AN ARTICULATED ANKLE EXTERNAL FIXATION SYSTEM THAT CAN BE ALIGNED WITH THE ANKLE AXIS

Daniel C. Fitzpatrick, M.S.
Wendy S. Foels, B.S.
Douglas R. Pedersen, M.S.E.
J. Lawrence Marsh, M.D.
Charles L. Saltzman, M.D.
Thomas D. Brown, Ph.D.

ABSTRACT

Aligning an articulated ankle external fixator with the ankle axis located using a mechanical axis finder has been shown to preserve normal ankle joint kinematics while the fixed hinge device is attached. However, several problems exist preventing the clinical application of this finding for fractures of the tibial plafond. We initiated a series of studies to resolve these issues. First, the accuracy of the mechanical axis finder in biological systems was quantified by comparing it to that of a computationally derived helical axis. Second, a prototype fixator design was developed in the biomechanics lab to increase the versatility of intraoperative fixator placement. Finally, a radiographic method of locating the ankle axis was developed which is based on talar morphology independent of the fractured tibia. The prototype fixator has been accurately aligned along the ankle axis in cadaveric specimens using this method.

Open reduction and internal fixation (ORIF) is the accepted method of treatment for tibial plafond fractures. It holds the advantage of sufficient fracture fixation to permit early joint motion. Good results have been reported using this method[3,11], but some authors have reported complication rates up to 50%[2,4,9,10,14]. The wide surgical approaches required, in conjunction with pre-existing soft tissue injury, are thought to significantly increase the risk of soft tissue complications. In response to these problems, many investigators are beginning to utilize external fixation as an alternate treatment modality.

One external fixation system which has shown particularly good results is a monolateral cross-ankle articulated fixator (Orthofix SRL., Verona, Italy) which allows motion at the ankle joint as the plafond fracture is healing (Figure 1)[1,8,12]. The fixator is applied with two pins distally, one in the talus and one in the calcaneus, and two pins proximally in the tibia. The distal clamp is attached to the fixator body by a uniaxial hinge that is centered over the medial side of the talus. The current clinically recommended application technique aligns the hinge along a horizontal ankle axis. The hinge is released post-operatively and the patient performs passive and active motion.

The current technique for applying the articulated external fixator requires the imposition of a non-physiologic (horizontal) axis at the ankle. This abnormal axis of rotation may lead to altered joint kinematics, decreased range of motion and possibly to changes in the contact forces at the joint surfaces.

We have quantified the degree of alteration of the normal kinematics of the ankle with three different fixator orientations by performing a biplanar kinematic analysis of cadaveric ankles[5]. The fixator applications simulated a horizontal axis (the configuration currently used), an ap-

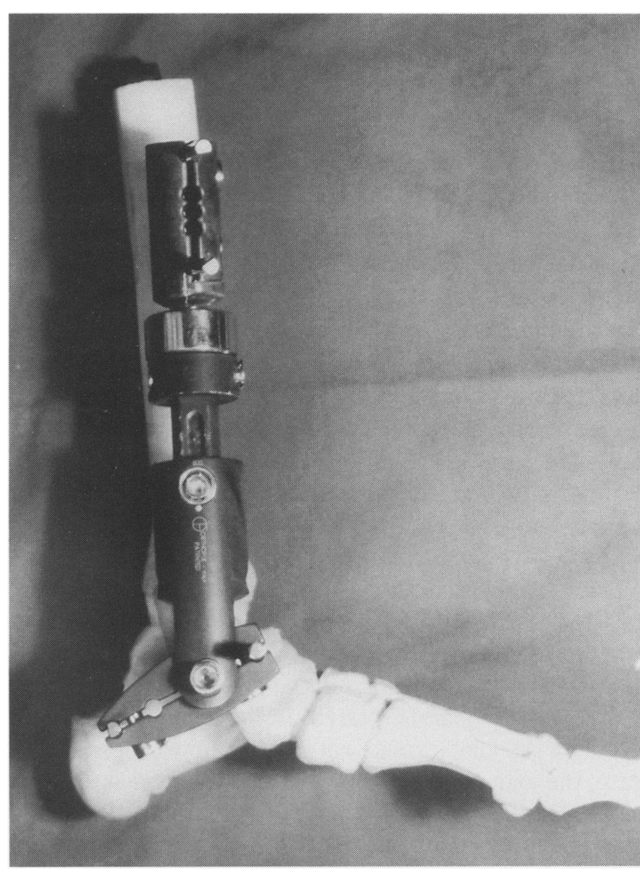

Figure 1. The Orthofix articulated ankle external fixator aligned with the current clinically recommended hinge orientation.

Correspondence to: J. Lawrence Marsh, M.D., University of Iowa, Department of Orthopaedics, 200 Hawkins Dr., Iowa City, Iowa 52242-1009, Telephone: (319) 356-0430

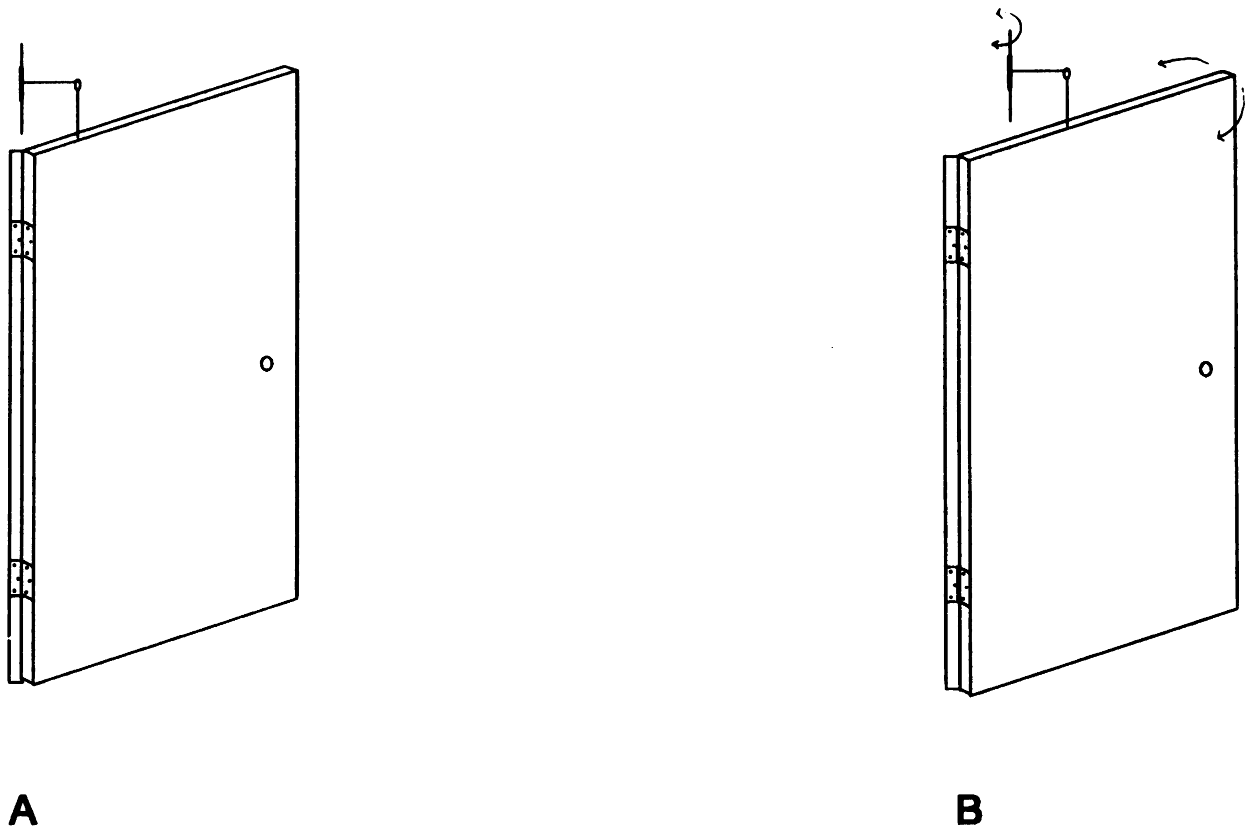

Figure 2. If the axis finder is aligned with the hinge of a door (a), the axis pin will rotate about itself as the door is opened and closed. If, however, the axis finder is not aligned with the hinge (b), the pin will move in an arc as the door is opened and closed.

proximate ankle axis described by Inman[7], and an axis located using a new mechanical axis finder[6,13]. The current clinical application technique, which approximates a horizontal ankle axis, significantly disturbed normal ankle joint motion and decreased the total range of motion possible. Aligning the fixator with the average ankle axis described by Inman resulted in significant differences from normal motion about one of three possible rotational axes. With the fixator hinge applied along the axis determined by the axis finder, ankle motion was not altered from normal. This result indicated that applying a fixator aligned along the true ankle axis might have significant clinical advantages.

The axis finder is a mechanical device described by Hollister et al.[6]. It works on the principle that if a pin is attached to a body undergoing fixed-axis rotation in alignment with the axis of rotation, the pin will rotate about its own axis as the joint is rotated. If, however, the pin does not lie on the joint's rotational axis, its tip will describe an arc as the joint rotates. This principle can be visualized by thinking of the joint as a door hinge (Figure 2). If a pin is attached to the door such that it is coincident with the hinge of the door, the pin will appear to rotate about itself as the door is opened and closed. However, if the pin is attached eccentrically from the door hinge, and/or if the pin is not aligned parallel to the hinge, it will describe an arc as the door is opened and closed.

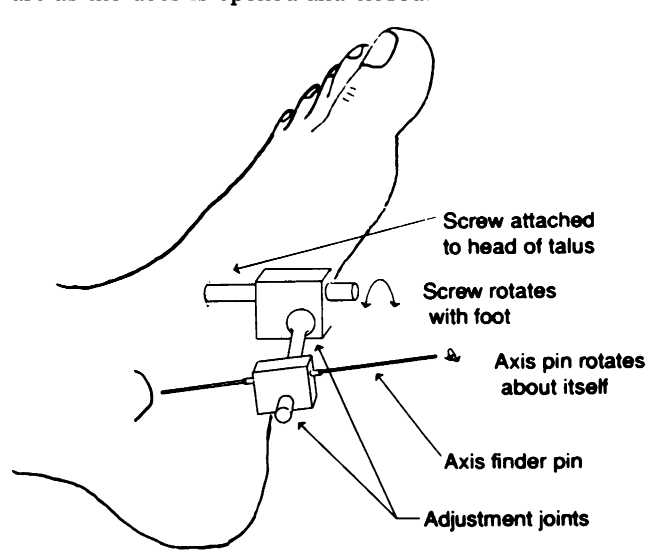

Figure 3. When used on the ankle joint, the axis finder is attached to the head of the talus and the axis pin is adjusted until minimal motion occurs.

Table 1. The angular disparity between the calculated helical axis and the axis finder for the hinge model and cadaver ankle.

	20° PF → neutral	neutral → 10°DF	20° PF → 10° DF
hinge model	2.74° (0.42)	4.06° (0.26)	2.36° (0.35)
cadaver ankle	9.88° (0.72)	10.94° (1.42)	9.10° (0.25)

In the case of the ankle joint, motions of an adjustable pin attached to the talus are monitored as the ankle is moved (Figure 3). This is best done by looking down the long axis of the pin. If the pin is coincident with the ankle's axis of rotation, no pin motion will be apparent. If the pin is not aligned with the ankle's axis of rotation, the end of the pin will either describe an arc or ellipse. The pin must then be adjusted in a direction perpendicular to its arc of observed motion to orient it coincident with the ankle's axis. Through a series of iterative adjustments of the axis finder pin, one can locate the axis of rotation of the joint.

At the completion of this kinematic study, a number of hurdles remained before the goal of clinically aligning a fixator hinge along the ankle axis could be realized for fractures of the tibial plafond. Some of these issues were addressed in a series of additional studies described here. First, the accuracy of the axis finder was investigated in order to determine the reliability of its use in biological systems; second, alternate fixator design prototypes were developed to increase the ease and versatility of intraoperative hinge placement; and third, a radiographic method was developed for locating the ankle axis.

Accuracy of the axis finder

In theory, the axis finder is able to precisely locate the axis of rotation of a simple hinge joint. However, the ankle joint does not behave as a simple perfect hinge, and therefore some error in the location of the ankle axis by the axis finder is unavoidable. This error, along with its ramifications for fixator hinge orientation, was quantified and addressed.

A series of biplanar radiographic analyses were conducted in order to compare the experimentally determined axis finder ankle axis to a computationally defined helical axis. A surrogate hinge model of the foot was designed and instrumented with tantalum marker beadlets for formal biplanar radiographic analysis. The axis finder was attached and adjusted until it was visually aligned with the hinge axis of the model. Biplanar radiographs were exposed and the three-dimensional locations of the model and the axis finder endpoints were computed. From these locations, the three dimensional helical axis about which the model was rotating was computationally determined. The vectoral dot product of this helical axis and the axis finder axis was used to determine the angular disparity between these two axes. Subsequently, a similar procedure was used to determine the angular disparity between the computed helical axis versus the axis finder axis in two cadaver specimens.

The axis finder was able to consistently locate the axis of rotation of the hinged surrogate model to within 4° in all cases. In the cadaver ankles, the axis finder was able to approximate to within 10° the true axis of rotation of the ankle, as defined by the computationally determined helical axis (Table 1). Even though the axis finder was only able to locate the "true" ankle axis to within 10°, the kinematic study suggests that the ankle still moves well with the fixator aligned along the axis finder axis. Gross observations on several cadaver specimens indicated that the axis finder does not locate a unique axis, but instead finds a locus of axis orientations, all of which show minimal pin movement. When the fixator hinge is aligned with any of these axes, the normal kinematics of the ankle are not altered within the sensitivity of the kinematic measurements described above.

Redesign of the distal fixator clamp

With the current commercially available fixator, the hinge can be oriented only in line with the distal fixator pins. Anatomic constraints require that these pins be placed horizontally, parallel to the dome of the talus, thus in effect prescribing a non-physiologic orientation of the fixator rotation axis. In order to allow the fixator to be aligned with the physiologic ankle axis, the distal clamp was redesigned to allow much more freedom in its placement.

The first design modification was to replace the rigid distal clamp with a ball joint, similar to that which attaches the proximal clamp to the fixator body (Figure 4a and 4b). This modification allowed the distal clamp to be angulated at least 17° relative to the fixator body. With this modification, the distal clamp could be angulated enough to allow the fixator hinge to be aligned with the physiologic ankle axis. However, this required that the fixator screws be parallel with the ankle axis, a situation which is technically difficult to achieve. Even if the screws could be reproducibly aligned parallel to the fixator axis, they would often have to be inserted in a manner which would disrupt either the talonavicular or subtalar joints.

The next step was to redesign and modify the fixator hinge and screw-clamp mechanisms. The major design criterion here was to allow the screws to be inserted into the talus and the calcaneus in the recommended horizontal orientation while allowing the fixator hinge to be indepen-

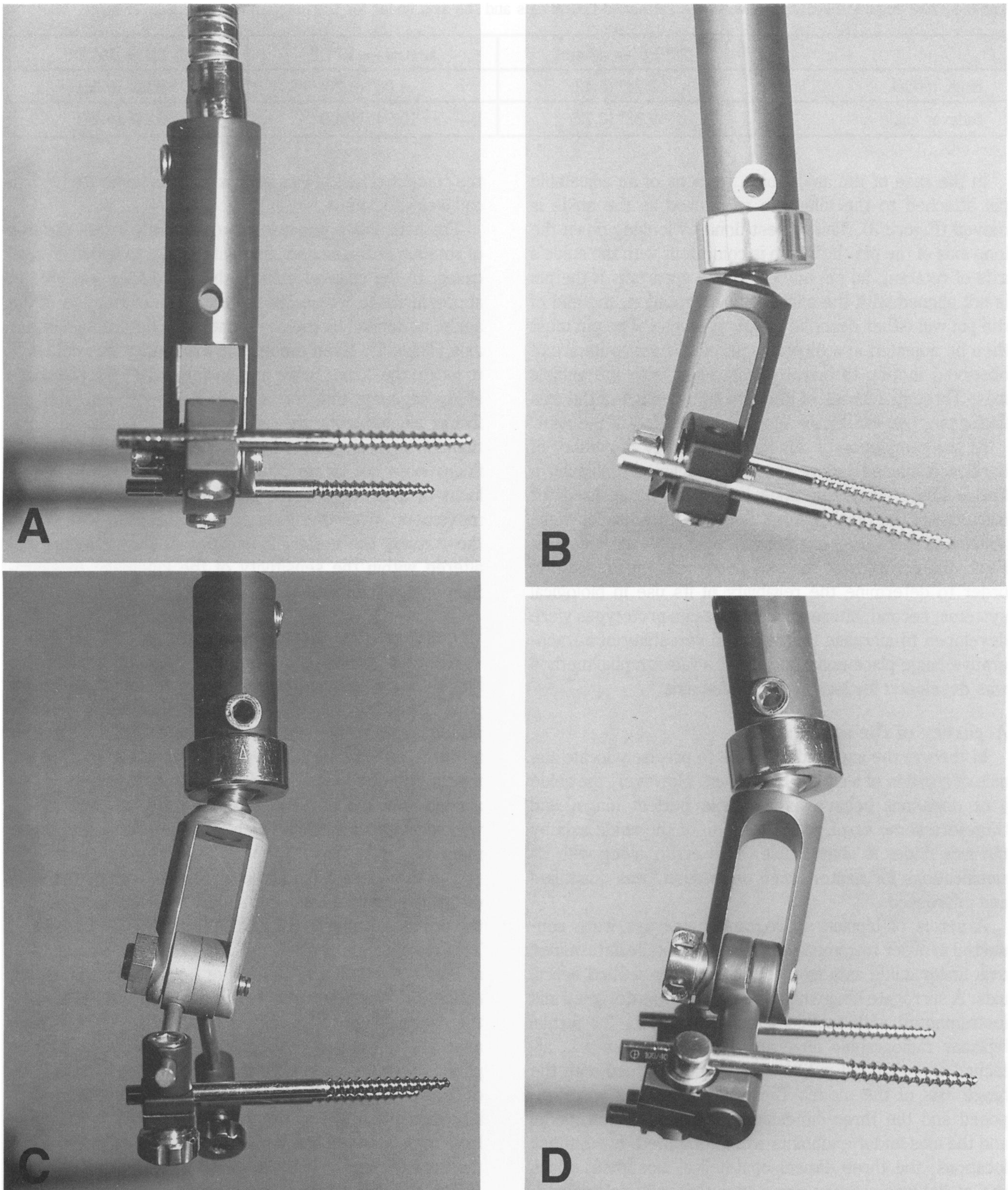

Figure 4. The evolution of the distal clamp. The original rigid distal clamp (a) only allowed the hinge to be oriented along a horizontal axis. The first design modification added a ball joint in place of the rigid clamp (b). This allowed the distal clamp to be angulated 17° with respect to the fixator body. The next modification was to add accessory joints at the screw-clamp interfaces and a screw within a screw joint at the fixator hinge. The in-house prototype (c) and the Orthofix version (d) are shown.

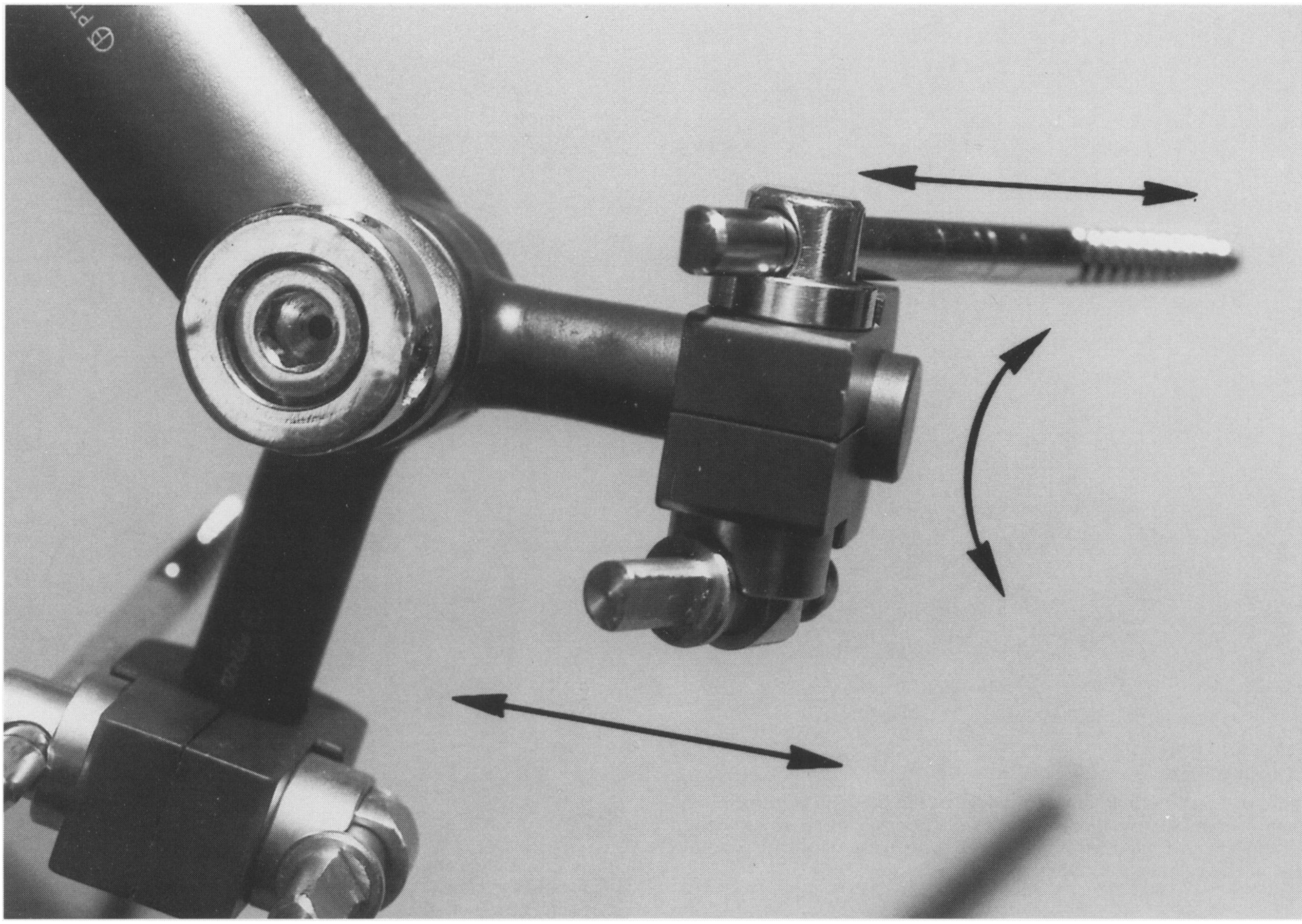

Figure 5. The new screw clamp design allows the clamp to be independently adjusted in the three planes shown. These additional degrees of freedom allow the fixator hinge to be aligned with the axis of the ankle independent of the screw orientation.

dently aligned with the axis of rotation of the ankle joint. To accomplish this, accessory joints were introduced at the junction between each of the fixator screws and the screw clamp (Figure 5). These accessory joints have three degrees of freedom and allow the hinge to be aligned with the axis of the ankle, independent of the orientation of the fixator screws. Additionally, the entire clamp is allowed to slide along the arm of the fixator in order to adjust the hinge position relative to the talar screw.

To allow additional surgical freedom in the placement of the talar and calcaneal screws, an additional joint was added to the distal clamp. This joint is at the junction between the two arms and allows the angle between each of the arms to be changed relative to each other (Figure 6). This modification allows greater freedom in the placement of the calcaneal fixator pin. This necessitated the development of a double locking mechanism (i.e., a screw within a screw), one for the two arms of the fixator clamp and one for the main ankle articulation.

An in-house prototype of the new distal clamp was fabricated (Figure 4c) and tested on several cadaver specimens. Initial success in the application of the fixator, and the resulting improvement in ankle motion, prompted Orthofix to build a refined prototype that conformed more closely to the existing Orthofix external fixation system (Figure 4d). In addition, the refined prototype incorporated standard Orthofix screw clamps, which were not available for the in-house version of the fixator. This refined prototype has also been successfully tested on several specimens.

Radiographic determination of the ankle axis

Plafond fractures usually involve extensive comminution of the distal articular surface of the tibia. This invariably results in the disturbance of the normal anatomy and dynamics of ankle motion. All methods currently available to locate the axis of rotation of the ankle, including the axis finder, implicitly rely on normal ankle anatomy and kinematics. If the normal anatomy is severely compromised, the kinematics will be altered, and there is no way to recover the pre-fracture rotation axis, regardless of whether one uses a malleolar-based axis definition or an axis-finder-based axis definition.

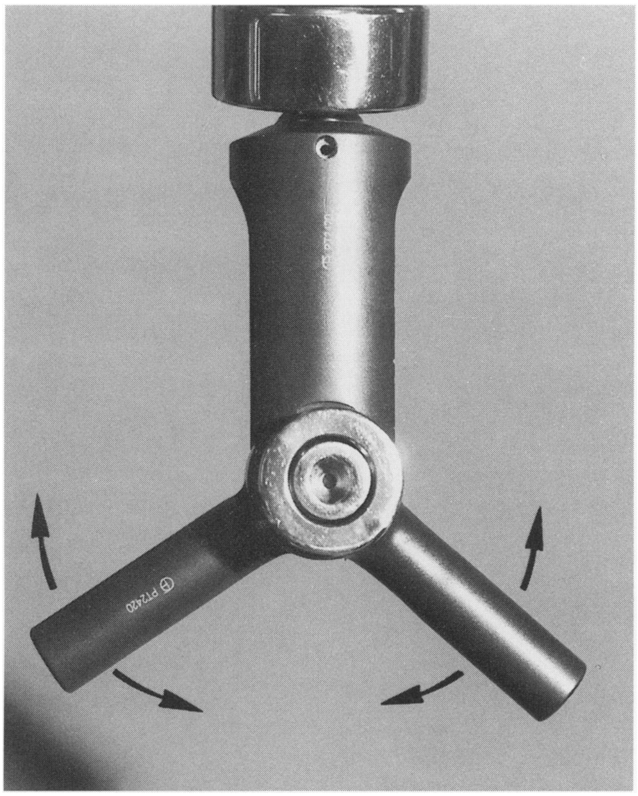

Figure 6. An additional joint was added at the junction between the clamp arms. This modification allows the arms to be positioned independent of each other, allowing greater freedom in the placement of the calcaneal fixator pin.

Fortunately, although plafond fractures often involve significant injury to the distal tibia, the talus is usually spared from significant bony damage. Theoretically, a method of locating the ankle axis based solely on the talus would allow the orientation of the fixator hinge axis to be determined independent of the damaged tibia, and therefore would have application to fractures of the tibial plafond.

It was noted by Inman[7] that the trochlea of the talus was not shaped as a cylinder, as previous authors had stated, but rather as a segment of a cone. The base of this cone is located on the lateral side of the talus, and the apex of the cone is on the medial side. Inman postulated that the long axis of this cone was the axis of rotation of the talus in the mortise. More recently, Singh et al. made use of talar anatomy when using an axis finder to locate the ankle axis[13]. Serial magnetic resonance images of the talus were obtained in a plane perpendicular to the axis of rotation, as inferred by the axis finder. They then fit a circle to the arc of the talar trochlea apparent on each of the slices. The center of this circle was found to be reasonably coincident with the mechanically determined axis of the ankle joint.

If a radiograph is exposed along the long axis of a truncated conical segment, a double shadow representing

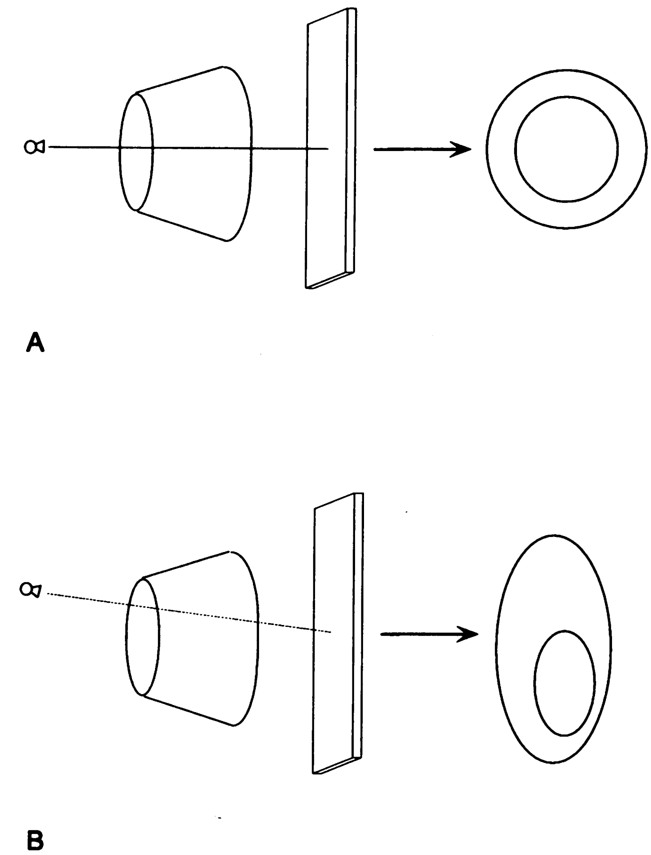

Figure 7. If a truncated cone is exposed to an x-ray beam along the long axis of the cone (a), the resulting image will be two concentric circles. If, however, the truncated cone is exposed to an eccentrically oriented beam (b), the resulting image will be two nonconcentric ellipses.

two concentric circles appears (Figure 7a). The inner shadow depicts the surface nearest the apex of the cone, and the outer shadow depicts the surface nearest to the base of the cone. If a radiograph is exposed at an angle to the long axis of the cone, these two shadows will be non-concentric and will form ellipses (Figure 7b). A radiograph exposed along the long axis of this cone will result in segments of two concentric circles with their common center being coincident with the cone's axis. In the case of the ankle, by using this concept in reverse (i.e., by locating that specific position of the talus which casts concentric radiographic double shadows), one should be able to locate the axis of rotation of the ankle joint.

Six cadaveric specimens were used to test this hypothesis. The axis of rotation of the ankle was first determined on each using an axis finder. Then a radiograph of the ankle joint was exposed with the central beam of the fluoroscope aligned coincident with the axis finder pin. In all cases, the expected double arc was located, although in many cases only small segments of the arcs were visible (Figure 8). The distance between the circle segments was variable ranging from 5 - 10 mm. The center of the two

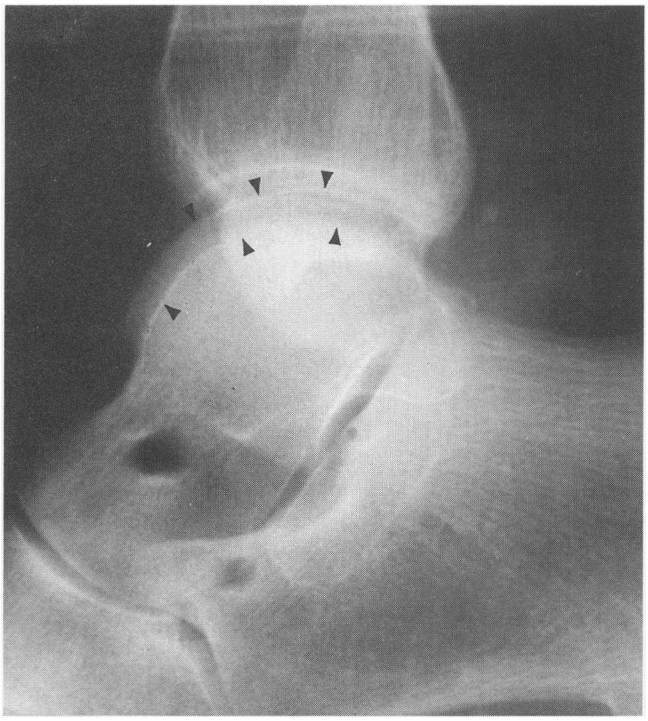

Figure 8.
Fluoroscopic image of the talus aligned with the axis of rotation of the ankle. Notice the double shadow of the talar dome.

arcs was within five millimeters of each other, indicating that the arcs were segments of two concentric circles. As expected, the tips of the medial and lateral malleoli were superimposed upon one another.

With the radiographic appearance of the ankle axis quantitatively defined relative to the talus, the next task was to locate the axis of rotation of the talus, independent of the axis finder. Using fluoroscopy, the characteristic double shadow was located on the same cadaveric specimens. This was accomplished by placing the ankle in the fluoroscopic field such that a lateral image of the talus was exposed. By manipulating the ankle in an iterative process, the image of the talus in its double shadow formation was obtained. The center of the circle formed by the two arcs was then located, and an axis positioning guide (i.e. the axis finder) was attached via a previously inserted talar pin. The positioning guide was adjusted until it was coincident with the fluoroscopic beam and was then locked into place. At this point, the pin of this positioning guide was coincident with the radiographically determined axis of rotation of the ankle joint.

In order to determine if this orientation was similar to that previously obtained using the axis finder, the ankle was moved and the amount of motion in the axis positioning pin was observed. The amount of pin motion was similar to that observed when locating the axis using the axis finder alone. Prototype fixators were then applied along the radiographically determined axis of rotation. The total range of motion qualitatively and quantitatively appeared unaffected relative to the unrestricted ankle.

REFERENCES

1. Bonar, S.K., Marsh, J.L., Unilateral External Fixation for Severe Pilon Fractures. Foot and Ankle, 14:57-64, 1993.
2. Bourne, R.B., Rorabeck, C.H., and Macnab, J., Intra-articular Fractures of the Distal Tibia: The Pilon Fracture. J. of Trauma, 23:591-596, 1983.
3. Kellam, J.F., and Waddell, J.P., Fractures of the Distal Tibial Metaphysis with Intra-articular Extension - The Distal Tibia Explosion Fracture. J. of Trauma, 19:593-601, 1979.
4. Dillin, L., Slabaugh, P., Delayed Wound Healing, Infection and Nonunion Following Open Reduction and Internal Fixation of Tibial Plafond Fractures. J. of Trauma, 26:1116-1119, 1986.
5. Fitzpatrick, DC, Marsh, JL, Brown, TD, The Kinematic Analysis of an Articulated External Fixator for Tibial Pilon Fractures. J. Orthop. Trauma, 9:76-82, 1995.
6. Hollister, A., Buford, W.L., Myers, L.M., Giurintano, D.J., and Novick, A. The Axis of Rotation of the Thumb Carpometacarpal Joint. J. Orthop. Res., 10:454-460, 1992.
7. Inman, V.T., Joints of the Ankle. Williams and Wilkins, Baltimore, 1976.
8. Marsh, J.L., Bonar, S.K., Nepola, J.V., DeCoster, T., Hurwitz, S., LeClare, W., Fractures of the Tibial Plafond - Treatment with Articulated External Fixation. Unpublished, 1992.
9. McFerran, M.A., Smith, S.W., Boulas, H.J., Schwartz, S.S., Complications Encountered in the Treatment of Pilon Fractures. J. Orthop. Trauma, 6:195-200, 1992.
10. Pierce, R.O., Heinrich, J.H., Comminuted Intra-articular Fractures of the Distal Tibia. J. of Trauma, 19:828-832, 1979.
11. Rüedi, T.P., Allgöwer, M., Fractures of the Lower End of the Tibia into the Ankle-Joint. Injury, 1:92-99, 1969.
12. Salah, M., Shanahan, M.D.G., Fern, E.D., Intra-articular Fractures of the Distal Tibia: Surgical Management By limited Internal Fixation and Articulated Distraction. Injury, 24:37-40, 1993.
13. Singh, A.K., Starkweather, K.D., Hollister, A.M., Jantana, S., Lupichuck, A.G., Kinematics of the Ankle: A Hinge Axis Model. Foot and Ankle, 13:439-446, 1992.
14. Teeny, S., Wiss, D.A., Tibial Plafond Fractures: Errors, Complication and Pitfalls in Operative Treatment. Orthop. Trans. 14:265, 1990.