixation were insignificant ($P = 0.38$). Peak contact pressure measured in the medial and lateral gutters was very low (mean 1.30 ± 1.22; range 0–6.2 MPa) without syndesmotic fixation. Mean peak pressure in the medial gutter increased 25% to 454% of the intact pressures depending on ankle flexion and fixation. Mean peak pressure increased 127% to 813% in the lateral gutter depending on ankle flexion and fixation. The large percent increases were due in part to the very low peak pressures in the gutters without syndesmotic fixation, and they reflect a mean increase in gutter contact pressure of 2.7 ± 4.4 MPa. 2-way ANOVA indicated the effects of fixation on measured contact pressure was significant in both the medial and lateral gutters ($P < 0.001$ in both locations) (Fig. 6).

4. Discussion

The goal of this work was to investigate the effects of rigid syndesmotic fixation on ankle contact mechanics using a cadaveric model. Single and double screw fixation was performed with an intact fibula, intact syndesmotic ligaments, and a “two-fingers-tight” technique to prevent screw overtightening. In this best-case surgical repair scenario, with adequate fibular length, a well-aligned syndesmosis, and without syndesmotic clamping, our data suggested only isolated instances of abnormal talar movement at the ankle, but consistent abnormalities in contact mechanics at the ankle joint after screw-fixation of the syndesmosis. In the few specimens with abnormal talar movement, the talus subluxated anteriorly and inferiorly within the ankle mortise after screw insertion, and the axis of talar rotation in the sagittal plane shifted anteriorly and superiorly toward the lip of the tibial plafond. Yet, even without obvious changes in talar functional position, there was a consistent increase in contact area and higher contact pressure in the medial and lateral gutters, and decreased contact area and pressure on the talar dome with the presence of syndesmotic screw fixation.

The mechanical alterations to the ankle joint after rigid screw fixation could be partly explained by our use of common surgical techniques for syndesmotic fixation, particularly, the 20° plantarflexion position that was used during screw fixation to replicate an unloaded intraoperative resting condition. Fixing the intermalleolar distance while the mortise was accommodating the relatively narrower more posterior talar dome potentially minimized the intermalleolar distance, causing effective syndesmotic overcompression despite reasonably inserted and tightened trans-syndesmotic screws. Then, when the ankle was brought into dorsiflexion, the wider anterior talar dome could not naturally glide posteriorly, but rather the talus demonstrated some rolling antero-inferiorly underneath the anterior lip of the tibial plafond. Interestingly, the anteroinferior talar displacement was also evident during testing at 20° plantarflexion, suggesting that other factors such as joint loading conditions when the screw was inserted may also influence subsequent changes in talar mechanics. For example, placing the screw while in the resting equinus condition, when the talus is likely slightly subluxed from its fully weightbearing position, may prevent complete engagement of the talar dome against the mortise when loading is applied, given that the talar body is also wider inferiorly and may not be able to translate superiorly within a narrowed mortise.

This subtle movement in talar functional position corresponds well with contact pressure data reported in literature and that measured in this work. A talus which cannot fully seat within the mortise would have the reduced talar dome contact pressure found in this and in other authors' work [18,28,29]. Our finding of increased contact stress in the medial and lateral gutter articulations was particularly noteworthy. While such findings may occur simply as a result of a mortise that no longer has a flexible syndesmotic articulation after screw fixation, the magnitude of the increase in gutter contact pressure suggest that fixing the syndesmosis with the ankle in plantar flexion had negative biomechanical consequences even without limiting range of motion [15]. Overall talar translations were extremely modest, which relates well to the relatively small changes (<20%) in measured talar dome contact area and peak contact stress. Interestingly, several of the studies that identified alterations in talar contact areas and pressure with syndesmotic fixation also noted large variability in fibular and talus translation [28,29], which may suggest rigid syndesmotic fixation places some ankles at a much higher risk for unpredictable large abnormal talar translations, with implications for contact pressure.

While other authors have only been able to speculate about the increased contact pressure in the gutters associated with a decrease in talar dome contact after fixation [18], we directly measured these forces and confirmed the expected increase in medial and lateral gutter contact pressure. The changes in gutter contact pressure were very large relative to the unfixed case, which was primarily a result of very little load in the medial and lateral gutters without syndesmotic fixation. These greatly increased contact pressures could have serious implications for long-term cartilage wear, as well as fibula healing. In this work we used an intact fibula, which was more structurally rigid than a fractured and plated fibula which would be more common in syndesmotic injuries. A fractured and plated fibula may bend to reduce the increased gutter contact stresses, which could alter fibular alignment or increase chances of non-unions.

Magnitudes of talar dome peak contact pressure reported in this work (Supplemental Table S-4) are in the upper range of values reported in the literature for intact ankles (6–13 MPa [30,31]) that were loaded similarly. We attribute this primarily to the algorithm used to convert Tekscan® raw output values into contact pressures, which assumed a linear adjustment to output signal from the pre-testing calibration to the post-testing calibration. The assumption of the linear change in Tekscan® sensor output potentially introduced a very slight over-correction of the pressures in some specimens.

A key limitation to this work was the use of below-knee cadaveric specimens that were rigidly anchored with the proximal tibia and fibula in PMMA bone cement within our testing setup. This was done to allow for the use of experimental fixturing that permitted A/P and M/L translational and axial rotational freedom of the leg while including simultaneous tibia and fibular loading. While the fibula rotates and translates during walking gait, during axial loading with the syndesmotic ligaments intact (as was the case for this work) fibular rotations and translations are nearly zero [24]. Constraining the proximal fibula as it was in this experimental setup would limit fibular motion in measurements made prior to screw fixation, and potentially increase contact stress measurements due to a stiffened mortise. However, rigid fixation of the fibula to the tibia with syndesmotic screws eliminates distal fibular motion [13], and proximal treatment of the fibula becomes much less of a limitation. The increases in contact stress found in this work may in fact be underestimations as the contact stresses we used for normal may be elevated due to limited ability of the ankle mortise to change shape with constrained proximal fibular motion.

Other limitations of this work stemmed from the use of a cadaveric model, including specimen-specific variability in soft tissue quality, lack of active muscle tension, and no ligament healing. The applied 600 N axial load and the 45 N Achilles tendon load were more indicative of standing loads than walking. The order of testing was consistent between specimens and no retesting was performed with the screws removed at the completion of the fixed experiments. No a priori power analysis was performed, and it is possible that inclusion of additional specimens may modify the significance of some of the results found in this work. And while testing was performed over a range of ankle flexion positions, the quasi-static loading may not replicate dynamic conditions during normal locomotion. Also, due to the design of the ankle-specific Tekscan® sensor in which the wires transmitting the data are positioned in the medial and lateral gutters, contact pressure could not be simultaneously measured in the talar dome and the gutters without major artifact from sensor overlap.

While the importance of anatomic reduction and stable fixation to promote healing of the syndesmotic complex is well supported, there continues to be no uniform recommendation regarding many aspects of treatment, including optimal method of stabilization, ankle position at the time of fixation, screw size, screw number, or need for screw removal after healing [32–34]. The information obtained during this study supported the hypothesis that screw fixation would alter contact pressure in the talar dome and gutters with minimal effect on talar kinematics. It remains unclear if such dramatic increases in gutter contact stress would occur if screw fixation was performed with the ankle positioned in neutral or dorsiflexion. However, these data would support caution when choosing to perform screw fixation with the ankle in plantar flexion, as an artificially narrowed mortise may cause hard-to-detect, but several-fold increases in gutter contact pressures without obvious changes in talus orientation.

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Conflict of interest

Goetz, JE — received a research grant from Mortise Medical LLC. This grant was not directly related to this work and was obtained well after the completion of this work. It is only relevant as it involves mechanical testing of a prototype syndesmosis fixation device and it is not directly related to this work. Funds associated with that project were administered through the Division of Sponsored Programs at the University of Iowa.

Rungprai, C; Rudert, MJ; Warth, LC— Nothing to report.

Phisitkul P — serves as an advisor and owns stock in Mortise Medical LLC.

Mortise Medical is a company developing a syndesmosis fixation device, and Dr. Phisitkul's involvement with the company began after the completion of the work described in this manuscript.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.fas.2018.05.003.

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