Introduction

Current management of intra-articular calcaneus fractures remains challenging and controversial. Between 50% and 75% of calcaneal fractures involve the subtalar joint. The rate and development of symptomatic posttraumatic subtalar arthritis after intra-articular calcaneal fractures is multifactorial and still poorly understood. Clinical studies have shown that patients with anatomic or near anatomic positioning of the posterior facet (<2-mm gap or step-off) had better functional outcomes at 2 years (in patients not receiving workers compensation). Along with restoring heel height, alignment, width, and lateral column length, surgical intervention provides the opportunity to restore articular congruity. Rammelt et al found the severity of articular comminution related clinically to subsequent foot function and quality of life. Despite anatomic reduction and internal fixation, many patients develop symptomatic posttraumatic subtalar arthritis and require a late subtalar arthrodesis.

Effect of Calcaneus Fracture Gap Without Step-Off on Stress Distribution Across the Subtalar Joint

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Abstract

Background: Subtalar arthritis is a common consequence following calcaneal fracture, and its development is related to the severity of the fracture. Previous calcaneal fracture models have demonstrated altered contact characteristics when a step-off is created in the posterior facet articular surface. Changes in posterior facet contact characteristics have not been previously characterized for calcaneal fracture gap without step-off.

Methods: The contact characteristics (peak pressure, area of contact, and centroid of pressure) of the posterior facet of the subtalar joint were determined in 6 cadaveric specimens. After creating a calcaneal fracture to simulate a Sanders type II fracture, the contact characteristics were determined with the posterior facet anatomically reduced followed by an incremental increase in fracture gap displacement of 2, 3, and 5 mm without a step-off of the articular surface.

Results: Peak pressure on the medial fragment was significantly less with a 5-mm gap compared to a 2- or 3-mm gap, or reduced. On the lateral fragment, the peak pressure was significantly increased with a 5-mm gap compared to a 2- or 3-mm gap. Contact area significantly changed with increased gap.

Conclusion: In this study, there were no significant differences in contact characteristics between a <3-mm gap and an anatomically reduced fracture, conceding the study limitations including limiting axial loading to 50% of donor body weight.

Clinical Relevance: A small amount of articular incongruity without a step-off can be tolerated by the subtalar joint, in contrast to articular incongruity with a step-off present.

Keywords: calcaneal fracture, posterior facet, step-off, fracture gap
Materials and Methods

Six unpaired, fresh-frozen, below-the-knee cadaveric specimens (average age 75 years, 89 kg, 3 male, 3 female) were tested in 5 physiological foot positions. In each specimen, skin and soft tissue of the leg was removed from the knee to the ankle, while preserving the Achilles tendon for use during testing. In this cadaver-based study, institutional review board approval was not required. The skin was removed circumferentially from around the ankle and dorsal foot to the metatarsal phalangeal joints with preservation of the heel pad. Although the proximal muscles were removed, tendons of the foot and associated structures around the ankle were preserved. The tibia was cut to a length of 28 cm, and the fibula was cut to a length of 18 cm. The tibia and fibula were potted so that the midline of the foot would be colinear with the inversion/eversion pivot point of the loading frame and so that the plantarflexion and dorsiflexion pivot was colinear with the medial and lateral malleoli. The tibia and fibula were individually potted using fiberglass resin.

A lateral sinus tarsi incision was used to expose the subtalar joint to allow placement of the pressure sensor packet (Figure 1). The subtalar interosseous ligament was sacrificed to allow insertion of the pressure sensor. Examination of the posterior facet, after testing was concluded, showed no damage to or degeneration of the subtalar joint. No ankle or subtalar joint instability was noted before or after dissection and testing. Medial- to lateral-oriented holes were predrilled in the calcaneus inferior to and parallel with the posterior facet surface for placement of 2 steel dowels with locking collars that held reduction (Figure 2) of the simulated fracture without any joint step-off.

The 4 arms of the sensor (Sensor 6900; Tekscan, Boston, MA) were taped together as a packet to cover the posterior facet of the calcaneus in each foot. Each arm of the 6900 sensors has a measuring grid of 11 columns by 11 rows of pressure-sensing elements. By taping the arms together with varying amounts of overlap, a sensor could be made as a packet that could maximally cover the articular surface. All pressure sensors were 22 rows wide to have maximal coverage of the posterior facet in a medial-lateral direction. Any excess rows were allowed to remain lateral to the joint space and were removed from analysis when the map of the sensor was made (described later). During pilot testing, it was found that a pressure sensor needed to be about 4% of the total length of the foot to provide anterior-to-posterior coverage of the posterior facet given the space available. This allowed each sensor to provide similar coverage of the posterior facet based on the individual foot size. A pressure sensor of roughly this size provided coverage of the facet anterior to the dome. Before sealing the combined arms of the sensor, it was surrounded by fishing line to provide an anchor for the sutures. The sensor was calibrated after it was sealed in the tape so that the loading conditions during calibration were similar to those during the testing. Sutures were passed through the 4 corners of the sensor, capturing the fishing line reinforcement to the packet (Figure 1), to tether the sensor. Sutures were passed medially through the remaining soft tissue, with paired sutures tied to a button.
medially—one for the posterior and one for the anterior corners of the pressure packet. Four screw eyes were placed laterally in bone, to which the sutures were permanently secured.

Before loading the foot, the pressure sensor was removed from the joint to allow for the creation of a simulated fracture. The sutures used to anchor the pressure sensor were untied from the buttons on the medial side of the foot, and the ends of each pair of sutures were tied together to prevent the sutures from being totally removed from their current position, ensuring the sensor could be placed back in its original location. Leaving the sutures tied to the lateral screw eyes, the sensor was removed laterally, taking care not to fold the sensor or any of the electronic leads. At this time, an incision along the plantar surface of the calcaneus was made using mini C-arm imaging. Kirschner wires were placed perpendicular to the plane of the posterior facet to serve as a guide for the simulated fracture. The wires were centered along the midline of the posterior facet, as judged by lateral ankle, Harris axial, and Broden views. A sagittal cut was made from the posteromedial to anterolateral calcaneus with a surgical oscillating saw with a blade of 1 mm width, and care was taken to avoid entering the subtalar joint. The simulated fracture was completed with an osteotome, creating 2 separate fragments (Figure 3).

Once the cut was made, the 6.3-mm-diameter steel dowels were inserted and the fragments were fully reduced. The sensor was replaced and the sutures tied to the buttons on the medial aspect of the foot. The soft tissue on the plantar surface of the foot that had been incised was sutured. The foot was then tested with the fracture reduced. Direct visualization and predrilling ensured that there was no step-off after reduction of the fracture.

Each foot was then positioned into a testing frame, incorporated into an MTS frame (MTS, Eden Prairie, MN), that allowed ankle dorsi- and plantarflexion and inversion/eversion (Figure 4). To maintain the foot position in the frame, a wood screw was placed through the distal metaphysis of the first metatarsal into the wooden base attached to the frame. Stabilizing blocks were secured on either side of the foot to prevent the heel from slipping medially or laterally during testing. The foot was then tested in 5 positions (neutral, 10 degrees of plantarflexion, 10 degrees of dorsiflexion, 10 degrees of inversion, and 10 degrees of eversion). An axial load equal to 50% of the donor’s body weight (BW) was applied and distributed to the tibia and fibula in a 5:1 ratio using a pivot joint connected between the 2 pots. A clamp was placed on the Achilles tendon and a force of 35% BW was simultaneously applied through the Achilles tendon to create tension during the compressive foot loading. Sinusoidal loading was applied for 5 cycles in each foot position. Pressure data were continuously recorded during foot loading.

On completion of this testing, the foot was removed from the loading frame. The dowels were removed, and a 2-mm shim was placed in the fracture line; the dowels were replaced, and the calcaneus was reduced into contact with the shim, creating a uniform gap (Figure 3). The foot was then placed back into the loading frame and was tested again under the same conditions and positions. The foot was

Figure 3. Posterior view of foot showing dowels to reduce calcaneal fragments and shim between the fragments. In this view, the soft tissue closed down around the bone cut, suggesting that the bone cut was conical. However, the bone cut was a straight cut of the saw blade causing a rectangular gap, as verified in C-arm images taken after making the cuts.

Figure 4. Foot loading frame allowing ankle dorsi- and plantarflexion and inversion/eversion. The base of the frame was sequentially locked in 5 testing positions (neutral, 10 degrees of plantarflexion, 10 degrees of dorsiflexion, 10 degrees of inversion, and 10 degrees of eversion).
then removed and the same procedure was repeated for the 3- and 5-mm shims. Even though the bone cut caused a 1 mm reduction in bone width such that these shims caused the equivalent of a 1, 2, and 4 mm separation of the medial and lateral portions of the calcaneus at the articular surface, we considered the fully reduced condition as the starting point and that the 2-, 3-, and 5-mm shims caused 2-, 3-, and 5-mm gaps between the fragments.

On conclusion of the testing, the location of the pressure sensor on the articular surface was mapped. The foot was dissected with the sensor in place and the location of the bone cut where the medial and lateral portions of the calcaneus contacted the sensor were identified. This was done by drawing on the sensor while it was tied in place to determine the borders of the posterior facet as well as the location of the fracture line. Once the outline and location had been drawn, the individual pressure-sensing element locations were mapped to a virtual overlay. This was used to identify which pressure elements (and their pressure values) were in contact with the medial and lateral fragments and which were adjacent to or at the fracture line.

Because the sensor remained with the lateral fragment, it was necessary to determine how the mapping changed on the medial fragment with insertion of each shim. At the conclusion of each experiment, we inserted each shim and determined the amount of sensor shift occurring with each Shim by direct visualization and by comparison with the pressure data videos collected with the foot reduced and with each of the shims. These methods allowed us to determine which pressure-sensing elements on the sensor lay above the gap in the reduced condition and with insertion of each shim.

For each foot position, the peak pressure on the articular cartilage on the medial and lateral fragments was determined. In addition, the amount of articular surface that experienced pressure and its pressure-weighted centroid were computed. Lastly, the peak pressure 1.3 mm on either side of the gap was analyzed to determine if an increase of pressure occurred immediately adjacent to the gap.

The effect of the gap distance was evaluated by examining changes in the peak pressure, contact area, and pressure centroid separately on the medial and lateral fragments using a 2-way repeated measures ANOVA based on a level of significance of $P < .05$. One factor in the ANOVA was foot position. The other factor was gap distance: reduced, 2 mm, 3 mm, or 5 mm. For each statistical comparison, the Mauchly test of sphericity was performed, and depending on when sphericity could be assumed, a test of within subject effects was performed using either the assumption for sphericity or the Greenhouse-Geisser method. When appropriate, post hoc tests were performed using the Bonferroni adjustment for multiple comparisons. A post hoc power study was performed to determine the required sample size to have 90% power at a level of significance of $P < .05$.

### Results

Peak pressure significantly changed with increased fracture gap displacement on the medial and lateral fragments. On the medial fragment, the test of within-subject effects indicated there was a difference in pressure (Figure 5, Supplemental Table 1) with gap distance ($P = .001$). Post hoc testing showed the peak pressure was significantly less with a 5-mm gap compared to a 2-mm gap ($P = .026$), a 3-mm gap ($P = .031$), and the fragments reduced ($P = .030$). There was no significant difference between the 3-mm gap and when the fragments were reduced ($P = .29$).

In regard to the lateral fragment, the test of within subject effects indicated there was a difference in pressure (Figure 6, Supplemental Table 2) with gap distance ($P = .007$). The post hoc tests showed that the peak pressure significantly increased with a 5-mm gap compared to a 2-mm gap ($P = .026$) or a 3-mm gap ($P = .011$). There was no significant difference between the 3-mm gap and when the fragments were reduced ($P = .99$).
Table 1. Peak Pressure Immediately Adjacent to Medial Side of the Fracture Line Gap (MPa).a

<table>
<thead>
<tr>
<th>Foot Position</th>
<th>Reduced 2-mm Gap</th>
<th>3-mm Gap</th>
<th>5-mm Gap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutral</td>
<td>2.4 (1.4)</td>
<td>2.0 (1.4)</td>
<td>0.7 (0.7)</td>
</tr>
<tr>
<td>Plantarflexion</td>
<td>2.4 (1.8)</td>
<td>1.5 (0.9)</td>
<td>0.4 (0.4)</td>
</tr>
<tr>
<td>Dorsiflexion</td>
<td>2.4 (1.4)</td>
<td>1.9 (1.3)</td>
<td>1.0 (0.8)</td>
</tr>
<tr>
<td>Eversion</td>
<td>2.6 (1.6)</td>
<td>2.5 (2.0)</td>
<td>1.1 (0.5)</td>
</tr>
<tr>
<td>Inversion</td>
<td>2.1 (1.3)</td>
<td>1.0 (0.9)</td>
<td>0.5 (0.7)</td>
</tr>
</tbody>
</table>

aStandard deviations are shown in parentheses. Calculations are based on 6 specimens.

Table 2. Contact Area on Medial Fragment (mm²).a

<table>
<thead>
<tr>
<th>Foot Position</th>
<th>Reduced 2-mm Gap</th>
<th>3-mm Gap</th>
<th>5-mm Gap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutral</td>
<td>158 (60)</td>
<td>152 (56)</td>
<td>147 (68)</td>
</tr>
<tr>
<td>Plantarflexion</td>
<td>146 (53)</td>
<td>146 (50)</td>
<td>139 (64)</td>
</tr>
<tr>
<td>Dorsiflexion</td>
<td>158 (62)</td>
<td>159 (61)</td>
<td>152 (65)</td>
</tr>
<tr>
<td>Eversion</td>
<td>166 (57)</td>
<td>163 (63)</td>
<td>151 (73)</td>
</tr>
<tr>
<td>Inversion</td>
<td>140 (63)</td>
<td>138 (57)</td>
<td>122 (59)</td>
</tr>
</tbody>
</table>

aStandard deviations are shown in parentheses. Calculations are based on 6 specimens.

A post hoc test showed that a sample size of 6 feet had 90% power at a 5% level of significance to show the above-mentioned differences among the different gap comparisons.

With examination of the peak pressure immediately adjacent to the fracture gap, the test of within-subject effects showed a significant difference \((P = .002)\) on the medial side of the gap (Table 1, Supplemental Table 3) but not on the lateral side \((P = .28); \) Supplemental Table 4.

With respect to changes in the contact area, the test of within-subject effects showed there was a significant difference in the contact area on both the medial fragment \((P = .002, \) sphericity assumed; Table 2, Supplemental Table 5) and the lateral fragment \((P = .048, \) sphericity assumed; Table 3, Supplemental Table 6) with gap distance. However, post hoc testing did not identify any specific significant differences with gapping between the fragments.

With respect to the location of the pressure centroids, the test of within-subject effects showed there was a significant difference in the medial-lateral location of the pressure centroid on the medial fragment \((P = .024, \) Greenhouse-Geisser test; Table 4, Supplemental Table 7) but not on the lateral fragment \((P = .24); \) Supplemental Table 8. The changes on the lateral fragment were at most 1.3 mm and deemed to not be clinically remarkable even if there were significant changes. In the anterior-posterior direction, the test of within-subject effects did not show a significant difference in the centroid location on either the medial \((P = .35; \) Supplemental Table 9) or the lateral fragment \((P = .7; \) Supplemental Table 10).

Table 3. Contact Area on Lateral Fragment (mm²).a

<table>
<thead>
<tr>
<th>Foot Position</th>
<th>Reduced 2-mm Gap</th>
<th>3-mm Gap</th>
<th>5-mm Gap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutral</td>
<td>98 (37)</td>
<td>100 (51)</td>
<td>108 (47)</td>
</tr>
<tr>
<td>Plantarflexion</td>
<td>81 (29)</td>
<td>95 (58)</td>
<td>102 (51)</td>
</tr>
<tr>
<td>Dorsiflexion</td>
<td>108 (45)</td>
<td>107 (52)</td>
<td>116 (46)</td>
</tr>
<tr>
<td>Eversion</td>
<td>110 (50)</td>
<td>115 (50)</td>
<td>125 (48)</td>
</tr>
<tr>
<td>Inversion</td>
<td>71 (15)</td>
<td>85 (43)</td>
<td>91 (42)</td>
</tr>
</tbody>
</table>

aStandard deviations are shown in parentheses. Calculations are based on 6 specimens.

Table 4. Medial-Lateral Centroid Position on Medial Fragment (mm).a

<table>
<thead>
<tr>
<th>Foot Position</th>
<th>Reduced 2-mm Gap</th>
<th>3-mm Gap</th>
<th>5-mm Gap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutral</td>
<td>23.6 (2.1)</td>
<td>23.7 (1.6)</td>
<td>24.0 (1.5)</td>
</tr>
<tr>
<td>Plantarflexion</td>
<td>23.9 (2.0)</td>
<td>23.9 (1.5)</td>
<td>24.3 (1.4)</td>
</tr>
<tr>
<td>Dorsiflexion</td>
<td>23.4 (2.2)</td>
<td>23.5 (1.9)</td>
<td>23.8 (1.8)</td>
</tr>
<tr>
<td>Eversion</td>
<td>23.2 (2.2)</td>
<td>23.7 (1.8)</td>
<td>23.7 (1.8)</td>
</tr>
<tr>
<td>Inversion</td>
<td>24.0 (1.8)</td>
<td>24.0 (1.5)</td>
<td>24.4 (1.5)</td>
</tr>
</tbody>
</table>

aStandard deviations are shown in parentheses. Calculations are based on 6 specimens. The centroid positions were computed relative to the anterior, lateral corner of the pressure sensor. An increase in the medial-lateral location of the centroids means the centroid has moved medially.

Discussion

Intra-articular calcaneal fractures are a devastating injury with a guarded long-term prognosis. Subtalar arthritis following these fractures has been reported as high as 100% in one study, with 29% requiring subtalar fusion at final follow-up.11 Intra-articular step-offs have been shown to alter the pressure and contact area of the posterior facet in previous biomechanical studies.7,12

A biomechanical model involving a fracture gap without a step-off through the posterior facet has not been developed previously. Prior cadaveric studies have evaluated the contact characteristics of the posterior facet with varying degrees of intra-articular incongruity associated with a step-off deformity. Sangeorzan et al evaluated the contact characteristics with plantar displacement of the posterolateral articular fragment.12 They showed there was a significant decrease in contact area of the posterolateral fragment with 2 mm of displacement when compared to the intact model, but showed no significant differences when comparing 2 mm of displacement with greater degrees of displacement. Mulcahy et al showed that with 1 mm of lateral depression of the posterolateral fragment, the contact area decreased by up to 40% on the posterolateral fragment when compared to an intact model, while simultaneously increasing the contact area on the posteromedial fragment.7
In this study, a primary calcaneal fracture line was created to simulate fracture gap displacement without a step-off and to evaluate the resulting contact pressure changes across the posterior facet. There was no significant difference in peak pressure on the medial or lateral fragments when <3 mm of gap displacement was compared to the anatomically reduced fracture. However, there was a significant difference in peak pressure of both fragments when comparing 5 mm of displacement with 3 mm of displacement. The test of within-subjects ANOVA showed that there was a significant decrease in contact area of the medial fragment with gap displacement that occurred simultaneously with a significant increase in contact area of the lateral fragment with fracture gap displacement.

A limiting factor of this study is possible incomplete coverage of the posterior facet with the sensor. The confines of the subtalar joint and the irregular shape of the posterior facet make it difficult to build a sensor to achieve complete coverage. A rectangular sensor was used to allow for the sensor rows and columns to be aligned properly for analysis. A second limitation is that the interosseous talocalcaneal ligament was sectioned. Loss of this structure has been shown to introduce a small amount of increased motion; however, on gross inspection, no subtalar instability was noted after resection. In extrapolating these data, it should be noted this was a cadaveric model intended to replicate a Sanders type II intra-articular fracture and should not be interpreted for more complex fracture patterns. Another limitation to this study is that axial loading of each specimen was limited to 50% of the donor’s body weight to prevent damage to the pressure sensor. Also, a possible further limitation is that we chose to compare the effect of increasing fracture gap, without step-off, to an anatomically reduced fracture instead of comparing it to the uninjured anatomic condition. Lastly, changes in contact characteristics do not dictate clinical outcome, as the development of posttraumatic arthritis is multifactorial.

In conclusion, this study suggests that a small amount of articular incongruity without a step-off can be tolerated by the subtalar joint, in contrast to articular incongruity with a step-off present. We showed that near anatomic reduction (<3 mm) without an articular surface step-off does not significantly alter the contact characteristics of the posterior facet when compared to an anatomic reduction in a biomechanical model. However, significant changes do occur between 3 and 5 mm of gap displacement. These findings may guide clinicians who are counseling patients regarding optimal treatment strategies for these challenging fractures.

Declaration of Conflicting Interests
The author(s) declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: Frederick W. Werner, MME, research support from Moximed and Conventus and owns stock in Moximed. The other authors have no conflicts of interest to declare.

Funding
The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: Funded by the Department of Orthopedic Surgery, SUNY Upstate Medical University, Syracuse, NY, USA.

Supplemental Material
Supplemental appendix tables for this article is available on the Foot & Ankle International website at http://fai.sagepub.com/supplemental.

References