A New Interpretation of the Mechanism of Ankle Fracture

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Background: Researchers have found it difficult to recreate a Lauge-Hansen supination-external rotation-type ankle fracture in experimental settings. We hypothesized that a pronation-external rotation mechanism could cause both distal, short oblique and high fibular fractures and that the fracture type would be affected by associated, laterally directed forces applied to the foot.

Methlods: Twenty-three cadaver ankles were subjected to fracture loading that replicated the Lauge-Hansen pronation-external rotation mechanism with or without applying an external lateral force. In Phase I, an axial load was applied to fifteen specimens mounted on a materials testing machine. Each foot was rotated externally to failure. In Phase II, eight specimens were tested according to the Phase-I protocol, but external forces were applied laterally at the foot to increase the abduction moment at the ankle. Load and position versus time curves were recorded and were correlated with video image data to establish the sequence of failure of specific anatomic structures.

Results: Eight specimens tested in Phase I sustained an oblique fracture of the distal end of the fibula with both medial and posterior injuries that occurred after the fibular fracture. Increasing the external lateral force and hence the abduction moment within the ankle (Phase II) resulted in three of eight specimens sustaining a high fibular fracture with a reversed fracture line (anterosuperior to posteroinferior) and/or a comminuted high fibular fracture. The distribution of traditional pronation-external rotation-type fractures differed significantly between Phase I and Phase II ($p = 0.032$).

Conclusions: This study generated counterexamples to the Lauge-Hansen classification system by showing that a short oblique fracture of the distal end of the fibula can occur with the foot in the pronated position. Furthermore, a high fibular fracture was recreated by increasing the abduction moment at the ankle.

Clinical Relevance: The pattern of ankle fracture is related directly to the applied loads, including specifically the combination of the external rotational moment and the abduction moment. The results of the current study could provide the basis for a more straightforward classification of ankle fractures based on applied loads.

Despite extensive research, identification of the mechanisms of ankle fracture and the correlation of this information with clinical radiographs remain problematic. Knowing the precise mechanism of ankle fracture is important because it helps surgeons to assess the extent of soft-tissue injury and the sequence of injury on the basis of the fracture pattern seen on radiographs. It also assists surgeons in determining which forces to apply to obtain and maintain closed or open reduction of an ankle fracture-subluxation or dislocation. Furthermore, an ideal fracture classification system should describe the mechanism of injury in a way that allows reproducible description among health professionals, identifies distinct natural history, and permits comparison of clinical outcomes with different treatments[1,2].

Under the Lauge-Hansen classification system, the two factors determining ankle fracture pattern are the position of the foot at the time of the traumatic event (supination or pronation) and the direction of the deforming force (abduction,

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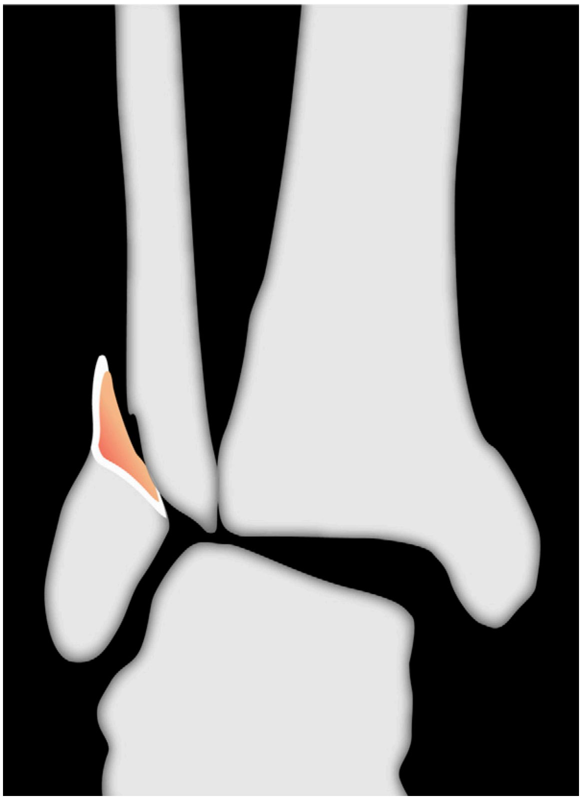

Fig. 1-A

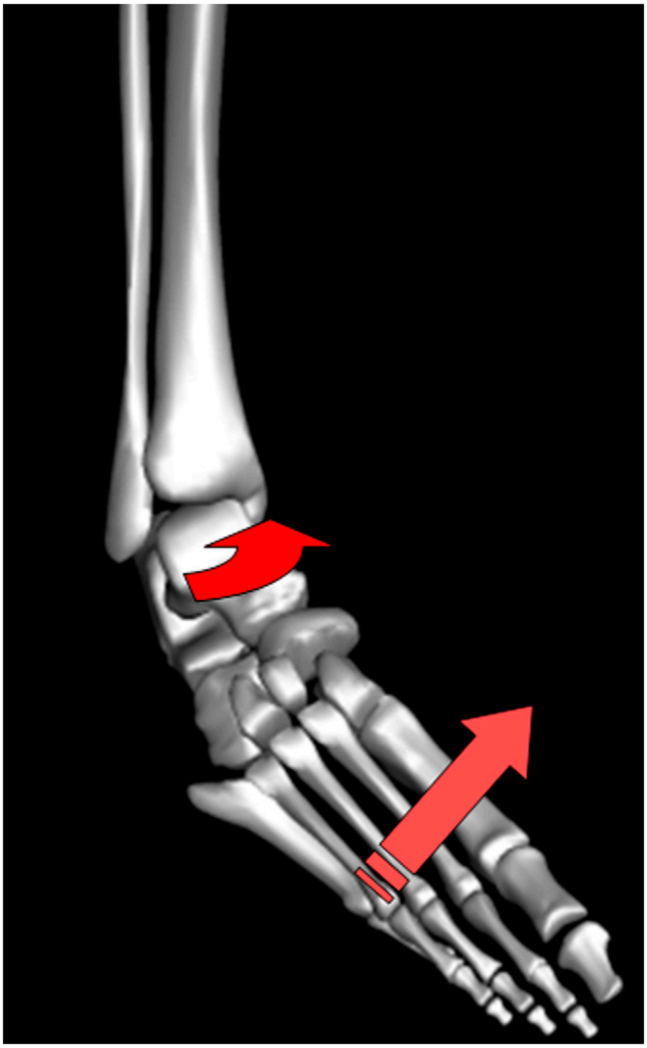

Fig. 1-B

Figs. 1-A through 1-D Two common ankle fracture patterns and foot positions at the traumatic event. **Fig. 1-A** A short oblique fracture of the distal end of the fibula (the Lauge-Hansen supination-external rotation fracture). **Fig. 1-B** The supination position at the traumatic event. When an individual sustains an injury with the foot supinated, the lateral border of the foot strikes the ground and the foot is internally rotated, rather than externally rotated, against the lateral malleolus.

adduction, or external rotation)[3]. The Lauge-Hansen system classifies ankle fractures into thirteen subgroups according to these two factors[3]. The most common ankle fracture pattern seen clinically is that of a short oblique fracture of the distal end of the fibula (Fig. 1-A), with or without medial and/or posterior injury (a Lauge-Hansen supination-external rotation fracture[3]); this pattern accounts for about 60% of all ankle fractures seen clinically[4,5]. Since the beginning of the last century, this type of fracture has been thought to occur when the talus is rotated externally with the foot in the supinated position[3,6,7].

However, clinical inconsistencies exist with the Lauge-Hansen classification system. First, when an individual sustains an injury with the foot supinated, the lateral margin of the foot strikes the ground and the foot is internally rotated rather than externally rotated against the lateral malleolus (Fig. 1-B). Furthermore, although reversing the deforming forces should achieve fracture reduction, we noted that placing the foot in the supinated rather than the pronated position assists in reducing this type of fibular fracture during surgery.

Since Lauge-Hansen's experiment, several investigators have tried to reproduce ankle fractures experimentally with the foot in the supinated position[8-12]; however, none of those studies successfully reproduced the stage-4 supination-external rotation-type fracture, which includes all injuries from stage 1 to stage 4. The difficulty in recreating the supination-external rotation-type fracture may be due to the supination position used and hence the lack of abduction moment within the ankle.

These clinical and experimental inconsistencies motivated us to reinvestigate the mechanism of ankle fracture. Our experiment was specifically designed to provide counterexamples to the Lauge-Hansen classification system. We hypothesized that a pronation-external rotation mechanism (Fig. 1-C)

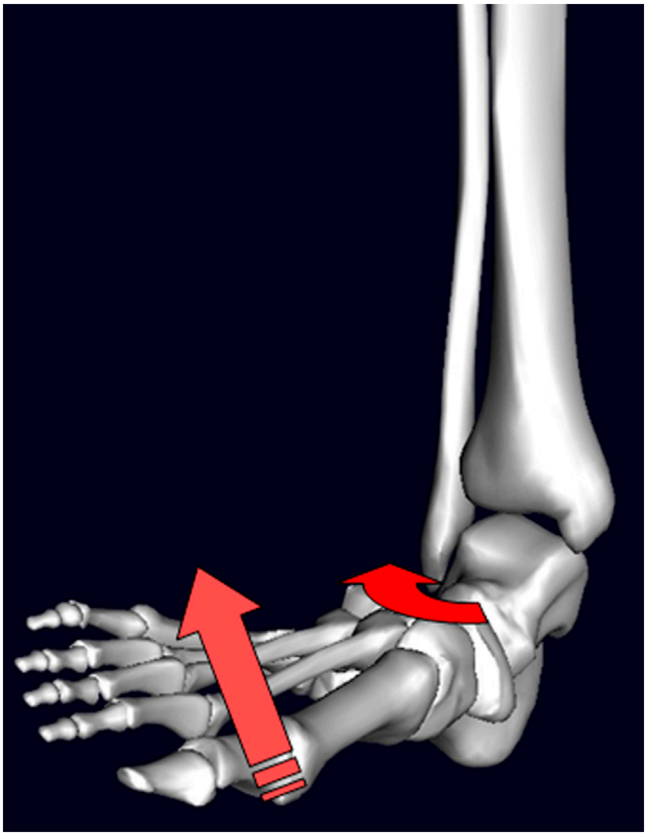

Fig. 1-C

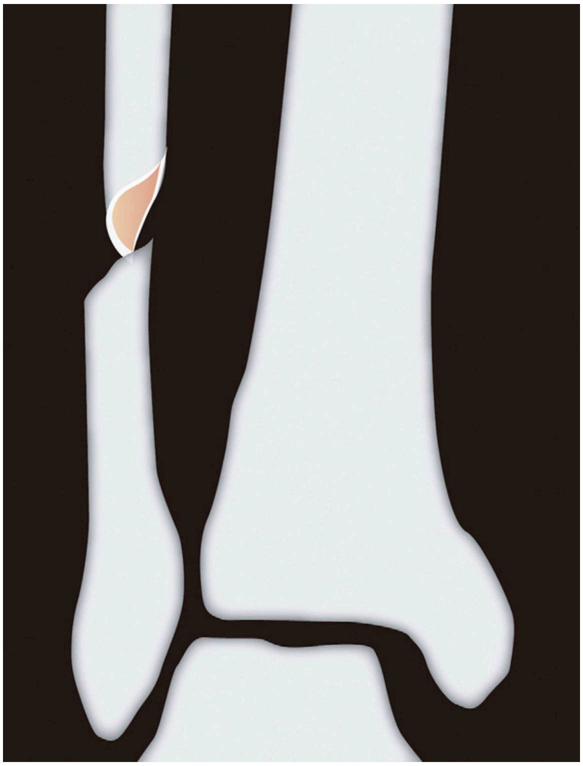

Fig. 1-D

Fig. 1-C Pronation. The foot is rotated externally in this position. **Fig. 1-D** The Lauge-Hansen pronation-external rotation fracture.

could cause both distal, short oblique fractures and high fibular fractures with a reversed fracture line (anterosuperior to posteroinferior) and/or comminution (the traditional pronation-external rotation fracture[3]) (Fig. 1-D). Within the pronation-external rotation mechanism, we proposed that the fracture type would be affected by increasing both the abduction moment and the shear force within the ankle joint by means of an externally applied lateral load below the foot. The present study evaluated this hypothesis in a cadaver model by monitoring the forces delivered to, and the traumatic deformations of, the ankle joint.

Materials and Methods

Twenty-three cadaver ankles were subjected to fracture loading that replicated the Lauge-Hansen pronation-external rotation mechanism with or without applying an external lateral force. Experimental specimens for this study were obtained from apparently normal, fresh-frozen cadaveric lower extremities from eleven female and twelve male donors with an average age of 80.6 years (range, fifty-nine to ninety-seven years) at the time of death (State Anatomy Board, Department of Health and Mental Hygiene, Baltimore, Maryland). The specimens contained mechanically stable ankles without any intra-articular defects or degenerative changes. We confirmed the absence of degenerative changes in the ankle by inspection of the dissected specimen after the experimental protocol was completed. The specimens were stored at $-20°C$ until the time of testing.

The specimens were thawed at room temperature for twenty-four hours before dissection. Each extremity was disarticulated at the knee, and upper tibial and fibular osteotomies were made at the level of the proximal tibiofibular joint. The skin, subcutaneous tissue, and muscles were removed to expose the superficial ligaments and interosseous membrane and thus allow adequate visualization during testing. The posterior tibial tendon and muscle and flexor hallucis longus tendon and muscle were preserved to prevent the collapse of the longitudinal arch of the foot when an axial load was applied (we preserved the origins of these muscles but did not apply forces to them).

Polymethylmethacrylate was packed into the tibial canal after reaming, and a custom-made nail was set in it. The proximal end of the tibia was firmly attached to the jig through the medullary nail. In addition, the proximal parts of both the tibia and the fibula were potted into a square container. Polymethylmethacrylate was poured into the container to a level 2 to 3 cm distal to the proximal tibiofibular joint. The foot was clamped to a plate with the use of two metal brackets: one placed over the tarsal bones and the other placed over the posterior surface of the calcaneus. Wood screws were placed through the brackets to stabilize the forefoot and the calcaneus on the foot plate. The specimens were then mounted onto the load frame of

TABLE I Phase I Experiment—Resultant Pathology

Ankle*	Anterior Tibiofibular Ligament	Lateral Malleolus	Medial Injury	Posterior Injury
1	Rupture	Fracture starting at the plafond level	Medial malleolar fracture	Posterior malleolar fracture
2	Fibular avulsion	Fracture starting at the plafond level	Deltoid ligament rupture	Posterior tibiofibular ligament rupture
3	Fibular avulsion	Fracture starting at the plafond level	Deltoid ligament rupture	Posterior malleolar fracture
4	Rupture	Fracture starting at the plafond level	Deltoid ligament rupture	Posterior malleolar fracture
5	Fibular avulsion	Fracture starting at the plafond level	Deltoid ligament rupture	Tibial avulsion
6	Tibial avulsion	Fracture starting at the plafond level	Medial malleolar fracture	Tibial avulsion
7	Fibular avulsion	Fracture starting at the plafond level	Deltoid ligament rupture	Tibial avulsion
8	Tibial avulsion	Fracture starting at the plafond level	Medial malleolar fracture	Posterior malleolar fracture
9	Intact	Fracture below the plafond	Deltoid ligament rupture (partial)	Partial avulsion from fibula
10	Intact	Transverse fracture	Medial malleolar fracture	None
11	Intact	Tip fracture (avulsion)	Medial malleolar fracture	None
12	Rupture	High fracture (anteroinferior to posterosuperior)	Deltoid ligament rupture	Posterior malleolar fracture
13	Extensive disruption of interosseous membrane			
14	Ankle joint dislocation			
15	Tibial shaft fracture			

*The ankles are listed by injury type (nonchronologically).

a servohydraulic materials testing machine (model 858; MTS Systems, Eden Prairie, Minnesota).

Fifteen fresh-frozen cadaveric lower extremities were tested in Phase I of the study. Lauge-Hansen defined the pronation position as a combination of external rotation of the foot around its longitudinal axis, abduction of the hindfoot, and outward rotation of the forefoot. According to this definition and current standardized terminology[13,14], we made a foot plate with shims at a 30° lateral slope and a 15° anterior slope that allowed placement of the foot at 30° of pronation and 15° of dorsiflexion. The foot plate was constrained to two parallel sliders that allowed linear motion in the medial-lateral direction. The sliders were rigidly fixed within an aluminum channel that was mounted at 10° of medial inclination with respect to the horizontal. Application of an axial load would thus result in lateral displacement of the foot that would in turn produce both an abduction moment of the talus against the lateral malleolus and a lateral shear force at the level of the ankle. We mounted the 30° pronated foot on the slider apparatus at 10° of medial inclination, which resulted in 20° of pronation of the foot relative to the axial (tibial) direction (see Appendix).

In Phase II, an additional eight specimens were tested according to a modified Phase-I protocol, which included an additional external force applied laterally to the foot carriage by means of weight plates with a total mass of 45.4 kg (100 lb) connected through a pulley mechanism (assumed frictionless). Hence, the effective lateral force was 445 N (see Appendix). This external force applied at the foot increased both the abduction moment and the lateral shear force in the coronal plane of the ankle joint and altered the ratio of these force components relative to the external rotational moment. The Phase-II experimental configuration was designed specifically to increase the abduction moment acting within the ankle joint.

In both phases, an axial force was applied to the shank at 100 N/sec and then was maintained at 700 N, at which point the tibia was rotated internally at a constant rate of 36°/sec up to a maximum excursion of 90°. The tibial internal rotation rate was chosen on the basis of previous studies[10,12] and our own prior experience with the device in creating controlled experimental bone fractures. The foot plate allowed motion only in the mediolateral direction; all other motions were constrained. The tibia was maintained perpendicular to the ground surface, and the axis of tibial rotation was maintained at the center of the ankle joint.

During testing, digital video cameras recorded the failure sequence of specific anatomic structures (anterior talofibular ligament, fibula, posterior talofibular ligament or posterior malleolus, and medial malleolus or deltoid ligament). An axial-torsional load cell and displacement sensors continuously

Fig. 2-A

Fig. 2-B

Figs. 2-A and 2-B External-rotational torque applied to the pronated foot in Phase I resulted in a typical stage-4 supination-external rotation-type fracture. **Fig. 2-A** Anteroposterior radiograph of the specimen showing a short oblique fracture of the distal end of the fibula starting at the level of the tibial plafond. **Fig. 2-B** Lateral radiograph of the specimen showing a posterior malleolar fragment.

transduced the load and position versus time during testing. These data sets were correlated with the video image data to establish the sequence of failure of specific anatomic structures.

After completion of the tests, anteroposterior, lateral, and oblique radiographs of the ankle were made. The specimens were dissected, the failure patterns (fractures or ligamentous ruptures) were recorded, and the locations of the pathologic changes were photographed. Using both radiographic data and macroscopic dissection data, we determined the fracture types using Lauge-Hansen's objective criteria as follows[3,15]: the short oblique fracture of the distal end of the fibula (a traditional supination-external rotation-type fracture) must begin at the level of the tibial plafond, and the fracture line must be anteroinferior to posterosuperior through the syndesmosis; the high fibular fracture (traditional pronation-external rotation-

TABLE II Phase II Experiment—Resultant Pathology

Ankle*	Anterior Tibiofibular Ligament	Lateral Malleolus	Medial Injury	Posterior Injury
16	Rupture	High fracture (comminuted)	Deltoid ligament rupture	None
17	Tibial avulsion	High fracture (anterosuperior to posteroinferior)	Deltoid ligament rupture	None
18	Tibial avulsion	High fracture (comminuted)	Medial malleolar fracture	Tibial avulsion
19	Tibial avulsion	Fracture starting at the plafond level	Deltoid ligament rupture	Tibial avulsion
20	Rupture	Fracture starting at the plafond level	Deltoid ligament rupture	Posterior tibiofibular ligament rupture
21	Tibial avulsion	Fracture starting at the plafond level	Deltoid ligament rupture	Tibial avulsion
22	Tibial avulsion	Fracture starting at the plafond level	Medial malleolar fracture	None
23	Intact	Fracture below the plafond	Medial malleolar fracture	None

*The ankles are listed by injury type (nonchronologically).

Fig. 3
Anteroposterior radiograph of a specimen after the Phase-II experiment showing a high fibular fracture.

type fracture) must begin beyond the level of the syndesmosis, and the fracture line is reversed (anterosuperior to posteroinferior) and/or comminuted and never extends into the syndesmosis.

Statistical Analysis

The frequencies of high fibular fracture were compared between Phase I and Phase II. Frequency tables were analyzed for significance with use of the Fisher exact test. Significance was defined as $p < 0.05$.

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We did not receive any external funding or grants in support of our research or in the preparation of this work.

Results

Both types of fracture were created as hypothesized, and the rate of high fibular fracture was affected by the external lateral force. Among the fifteen specimens tested in Phase I (Table I), short oblique fractures of the distal end of the fibula with disruption of the anterior tibiofibular ligament complex occurred in eight specimens despite the pronated position (Figs. 2-A and 2-B and Appendix). All eight specimens had a medial injury that occurred after fibular fracture. Posterior injury occurred before the medial injury in three of the eight specimens and after medial injury in four (in the last specimen of this group, we could not determine the sequence because the injuries happened quickly and nearly simultaneously). Of the remaining seven specimens in Phase I, one had an oblique fracture of the distal end of the fibula that started just distal to the attachment site of the anterior tibiofibular ligament (the anterior tibiofibular ligament remained intact), and another had an oblique fracture of the fibula with rupture of the anterior tibiofibular ligament (the fracture started 40 mm proximal to the level of the tibial plafond and ran anteroinferiorly to posterosuperiorly). In these two specimens, medial injury occurred after the fibular fracture. No specimen had a high fibular fracture in which the fracture line was anterosuperior to posteroinferior (a reverse oblique fracture) and/or comminuted.

In Phase II, the addition of an external lateral force (Table II) resulted in a high fibular fracture in three of the eight specimens with a reversed fracture line (anterosuperior to posteroinferior) and/or a comminuted high fibular fracture (i.e., a traditional pronation-external rotation-type fracture) (Fig. 3 and Appendix). In these three high fibular fractures, the highest point of the fracture line was located 90 mm, 48 mm, or 69 mm from the lateral edge of the tibial plafond. In two specimens, medial injury occurred before lateral injury, and we could not determine the sequence of the injuries in the other specimen because they occurred nearly simultaneously. The distribution of traditional pronation-external rotation-type fractures differed significantly between Phase I and Phase II ($p = 0.032$) (Table III).

Discussion

The results of this study support our hypothesis that a pronation-external rotation mechanism could cause both distal, short oblique and high fibular fractures and that the fracture type would be affected by associated, laterally directed forces. To our knowledge, we are the first to show that a short oblique fracture of the distal end of the fibula can occur with the foot in the pronated position prior to medial injury, the latter preceding or following the posterior ligament rupture or avulsion fracture of the posterior malleolus. Furthermore, by adding an externally applied lateral force to increase the abduction moment and shear force within the ankle, we recreated a traditional pronation-external rotation-type fracture.

Lauge-Hansen conducted experiments on cadavera and concluded that the determining factor between two different

TABLE III Distribution of the Traditional Pronation-External Rotation-Type Fractures in Phase I and Phase II

	Phase I	Phase II	Total
High fibular fracture	0	3	3
Other fracture types	15	5	20
Total	15	8	23

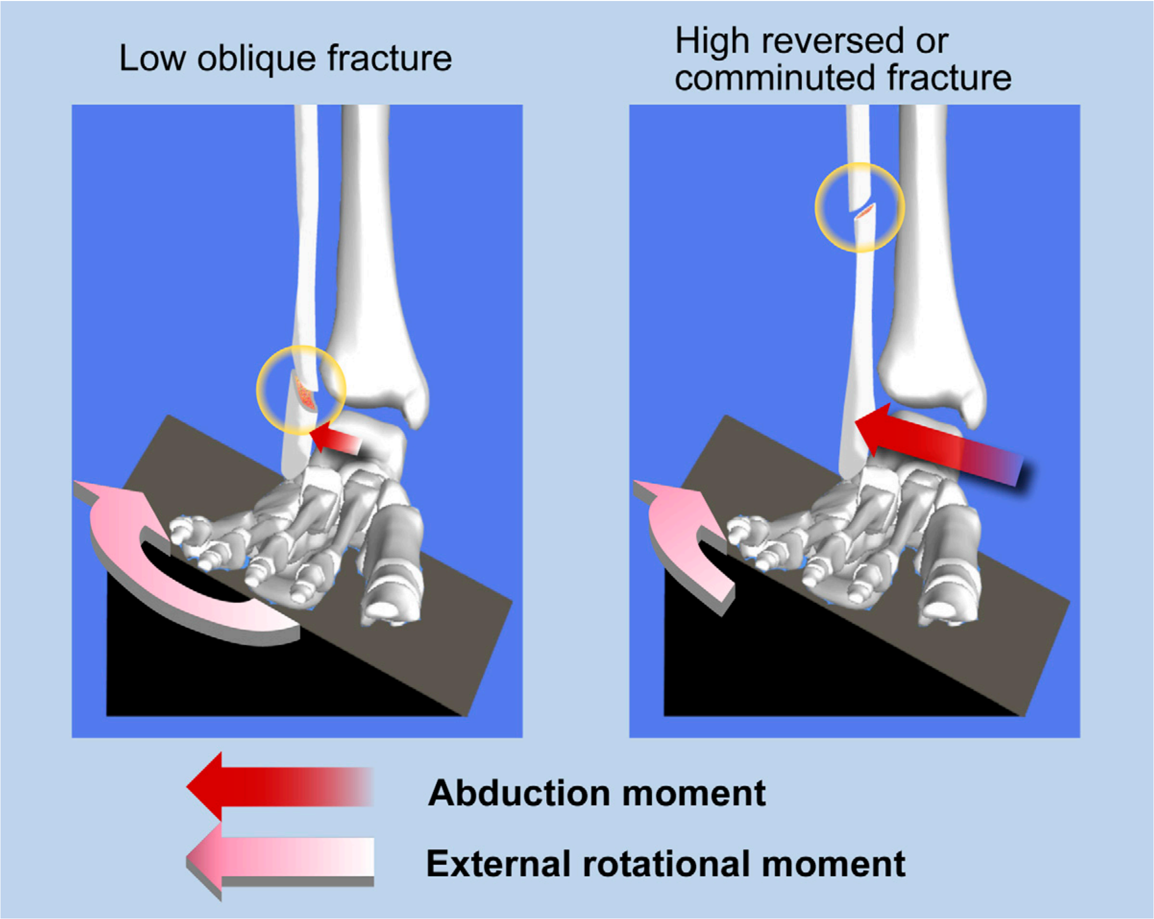

Fig. 4

Our proposed fracture mechanism. Most ankle fractures occur in the pronated foot. A combination of the external rotational moment and the abduction moment determines the fracture pattern in the ankle. A low oblique fibular fracture involves mainly an external rotational moment, whereas increasing the abduction moment (and lateral shear) within the ankle results in an external rotation-abduction fracture (the fibular fracture is reversed and sometimes comminuted above the level of the syndesmosis after medial injury).

types of ankle fracture (a high fibular fracture or a low oblique fibular fracture) was the position of the foot (supination or pronation) at the time of the traumatic event. Although several other classification systems exist, the Lauge-Hansen system remains useful for understanding the mechanism of injury and for directing manual reduction of the fracture by operative or conservative methods. However, the Lauge-Hansen classification system is complicated and cumbersome for routine use because it has thirteen to fifteen subgroups and because interobserver reliability is poor[16,17].

Our review of the original Lauge-Hansen study[3] revealed that neither the position of the foot nor the applied force was consistently controlled in the study. Lauge-Hansen's description of resultant lateral talar displacement and valgus talar tilt producing stage-2 and 3 injuries suggests that a lateral force was applied to the ankle in addition to the external rotational moment. Furthermore, to produce a stage-4 injury, Lauge-Hansen moved the upper end of the tibia laterally, which suggests that the foot was in the pronated position. In a biomechanical study utilizing controlled mechanical testing devices, Michelson et al.[10] clearly showed that pure supination and external rotation did not result in the Lauge-Hansen supination-external rotation-type fracture.

Several authors have attempted to recreate supination-external rotation-type fractures in the supinated foot using modern mechanical testing methodologies[8-12]; however, none of those studies successfully reproduced the stage-4 supination-external rotation-type fracture, which includes all injuries from stage 1 through stage 4. We believe that the difficulty was due to the supinated position and hence the lack of an abduction moment. In the current study, by applying an external rotational force to the ankle with a pronated foot, we successfully reproduced a short oblique fracture of the distal end of the fibula (the Lauge-Hansen supination-external rotation fracture) prior to medial injury. All trans-syndesmotic oblique fractures in Phase I showed disruption of both anterior and posterior tibiofibular ligament complexes (four of eight were posterior malleolar avulsion fractures) and medial injury. We believe that we recreated this injury pattern successfully because of the pronated position, which produced both an increased abduction moment of the talus against the lateral malleolus and an increased lateral shear force at the level of the ankle. The lateral shear force and the abduction moment indirectly delivered to the ankle in this experimental configuration should occur at the level of the ankle in real traumatic events as well. Conversely, in the supinated foot, the same internal stress would not develop at the ankle because more motion would occur in the coronal plane.

The inclined slider table used in the experimental setup generated an abduction torque within the ankle because of axial loading, and that torque increased when an external lateral force was applied to the foot carriage. In this study, however, abduction torques were neither locally controlled nor measured by direct means and, as such, the specific ratio of abduction moment to external rotation at the level of injury could not be ascertained. Because we were unable to calculate the ratio of force and torque components at the ankle, no quantifiable relation between fracture type and loading can presently be defined beyond the general trend that more high fibular fractures occurred in the presence of an external lateral force at the foot than in its absence.

Our results suggest that the factor that determines the fracture pattern in the ankle may be the combination of the external rotational moment and the abduction moment (Fig. 4) and that, with the exception of "supination-adduction" fractures[3], most ankle fractures occur with the foot in the pronated position. We suggest a more direct classification system based on the injury-producing loads in which an ankle fracture is classified as an external rotation fracture (a low oblique fibular fracture at the level of the syndesmosis, and the lateral injury occurs first) or an external rotation-abduction fracture (the fibular fracture is reversed and sometimes comminuted above the level of the syndesmosis, and the medial injury occurs first). However, because both types of ankle fractures occur in the pronated position by means of a single mechanism, a description of the foot position is superfluous and fracture types should be described by associated injury loads alone.

Our study had some limitations. First, our system did not include dynamic stabilizers, such as muscle-tendon units, despite the fact that muscles undoubtedly play a role in preventing ankle fracture by stabilizing the ankle and absorbing energy. Currently, however, it is difficult, if not impossible, to model the appropriate degree of contraction for every muscle with the reflex time such as would occur during the actual traumatic event. Second, the bone quality of the ankles from cadavera of elderly persons probably influenced our results. Epidemiological studies of ankle fractures[4,18] have shown that oblique fractures of the distal end of the fibula are far more common in elderly patients than in younger patients and that more fractures are of the high fibular type in patients who are less than fifty years of age than in older patients. This may be related to the interosseous membrane, which must rupture to the level of the fibular fracture for a high fibular fracture to occur. If the bone is osteoporotic, fibular fracture may occur before the interosseous membrane ruptures, resulting in a greater number of low fibular fractures in the elderly. In both phases of this study, a low oblique fracture of the distal end of the fibula was the most common injury (although the distribution of traditional pronation-external rotation-type fractures differed significantly between Phase I and Phase II). A third limitation of this study relates to our method of constraining the shank, which included potting the proximal parts of both the tibia and the fibula. While it was necessary for ample holding power, constraining the proximal tibiofibular syndesmosis may have affected mobility of the fibula with respect to the tibia, thus altering trauma-inducing strain in the fibula. To minimize the effect of constraining the proximal tibiofibular syndesmosis, we utilized polymethylmethacrylate to a level 2 to 3 cm distal to the proximal tibiofibular joint, which was more proximal than in previous studies. Fourth, we acknowledge that the rate of load application was slower than during an actual traumatic event. The loading rate certainly affects the viscoelastic response of both bone and ligament and potentially their failure modes as well. Despite this fact, the testing protocol used in this study was able to reproduce fractures seen clinically and allowed visual confirmation of the sequence of injury. The magnitude of axial-compressive preload (700 N) was held constant for all specimens and was selected on the basis of a gross approximation of body weight. During the Phase-II study, the external lateral force (445 N) was applied to the foot carriage by means of two standard 50-lb (22.7-kg) weight plates. The intent was to safely apply as much lateral force as possible. Finally, this study does not rule out the possibility that other injury mechanisms could result in fracture patterns similar to that presented.

In conclusion, this study generated counterexamples to the Lauge-Hansen classification system by showing that a short oblique fracture of the distal end of the fibula can occur with the foot in the pronated position prior to medial injury, the latter preceding or following the posterior ligament rupture or avulsion fracture of the posterior malleolus. Furthermore, the potential effect of the increased lateral force and hence the abduction moment upon the injury pattern was also suggested. Our results suggest that the factor determining the fracture pattern in the ankle may be a combination of the external rotational moment and the abduction moment.

Appendix

eA Illustrations of the experimental test configuration and videos of the fractures being produced are available with the electronic version of this article on our web site at jbjs.org (go to the article citation and click on "Supplementary Material"). The figures are also available on our quarterly CD/DVD (call our subscription department, at 781-449-9780, to order the CD or DVD). ■

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