Posttraumatic ankle osteoarthritis: How initial cartilage lesions, the deltoid ligament and hindfoot alignment affect the outcome of operatively treated ankle fractures

Stufkens, Sjoerd

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CHAPTER 8

THE ROLE OF DISTAL TIBIAL VARUS AND VALGUS ON ANKLE JOINT PRESSURES

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Introduction

Malalignment of the hindfoot has been found to be one of the main risk factors for osteoarthritis (OA) of the ankle joint. \(^1,11,12,14,17,19,22,25\) Earlier reports described excessive cartilage wear particularly in the presence of associated ligamentous instability and muscular imbalance. \(^24\) It has been suggested that asymmetric OA with frontal plane deformity can be addressed with realignment surgery. \(^1,11,14,19,20\) However, no biomechanical data on the effect of supramalleolar osteotomies has been published and clinical data on the outcome of this procedure is sparse. Therefore recommendations for the treatment of asymmetric osteoarthritis remain arbitrary. \(^1,8,11,14,19,20\)

To get a more deeper understanding of the nature of supramalleolar deformities, we sought to characterize and quantify the effect of distal tibial malalignment on the intra-articular changes of pressure and force transmission in the ankle joint. In this cadaveric study, we introduced the concept that two types of supramalleolar deformities should be recognized: an isolated frontal plane deformity with preserved joint congruency and a frontal plane deformity in combination with impaired congruency of the ankle joint.

Materials and methods

We assessed the intra-articular pressure distribution in the ankle joint for various supramalleolar varus and valgus deformities. In a first Group A, 11 specimens (mean specimen age 67 (range, 62 to 86) years; eight male, three female) were placed in a loading apparatus, deformities created and the intra-articular pressure changes recorded. To exclude a bias resulting from the offset of the calcaneal tuberosity due to the supramalleolar deformity (Figure 1) the experiments were carried out twice: once with the position of the calcaneus fixed on the base plate (Figure 1B) and once with the calcaneus displaced medially or laterally according to the degree of the created deformity in the supramalleolar area (displacement \(x = \sin (a) \times H\); \(x\): offset, \(a\): angle of deformity, \(H\): Height of the osteotomy). Because of the unexpected results in this setup, a third set of measurements was analyzed (Group B). In these six additional specimens (mean specimen age 68 (range, 57 to 86) years; five
male, one female) an additional osteotomy of the fibula above the syndesmosis was performed to mimic incongruency within the ankle mortise.

Prior to testing, all limbs were allowed to thaw at room temperature for at least 24 hours. Bony malalignment was excluded radiologically and a normal range of motion in the ankle joint verified clinically. The specimens were prepared by disarticulation at the level of the knee joint, paying attention not to damage the proximal tibio-fibular joint. The tibial plateau was then flattened using an oscillating saw. The skin and subcutaneous tissue were removed and the ligaments, the interosseous membrane and capsules preserved.

For both Groups A and B, angular deformities of up to 15 degrees varus and valgus were created with a custom-designed plate-wedge (Figure 2). These are the maximum deformities that are considered for supramalleolar correction in clinical studies. To achieve this deformity a wedge of bone that resulted in a deformity of 15 degrees varus was removed from the supramalleolar area after having secured the lateral cortex with a 1/3 tubular plate anterolaterally. Subsequently, aluminium wedges of 5 degrees, 10 degrees, 15 degrees, 20 degrees, 25 degrees, and 30 degrees were used to create deformities from 15 degrees varus to 15 degrees valgus. In Group B, where an osteotomy of the fibula was performed, only three conditions were compared: neutral, 15 degrees valgus and 15 degrees varus. The order in which the deformities were created was randomized prior to testing. The fibula osteotomy in Group B was carried out with an oscillating saw in an oblique direction: from distally anterior to proximally posterior, starting proximal to the syndesmosis. The direction of the cut allowed unrestricted shortening of the fibula in valgus deformities. Before the first and after the last test, neutral alignment was restored with a 15-degree wedge and the results compared.

Pressure measurements were taken using Tekscan 5033 pressure sensors (TekScan Inc., South Boston, MA). Anterior and posterior ankle arthrotomies were performed in order to introduce the sensors. The system consisted of a thin, flexible pressure sensor (0.10 mm) that output data to proprietary Tekscan software via a scanning handle. The sensors were two-point calibrated to a load of 700 N according to the manufacturer’s instructions, using a specially fabricated calibration jig mounted onto the testing device similar to that used by other authors. The sensitivity of the sensors was set to ‘high-2’. The measurements were processed with I-scan© software version
3.75. The threshold sensitivity was set to 0.10 MPa in order to reduce interference of irregularities. The software presented an x-y coordinate grid on the sensor. Using the ‘center of force’ tool and the ‘peak pressure’ tool, the location was measured for each of the two parameters on the sensor for every varus or valgus deformity in all specimens. The total matrix area was 1023 mm$^2$ (46 × 32 sensels, 38.3 mm × 26.7 mm), resulting in a spatial resolution of 0.695 mm$^2$ per sensel.

Each leg was mounted onto a load frame (Instron model 8872, Instron Corp., Canton, MA) to simulate single-leg stance (Figure 2). The load transmitter on the tibial side consisted of an intramedullary stem which was attached to a plate. The plate had a small cavity which served as a receiver for the spherical male die part of the loading apparatus. This allowed for free axial rotation and angulation of the tibia during the loading process. Vertical alignment was adjusted with a pendulum which was attached to the loading apparatus. The ankle was plantarflexed to expose the talar dome and the tip of the pendulum centered over the talar dome. To avoid displacement of the Tekscan pressure sensors, two pins were used to secure the sensor onto the talar dome (one anterior at the talar neck and one posterior above the subtalar joint).

The limbs were preconditioned by cyclic loading (20 times with a load of 700 N). Thereafter the deformities were created and static axial compression was applied, starting from 50 N preload to 700 N. Maximal load was then held for two seconds prior to complete unloading. Center of force transmission and peak pressure were captured at 50 Hz. The shift of mean peak pressure and center of force were calculated in relation to the neutral position.

Statistical analysis

Repeated measures analysis of variance (Friedman two-way ANOVA for ranks) was performed for all parameters to assess differences between the groups. The Wilcoxon test was used for pairwise comparisons. The level of statistical significance was $p = 0.05$. A power analysis revealed that testing with six specimens resulted in sufficient power to detect a difference of one megapascal with a standard deviation of 0.8 and a significance level of 0.05; eleven specimens resulted in a power of 98.6%, and six specimens resulted in a power of 86.5%, when two-sided testing was selected.
Figure 1: Illustration of a normally aligned ankle (a), an ankle with a supramalleolar valgus deformity with a fixed heel (b) and the setup after a compensatory translation (x) of the calcaneal tuberosity (c).

Figure 2: Test set-up. Wedges of different sizes were used to simulate various degrees of angular deformity in the supramalleolar area: 1) cadaveric leg, stripped of soft tissue, 2) custom plate with a stem attached which inserted into the tibial marrow cavity for axial loading, 3) Instron actuator.
Results

One specimen (female, 78 years old) was excluded from the study after a fracture of the fibula occurred during loading of the ankle with a deformity of 15 degrees valgus. Compensatory medial/lateral translation of the calcaneal tuberosity did not change the intra-articular measurements. The presented results represent the non-translated configuration.

Group A

Intact fibula (n = 11). Supramalleolar varus deformity in this group led to a posterolateral shift of the center of force and peak pressure. Valgus deformities showed a shift of both parameters in an anteromedial direction. Changes occurred concurrently with increasing deformity (Figure 3). Significant changes were mainly found in the valgus group (p < 0.05) whereas the varus group showed only tendencies (Table 1).

Group B

Osteotomized fibula (n = 6). The shift of the center of force and peak pressure in this group was in an anteromedial direction for varus deformities and posterolateral direction for valgus deformities (Figure 4). With the exception of the anterior transfer in the varus deformities, all changes were statistically significant (p < 0.05) (Table 2). The mean control measurement on return to 0 degrees showed no significant change for the shift of mean peak pressure and for the shift of center of force in both groups (Wilcoxon test, p > 0.05). The largest deviation was found for the mean peak pressure in Group A (anterior shift, mean 0.8 mm).
Figure 3: Illustration of the shift of the center of force and mean pressure for the specimens without a fibular osteotomy. Illustration of the different deformities form 15 degrees varus to 15 degrees valgus, including the standard error of the mean. mm, millimeter.

Figure 4: Illustration of the shift of the center of force and mean pressure for the specimens with a fibular osteotomy. Illustration of the measures for 15 degrees varus, neutral and 15 degrees valgus, including the standard error of the mean. mm, millimeter.
### Table 1a: Supramalleolar Valgus with Intact Fibula (n = 11)

<table>
<thead>
<tr>
<th>Position</th>
<th>5°</th>
<th>10°</th>
<th>15°</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center of force shift</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>to anterior [mm]</td>
<td>mean</td>
<td>95% CI</td>
<td>mean</td>
<td>95% CI</td>
</tr>
<tr>
<td>Center of force shift</td>
<td>0.63*</td>
<td>0.25 - 1.01</td>
<td>1.64*</td>
<td>1.00 - 2.26</td>
</tr>
<tr>
<td>to medial [mm]</td>
<td>0.67</td>
<td>-0.07 - 1.42</td>
<td>1.55*</td>
<td>0.06 - 3.04</td>
</tr>
<tr>
<td>Peak pressure shift</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>to anterior [mm]</td>
<td>3.34</td>
<td>-0.40 - 7.08</td>
<td>4.95*</td>
<td>0.70 - 9.21</td>
</tr>
<tr>
<td>to medial [mm]</td>
<td>2.31</td>
<td>0.22 - 4.40</td>
<td>3.94*</td>
<td>1.10 - 6.78</td>
</tr>
</tbody>
</table>

* significant compared to neutral position; ** significant changes between the different groups; mm, millimeters; CI, confidence interval. p < 0.05.

### Table 1b: Supramalleolar Varus with Intact Fibula (n = 11)

<table>
<thead>
<tr>
<th>Position</th>
<th>5°</th>
<th>10°</th>
<th>15°</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center of force shift</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>to posterior [mm]</td>
<td>0.43</td>
<td>-0.08 - 0.95</td>
<td>0.54</td>
<td>-0.13 - 1.20</td>
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<tr>
<td>to lateral [mm]</td>
<td>0.33</td>
<td>-0.16 - 0.81</td>
<td>1.07</td>
<td>-0.47 - 2.61</td>
</tr>
<tr>
<td>Peak pressure shift</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>to posterior [mm]</td>
<td>0.14</td>
<td>-0.26 - 0.54</td>
<td>0.21</td>
<td>-0.59 - 1.01</td>
</tr>
<tr>
<td>to lateral [mm]</td>
<td>0.61</td>
<td>-0.02 - 1.24</td>
<td>0.90</td>
<td>-0.01 - 1.81</td>
</tr>
</tbody>
</table>

* significant compared to neutral position; ** significant changes between the different groups; mm, millimeters; CI, confidence interval. p < 0.05.

### Table 2a: Supramalleolar Valgus - Osteotomized Fibula (n = 11)

<table>
<thead>
<tr>
<th>Position</th>
<th>15°</th>
<th>15° - fib#</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center of force shift</td>
<td></td>
<td>mean</td>
</tr>
<tr>
<td>to posterior [mm]</td>
<td>1.98*</td>
<td>0.93 - 3.04</td>
</tr>
<tr>
<td>to lateral [mm]</td>
<td>2.1*</td>
<td>1.16 - 3.04</td>
</tr>
<tr>
<td>Peak pressure shift</td>
<td></td>
<td></td>
</tr>
<tr>
<td>to posterior [mm]</td>
<td>6.72*</td>
<td>0.78 - 12.65</td>
</tr>
<tr>
<td>to lateral [mm]</td>
<td>2.43*</td>
<td>1.24 - 3.63</td>
</tr>
</tbody>
</table>

* significant compared to neutral position; CI, confidence interval. p < 0.05.

### Table 2b: Supramalleolar Varus - Osteotomized Fibula (n = 11)

<table>
<thead>
<tr>
<th>Position</th>
<th>15°</th>
<th>15° - fib#</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center of force shift</td>
<td></td>
<td>mean</td>
</tr>
<tr>
<td>to anterior [mm]</td>
<td>1.58*</td>
<td>1.14 - 2.03</td>
</tr>
<tr>
<td>to medial [mm]</td>
<td>1.6*</td>
<td>0.47 - 2.73</td>
</tr>
<tr>
<td>Peak pressure shift</td>
<td></td>
<td></td>
</tr>
<tr>
<td>to anterior [mm]</td>
<td>3.13</td>
<td>-2.87 - 9.14</td>
</tr>
<tr>
<td>to medial [mm]</td>
<td>3.52*</td>
<td>0.80 - 6.23</td>
</tr>
</tbody>
</table>

* significant compared to neutral position; CI, confidence interval. p < 0.05.
Discussion

In order to get a deeper understanding of the biomechanical changes in the ankle joint of a malaligned hindfoot, we performed a cadaveric study simulating various degrees of varus and valgus deformities. Two groups of specimens were assessed: isolated supramalleolar deformities and deformities in combination with incongruency of the ankle mortise. In both groups the changes of the center of force and pressure within the ankle joint were analyzed.

Earlier in vitro studies of load transfer across the tibio-talar joint focused on the effect of a calcaneal displacement osteotomy \textsuperscript{2,6,10,15} cavovarus deformity,\textsuperscript{9} flatfoot deformity \textsuperscript{4,6} tibiotalar incongruence \textsuperscript{13,23,26} tibial malrotation,\textsuperscript{18} and tibial deformities on different heights of the tibia.\textsuperscript{21} The present study is, to the best of our knowledge, the first quantitative analysis of intra-articular pressure distribution with a supramalleolar deformity.

Corrective osteotomies in the supramalleolar area aim to unload the medial compartment in varus deformities and the lateral compartment in valgus deformities.\textsuperscript{1,11,14,19,20} Our model, however, did not suggest that a supramalleolar varus deformity inevitably leads to a medial overload or that a valgus deformity inevitably leads to lateral overload. We found that an isolated change of the distal tibial articular surface angle lead to a paradox shift of the center of force and peak pressure in an anteromedial direction in valgus deformities and in a posterolateral direction in varus deformities. In a second group, an osteotomy of the fibula was added to the frontal plane deformity in order to exclude the fibula and to simulate incongruency of the ankle mortise. In this group we found an anteromedial transfer in varus deformities and a posterolateral shift in valgus deformities. These findings are in accordance with earlier observations in cavovarus feet\textsuperscript{9} and in planovalgus deformities.\textsuperscript{4}

We believe that the unexpected shift in Group A was due to a tension band effect of the collateral ligaments of the ankle (Figure 5). Secondly, the fibula may restrict the adjustment of the talus within the ankle mortise. This hypothesis is supported by earlier reports that analyzed the etiology and the nature of hindfoot malalignment \textsuperscript{4,9,17} and the development of asymmetric ankle joint osteoarthritis.\textsuperscript{5,16}

Based on these findings, we suggest that in congruent joints, e. g.,
joints with maintained interosseous ligament complex and collateral ligaments, an isolated correction of the distal tibial joint surface angle may not re-establish a physiological load pattern in the tibiotalar joint. In these patients the ligaments and the fibula may prevent the normalization of the tibiotalar load transfer. Balancing these joints may require additional procedures such as ligament balancing and / or an ostetomy of the fibula (‘osseous balancing’ of the joint). This may also be the case in large deformities where the fibula may hinder the talus from following the tibial articular surface. In the second group, probably the majority of clinical cases, the frontal plane deformity is associated with an unstable or incongruent ankle mortise. Clinically, this would characteristically be the case in a longstanding deformity, with or without arthritic changes, including the collateral ligaments and the interosseous ligament complex. Data from this study leads us to suggest that an isolated correction of the distal tibial joint angle without addressing the fibula may be the main step in these cases to normalize the force/pressure distribution in the tibiotalar joint.

Earlier biomechanical studies on frontal plane deformities focused on intra-articular changes which occurred in a medio-lateral direction. Davitt et al. found that the center of force moved about 1.5 mm medially in a medial displacement osteotomy of 1 cm, and Steffensmeier et al. found a 1 mm lateral shift in a lateral displacement osteotomy. We observed that the intra-articular changes did not only occur in a medio-lateral but also in an antero-posterior direction. A varus deformity of 15 degrees in the supramalleolar area led to a shift of 1.6 mm anteriorly and 1.6 mm medially. A valgus deformity of 15 degrees led to a shift of 2.0 mm posteriorly and 2.1 mm laterally. These studies emphasize that many deformities associated with asymmetric osteoarthritis of the ankle may have an underlying multiplanar pathology, i.e., not an isolated frontal plane deformity.

The strength of the study is that we used through-knee amputations which maintained the entire tibio-fibular complex intact. Additionally, direct intra-articular measurements were performed. Limitations include that this was a cadaveric, biostatic model. Dynamic forces from the muscles and soft tissue were not included. The healcorder may especially play a significant role in intra-articular load distribution in varus or valgus hindfoot deformities. Furthermore, load transfer via the medial and lateral gutter was not captured.
Especially in valgus deformities, the fibula may take part in the load transfer. Finally, the effect of the subtalar joint remains unclear in supramalleolar deformities. An earlier study described the effect of varus deformity on the subtalar joint and showed that valgus inclination of the subtalar joint progressed linearly with increasing varus deformity of the tibiotalar joint until the intermediate stage and converted to varus position at the later stage. In our pilot study we observed a concurrent shift of the center of pressure and force with increasing deformity and therefore abandoned the initial setup of subtalar joint fixation.

Figure 5: Tension band effect of the lateral collateral ligaments in varus malalignment (A) and restriction of the adjustment of the talus within the mortise by the fibula / interosseous ligament complex in valgus malalignment (B).
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Conclusion

From a biomechanical perspective two essentially different groups of varus and valgus deformities of the ankle joint should be distinguished. In the first group an isolated frontal plane deformity is found. The second group presents with a combined alteration in both the bony alignment and the congruency of the ankle joint. Secondly, in the majority of cases asymmetric osteoarthritis is not a single frontal plane deformity. The changes of load distribution / force transfer across the ankle joint occur in a biplanar pattern and not only in a medio-lateral direction.

References

7. Hayashi, K; Tanaka, Y; Kumai, T; Sugimoto, K; Takakura, Y: Correlation of compensatory alignment of the subtalar joint to the progression of primary osteoarthritis of the ankle. Foot Ankle Int. 29(4):400 – 406, 2008.


