FOOT AND ANKLE: RESEARCH

The role of the fibula in varus and valgus deformity of the tibia

A BIOMECHANICAL STUDY

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It has been suggested that a supramalleolar osteotomy can return the load distribution in the ankle joint to normal. However, due to the lack of biomechanical data, this supposition remains empirical. The purpose of this biomechanical study was to determine the effect of simulated supramalleolar varus and valgus alignment on the tibiotalar joint pressure, in order to investigate its relationship to the development of osteoarthritis. We also wished to establish the rationale behind corrective osteotomy of the distal tibia.

We studied 17 cadaveric lower legs and quantified the changes in pressure and force transfer across the tibiotalar joint for various degrees of varus and valgus deformity in the supramalleolar area. We assumed that a supramalleolar osteotomy which created a varus deformity of the ankle would result in medial overload of the tibiotalar joint. Similarly, we thought that creating a supramalleolar valgus deformity would cause a shift in contact towards the lateral side of the tibiotalar joint. The opposite was observed. The restricting role of the fibula was revealed by carrying out an osteotomy directly above the syndesmosis. In end-stage ankle osteoarthritis with either a valgus or varus deformity, the role of the fibula should be appreciated and its effect addressed where appropriate.

Valgus and varus malalignment of the ankle joint may be caused by trauma, neurological disorders, genetic predisposition and other unidentified factors, and result in asymmetrical joint loading.1-5 This may cause wear of the articular cartilage in areas that are normally accustomed to less loading. Osteoarthritis may also develop in the presence of ligamentous laxity and muscular imbalance.6 The nature of eccentric osteoarthritis of the ankle is not well understood, but, despite this, correction of angular deformities by supramalleolar and calcaneal osteotomies have become more popular.2,5,7-9 There is limited data about the biomechanical changes that occur after corrective osteotomy. Consequently, it is not currently possible to plan the precise level and degree of correction of an osteotomy, nor is it possible to accurately predict its outcome. The ankle joint has been the subject of many biomechanical studies, in which cadaver specimens have been modified to simulate pathological processes that affect the tibiotalar joint.10-14 Our study aimed to describe the effect of varus and valgus deformity of the distal tibia on the contact area and force transmission through the tibiotalar joint. We believe this to be of importance to our understanding of the predisposition of malalignment in the coronal plane to the development of osteoarthritis.

Materials and Methods
We used 17 fresh-frozen cadaveric lower legs; of which 11 were tested with an intact fibula (group A), and as a consequence of our findings in the remaining six we osteotomised the fibula directly above the level of the syndesmosis (group B). Before testing them, the limbs were thawed at room temperature for at least 24 hours. A normal range of movement in the ankle joint was established clinically, and malalignment was excluded radiologically. The specimens were prepared by disarticulation at the knee joint. The tibial epicondyles were removed with an oscillating saw and the medullary canal opened with a drill. A customised load transmitter with a stem in the tibial medullary canal was used to apply the axial load. The skin and subcutaneous tissues were removed down to the tarsus. The ankle ligaments and interosseous membrane were preserved. Each leg was mounted into a load frame (Instron model 8872; Instron Corp., Canton, Massachusetts) to simulate a single-leg barefoot stance (Fig. 1). The foot was strapped to a friction plate with a band which only covered the forefoot. Cyclical loading of the limb was then performed 20 times with a load of 700 N. The preconditioning cycle was sufficient to absorb all plastic deformation of the lower leg.
Pressure measurements were obtained using a TekScan 5033 ankle sensor (TekScan Inc., Boston, Massachusetts) calibrated according to the manufacturer’s guidelines. A custom-made calibration jig was mounted to the Instron actuator as previously described. The total matrix area of the ankle sensor is 1023 mm² (46 by 32 sensels, 38.3 mm by 26.7 mm), which gives a spatial resolution of 0.695 mm² per sensel. The sensor was gently placed into the tibiotalar joint space from the front. Special care was taken to prevent it wrinkling or folding (Fig. 2). The loading pattern consisted of a pre-load of 50 N maintained for five seconds, followed by a load increase up to 700 N within one second. The 700 N load was maintained for two seconds before decreasing to an after-load of 50 N.

Angular deformities of the distal tibia were created. In order to determine the height of the wedge (H) to be removed, the width of the distal tibia (W) was measured with a calliper at a point 10 mm above the anterolateral corner of the ankle mortice. The height of a 15° wedge to be removed was then calculated (H = tan 15° x W). A Kirschner (K-)-wire was inserted approximately 15 mm above a line perpendicular to the tibial cortex, from medial to lateral so that it perforated the lateral cortex 10 mm above the joint line. A second K-wire was placed according to the calculation of the wedge height. In order to secure the lateral cortex of the tibia, a one-third tubular plate was placed on the lateral side, taking care not to interfere with the movement of the distal tibiofibular joint. The wedge was removed with an oscillating saw. Aluminium wedges of 5°, 10°, 15°, 20°, 25° and 30° were used to create the 5°, 10° and 15° of varus position, the neutral position, and 5°, 10° and 15° of valgus deformity in the supramalleolar area (Fig. 3 and Table I). The wedges were firmly secured using a custom-made device which prevented displacement of the wedge. After osteotomy, the specimen was placed back into the load frame and a baseline measurement was made with the 15° wedge in position. The specimen was tested at 700 N and the static pressure distributions recorded by computer.
Two K-wires were used to secure the TekScan pressure sensor to avoid displacing it. In order to ensure that it had not been displaced during testing, the collateral ligaments of the ankle joint were divided after the testing cycle and the position of the sensor confirmed before removing the fixation pins.

The order of the experiments was randomised prior to testing by random wedge selection. Contact area, force transmitted and pressure were captured at 50 Hz for each measurement. The sensitivity of the sensors was set to ‘high’ in order to reduce interference of irregularities, such as pressure on the sensor outside of the joint area.

**Statistical analysis. A power analysis revealed that testing with six specimens resulted in sufficient power to detect a difference of one MPa with a SD of 0.8 and a significance level of 0.05: 11 specimens would provide a power of 98.6%, and six specimens a power of 86.5%, if two-sided testing were selected. Linear mixed model (LMM) analyses were performed to estimate mean change of the dependent variable (contact area, force transmitted, mean pressure and peak pressure) from the neutral position to 5°, 10° and 15° of valgus- or varus position as the main effect. The best fitting variance-covariance structure was assessed with the aid of the Akaike's Information Criterion. This is a measure of the relative goodness of fit of a statistical model. It can be said to describe the trade-off between accuracy and complexity of the model. Additionally, paired t-tests were performed to verify the significance of differences seen between the varus, valgus and neutral positions in group B. A p-value < 0.05 was considered to be statistically significant for all analyses.

**Results**

In each specimen three baseline measurements were made in group A before the distal tibial osteotomy, after the osteotomy of the tibia with the 15° wedge in situ, and after the series of experiments. No significant differences were found between the contact areas (mean difference 7.1 mm², p = 0.86), forces (mean difference 17.9 N, p = 0.70) and pressures (mean difference 0.08 Mpa, p = 0.37) before and after the series of measurements.

One specimen in group A (female, 78 years old) accidentally sustained a fracture of the fibula at the level of the suprasynovial synovial fibular osteotomy and was included in group B for evaluation. The pronation-abduction fracture occurred during loading of an ankle with a valgus deformity of 15°.

In group A the baseline values before experimentation were: mean contact area 408 mm² (SD 111.2), mean tibiotalar force 436 N (SD 101.7), mean pressure 1.22 MPa (SD 0.52) and mean peak pressure 2.59 MPa (SD 0.44). In group B the baseline values before experimentation were: mean contact area 535.2 mm² (SD 113.5), mean tibiotalar force 498.7 N (SD 62.6), mean pressure 0.91 MPa (SD 0.32) and mean peak pressure 2.00 MPa (SD 0.40).

**Valgus position group A.** In 5° of valgus of the distal tibia there was a mean reduction in contact area of 34 mm² (95% confidence interval (CI) 16 to 52). In 10° of valgus the mean reduction in contact area was 95 mm² (95% CI 58 to 132) and in 15° of valgus 147 mm² (95% CI 85 to 208) (Tables II and III, Fig. 4a). In 5° of valgus there was a mean reduction in tibiotalar force transmission of 46 N (95% CI 21 to 70), in 10° of valgus 92 N (95% CI 54 to 131), and in 15° of valgus 130 N (95% CI 83 to 177) (Tables II and III, Fig. 4b). However, with increasing valgus

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**Table I.** Size of inserted wedges and corresponding resulting supramalleolar angles.

<p>| Inserted | Valgus | Valgus |</p>
<table>
<thead>
<tr>
<th>wedge (*)</th>
<th>deformation (*)</th>
<th>deformation (*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>25</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>30</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

**Table II.** Estimated changes of each of the four parameters, per degree of valgus or varus produced in Group A (n = 11).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Per degree</th>
<th>Estimate (95% CI)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact area (mm²)</td>
<td>Valgus position</td>
<td>-9.78 (-12.83 to -6.72)</td>
<td>0.00</td>
</tr>
<tr>
<td>Tibiotalar force (N)</td>
<td>Valgus position</td>
<td>-8.69 (-11.01 to -6.36)</td>
<td>0.00</td>
</tr>
<tr>
<td>Mean pressure (MPa)</td>
<td>Valgus position</td>
<td>0.01 (0.00 to 0.02)</td>
<td>0.01</td>
</tr>
<tr>
<td>Peak pressure (MPa)</td>
<td>Valgus position</td>
<td>0.02 (0.00 to 0.03)</td>
<td>0.04</td>
</tr>
</tbody>
</table>

* CI, confidence interval
† linear mixed-model analysis

**Table III.** Changes observed in the mean contact area, tibiotalar force, mean and peak pressure compared with the neutral position, resulting from the supramalleolar deformities tested in Group A (n = 11).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Valgus position</th>
<th>5° (% change)</th>
<th>10° (% change)</th>
<th>15° (% change)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact area (mm²)</td>
<td>-34 (-8)</td>
<td>-95 (-23)</td>
<td>-147 (-38)</td>
<td></td>
</tr>
<tr>
<td>Tibiotalar force (N)</td>
<td>-46 (-11)</td>
<td>-92 (-21)</td>
<td>-130 (-30)</td>
<td></td>
</tr>
<tr>
<td>Mean pressure (MPa)</td>
<td>0.00 (0)</td>
<td>0.08 (7)</td>
<td>0.20 (16)</td>
<td></td>
</tr>
<tr>
<td>Peak pressure (MPa)</td>
<td>-0.05 (-2)</td>
<td>0.17 (7)</td>
<td>0.26 (10)</td>
<td></td>
</tr>
</tbody>
</table>

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* CI, confidence interval
tilt the decreasing contact area remained on the anteromedial side of the tibiotalar joint (Fig. 5). We had anticipated that the calcaneum would shift laterally with the valgus position of the tibiotalar joint, and hence leading to lateral overload (Fig. 6).

Valgus position group B. Only when a fibular osteotomy was added to 15° of distal valgus of the tibia was there a mean contact area reduction of 181 mm² (95% CI 62.72 to 298.61) with a shift to the posterolateral joint space. When a fibular osteotomy was added to a distal tibial deformity of 15° of valgus there was a mean reduction in tibiotalar force transmission of 120 N (95% CI 20.21 to 220.76) (Table IV, Figs 6, 7a and 7b).

Varus position group A. In 5° of varus there was a mean increase in contact area of 32 mm² (95% CI 3 to 62). The mean increases in 10° and 15° of varus were 32 mm² (95% CI -8 to 73; \( p = 0.15 \)) and 16 mm² (95% CI -18 to 50; \( p = 0.37 \)) respectively, but these differences were not statistically significant using paired \( t \)-tests. (Tables II and III, Fig. 4a). In 5° degrees of varus, there was a mean increase in tibiotalar force transmission of 21 N (95% CI 1 to 42). In 10° and 15° of varus, the mean increases were 19 N (95% CI -5 to 43; \( p = 0.15 \)) and 2 N (95% CI -25 to 30; \( p = 0.87 \)) respectively, but these differences were not statistically significant, using paired \( t \)-tests (Tables II and III, Fig. 4b). As found with valgus deformity, as varus tilting of
Three read-outs of the ankle sensor are projected over the talus with the talar head and neck pointing up and the medial side on the right. Warmer colours indicate higher pressures. In 15° varus without a fibular osteotomy there is a pressure shift in a posterolateral direction; in 15° valgus without a fibula osteotomy there is a pressure shift anteromedially.

The tibiotalar joint increased, the decreasing contact area remained unexpectedly on the posterolateral side of the tibiotalar joint (Fig. 5). We had expected the entire hindfoot, which was not immobilised, to adopt a varus position and produce anteromedial overload (Fig. 6).

Varus position group B. When a fibular osteotomy was added to a distal tibial deformity of 15° of varus there was a non-significant decrease in mean contact area of 40 mm² (95% CI -85.12 to 165.45; p = 0.45, paired t-test). When a fibular osteotomy was added to a distal tibial deformity of 15° of varus there was a non-significant decrease in the mean tibiotalar force transmission of 146 N (95% CI -11.15 to 303.92; p = 0.06, paired t-test) (Table IV and Fig. 7). Again, only when the fibular osteotomy was added was there a shift in loading anteromedially (Fig. 6).

Discussion

Both varus and valgus deformity of the distal tibia caused significant changes in the contact area of the tibiotalar joint. There was a mean reduction in contact area of up to 36% in 15° of tibial valgus, a mean increase in contact area of approximately 8% in 15° of tibial varus and a mean reduction in tibiotalar force transmission of up to 30% in 15° valgus. There was a mean increase in tibiotalar force transmission of about 5% with the ankle in 15° of varus. However, a mean decrease of 29% in tibiotalar force transmission was seen with 15° of varus deformity in combination with a fibular osteotomy, probably because the medial tilting of the talus directed the vector of force through the medial malleolus which was outside the area of our sensor.

The second significant finding was of paradoxical pressure distribution after supramalleolar tibial osteotomy when the fibula was left intact. With distal tibial varus we found lateral pressure overload. Only when the fibula was divided did the hindfoot adopt a varus position and the pressure shift medially. An identical phenomenon was seen with supramalleolar valgus (Fig. 6).

We reviewed the literature about contact area and pressure in the normal ankle joint, changes due to altered foot position, fibular malreduction, and angular deformities of the tibia. It has been shown that rotational deformities result in a significant decrease in the contact area and an increase in peak pressures. Tarr et al noted that the more distal the angular deformity of the tibia the greater the changes in the contact area in the ankle joint. The contact area of the ankle can decrease by up to 30% when the distal fibula is divided and translated by 1 mm to 2 mm. By manipulating the distal fibula into a varus or valgus position by 1°, the contact area is reduced by more than 50%: with 1 mm of lateral displacement of the talus the contact area is reduced by 42%. Displacement or shortening of the fibula by 2 mm or more, or lateral rotation of 5° or more, significantly increases the contact pressure across the ankle joint. Changes in the distal fibula play an important role in determining the contact areas and pressure distribution at the ankle. Our data show that the effect of the fibula on the characteristics of the tibiotalar joint is more marked with valgus deformity than with varus.

Ting et al showed that the tibiotalar contact area decreases significantly when subtalar motion is restricted by fixing the subtalar joint. Osteotomies of the hindfoot...
not only affect the tibiotalar but also the subtalar joint. Subtalar joint compensation occurs particularly in a valgus ankle, as inversion has been shown to be greater (25°, SD 4) than eversion (15°, SD 6) in a three-dimensional CT study.

Hayashi et al. using a spring model, showed that the complex varus inclinations of the ankle and subtalar joint, but not the independent varus inclination of the ankle alone, cause medial stress concentration in the ankle. They concluded that the crucial factor was the varus inclination of the subtalar joint. The subtalar joint might be able to compensate for distal tibial varus with a progressive valgus inclination up to a certain point, but after this it tilts into varus, thereby drastically shifting the tibiotalar pressure distribution medially. Additional fibular deformity or ligamentous instability must therefore contribute to the progression of osteoarthritis of the ankle in patients with distal deformity of the tibia, especially where there is chronic lateral instability and varus deformity. We observed this combined tibiotalar and subtalar tilting only after additional fibular osteotomy.

The strength of our study is that we used the limbs from through-knee amputees with an intact tibio-fibular complex

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**Table IV.** Paired samples t-test showing the differences in means of each of the four main parameters, for the 15° varus and 15° valgus positions compared with the neutral position in cases with an added fibula osteotomy (group B, n = 6).

<table>
<thead>
<tr>
<th>Pairs</th>
<th>Mean difference (95% CI)</th>
<th>% difference</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Contact area (mm²)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valgus 15° Neutral</td>
<td>-180.67 (-298.61 to -62.72)</td>
<td>-34</td>
<td>0.01</td>
</tr>
<tr>
<td>Varus 15° Neutral</td>
<td>-40.17 (-165.45 to 85.12)</td>
<td>-7</td>
<td>0.45</td>
</tr>
<tr>
<td><strong>Tibiotalar force (N)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valgus 15° Neutral</td>
<td>-120.48 (-220.76 to -20.21)</td>
<td>-24</td>
<td>0.03</td>
</tr>
<tr>
<td>Varus 15° Neutral</td>
<td>-146.38 (-303.92 to 11.15)</td>
<td>-29</td>
<td>0.06</td>
</tr>
<tr>
<td><strong>Mean pressure (MPa)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valgus 15° Neutral</td>
<td>0.02 (-0.34 to 0.37)</td>
<td>2</td>
<td>0.91</td>
</tr>
<tr>
<td>Varus 15° Neutral</td>
<td>0.05 (-0.41 to 0.51)</td>
<td>6</td>
<td>0.79</td>
</tr>
<tr>
<td><strong>Peak pressure (MPa)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valgus 15° Neutral</td>
<td>0.42 (-0.64 to -0.19)</td>
<td>21</td>
<td>0.00</td>
</tr>
<tr>
<td>Varus 15° Neutral</td>
<td>0.05 (-0.22 to 0.32)</td>
<td>3</td>
<td>0.66</td>
</tr>
</tbody>
</table>

* CI, confidence interval
as have been used elsewhere.\textsuperscript{13,14} We chose to apply pressure to the tibial plateau to ensure physiological loading of the fibula. Additionally, direct intra-articular measurements were performed using a high resolution sensor. We used the approximated equivalent of one full body weight to load the ankle, although the peak load through the ankle joint can be almost four times body weight during walking.\textsuperscript{29} In our study, the deltoid ligament was not divided, to allow talar lateral shift as had been done in previous studies,\textsuperscript{14} nor had it ruptured – therefore the changes in contact area and pressure were solely the result of the supramalleolar osteotomies. We also simulated natural barefoot standing to allow the foot to adjust to a neutral ground-force situation.

We recognise the limitations of using a static cadaver model. Dynamic muscle forces were not assessed which may therefore limit the interpretability of our results. This is a potential source of bias as osteotomies around the ankle joint change the mechanical axes. Additionally, cartilage deformation may have occurred during repeated loading. During weight-bearing, about 42.4% of the contact area has a contact strain higher than 15%.\textsuperscript{30} Cartilage may undergo considerable deformation under normal loading conditions. We tried to compensate for this by randomising the order of the experiments. Finally, this was an in vitro study with 17 different legs which differed in age and gender.

Box plots showing a) contact area changes in group B resulting from the 15° varus and valgus positions, b) tibiotalar force changes in group B resulting from the 15° varus and valgus positions, c) mean pressure changes in group B resulting from the 15° varus and valgus positions and d) peak pressure changes in group B resulting from the 15° varus and valgus positions. The transverse line represents the median, the box the lower to upper quartiles and the whiskers the 95% confidence interval.
In conclusion, we examined the effect of supramalleolar varus and valgus malalignment on various characteristics of the tibiotar joint. We had assumed that a supramalleolar varus osteotomy would cause medial overloading of the tibiotalar joint and supramalleolar valgus would lead to lateral shift. The opposite was observed. The restricting role of the fibula was revealed by performing an osteotomy directly above the syndesmosis: only when this additional osteotomy was made did the expected changes in loading occur. Furthermore, the findings of the present study support the belief that supramalleolar osteotomies are justified, since significant tibiotalar pressure changes occur with distal tibial varus and valgus malalignment.

The authors would like to thank I. N. Sierewelt, epidemiologist at the Academic Medical Centre in Amsterdam, Netherlands, for her statistical analysis. The authors would also like to acknowledge the support of A. van der Veen, engineer at the biomechanical laboratory of the Free University Medical Center in Amsterdam. This study was supported by a grant from the Robert Mathys Foundation (Bettlach, Switzerland). Plates and screws were generously donated by Synthes Gmbh (Oberdorf, Switzerland).

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

References

3. Stamatis ED, Cooper PS, Myerson MS. Supramalleolar osteotomy for the treatment of distal tibial angular deformities and arthritis of the ankle joint. Foot Ankle Int 2003;24:754-64.