Experimentally Produced Ankle Fractures in Autopsy Specimens

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Twenty-six unembalmed lower-leg specimens were mounted in an experimental test device with the foot placed at a fixed degree of pronation/supination, dorsiflexion/plantar flexion, or both. Torque versus rotation curves were determined as each foot was externally rotated to failure. Tor-sional stiffness was determined for the first 20° of external rotation, and energy to failure was noted at the point of initial failure. Anatomic dissection and roentgenographs delineated the degree of injury in all specimens. Gender had the greatest effect on both torque and energy parameters, and the injury pattern. In males, 67% of specimens had an oblique fibular fracture, torn anterior tibiofibular ligament, and torn deltoid ligament (SER2). In females, 45% had a transverse fibular fracture without syndesmotic or deltoid injury. Forty percent of females had the SER2 injury. Angle of supination/pronation did not correlate with a specific injury pattern. Peak axial load had a significant effect on stiffness, but increasing the load by more than three times body weight did not increase injury severity.

Previous attempts have been made to synthesize a reliable method for classifying ankle fractures. Ashhurst and Bromer developed the first comprehensive system based almost entirely on their clinical experiences. Lauge-Hansen used experimental and clinical data to establish what is perhaps the most widely used system today. The more recently developed AO system relies on a descriptive approach to classifying ankle fractures; this system does not depend on any postulated mechanism.

There is still debate, however, over the exact mechanism of ankle fractures, and over which specific injuries are most likely to be associated with each other. Knowledge of mechanism can offer strong clues as to which soft tissue injuries are associated with a given fracture; this would greatly facilitate proper diagnosis and treatment. One reason for the continued debate over the mechanism of ankle fractures is a lack of experimental data on ankle trauma. In the 19th and early 20th centuries, there were many studies in which ankle fractures were experimentally produced. These studies used vague and ill-controlled methodologies, however, including even Lauge-Hansen's well-known experiments, in which fractures were produced by hand.

Hirsch and Lewis tested 63 ankle specimens to failure in axial compression and internal/external rotation. They reported that soft tissue injuries were usually worse than expected, and there were often simultaneous multiple injuries. Their findings, however, did not offer much aid in arriving at a mechanistic classification of ankle fractures. Schaffer and Manoli evaluated different types of fixation of experimentally produced ankle fractures in 24 specimens. In all specimens, there was a short, oblique fracture just distal to the syndesmosis. Only two of these 24 had injury to the anterior tibiofibular liga-

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and none had a medial injury of any kind.\textsuperscript{11}

Markolf et al.\textsuperscript{9} evaluated torque and rotation in mounted anatomic specimens that were externally rotated to failure. That study tested specimens under no axial load, and rotation was manual. Very little description was given of the injuries produced in their tests. Important data regarding mean torque, rotation, and energy to failure were obtained, however.

Stormont et al.\textsuperscript{13} evaluated the contribution of both ligamentous structures and articular surface constraints to resistance with torque and loading. That study did not determine failure strength of tested specimens but demonstrated the importance of various ligaments with serial testing. With external rotation, the calcaneofibular and posterior talofibular ligaments gave most of the displacement resistance. With axial load, articular restraints accounted for more than 30\% of the articular stability.

**MATERIALS AND METHODS**

Seventeen specimens were tested in a preliminary series to develop an appropriate experimental model. Tests were carried out with an MTS 809 Axial-Torsion Test System (MTS Systems, Minneapolis, Minnesota), which can provide simultaneous load and torque during the test procedure. A DEC Micro PDP-11/1 computer (Digital Equipment, Maynard, Massachusetts) was used to operate the system by remote and record from the various transducers built into the system to measure load and displacement. In this preliminary testing, the effects of magnitude and rate of loading were observed. From these observations, a test protocol suitable for producing ankle fractures was developed. A minimum axial load of three times body weight of the specimen’s cadaver was required to consistently produce a fracture.

Twenty-six unembalmed anatomic specimens were included in the final series. Age of patients from which specimens were obtained ranged from 18 to 92 years of age (mean ages, 67 in men and 76 in women). The leg was transected at the junction of its proximal and middle thirds. All tissue except the interosseous membrane was cleaned from the most proximal two inches of the tibia and fibula. Polymethylmethacrylate (PMMA) was packed 10–12-cm deep into the tibial medullary canal, and a hexagonal key wrench was set in the PMMA. The cross-handle on this wrench allowed gripping of the specimen to the upper cross-head of the MTS load frame. The foot was fixed to a 45-cm × 15-cm steel plate with fiberglass cast tape. This plate was attached to the MTS load frame (Fig. 1).

Position of the foot was standardized for all tests. The longitudinal axis of the foot was a line between the center of calcaneal tuberosity and the space between the first two toes. The axis of rotation of the ankle joint was determined as a line running between the tips of the medial and lateral malleoli. The intersection of these two axes gave the approximate center about which the foot was rotated. The foot could be dorsiflexed or plantarflexed by inserting a 10° wedge under the foot. After alignment, the foot was held in place temporarily with a fabric adhesive. If the foot was to be supinated or pronated, the plate itself was then rotated approximately 15°.

A computer program dictated axial loading of the leg followed by external rotation of the foot. Using the known cadaver body weight from which each specimen was taken, a maximum load of five

![Fig. 1. Ankle specimen mounted on MTS machine with foot pronated.](image-url)
TABLE 1. Summary of Experimental Ankle Fracture Test Results

<table>
<thead>
<tr>
<th></th>
<th>Age (years)</th>
<th>Weight (kg)</th>
<th>Failure Angle (degrees)</th>
<th>Failure Torque (N-m)</th>
<th>Failure Energy (N-m/deg)</th>
<th>Torsional Stiffness (N-m/deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Males (n = 12)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avg.</td>
<td>67</td>
<td>76.7</td>
<td>47.3</td>
<td>64.5</td>
<td>1519</td>
<td>1.21</td>
</tr>
<tr>
<td>SD</td>
<td>19</td>
<td>9.2</td>
<td>12.7</td>
<td>20.6</td>
<td>990</td>
<td>0.43</td>
</tr>
<tr>
<td><strong>Females (n = 14)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avg.</td>
<td>76</td>
<td>62.3</td>
<td>41.4</td>
<td>27.5</td>
<td>523</td>
<td>0.65</td>
</tr>
<tr>
<td>SD</td>
<td>15</td>
<td>9.1</td>
<td>13.7</td>
<td>6.9</td>
<td>280</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Avg., average; SD, standard deviation.

times body weight was programmed for each specimen. Using a ramp function, a preload of 50% of the maximum determined axial load was applied before external rotation was initiated. The machine began external rotation of the foot at a rate of 45° per second up to a magnitude of 90°. Time to full load was one second.

On completion of the test, the specimen was thoroughly inspected for damage. Anteroposterior (AP) and lateral roentgenograms were taken. The ankle was dissected and inspected for ligamentous damage, and photographs were taken. The lateral, medial, and syndesmotic injuries then were categorized with a numerical system.

The record of torque versus external rotation was used to find values for several variables. The angle of external rotation and the torque at initial failure were noted. Torsional stiffness was determined for the first 20° of external rotation. Energy to failure was determined by measuring the area under the curve up to the point of initial failure.

An analysis of covariance (ANCOVA) statistical procedure was used. For cases in which there were spiral fractures of the tibia, the values for the lateral and medial injuries were not included in the statistical analysis. Gender and flexion were the factors in this analysis, with peak axial load as the covariate.

RESULTS

Magnitudes were significantly higher for male specimens for torque to failure, energy to failure, and torsional stiffness ($p < 0.01$). In female specimens, the torque to failure tended to be higher with the foot in plantar flexion than in dorsiflexion ($p < 0.05$). There was no such trend in the male specimens. Torsional stiffness was significantly affected by the peak axial load ($p < 0.02$). The ankle tended to be stiffer as axial load increased, and torque to failure was also significantly increased with greater axial loads ($p < 0.006$). There was no apparent increase in the injury severity with axial loads more than three times body weight (Table 1).

In comparing foot position, torque to failure tended to be higher with the foot in planter flexion than in dorsiflexion ($p < 0.05$) in male specimens. This trend was not seen in male specimens. Torsional stiffness increased from supination to pronation ($p < 0.003$). Syndesmotic injuries tended to be more severe in male specimens with the foot in dorsiflexion and in female specimens with the foot in plantar flexion.

Injury pattern differed markedly between male and female specimens (Fig. 2). In male specimens, 67% of the cases had an oblique fracture of the distal fibula and torn anterior tibiofibular and deltoid ligaments. In 25% of the cases, there was a spiral fracture of the distal tibia and fibula. Only one of the 12 tests did not result in fracture. This was the only specimen in which axial load was less than three times body weight and the resulting ligamentous injury involved the anterior talofibular and the calcaneofibular ligaments only. No medial malleolar fractures occurred in male specimens.

In female specimens, 28% had an oblique fracture of the lateral malleolus near the level of the tibial plafond without syndesmotic in-
jury. In 36% of the specimens, oblique fibular fracture occurred with a torn anterior tibiofibular ligament. Medial injuries were evenly divided between fracture of the medial malleolus and a torn deltoid ligament. There also were three avulsion fractures of the tip of the lateral malleolus, two spiral fractures of the distal tibia and fibula, three fractures of the distal anterior margin of the tibia, one fracture of the talus, and one specimen with medial and lateral ligamentous injury only.

Sixteen specimens had injury to the anterior tibiofibular ligament. Three of these included detachment of a pea-sized fragment from the tibia, and in two, there was a fragment detached from the fibula. In four cases, the interosseous ligament was also damaged. There was only one case with complete disruption of the syndesmosis; this occurred along with a spiral fracture of the distal tibia and fibula. With greater injury to the syndesmosis, there tended to be more proximal fractures of the fibula ($p < 0.001$).

Fourteen tests resulted in injury to the deltoid ligament. All of these included the anterior tibiotalar and deep tibiotalar sections of the ligament. In six cases, there was disruption of the entire deltoid ligament.

**DISCUSSION**

Torque-to-failure values in this study were comparable to those given in previous studies. Hirsch and Lewis found an average torque to failure of 74.6, 75.5, and 50 N·m for external rotation in neutral, pronation, and supination, respectively. Schaffer and Manoli reported an average of 47.2 N·m for external rotation with supination/dorsiflexion. Markolf et al. found a mean failure torque of 45.3 N·m for external rotation of the maximally supinated ankle. For the experiments of the current study, average
torque to failure was 44.5 N·m. Gender and age effects may explain differences in the current results compared with the previous studies, but no information was given on these variables in the previous studies. Age was not a statistically significant factor in this study, but all but two of the specimens were from donors older than 59 years of age. With a broader range, it seems likely that this effect would be more substantial, especially in female specimens because osteoporosis is much more prevalent with aging.

Markolf et al.\(^9\) found the mean rotation at failure to be 41.4°, which is close to the mean in the current study, 44°. Schaffer and Manoli\(^11\) reported a mean angle at failure of 30°. Statistical analysis for the current study showed no significant determinants of the angle at failure. The differences from the results of Schaffer and Manoli\(^11\) are probably attributable to the methods of fixation. With the fixation in this study, there was potential for movement in the transverse tarsal joints, as well as the subtalar and ankle joints. Also, there was room for movement because of the compression of the skin and subcutaneous fat. Schaffer and Manoli\(^11\) fixed screws directly to the calcaneus, which eliminates soft tissue compression and movement at all but the subtalar and ankle joints. This difference in fixation also may account partially for the higher average torsional stiffness values in the study by Schaffer and Manoli\(^11\) (2.1 versus 0.9 N·m/degree).

Torsional stiffness and torque and energy to failure were significantly higher in specimens from males than in those from females. This is not surprising given the typically higher bone density in male specimens, especially for the age bracket of the specimens in this study.\(^4\) It does point out the necessity for specifying gender in both clinical and experimental studies, however. Higher stresses would be needed to cause fractures in male specimens. Also, this gender effect may dictate the type of fracture fixation to be used. Schaffer and Manoli\(^11\) found that with weaker bones, there were more pronounced differences in the experimental performance of two different types of fracture fixation plates.

Axial load had a significant effect on the torque parameters in the current study. Fraser and Ahmed\(^8\) in a study of 20 cadaver specimens, found an increase in ankle joint stiffness with increases in axial load. Skrade et al.\(^12\) also found that axial load significantly increased ankle stiffness for external rotation. Only Markolf et al.\(^9\) previously reported on the energy to failure for normal ankle specimens. In those tests, mean energy to failure was 12.9 N·m, as compared with 17.1 N·m in the current study. A lower rotation to failure, 41.4° versus 44°, partially accounts for the lower energy. The fact that Markolf et al.\(^9\) used no axial load, however, also probably had an effect on the energy to failure. Axial load increases stiffness, particularly in the initial phases of external rotation. Therefore, although torque to failure was actually slightly higher in the experiments of Markolf et al.\(^9\), energy to failure was higher in the current study. Because Markolf et al.\(^9\) produced fractures without axial load, it is apparent that axial load is not critical for creating experimental fractures.

One of the more controversial aspects of ankle fracture classification is whether the oblique, distal fibular fracture always has an associated syndesmotic injury. In Lauge-Hansen's experiments,\(^8\) all 17 supination/external rotation fractures had associated syndesmotic injuries. In contrast, the results of Hirsch and Lewis\(^7\) and Schaffer and Manoli\(^11\) show that only 27% and 9%, respectively, of the fibular fractures had associated damage to the syndesmosis. In the experiments reported here, there were 17 oblique, distal fibular fractures, and 13 had a torn anterior tibiofibular ligament.

A noteworthy aspect of these differences in results is the location of the fibular fracture line. In the current study, the four oblique fibular fractures without an associated injury to the syndesmosis all started anteriorly below the joint line. This is analogous to the "short, oblique" fractures of Schaffer and Manoli.\(^11\) In contrast, in Lauge-Hansen's ex-
periments, the fibular fractures began at or above the joint line. In the current study, it was found that there was a significant correlation between the degree of syndesmotic injury and the location of the fibular fracture. Generally, there is evidence that oblique fractures below the joint line may occur without any disruption of the syndesmotic ligaments.

The bone strength of a given specimen may play a role also in whether an injury in the syndesmosis is associated with a fibular fracture. The specimen population of this study was of the older age group, with only one ankle obtained from an individual younger than 59 years of age. In the current study, all four cases of fibular fractures without syndesmotic injury were in female specimens. Three of these four specimens were extremely osteoporotic, elderly women. With weaker bone, it is likely that structural failure will be fracture and not ligamentous disruption. Moreover, the variability seen in female specimens could be related to the greater tendency of the bone to fracture, thus giving a more diverse pattern of injury. Where this fracture does not occur, it may be necessary for the anterior tibiofibular ligament to tear first, thereby allowing larger and more proximal torsional stresses on the fibula through external rotation of the talus.

The gender effect was notable with regard to medial injuries in that fractures of the medial malleolus occurred only in the female specimens. Clinically, it has been reported that fractures of the medial malleolus are more common in women. Cedell found that the percentage of fractures in cases with medial injuries was 81% in female specimens and 58% in men. Yde reported that 63% and 35% of medial injuries were fractures in female specimens and male specimens, respectively. The fact that none of the male specimens had medial fractures in the current study could indicate that bone quality, which is likely to be higher in male specimens, may predispose to ligament failure.

With respect to the lack of more proximal fibular fractures than those found in this study, one limitation is that only the distal two thirds of the leg was used. Obviously, this does not allow for the Maisonneuve fracture in the proximal one third of the fibula. Another limitation was that the fibula and tibia were cemented together within the methylnethylene. This may have affected mobility of the fibula with respect to the tibia, thus altering trauma-inducing strain in the fibula.

A more realistic study of ankle fractures would, therefore, include the entire leg, with an unconstrained fibula.

REFERENCES

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