

THE AXIS OF THE ANKLE JOINT

by

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THESIS

Submitted to the School of Graduate Studies  
in partial fulfillment of the requirements  
for the Degree of Master of Science

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Faculty of Medicine  
University of Ottawa

Ottawa, March 1974

Man's foot is all his own.  
It is unlike any other foot.  
It is the most distinctly human  
part of the whole of his anatom-  
ical make-up. It is a human  
specialisation and, whether he  
be proud of it or not, it is  
his hall-mark, and so long as  
Man has been Man and so long  
as he remains Man it is by his  
feet he will be known from all  
other members of the animal  
kingdom.

F. Wood Jones, 1944.

The foot is an important  
link between a person and the  
earth.

Philip Lewin

## ACKNOWLEDGEMENTS

I wish to express my sincere appreciation and gratitude to Dr. John Pegington for his guidance and encouragement throughout this investigation.

I am especially indebted to Dr. Marc Colonnier, Chairman of the Department of Anatomy, whose personal support, encouragement and financial assistance made this study possible.

Special thanks are due to Mr. Stanley Klosevych and his staff of the Medical Communication Services for their capable assistance in producing the figures and plates presented in this thesis.

Finally, I wish to express my sincerest appreciation to my wife Kathleen for her patience and invaluable assistance throughout this study.

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PART I

A. INTRODUCTION

The ankle joint was classically described as a hinge or ginglymoid variety of synovial joint. The term "ginglymus" had an ancient origin. It was first used to describe a hinge type of joint in the works of early Greek writers.\* Hippocrates (460-361 B.C.) seemed to be the first to use the term in this context in De Locis in Hominibus. Later Aristotle (384-322 B.C.) also mentioned the word in De Anima. Galen (130-210 A.D.) used ginglymus as one of his three-part classification of joints in the preface to Liber de Ossibus ad Tirones. There was no mention of the word "ginglymus" in Latin before the twelfth century. It was however used as a Latin word by Vesalius (1514-1564 A.D.) in the classification of joints in his work De Humani Corporis Fabrica (1542). This type of description was continued by many subsequent authors such as Gibson (1697), Harrison (1840), Gray (1858), Morris (1879), Holden (1885), and Gunningham (1893).

\* γιγγλυμος

By their definition, these early authors were comparing the joint to a mechanical hinge which would therefore have a fixed axis and would allow movement in only one plane. In Hunter's Lectures of Anatomy (1752) the following description of the ankle joint was found: "... where the parts of the Bone mutually receive and are receiv'd; this kind of Articulation only admits of Flexion and Extension." This inferred a true and accurate mechanical hinge which therefore allowed movement in only one plane. Indeed, Morris (1879) called it "a perfect ginglymus or hinge-joint." Harrison (1840) went even further and stated that the ankle joint was "the most perfect ginglymoid joint in the body, excepting that between the ulna and humerus..."

This classical description has subsequently been restated in innumerable textbooks and monographs written in this century. Random selection of a few editions of major textbooks illustrates this fact, for example: Cunningham (1902), Morris (1946), Testut and Latarjet (1948), Bonnier (1950), Paturet (1951), Grant (1952), Howorth (1952), Treves (1952), Steindler (1955), Turek (1959), Brunnstrom (1962), Thorek (1962),

Kaplan (1964), Rouvière (1967), and Hollinshead (1969).

During this century, however, some authors contended that the comparison of the ankle joint to a true mechanical hinge was incorrect; Piersol (1936) wrote that although the ankle was a hinge joint, it was not a "pure" one, but differed from a mechanical hinge. No further explanation was given. The views of Barnett, Davies and MacConaill (1961) and Last (1972) were the same, but they explained the "hinge" as having a variable axis.

Prior to the twentieth century, documented experimental confirmation of an axis of the ankle joint seemed to be lacking. All that existed were statements in textbooks and monographs. It remains possible, however, that these descriptions of the joint and its axis could have been based upon unrecorded experiments.

In the early part of this century several very detailed studies of the ankle region were made by Sewell (1904, 1905, 1906, 1907) and Inkster (1927). Many measurements of the talus were accumulated by these investigators, and comparisons were even drawn between the tali of different races. In spite of such voluminous data, it is remarkable that they made no measurements of the axis around which the talus moved!

It was not until 1952 that the first experiments to determine the axis of the ankle joint appeared in the literature (Barnett and Napier, 1952).

A peculiar situation therefore exists, since a review of the literature must take into account not only views expressed in recent articles but also those in textbooks because it is possible that the latter could have been based upon unrecorded experiments. It is also important to review textbook accounts since these give a very clear indication of the varying opinions that exist among anatomists and surgeons regarding the position of the ankle joint axis.

B. REVIEW OF THE LITERATURE

A review of opinions set out in standard textbooks presents certain difficulties. Each book usually has a history of several editions, and sometimes these are quite numerous. Review of each edition of every textbook does not seem practical. Indeed, it is not necessarily a useful exercise since a clear indication of the various opinions concerning the ankle joint axis can be obtained by random selection of editions. Two standard textbooks (Gray's Anatomy and Cunningham's Textbook of Anatomy) have in fact been traced throughout all their editions. On the other hand, a review of journal literature written on experimental determination of the axis presents no such problems.

Among those authors who described an ankle joint axis, some did not give a sufficiently precise account to allow complete understanding of its exact position and the resulting plane of ankle movement. Hamilton (1956), for example, described the axis as merely passing "through the body of the talus", and Hollinshead (1958) referred only to a "mediolateral" axis. Treves (1952) stated only that the axis was located "approximately  $\frac{1}{2}$  inch above the tip of the inner

malleolus", but he made no mention of its location of the lateral side.

Other authors tried to be more exact, their descriptions of the axis of motion in the ankle joint falling into two categories; some describing a single axis while others a variable axis. Even among those writers who considered a single axis, some believed it to be transverse and others oblique. The direction of the obliquity itself has also been the subject of varying opinions. It has been described as lying in either the horizontal or the vertical plane.

1. Descriptions of a Single Axis:

a) Transverse Axis Lying in Coronal Plane

Although Gray himself and several subsequent editors made no mention of the axis in the early editions of his textbook, the thirteenth edition (1893) finally referred to a single axis which "may be indicated by a transverse line drawn across the front of the lower leg, about half an inch above the level of the tip of the internal malleolus." Bonnin (1950) attempted a similar degree of accuracy by stating that the transverse axis of movement "runs from below the centre

of the medial malleolus through the sinus tarsi on the outer side, lying in front of the anterior margin of the fibular." Another account was given by Lapidus (1963) who described the transverse axis as passing under the tip of the medial malleolus, "crossing the tip of the lateral malleolus and running from side to side in the frontal plane." Other authors citing a transverse axis were not as exact. Piersol (1936) wrote only of a "transverse axis", making no mention of its relation to the malleoli. Morris (1946) and Kleiger (1956) stated only that the transverse axis passed through the body of the talus while Brunnstrom (1962) maintained that the transverse axis passed through the trochlea of the talus.

b) Transverse Axis Lying Oblique to Coronal Plane

Some authors wrote of an obliquely transverse axis of movement. The obliquity was always described as passing from the anteromedial to the posterolateral aspects of the ankle. Cunningham (1893) appeared to be the first anatomist to refer to such a position, stating that "this horizontal axis passes through or near the interosseous canal between the os calcis [calcaneus] and astragalus [talus]." He described its obliquity as

being "directed outwards and backwards", making an angle of approximately sixty degrees with the median plane of the body. Cunningham (1902) referred to an "obliquely transverse axis" of the ankle joint, and added that the obliquity was "indicated by the natural outward pointing of the toes." Although previously describing the ankle joint axis as being only transverse (Gray, 1893), Gray's textbook of 1918 ascribed an obliquity to this axis. Steindler (1935 and 1955) described the obliquity of the axis in relation to the patella, stating that the axis was oblique and was not in the frontal plane when the patella was facing directly forward. Pernkopf (1943) wrote of a slightly oblique axis, nearly in the frontal plane, running from the tip of the fibular malleolus to a point just under the tip of the medial malleolus.

An oblique, nearly transverse axis passing through the center of curvature of the pulley of the talus was reported by Testut and Letarjet (1948). These authors, together with Paturet (1951) and Rouvière (1967), described this type of obliquity as passing from inside out and from before backwards. In addition, Paturet observed that the position of the axis resulted in

the ankle moving obliquely to the sagittal plane. He estimated that the plane of movement of the ankle was twenty-five to thirty degrees outwards from the sagittal plane.

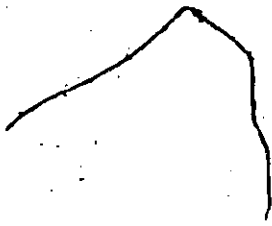
c) Vertically Oblique Axis in Coronal Plane

A single, vertically oblique axis of motion at the ankle joint was advocated by Wilson and Cochrane (1928). They believed that the axis was directed downwards and medially so that the foot would point laterally when plantar flexed.

d) Vertically and Transversely Oblique Axis

Isman and Inman (1969) described experiments to determine the axis of the ankle joint. Their experiments were performed on cadaver material with capsular and ligamentous structures removed. They observed the lateral and medial aspects of the talus under cross hairs during simulated rotation of the talus against the tibiofibular mortice. Points of minimal motion were therefore located on each side of the talus. The axis of rotation of the ankle joint was then found by passing a rod through the talus to connect the lateral and medial points of minimal motion. These experiments showed the ankle joint axis to be vertically

oblique, making an angle of approximately eighty degrees with the long axis of the tibia. They also found a certain amount of transverse obliquity. They described this in reference to a line which they called the midline of the foot which passed through the third toe. They found that the axis made an angle of eighty-four degrees with the reference line on the medial side.



2. Descriptions of a Variable Axis:

Barnett and Napier (1952) were the first investigators to discuss a variable axis of movement. They based their studies on the circles formed by the completion of the arcs of the lateral and medial profiles of the talus. They found that the lateral profile was the arc of a true circle but that the medial profile was part of an ellipse; they therefore concluded that the medial side had two centers while the lateral side had one. They then determined the axis by joining the centers on the medial and lateral sides. Two axes of movement were described: a downwards and laterally inclined "dorsiflexion axis" and a downwards and medially inclined "plantar-flexion axis." Hicks (1953) also agreed with Barnett and Napier's description of two axes and attempted measurements to correlate the ankle joint axes with anatomical landmarks. He stated that the dorsiflexion axis ran from a point 1.5 cm anterior to the tip of the medial malleolus to a point 0.5 cm inferior to the tip of the lateral malleolus; the plantar flexion axis ran from a point 1.5 cm anterior and 1 cm inferior to the tip of the medial malleolus to a point 0.5 cm superior to the tip of the lateral

malleolus. In spite of the apparent precision of these figures it should be noted that these experiments were crudely performed on undissected cadaver ankles!

Barnett, Davies and MacConaill (1961) agreed with the description of two axes and added that "it is doubtful whether any joints have a stationary transverse axis, even the so-called pure hinge joints." Wyller (1963), Wright, Desai and Henderson (1964), Frazer (1965) and Last (1972) agreed with Barnett and Napier's account of two variable axes of movement and referred extensively to it in their own works.

Using cineradiographic studies on ankles of normal patients, Sammarco, Burstein and Frankel (1973) arrived at different conclusions. They stated that "it is apparent that there does not exist a single or even double axis of rotation for the normal ankle joint motion as suggested by previous authors. In the normal weight bearing ankle, a series of instantaneous centers of rotation occur from the time motion is begun in plantar flexion to its termination at the limit of dorsiflexion." They also attempted to show that the basic pattern of motion in the ankle was the same in non-weight bearing as in weight bearing.

C. AIM OF THE PRESENT STUDY

A review of the literature reveals two important points. The first point concerns the widely diverging views existing in textbooks and monographs regarding the position and stability of the ankle joint axis. Those works containing references usually refer to other textbooks since articles on the subject have appeared only recently. This has resulted not only in diverging opinions but often in actual confusion. A good example of this confusion is seen in Buchanan's textbook of anatomy (1949) and in Wood Jones's monograph on the foot (1949). Buchanan stated that the ankle joint axis passed "almost directly below the mid-point of the fibular malleolus and nearly coinciding in level with the tip of the tibial malleolus." Wood Jones reversed the statement in his book by writing of the "mid-point of the tibial malleolus [and] nearly level with the tip of the fibular malleolus." It is especially interesting to note that Wood Jones edited this edition of Buchanan's textbook! Since both of these works are "standard" anatomy texts written by reputable anatomists, it is understandable how both versions could be quoted in subsequent works.

The second point is that few articles investigating the ankle joint axis have appeared in the literature, and all of these were written within the past twenty years. Some of the experiments upon which these articles were based were very inaccurate. A good example was the work of Hicks (1953). This investigator simply inserted needles into the bones on either side of undissected cadaver ankles and then plantar flexed and dorsiflexed the ankles. After locating the needle which did not move on either side, he connected them with a rod and assumed this to represent the axis of movement. When piercing the bone, however, skin, fascia, tendons, capsule and ligaments also had to be transfixed. This obviously affected needle movement and, hence, his results. It is also somewhat doubtful whether undissected cadaver ankles can be plantar flexed or dorsiflexed to any useful degree since the calf muscles undergo rigor mortis shortly after death, and the ankle becomes fixed. If the cadaver is embalmed and preserved, the ankles are usually found fixed in equinus; most cannot even be moved into the plantar grade position.

With these thoughts in mind the present study attempts to define the ankle joint axis by experiments

on embalmed and freshly amputated ankles. These are dissected so that only the capsule and ligaments of the ankle joints remain. Movement therefore depends only upon the shape of the articular surfaces and the capsule and ligaments of the joints. Markers are then placed on the bones and the ankles are filmed by high speed cinematography during their full range of movement. The study also evaluates some of the experiments recorded in recent literature clearly stating the drawbacks of each method (Barnett and Napier, 1952; Isman and Inman, 1969). The present study therefore determines the position of the ankle joint axis by several methods, each of which is checked against the others. In this way conclusions will be reached which, it is hoped, will clarify the present picture of the ankle joint axis.

PART II

MATERIALS AND METHODS

In the present study of the ankle joint axis two methods of analysis were employed. The first of these was a dynamic method involving observation of cadaver ankles during simulated movement. The second method was a static one involving geometrical analysis of tali.

The principal method used to determine whether or not a fixed axis existed was a dynamic one involving observation of the lateral and medial aspects of fifteen cadaver ankles during simulated movement. The principle underlying this method was based upon the fact that any point located along a fixed axis remained stationary during plantar and dorsiflexion while any surrounding point altered its position. With the aid of a dissecting microscope it was determined if a stationary point existed on the lateral and medial surfaces of each talus. Stationary points so found were then confirmed and documented by cinematography. A line joining the

lateral and medial axis points represented the axis of movement. If a stationary point was not located on one or both sides of a talus a single fixed axis could not be postulated, and a variable axis was said to exist.

A static method of geometrical analysis of tali was first used to determine the ankle joint axis by Barnett and Napier in 1952. Their determinations of the ankle joint axis were based solely upon static geometrical analysis of tali and not upon any dynamic studies of the joint. In spite of this and other drawbacks their work had a great impact upon subsequent opinions of the ankle joint axis. In the present study twenty tali were carefully analyzed geometrically in order to clarify the drawbacks of Barnett and Napier's work. By this method a clearer picture of the geometrical properties of tali was achieved and a refined static method of analysis was evolved.

With this clarified picture of the geometrical properties of tali in mind, the fifteen ankles used in the dynamic study of the ankle joint axis were then disarticulated. Their tali, together with their tibiofibular mortices, were analyzed by the refined

static method. It was then possible to compare the results obtained by this method of geometrical analysis with the results obtained from the dynamic method and to determine whether or not the results of these two methods coincided with each other. In those cases where the dynamic method showed that a variable axis existed the refined static method was used to determine the cause for such variability.

A. DYNAMIC METHOD OF ESTIMATION OF THE ANKLE  
JOINT AXIS AND CONFIRMATION BY CINEMATOGRAPHY  
AND RADIOGRAPHY

Fourteen embalmed legs and one freshly amputated leg were used to determine whether or not fixed lateral and medial axis points of the ankle joint existed during movement. Such a study would indicate whether the ankle joint had a fixed or variable axis. Cinematography was used to confirm and document the results.

Legs amputated just below the knee joint were used and all skin around each ankle was removed so that ~~no~~<sup>no</sup> skin bridges remained to restrict movement. On the medial side the flexor retinaculum was removed, and the tendons of tibialis posterior, flexor digitorum longus and flexor hallucis longus were sectioned. The tendons of peroneus longus and peroneus brevis on the lateral side of each ankle were cut, and the superior and inferior peroneal retinacula were removed. Behind the ankle the tendo calcaneus was sectioned just proximal to the tibiofibular mortice. Finally, the superior and inferior extensor retinacula with the tendons of tibialis anterior, extensor digitorum longus, extensor hallucis longus and peroneus tertius were removed in

order to expose the anterior capsule. The removal of skin, fascia and tendons therefore resulted in a freely mobile ankle whose movements were limited only by the joint capsule, the ligaments and the articular surfaces themselves.

The dissected leg was laid on a hinged L-shaped platform. The larger limb of the platform was made from a sturdy one and one-half inch thick wooden board from which a small oval piece had been removed to accommodate the heel (fig. 1). It was equipped with three clamps for securing the leg. The smaller limb was constructed from one-half inch thick plexiglass.

With the larger limb of the platform placed firmly on a table the three clamps were securely fastened around the leg. In all cases the leg was adjusted so that its anterior border was horizontal. The smaller limb of the platform was then raised to the vertical position so that the sole of the foot was in full contact with it and was therefore in the plantar grade position (fig. 2). With the foot in this position the subtalar joint was immobilized by inserting a two inch screw obliquely through the neck of the talus and into the calcaneus. This was easily

Figures 1 and 2

Fig..1. Hinged L-shaped platform  
used in dynamic method.  
The larger limb of the  
platform is equipped  
with three clamps for  
securing the leg.

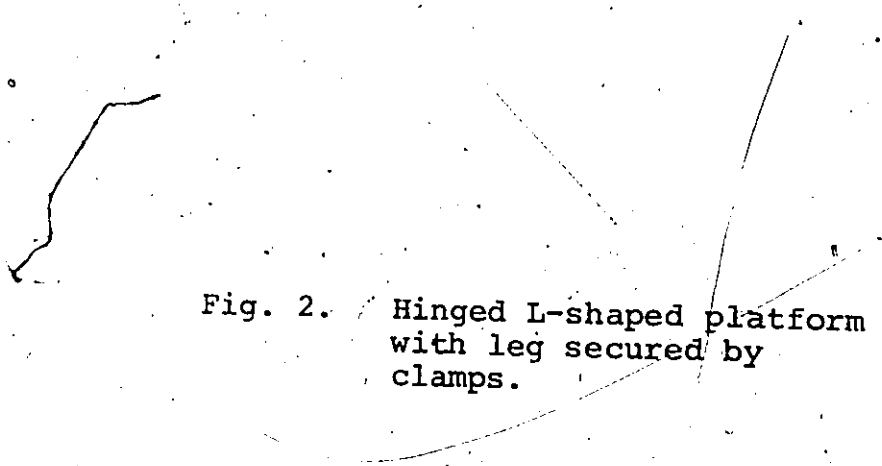
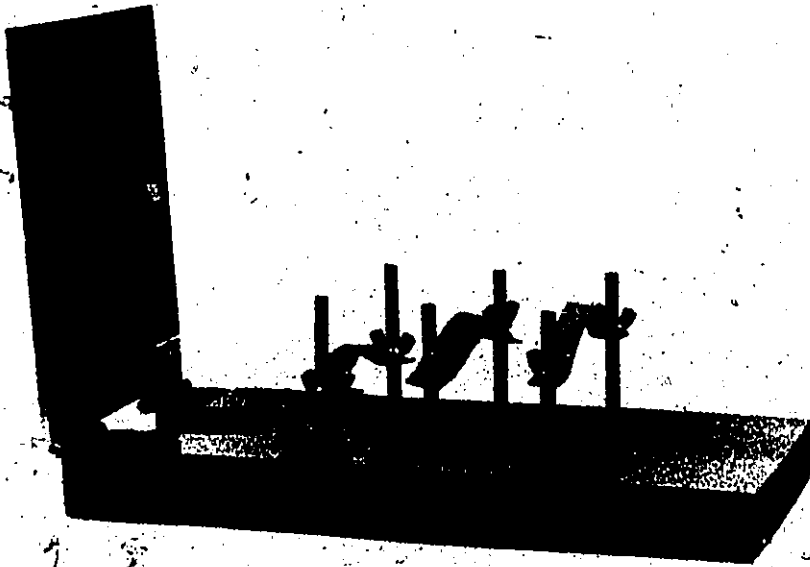


Fig. 2. Hinged L-shaped platform  
with leg secured by  
clamps.



achieved by inserting the screw downwards and posteriorly at an angle of approximately forty-five degrees to the long axis of the tibia. Antero-posterior and lateral X-rays of the ankle were then taken to check the screw placement (fig. 3 a and b). This procedure ensured that movement occurring during subsequent manipulations was restricted to the ankle joint. Having prevented unwanted movements at the subtalar joint, the smaller limb of the platform was then discarded by removing the bolts from the hinges.

With the three clamps attached securely around the leg, the lateral aspect of the ankle was examined. The three radiating bands of the lateral ligament were carefully exposed. The capsule between the anterior talofibular ligament and the calcaneofibular ligament was removed so that part of the lateral surface of the talus could be observed between these bands. In some instances a very small sliver of the calcaneofibular ligament was removed so that more of the lateral surface of the talus was visible. While the ankle was manually plantar, flexed and dorsiflexed, the small exposed part of the lateral surface of the talus was observed through

Figure 3

Fig. 3a. Anteroposterior X-ray of ankle showing screw inserted through the subtalar joint.

Fig. 3b. Lateral X-ray of ankle showing screw inserted through the subtalar joint.



a dissecting microscope (fig. 4). Care was taken both to ensure continuous contact between the articulating surfaces of the joint during movement and to avoid forcing the joint at the extremes of plantar and dorsiflexion. By this method it was possible to estimate whether or not a point of no movement existed on the lateral surface of the talus. If such a point was found it could be assumed to be the center about which rotation of the talus occurred during plantar and dorsiflexion. A straight pin with a black head of 0.069 inch in diameter was then inserted into this point on the talus.

The same procedure was employed to estimate whether or not a point of no movement existed on the medial side of the talus. In this case, however, a section of the deltoid ligament was removed in order to expose part of the medial surface of the talus. This was observed through a dissecting microscope during plantar and dorsiflexion, and if a point of no movement was found it too was marked with a black-headed straight pin.

In ankles where fixed lateral and medial axis points had been found, their positions were recorded by filming the exposed lateral and medial

Figure-4

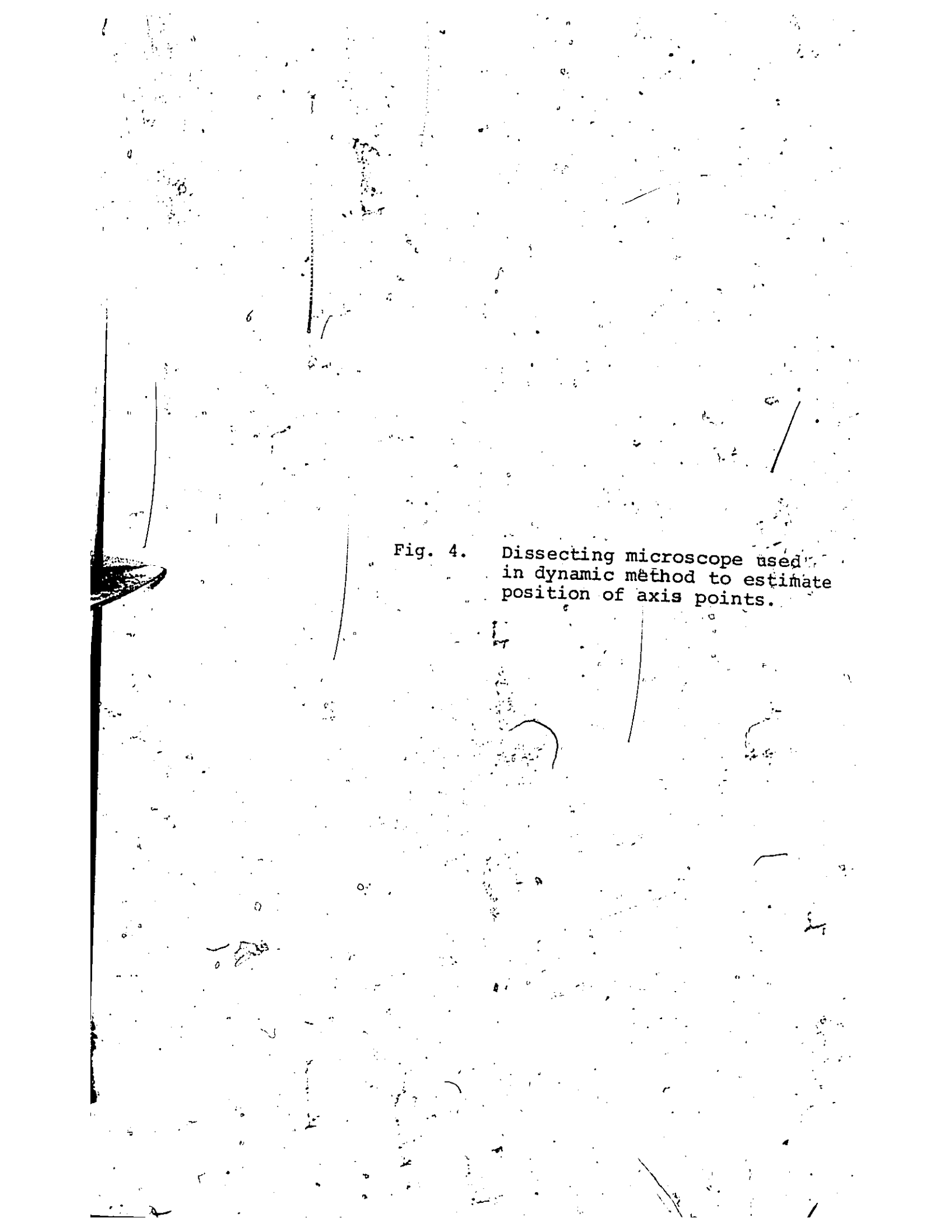
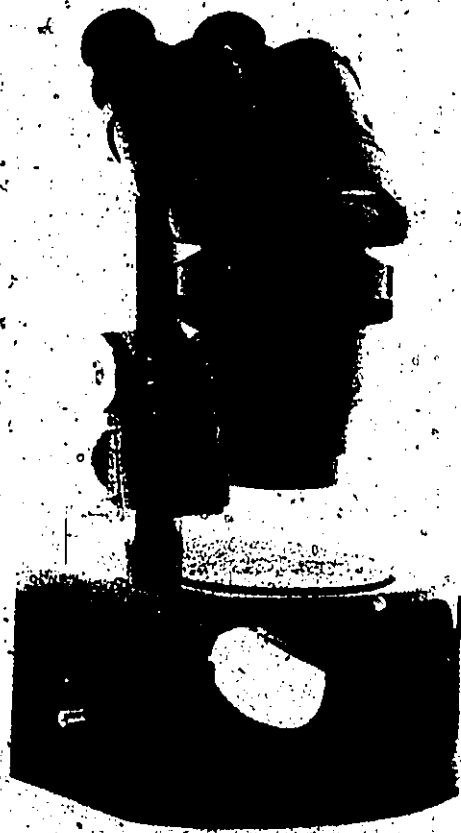
The image shows a dissection microscope, which is a type of microscope with a large field of view and low magnification. It is used for examining small objects in detail. The microscope is positioned in the center of the frame, and its components, including the eyepiece, objective lenses, and stage, are visible. The background is a plain, light-colored surface. The text 'Fig. 4. Dissecting microscope used in dynamic method to estimate position of axis points.' is printed below the microscope.

Fig. 4. Dissecting microscope used in dynamic method to estimate position of axis points.



aspects of the talus during movement. A 16 mm negative film was used at sixty-nine frames per second. In order to confirm that the axis points were indeed fixed it was necessary to have some stationary reference point in the film. The lateral and medial malleoli were used as the stationary references. Skin and subcutaneous tissue were removed from the malleoli, and four pins were inserted in a cross-like manner into each malleolus to act as stationary reference points. A few pins were also inserted around the talar axis pin in order to give some indication of the movement of the rest of the talus around its fixed axis (fig. 5 and fig. 6).

First, the lateral aspect of the ankle was filmed during two complete movements: the first movement being from full dorsiflexion to full plantar flexion and the second movement being from full plantar flexion to full dorsiflexion. The range of movement was noted. Care was taken to keep the articular surfaces of the talus and the tibiofibular mortice in continuous contact with each other during movement and to prevent forcing of the joint at extremes of movement. A ruler, calibrated in millimeters, was included in the filming. The film

Figures 5 and 6

Fig. 5. Lateral aspect of dissected ankle showing positions of stationary malleolar reference pins (MRP) and talar pins (TP). The calcaneofibular ligament (cf) is clearly visible.

Fig. 6. Medial aspect of dissected ankle showing positions of stationary malleolar reference pins (MRP) and talar pins (TP).



was developed and every fortieth frame was enlarged and printed on 4x5 photographic paper. The printed frames were numbered and arranged in order (fig. 7). An accurate tracing of the four malleolar pins and the talar pins was made from the first enlarged print (fig. 8). This tracing was then superimposed, in turn, on each of the remaining prints, the traced outlines of the four malleolar pins being accurately aligned with those in each photograph. With these stationary reference points accurately superimposed, attention was then focussed on the talar pins. The fixed axis point, marked by the first talar pin, was confirmed only if it remained stationary and in a fixed relationship to the malleolar pins in all the prints. The surrounding talar pins served the useful purpose of indicating surrounding talar movement (fig. 9).

The medial aspects of those ankles which had been estimated to have fixed axis points were then filmed during the same two complete movements. The articular surfaces were carefully maintained in continuous contact with each other while care was taken to prevent extremes of movement. The ranges of plantar and dorsiflexion were again noted. The

Figure 7




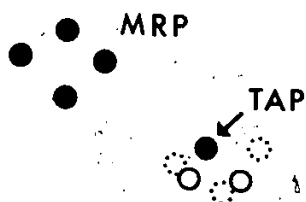
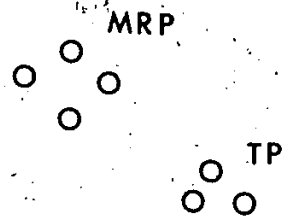
Fig. 7. A series of printed frames of the lateral aspect of a right ankle during movement from full dorsiflexion-(frame 1) to full plantar flexion (frame 9). The stationary malleolar reference pins (MRP), talar pins (TP) and the calcaneofibular ligament (cf) are clearly visible. Note that only three talar pins are visible in frame 1. As movement towards full plantar flexion proceeds, a fourth pin gradually appears from under cover of the lateral malleolus.



Figures 8 and 9

Fig. 8. Tracing of the four stationary malleolar reference pins (MRP) and three talar pins (TP) shown in frame 1 of fig. 7.

Fig. 9. A superimposition of the pin tracings from frame 1 and frame 9 of fig. 7. Stationary pins are indicated by black-filled circles. Only the stationary malleolar reference pins (MRP) and the talar axis pin (TAP) remain stationary and are therefore colored black. The remaining two talar pins from frame 1 are indicated as solid circles while the remaining three talar pins from frame 9 are indicated as dotted circles. It is readily seen that during movement from dorsiflexion to plantar flexion the nonstationary talar pins rotate clockwise while only the talar axis pin (TAP) remains stationary.



filming, developing, printing, numbering and tracings were performed as with the lateral side (fig. 10). The tracing of the first printed frame was superimposed on each subsequent print, and the positions of the four medial malleolar pins were accurately aligned. The center of rotation was determined by locating the talar pin which was in the same position both in the tracing and in the photographs (fig. 11).

In ankles where fixed lateral and medial axis points were estimated and later confirmed by cinematography a hole was drilled through the talus to connect these two points. This was made with an electric drill which was fitted with a drill point of 0.060 inch in diameter and which was mounted on a vertical stand. A metal plate with a one and one-half inch spike was bolted to the base of the stand so that the spike was directly in line with the drill point (fig. 12a and 12b). The pin marking the lateral axis point was removed, and its point of entrance into the talus was carefully placed directly on the spike. The pin marking the medial axis point was then removed, and the drill was lowered until it contacted this point (fig. 13). The electric drill was engaged and was slowly lowered

Figure 10




Fig. 10. A series of printed frames of the medial aspect of a left ankle during movement from full dorsiflexion (frame 1) to full plantar flexion (frame 8). The stationary malleolar reference pins (MRP), talar pins (TP) and the anterior fibers of the deltoid ligament (dl) are clearly visible. Note that the anterior portion of the deltoid ligament (dl) is lax in dorsiflexion (frame 1). As movement proceeds towards plantar flexion, however, the ligament becomes more taut (frame 8).

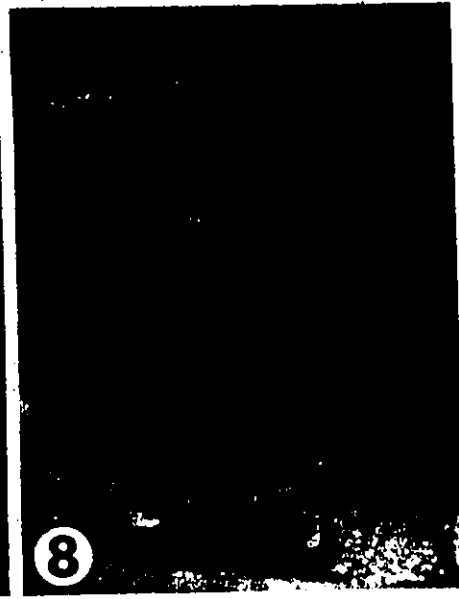
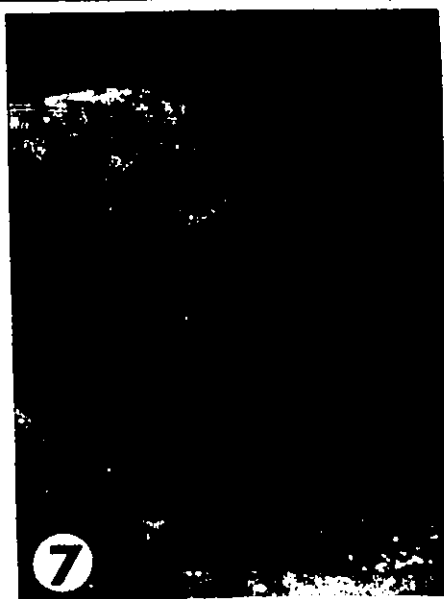
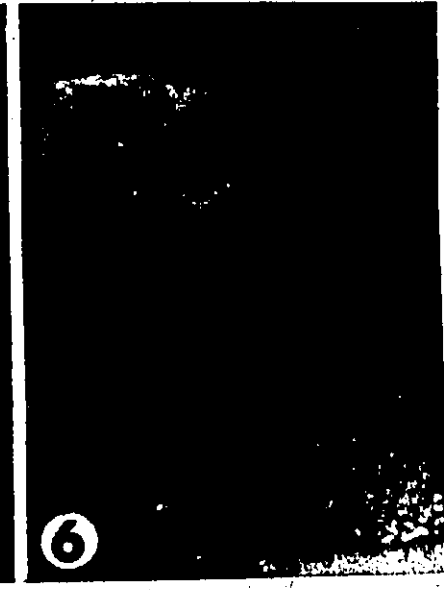
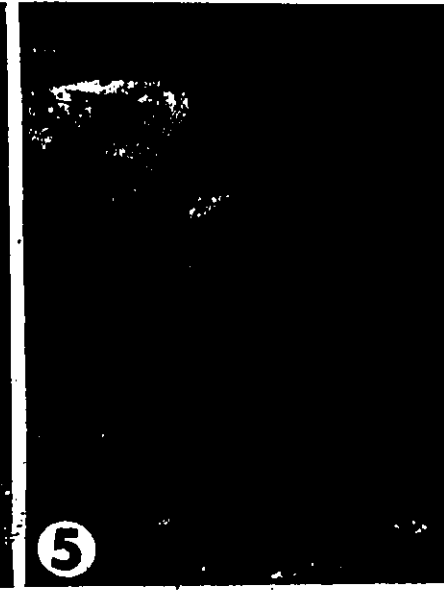
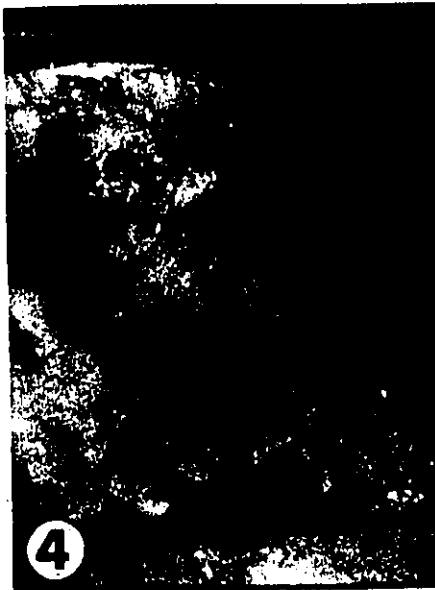


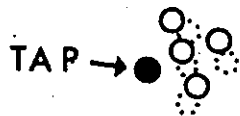
Figure 11

Fig. 11. A superimposition of pin tracings from frame 1) and frame 8 of fig. 10. Stationary pins are indicated by black-filled circles. Only the stationary malleolar reference pins (MRP) and the talar axis pin (TAP) remain stationary and are therefore colored black. The remaining pins from frame 1 are indicated as solid circles while those from frame 8 are indicated as dotted circles. It is readily seen that during movement from dorsiflexion to plantar flexion the nonstationary talar pins rotate clockwise while only the talar axis pin (TAP) remains stationary.

MRP

The label "MRP" is positioned to the right of four solid black dots. The dots are arranged in a small, irregular cluster.

TAP →

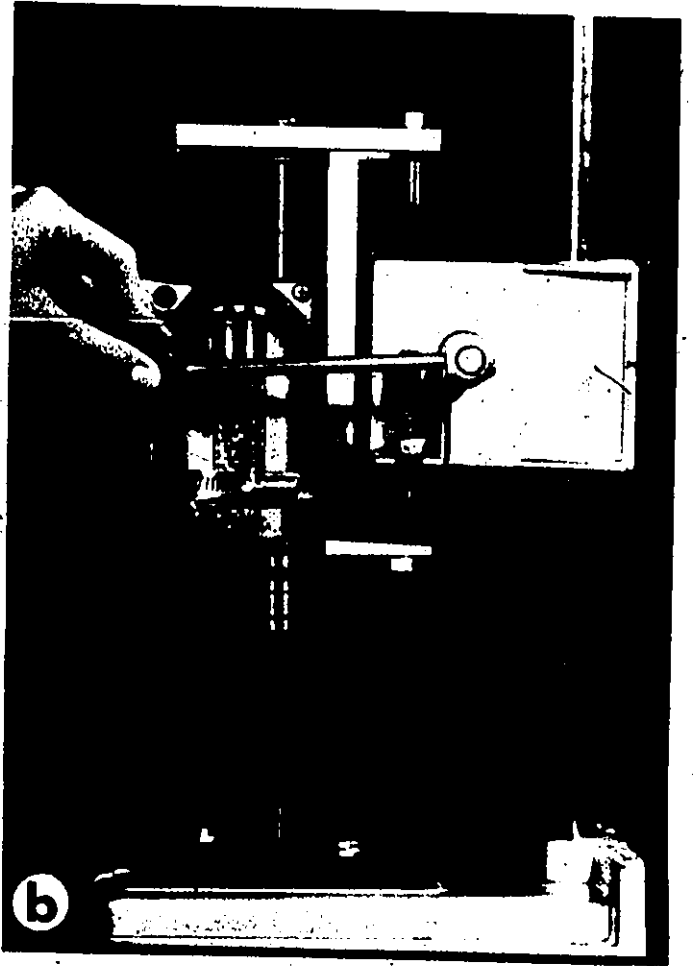
The label "TAP" is followed by a right-pointing arrow. The arrow points to a single solid black dot. This dot is the leftmost member of a small cluster of approximately six open circles.

Figures 12 and 13

Fig. 12a. Electric drill mounted on vertical drill stand with a metal plate and spike bolted to the base of the stand.

Fig. 12b. Electric drill is lowered so that drill point contacts spike.

Fig. 13. Lateral axis point of the ankle is placed directly on the spike and the drill is lowered until the drill point contacts the medial axis point. The drill is engaged and a hole is drilled between the two axis points.



so that a hole was drilled through the talus to connect the two axis points. A small rod of 0.058 inch in diameter was passed through the hole; this then represented the axis about which ankle movement occurred. The relationships of the lateral and medial axis points to the malleoli and the ligaments were noted.

As a final confirmation of a fixed axis, the specimens were X-rayed in plantar and dorsiflexed positions. If the metal rod remained in the same position relative to the stationary tibia, this was taken as final proof of a single fixed axis.

Ankles where no fixed point of rotation could be found were obviously not suited for this method of analysis. In such cases a variable axis was said to exist, and the cause for such a changing axis was determined by the application of the static method of analysis.

B. REFINED STATIC METHOD OF ESTIMATION OF THE ANKLE JOINT AXIS

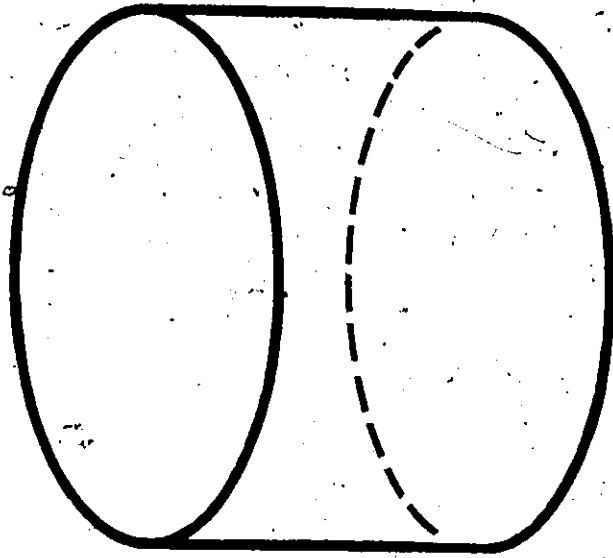
Geometrical descriptions of the articular surface of the talus have appeared both in anatomy texts and in journal literature. Although Goodsir (1868) stated that no joint surface was cylindrical, conical or spherical, subsequent authors disagreed. Bonnin (1950), for example, compared the upper articular surface of the talus to a "quadrant of a cylinder." Steindler (1955) and Lapidus (1963) also described the articular surface of the talus as cylindrical. Cunningham (1964) stated that the trochlea was "shaped like the upper part of a short cylinder placed transversely." Hollinshead (1969) gave a similar account, writing that the trochlea was "shaped somewhat like a short transversely placed segment of a rod..." Such geometrical descriptions of the articular surface of the talus were not, however, based upon actual geometrical analyses. Barnett and Napier (1952) seemed to be the first authors to base their descriptions upon such analyses. In so doing, they studied only the lateral and medial articular profiles of the talus. It must be emphasized that the term "articular profiles"

referred to the lateral and medial edges of the upper surface of the trochlea. It is important that this distinction be made since it is the upper surface of the trochlea which is in continuous contact with the inferior surface of the tibiofibular mortice and which therefore controls ankle movement. Barnett and Napier noted that in some instances the completion of the arcs of the lateral and medial articular profiles of a trochlea yielded identical circles. They wrote that in such cases "the upper articular surface of the talus may be said to resemble part of a cylinder..."

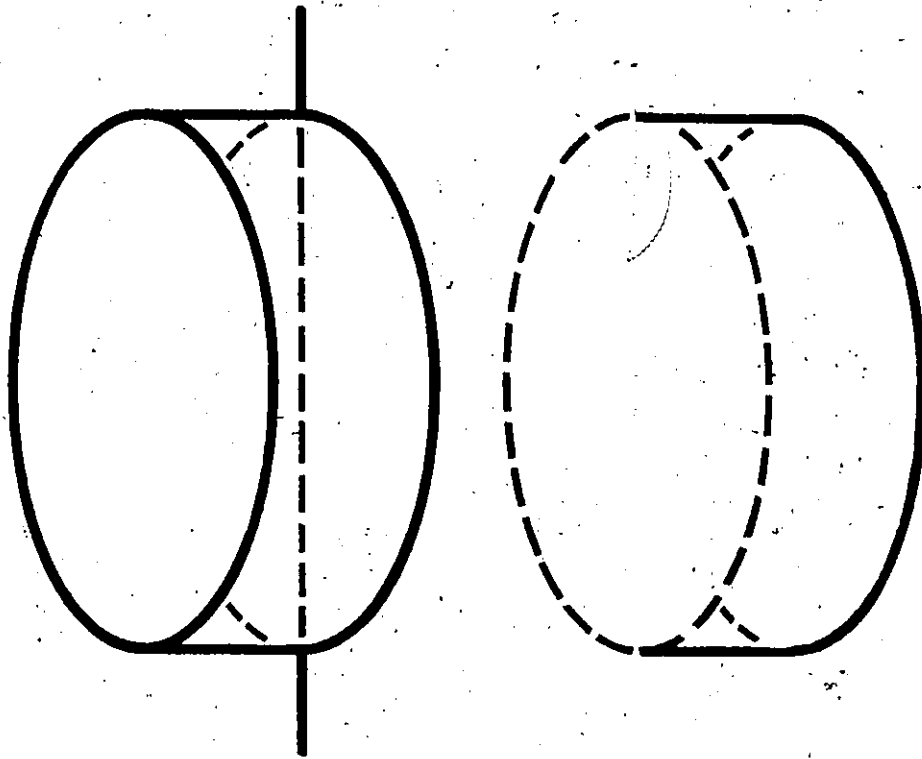
In order to understand the principles involved in such a geometrical study it is necessary to first consider some general properties of cylinders.

1. Theoretical Considerations of the Properties of Cylinders:

A cylinder (fig. 14a) is a "solid whose curved bounding surface is generated by the motion of a straight line at a given angle around two equal circles in parallel planes" (Funk & Wagnalls, 1963). It is clear that the two parallel bases are equal in area and that if a section of the cylinder is made parallel to a base, the cut surface is also of the same area (fig. 14b).



**Fig 14a**



**Fig 14 b**

Consider a cylinder with two parallel circular bases and an axis which passes through the center of each base (fig. 15). Each point ( $P_1, P_2, P_3, P_4, P_5, P_6$ ) on the edges of the cylindrical surface rotates around the axis at a fixed radius ( $r$ ).

If the cylinder is sectioned longitudinally along its axis (fig. 16), it may still be considered to rotate around the axis; each point ( $P_1, P_2, P_3, P_4, P_5, P_6$ ) on the edges of the cylindrical surface will continue to rotate around the axis at the same fixed radius ( $r$ ).

If a longitudinal section of the cylinder is made parallel to the axis but not along it (fig. 17), the cylinder may again be considered to rotate around its original axis. Each point ( $P_1, P_2, P_3, P_4, P_5, P_6$ ) on the edges of the cylindrical surface will therefore continue to maintain its original distance ( $r$ ) from the axis. Looking at this in another way, the axis of such a section of a cylinder can be determined by completing the arcs formed by the curved edges of the two circular bases. The completion of the arcs yields two circles identical in size to the original cylinder bases. A line joining the centers of the two circles

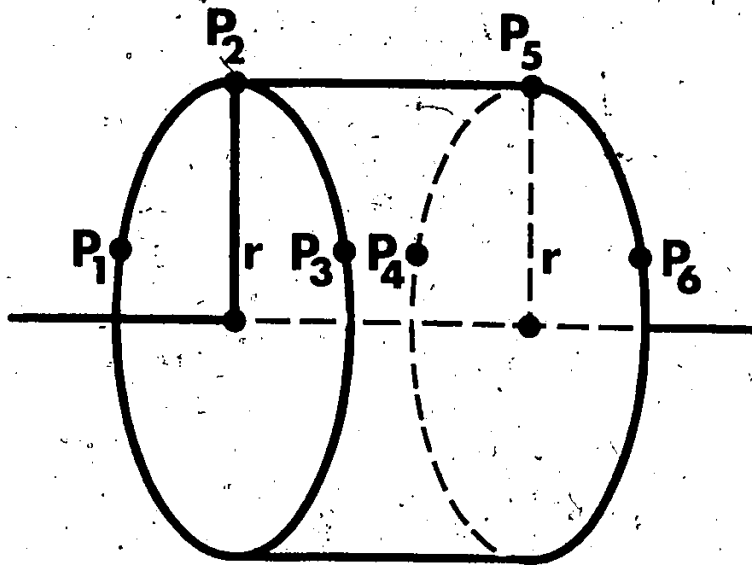


Fig 15

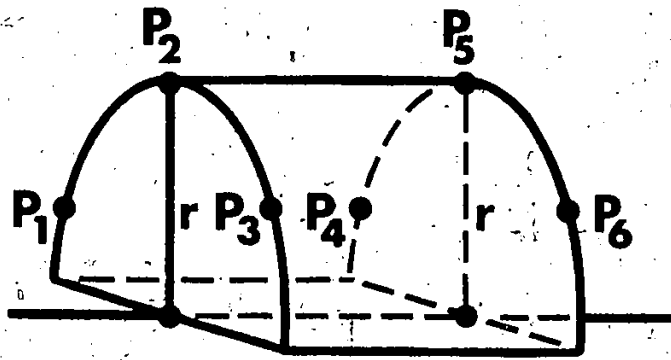


Fig 16

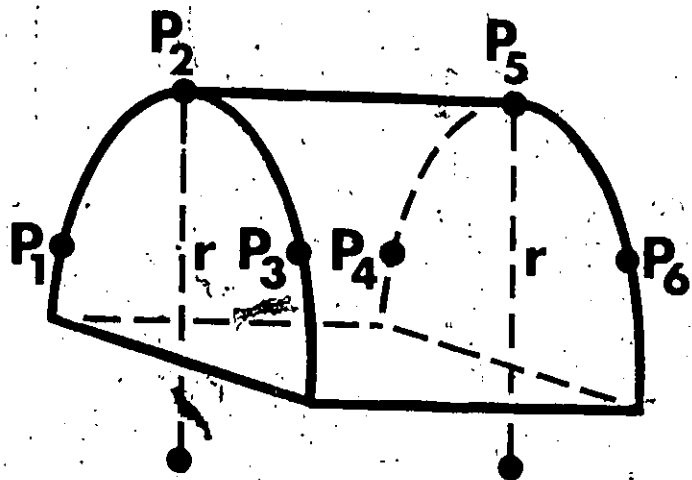


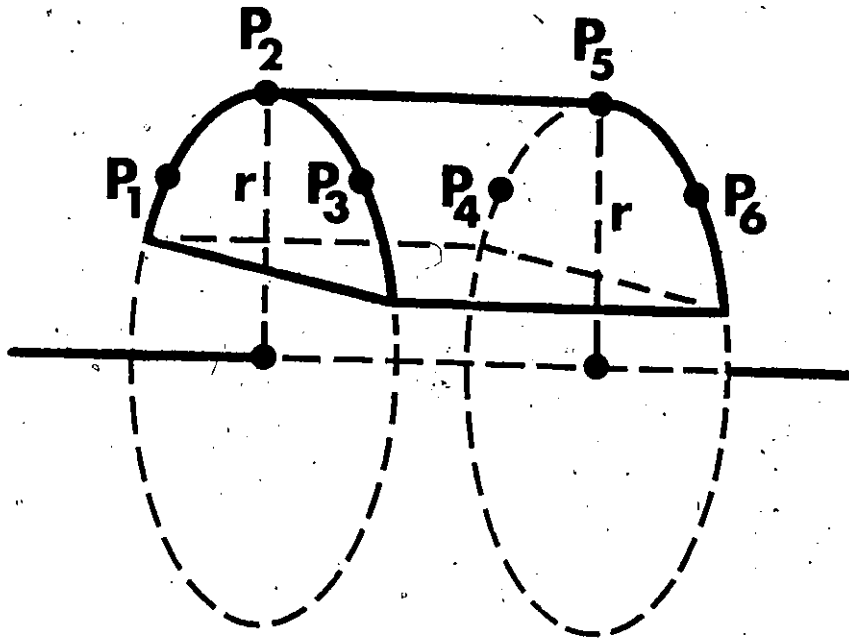
Fig 17

so constructed represents the axis (fig. 18).

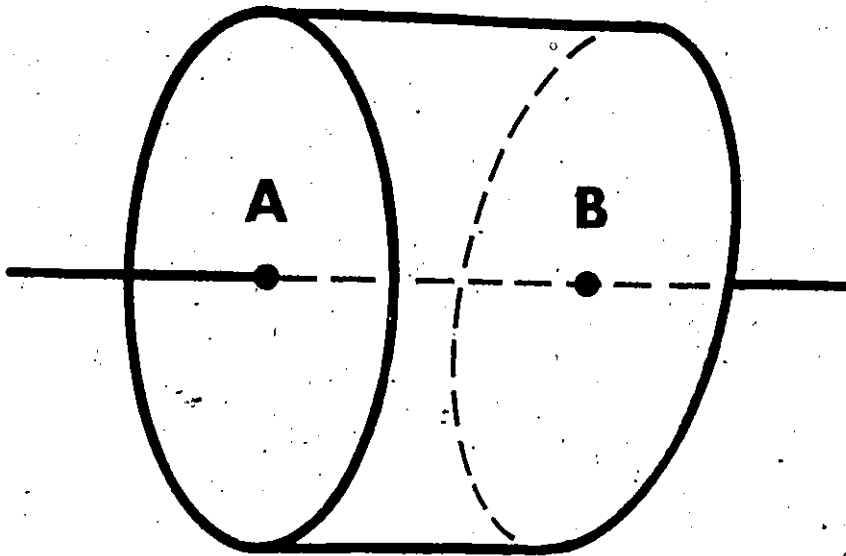
Property 1 of cylinders:

The axis of any longitudinal section of a cylinder whose original bases were circular may be determined by completing the arcs of its curved edges and joining the centers of the circles so formed. This axis will be found to be perpendicular to both bases.

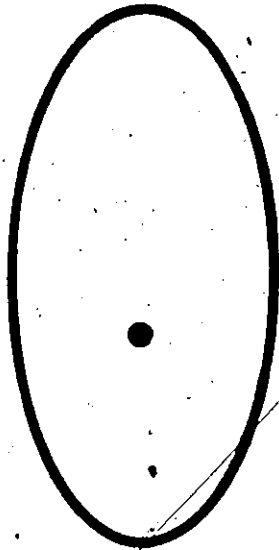
The above method, however, can only be used accurately for determining the original axis of a section of a cylinder whose original bases were circular. Consider now a cylindrical object such as that shown in fig. 19. Base A is circular, but base B, which has been cut obliquely to base A, does not present a circular edge (fig. 20). The axis clearly passes only through the center of base A. If a longitudinal section of such an object is made (fig. 21), the axis point of base A may be determined according to Property 1 by completing the arc of its curved edge. Base B clearly does not lend itself to such determination.



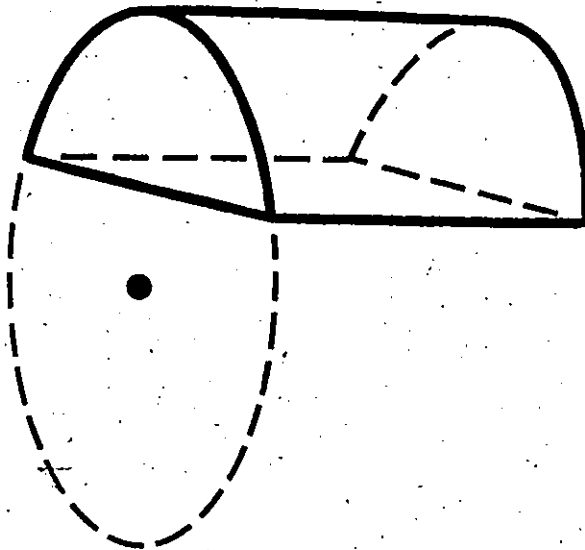
**Fig 18**



**Fig 19**



**Fig 20**



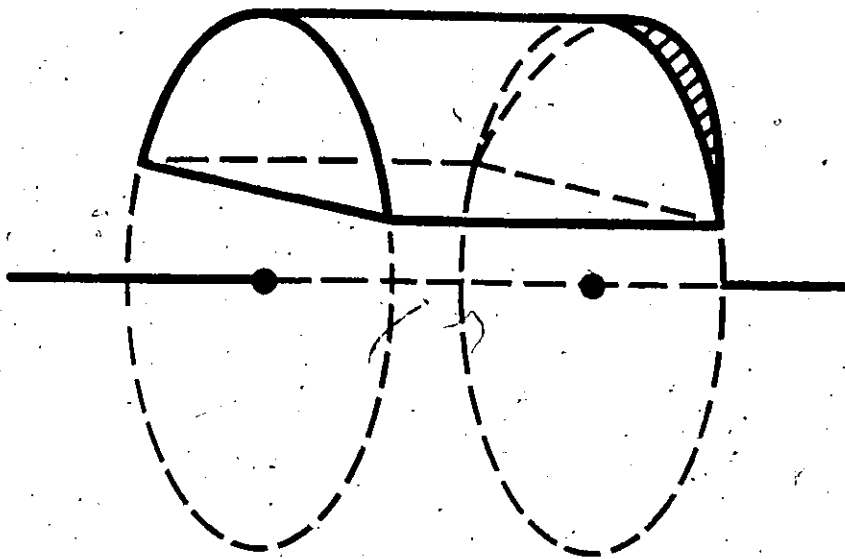
**Fig 21**

If, however, an oblique wedge is removed by cutting the cylindrical object parallel to base A (fig. 22), completion of the edge of the new surface will give a circle whose center represents the other axis point (Property 1). It is clear that if a base is circular it is perpendicular to the axis, and if it is not circular it is not perpendicular to the axis.

Property 2 of cylinders:

If, upon examination of the bases of a longitudinal section of a cylinder, the edge of a base is an arc of a circle, then completion of such an arc produces a circle whose center is an axis point. Such a base will be found to be perpendicular to the axis. If, on the other hand, the edge of a base is not an arc of a circle, this base must, by definition, be oblique to the circular base and cannot be perpendicular to the axis.

After inspecting the edges of the bases and determining whether or not they are parts of circles,



**Fig 22**

Property 1 or Property 2 of cylinders may then be applied to determine the axis points of the cylinder.

From the foregoing conclusions it is evident that the only type of trochlea to which Property 1 of cylinders may be applied is the type illustrated in fig. 23a. The completion of its edges will produce two circles of equal radii (fig. 23b and c). This means that the bases are perpendicular to the axis.

If, on the other hand, one articular edge of a talus is not an arc of a circle (fig. 24a), it follows (according to Property 2 of cylinders) that this edge is oblique to the circular base and is not perpendicular to the axis (fig. 24b). The trochlea of such a talus, then, may be considered, from the point of view of its articular edges, to be a section of a cylinder with one oblique base (as in fig. 19). The oblique edge cannot be used to determine the axis of rotation unless a wedge is removed, as shown in fig. 24c. The new articular edge, now parallel to the other base, is an arc of a circle whose center represents the axis point (fig. 24d).

-42-

Figure 23

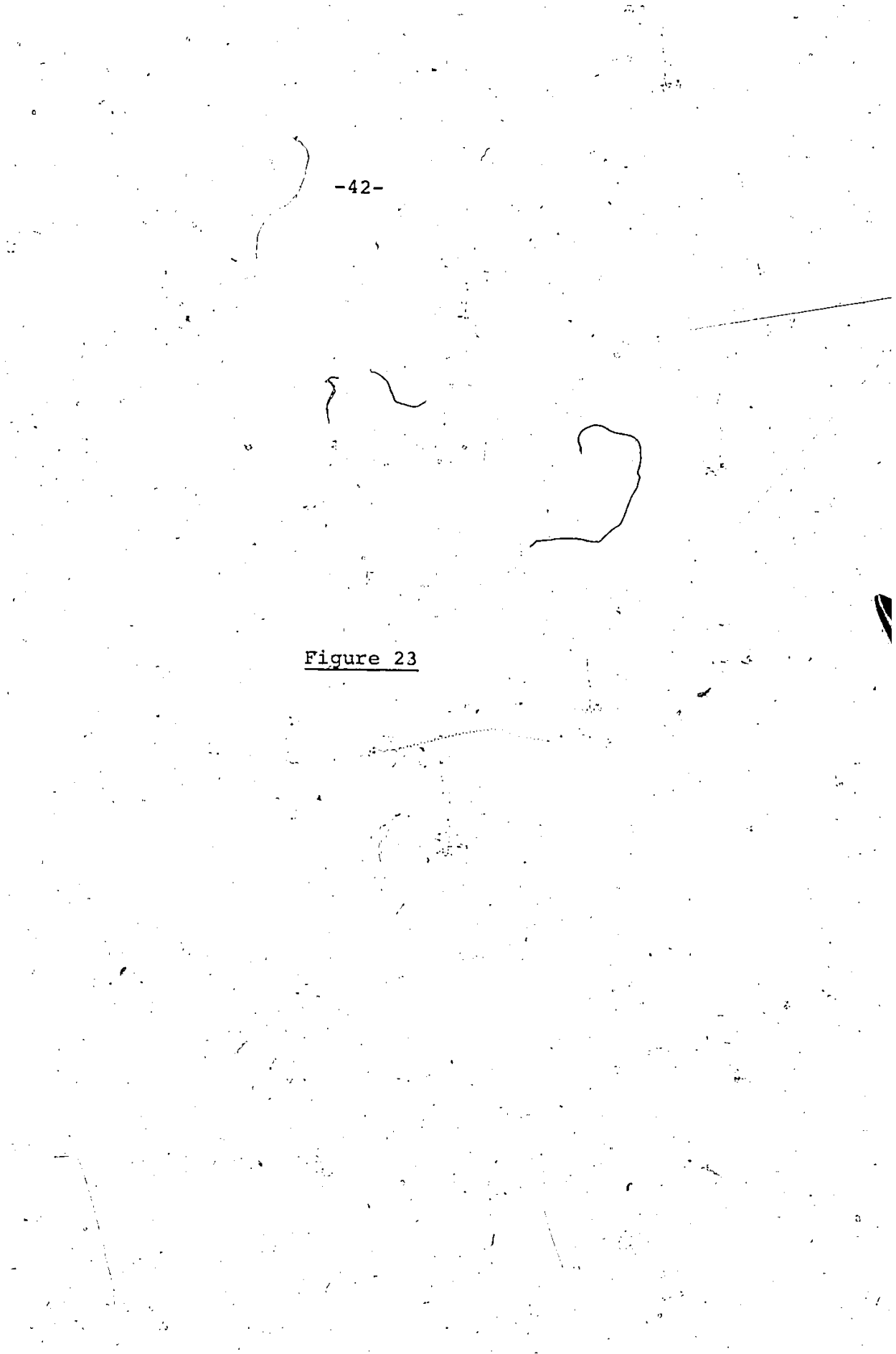


Illustration of a cylindrical trochlea with  
circular and parallel bases.

Fig. 23a.

The medial and lateral edges of the trochlea are parallel to each other, being distance 'a' apart throughout their entire lengths.

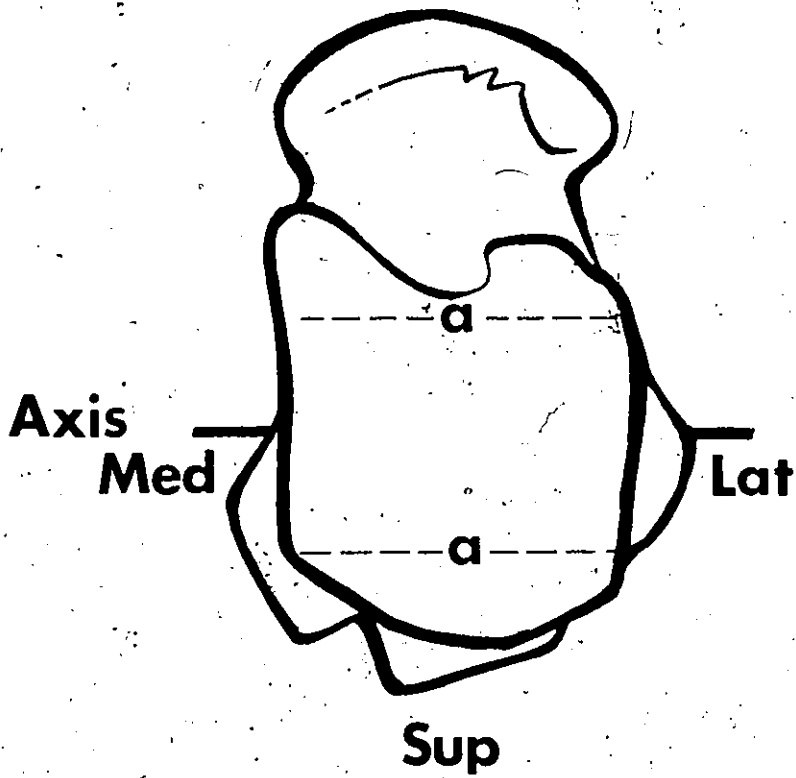
Fig. 23b.

The lateral edge is an arc of a circle whose center is an axis point.

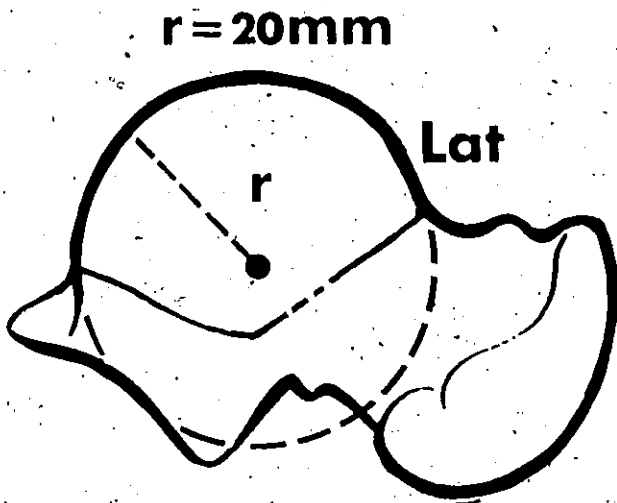
Fig. 23c.

The medial edge is an arc of a circle of the same radius; its center is also an axis point.

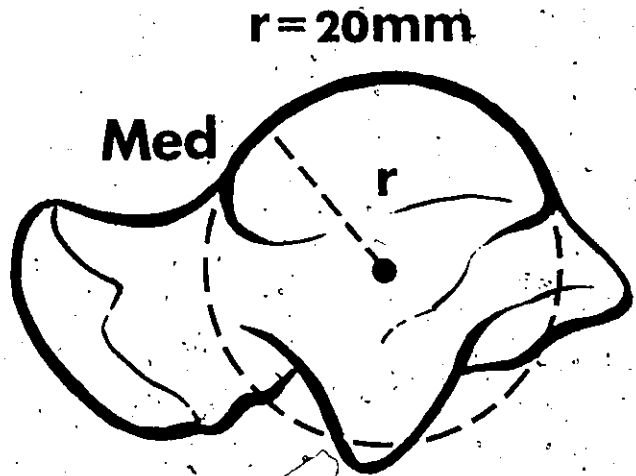
Since the lateral and medial edges are both parallel to each other and circular, they are perpendicular to the axis. Such a trochlea may thus be called a cylindrical type of trochlea.



**Fig 23 a**



**Fig 23 b**



**Fig 23 c**

Figure 24

Illustration of a cylindrical trochlea with one noncircular oblique base.

Fig. 24a.

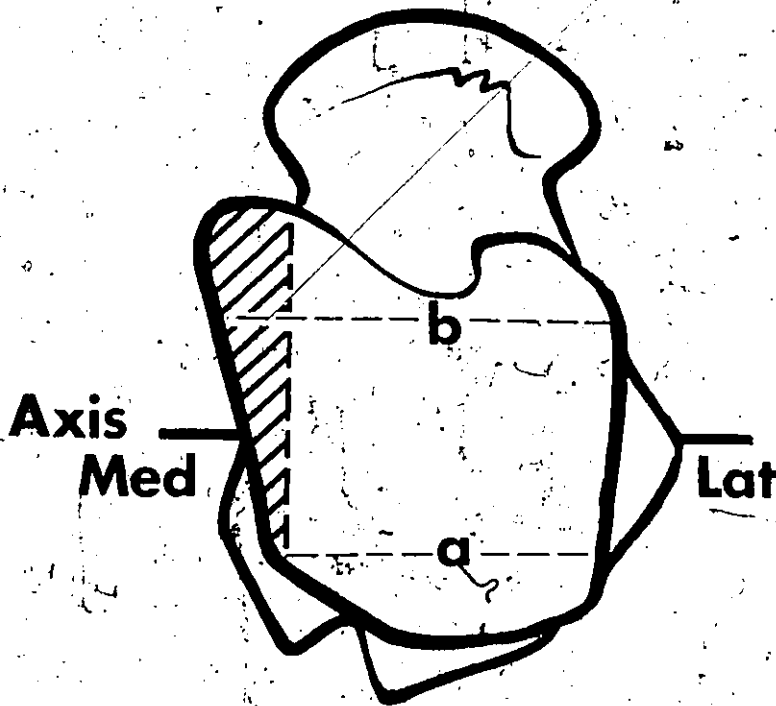
The medial edge of the trochlea is not an arc of a circle.

Fig. 24b.

The medial edge is oblique to the lateral edge and varies in distance from it, being a greater distance from it anteriorly ('b') than posteriorly ('a').



**Med**  
**Fig 24 a**



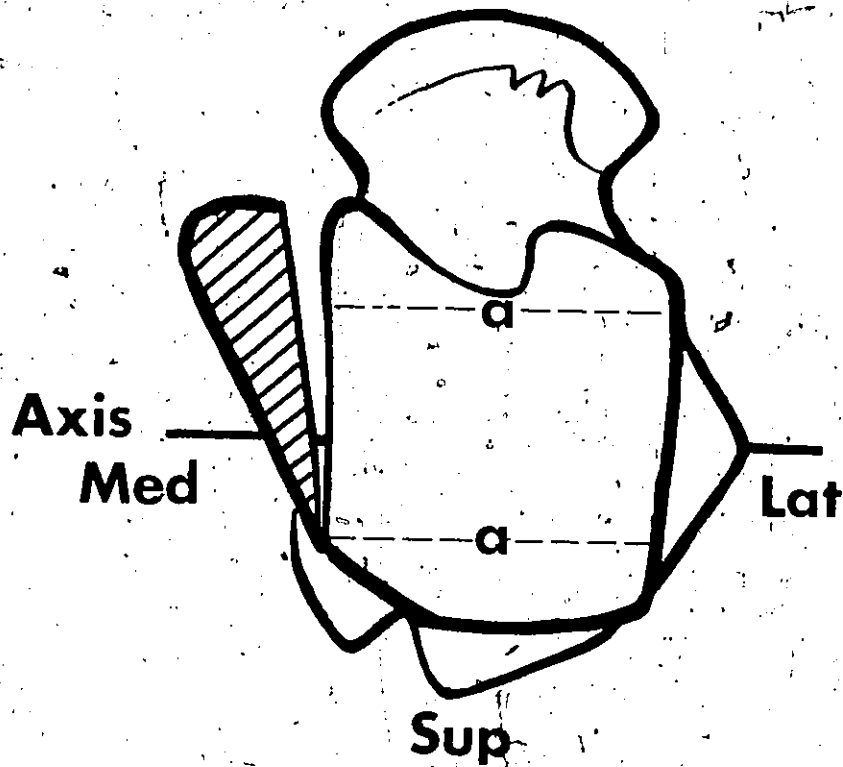
**Sup**  
**Fig 24 b**

Fig. 24c.

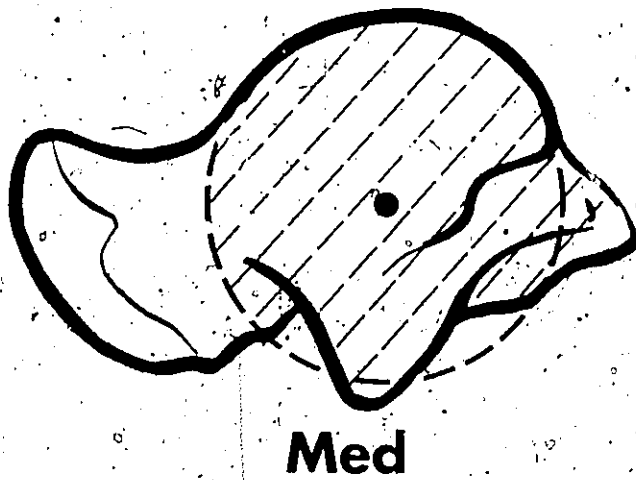
The obliquity of the medial edge is eliminated by removing a wedge so that new medial edge is parallel to the lateral. The two edges are now distance 'a' apart from each other throughout their entire lengths.

Fig. 24d.

The new medial edge is now an arc of a circle whose center is an axis point.



**Fig 24 c**



**Fig 24 d**


Similarly, if part of an articular edge is not an arc of a circle this part must be oblique to the axis and cannot be used accurately in determining an axis point (fig. 25a, b and c). The only accurate way of using the entire extent of the edges of such a trochlea would be to remove both lateral and medial oblique slices in such a way as to produce two parallel and circular edges (fig. 25d, e and f).

If only the edges of the bases of trochleae are taken into consideration the conclusion might be reached that trochleae could be described either as sections of cylinders (fig. 23), as cylinder sections with a noncircular oblique base or bases (fig. 24) or as cylinder sections with an oblique section or sections missing posteriorly (fig. 25). This, however, is not entirely accurate. The trochlea of tali are not, in fact, generated by a straight line, which is characteristic of cylinders, but by a curved line (fig. 26). It would be more precise, therefore, to describe each trochlea as a section of a pulley (fig. 27). Property 1 and Property 2 of cylinders can still be applied to a longitudinal section of a pulley. The trochlea of the talus shown in fig. 23 can now be more accurately described as a section of a pulley whose articular edges are parallel.

Figure 25

Illustration of a cylindrical trochlea with circular and parallel bases, but with oblique sections missing posteriorly from each edge.

Fig. 25a.



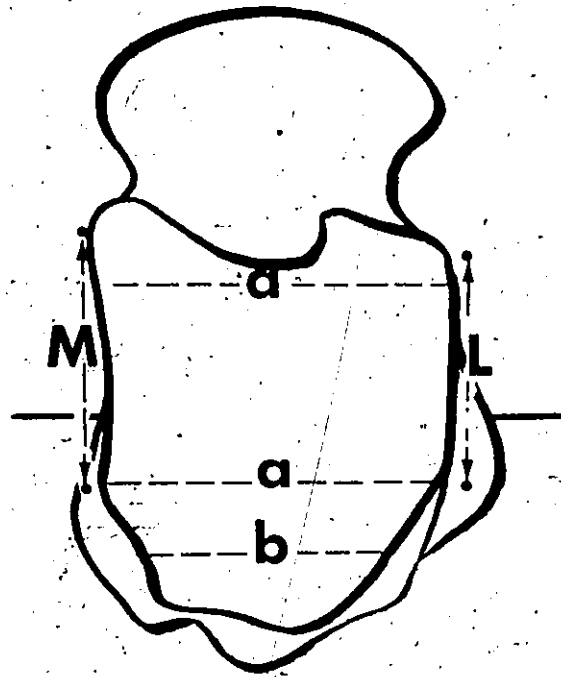
The medial and lateral edges of the trochlea are parallel to each other throughout only part of their lengths, being distance 'a' apart for this portion. Posteriorly both edges veer towards the midline of the trochlea 'b'.

Fig. 25b.

Completion of the arc of the lateral edge is slightly inaccurate in determining an axis point.

Fig. 25c.

Completion of the arc of the medial edge is also inaccurate in determining an axis point.



Sup

Fig 25 a



Fig 25 b

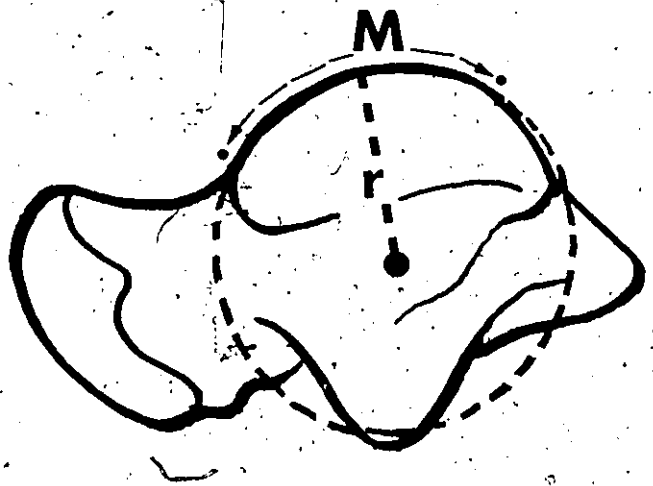


Fig 25 c

Fig. 25d.

The posterior oblique sections are eliminated by cutting each edge in such a way that the new medial and lateral edges are parallel to each other and are the same distance apart from each other throughout their entire lengths.

Fig. 25e.

The new lateral edge is now an arc of a circle whose center is an axis point.

Fig. 25f.

The new medial edge is an arc of a circle of the same radius whose center represents an axis point.

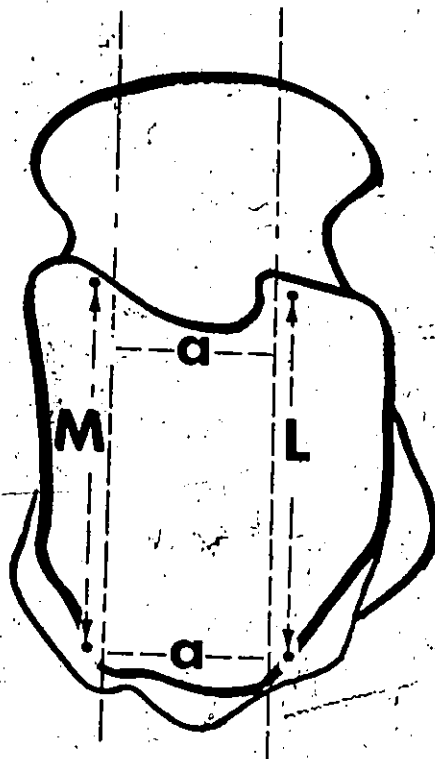


Fig 25 d

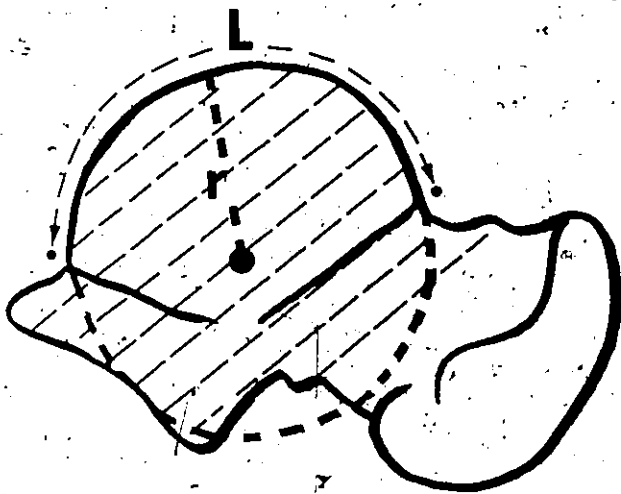


Fig 25 e

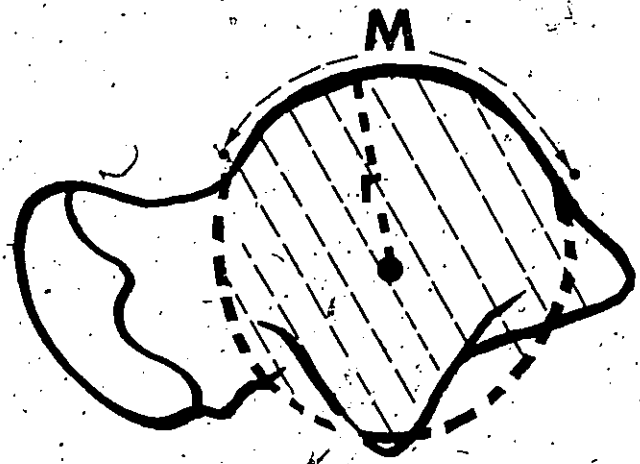
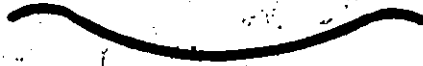
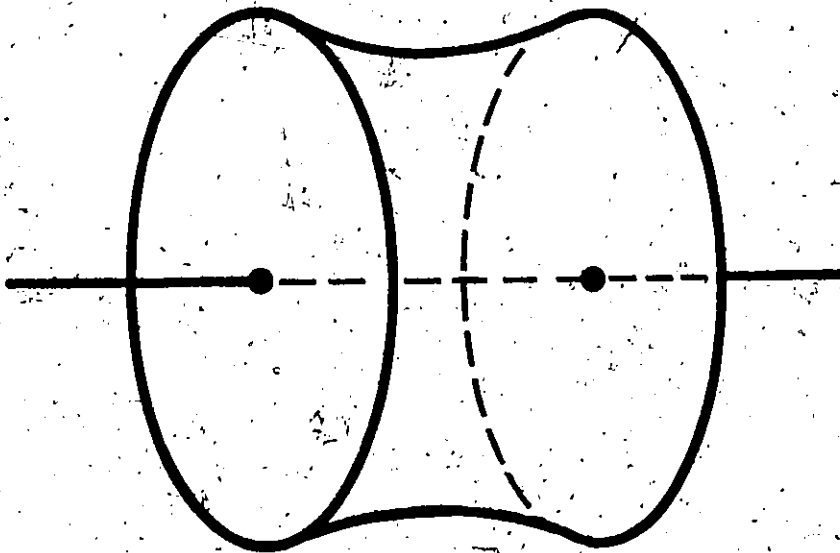


Fig 25 f



**Fig 26**

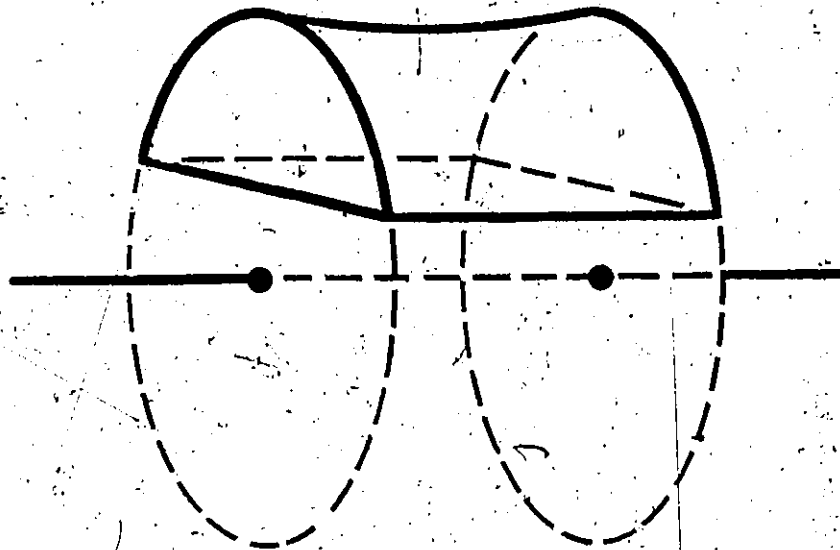


**Fig 27**

The edges are arcs of circles and can therefore be used to determine the axis points (fig. 28). A trochlea conforming to those geometrical standards illustrated in fig. 23 will now be called a cylindrical pulley-shaped trochlea with circular and parallel bases.

The trochlea of the talus shown in fig. 24 can be more accurately described as a section of a pulley having one articular edge oblique to the circular base and therefore not perpendicular to the axis. A trochlea conforming to those geometrical standards shown in fig. 24 will now be called a cylindrical pulley-shaped trochlea with one noncircular oblique base.

Similarly, the trochlea of the talus shown in fig. 25 may be more accurately described as a section of a pulley having only part of its articular edges parallel to each other. Posteriorly there is an oblique section missing from each edge so that these portions of the edges are no longer parallel to each other and may not therefore be used in geometrical analysis. A trochlea conforming to those standards illustrated in fig. 25 will now be called a cylindrical pulley-shaped trochlea with circular and parallel bases, but with oblique sections missing posteriorly from each edge.



**Fig 28**

Although Barnett and Napier (1952) found some tali to resemble cylinders, they described the articular surface of most tali as "consisting of two truncated cones lying side by side, apex to base..." Close (1964) reported a single cone-shaped articular surface with the apex of the truncated cone located medial to the ankle. In order to understand the principles involved in such a geometrical study it is necessary to first consider some general properties of cones.

2. Theoretical Considerations of the Properties of Cones:

A cone is a "solid generated by the rotation of a right triangle about one of its legs as axis" (Webster, 1951). It has a circular base which tapers to a vertex. If the vertex is removed by cutting it parallel to the base, the cone becomes truncated with two parallel but unequal circular ends.

Consider a truncated cone with its base ( $C_1$ ) and truncated portion ( $C_2$ ) parallel to each other (fig. 29). According to the definition of a cone,  $C_1$  must be larger than  $C_2$ . The axis of such a cone passes through the center of the circular base ( $C_1$ ) and through the center of the circular truncated end ( $C_2$ ).

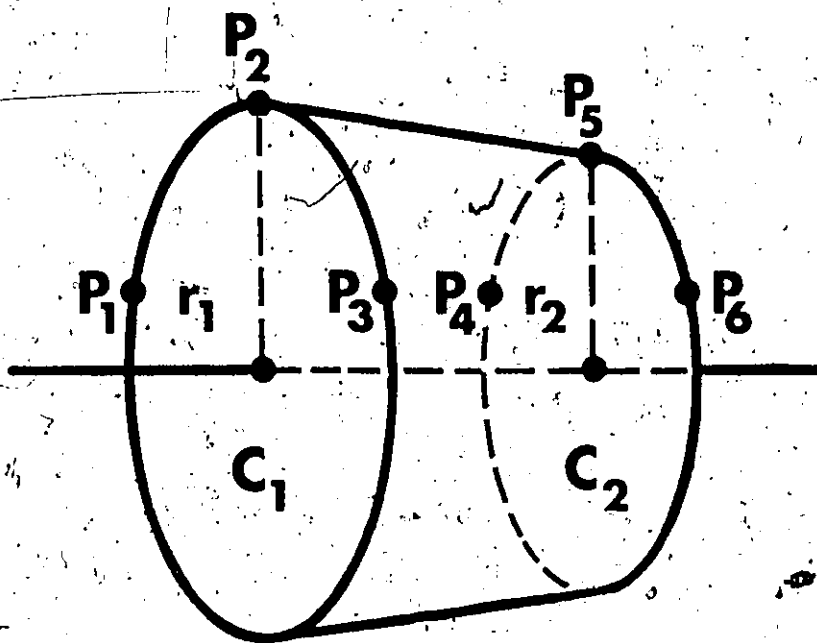


Fig 29

Both of these circular surfaces are perpendicular to the axis. Each point ( $P_1, P_2, P_3, P_4, P_5, P_6$ ) on the edges of the conical surface rotates around the axis at a fixed radius ( $r_1$  or  $r_2$ ).

If the truncated cone is sectioned longitudinally along its axis (fig. 30), it may still be considered to rotate around the axis; each point ( $P_1, P_2, P_3, P_4, P_5, P_6$ ) on the edges of the conical surface will continue to rotate around the axis at the same fixed radius ( $r_1$  or  $r_2$ ).

If a longitudinal section of a truncated cone is made parallel to the axis but not along it (fig. 31), the truncated cone may again be considered to rotate around its original axis. Each point ( $P_1, P_2, P_3, P_4, P_5, P_6$ ) on the edges of the conical surface will therefore continue to maintain its original distance ( $r_1$  or  $r_2$ ) from the axis. Looking at this in another way, the axis of any such section of a truncated cone can be determined by completing the arcs formed by the curved edges of the circular base and the circular truncated end. The completion of the arcs yields two circles identical in size to the original cone base and truncated end. A line joining the centers of the two circles so constructed represents the axis (fig. 32).

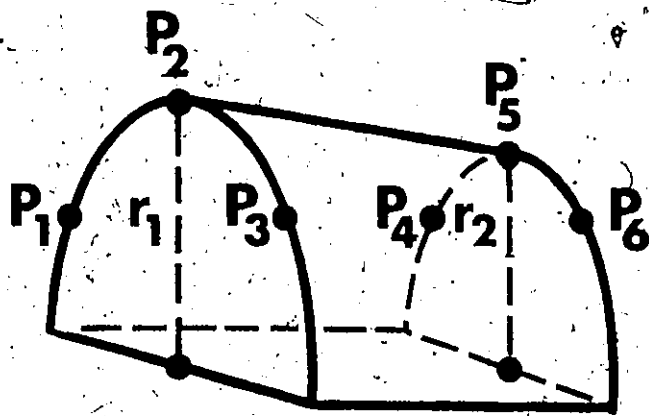


Fig 30

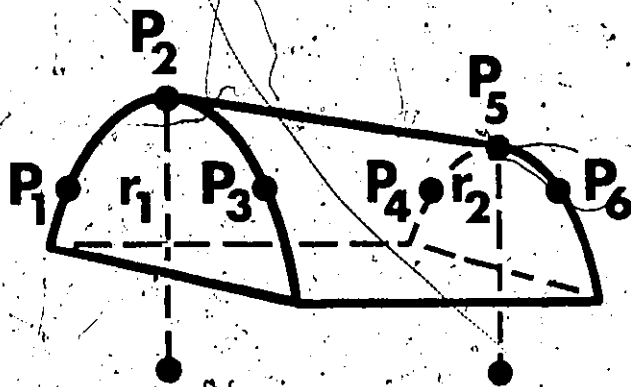
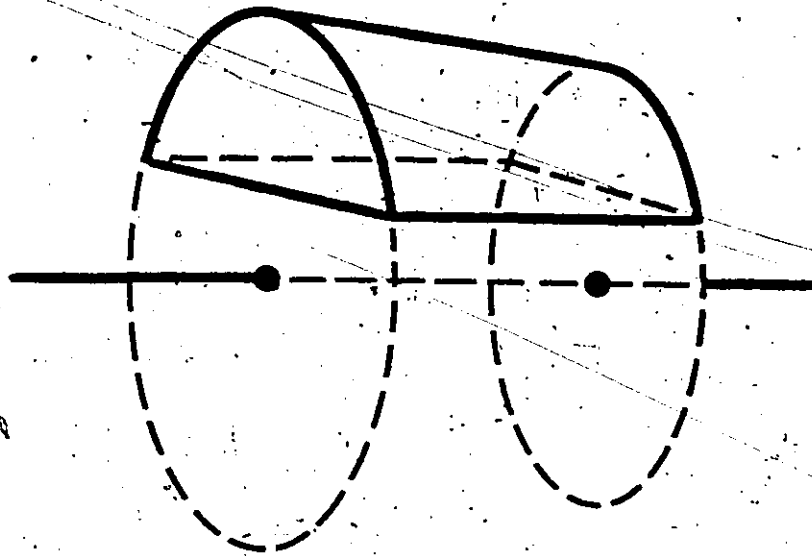


Fig 31

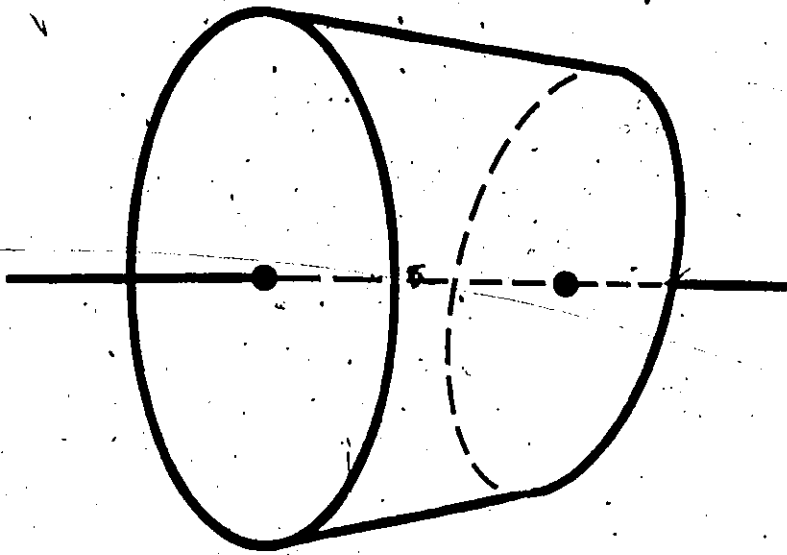


**Fig 32**

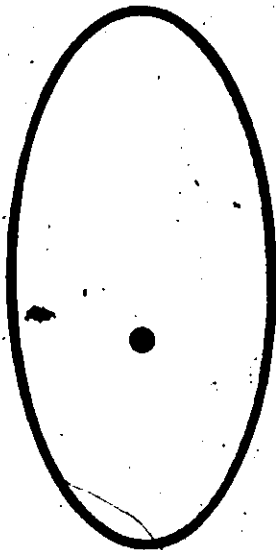
Property 1 of cones:

The axis of any longitudinal section of a truncated cone whose original base and truncated end were circular may be determined by completing the arcs of its curved edges and joining the centers of the circles so formed. This axis will be found to be perpendicular to the base and to the truncated end.

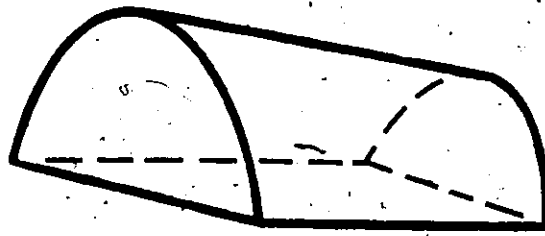
The above method, however, can only be used accurately for determining the original axis of a section of a truncated cone whose original base and truncated end were circular. Consider now a truncated conical object such as that shown in fig. 33. The base is circular, but the truncated end, which has been cut obliquely to the base, does not present a circular edge (fig. 34). The axis clearly passes only through the center of the base. If a longitudinal section of such an object is made (fig. 35), the axis point of the base may be determined according to Property 1 of cones by completing the arc of its curved edge (fig. 36). The truncated end clearly



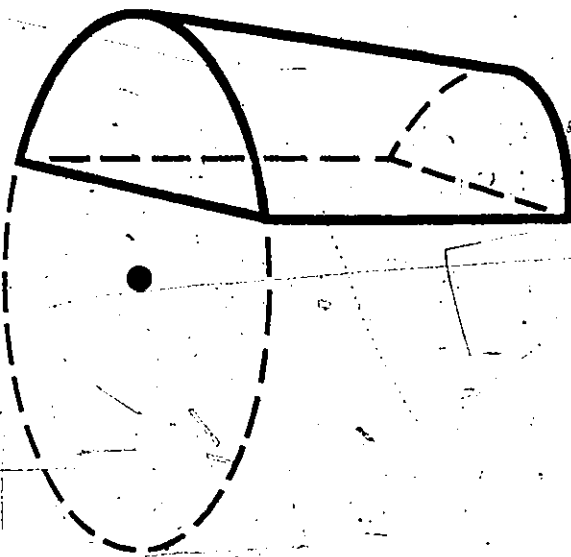
**Fig 33**



**Fig 34**



**Fig 35**

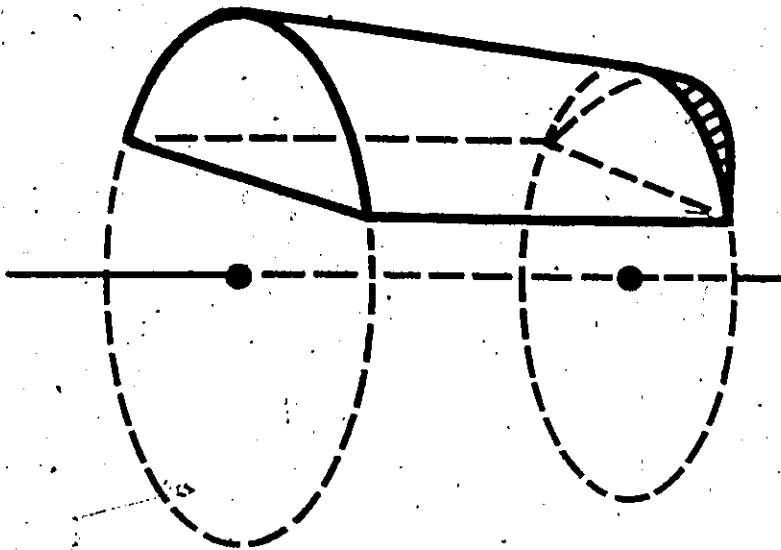


**Fig 36**

does not lend itself to such determination. If, however, an oblique wedge is removed by cutting the truncated conical object parallel to the base (fig. 37) completion of the edge of the new surface will give a circle whose center represents the other axis point (Property 1 of cones). It is clear that if a base or truncated end is circular it is perpendicular to the axis, and if one is not circular it is not perpendicular to the axis.

Property 2 of cones:

If, upon examination of the base and truncated end of a longitudinal section of a truncated cone, the edge of the base or truncated end is an arc of a circle, then completion of such an arc produces a circle whose center is an axis point. Such a base or truncated end will be perpendicular to the axis. If, on the other hand, the edge of the base or truncated end is not an arc of a circle, this must, by definition, be oblique to the other circular end and cannot be perpendicular to the axis.



**Fig 37**

After inspecting the edges of the base and truncated end and determining whether or not they are parts of circles, Property 1 or Property 2 of cones may then be applied to determine the axis points of the truncated cone.

From the foregoing conclusions it is evident that the only type of trochlea to which Property 1 of cones may be applied is the type illustrated in fig. 38a. The completion of its edges will produce two circles of different radii (fig. 38b and c). This means that the base and truncated end are perpendicular to the axis.

If, on the other hand, one articular edge of a trochlea, be it the base or the truncated end, is not an arc of a circle (fig. 39a), it follows (according to Property 2 of cones) that this edge is oblique to the other circular end and is not perpendicular to the axis (fig. 39b). The trochlea of such a talus, then, may be considered, from the point of view of its articular edges, to be a section of a truncated cone with either an oblique base or an oblique truncated end (as in fig. 33). The oblique edge cannot be used to determine the axis point unless a wedge is removed, as shown in fig. 39c. The new articular edge, now parallel to the other end, is an arc of a

Figure 38



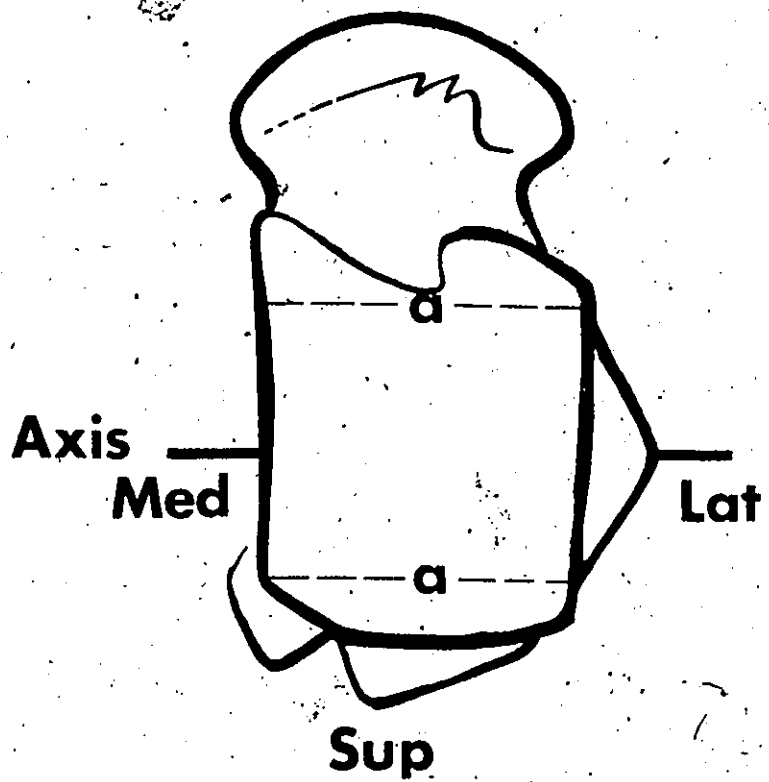
Illustration of a conical trochlea with a circular and parallel base and truncated end.

Fig. 38a. The medial and lateral edges of the trochlea are parallel to each other, being distance 'a' apart throughout their entire lengths.

Fig. 38b. The lateral edge is an arc of a circle whose center is an axis point.

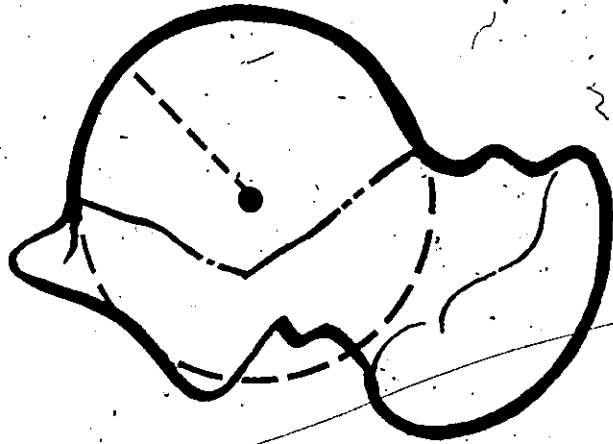
Fig. 38c. The medial edge is an arc of a circle of a different radius; its center is also an axis point.

Since the lateral and medial edges are both parallel to each other and circular, they are perpendicular to the axis. Such a trochlea may thus be called a conical type of trochlea.



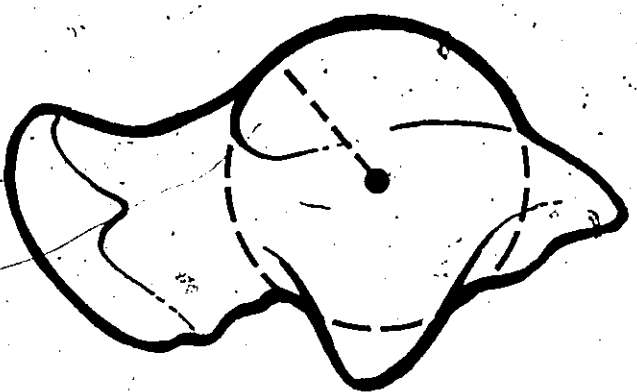
**Fig 38 a**

**r = 20mm**



**Lat**  
**Fig 38 b**

**r = 15mm**



**Med**  
**Fig 38 c**

Figure 39

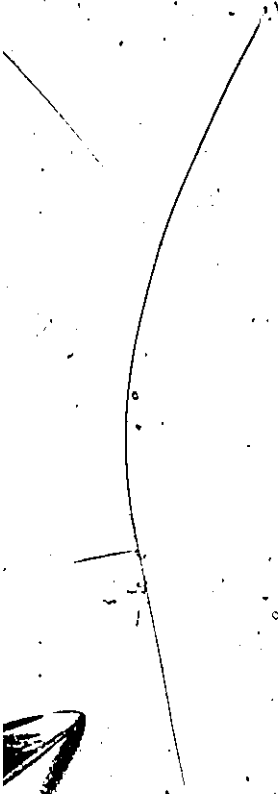
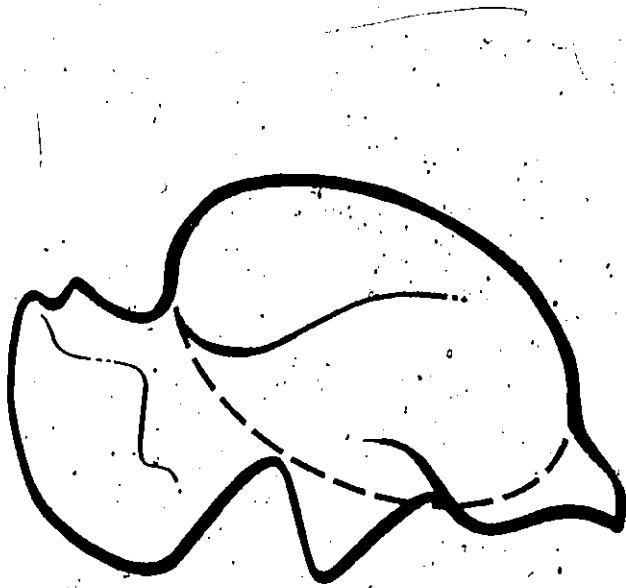


Illustration of a conical trochlea with either a noncircular oblique base or a noncircular oblique truncated end.

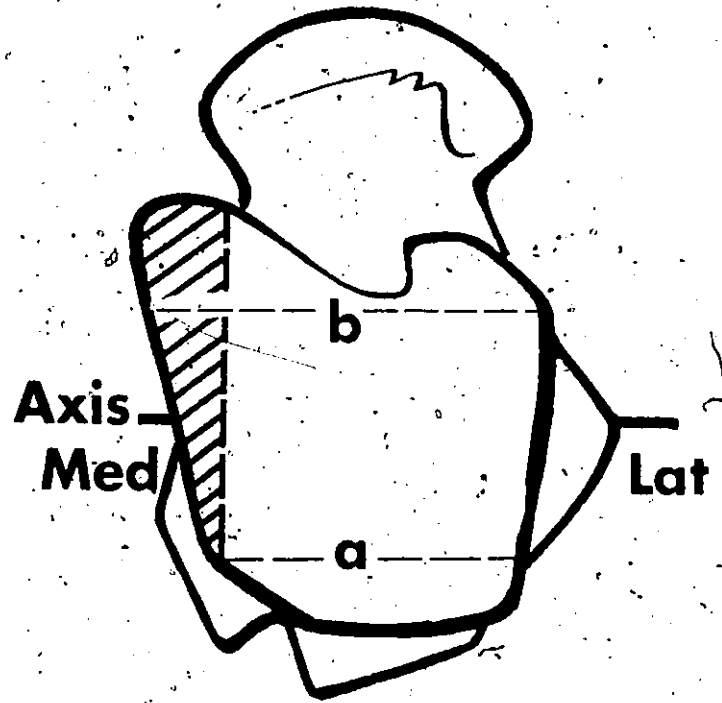
Fig. 39a. The medial edge of the trochlea is not an arc of a circle.

Fig. 39b. The medial edge is oblique to the lateral edge and varies in distance from it, being a greater distance from it anteriorly ('b') than posteriorly ('a').

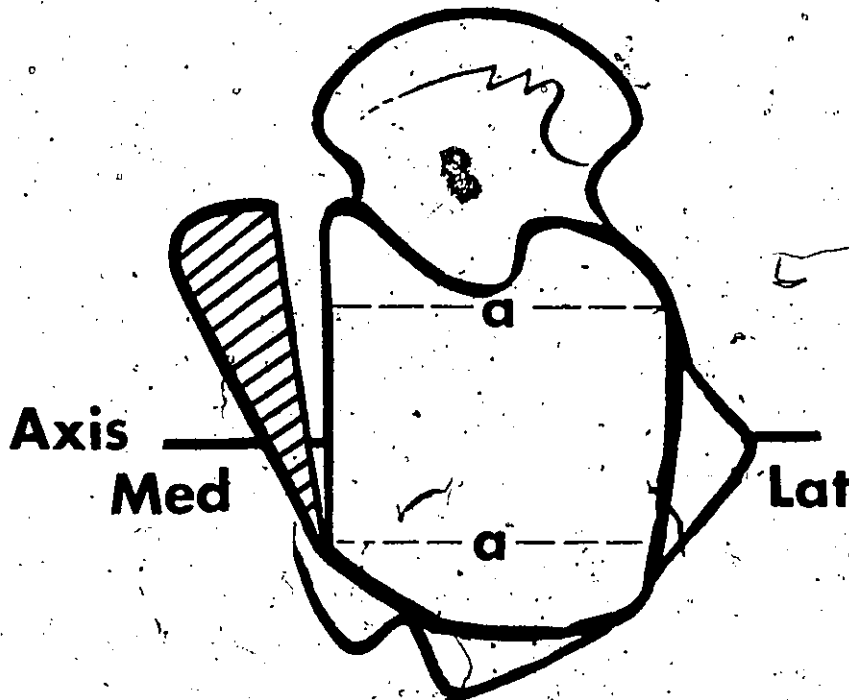
Fig. 39c. The obliquity of the medial edge is eliminated by removing a wedge so that the new medial edge is parallel to the lateral. The two edges are now distance 'a' apart from each other throughout their entire lengths. The new medial edge will then be an arc of a circle whose center is an axis point.



**Fig 39a**



**Fig 39b**



**Fig 39 c**

circle whose center represents the axis point.

Similarly, if part of an articular edge is not an arc of a circle this part must be oblique to the axis and cannot be used accurately in determining an axis point (fig. 40a, b and c). The only accurate way of using the entire extent of the edges of such a trochlea would be to remove both lateral and medial oblique slices in such a way as to produce two parallel and circular edges (fig. 40d, e and f).

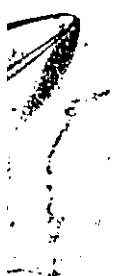
If only the edges of the base and truncated end of trochleae are taken into consideration, the conclusion might be reached that trochleae could be described either as sections of cones (fig. 38), as cone sections with a noncircular oblique base or truncated end (fig. 39) or as cone sections with an oblique section or sections missing posteriorly from the edge of the base and truncated end (fig. 40). This, however, is not entirely accurate. The trochlea of tali are not, in fact, generated by a straight line, which is characteristic of cones, but by a curved line (fig. 41). It would be more precise, therefore, to describe each trochlea as a section of a cone-shaped pulley (fig. 42). Property 1 and Property 2 of cones can still be applied

Figure 40



Illustration of a conical trochlea with circular  
and parallel base and truncated end, but with  
oblique sections missing posteriorly from each edge.

Fig. 40a.



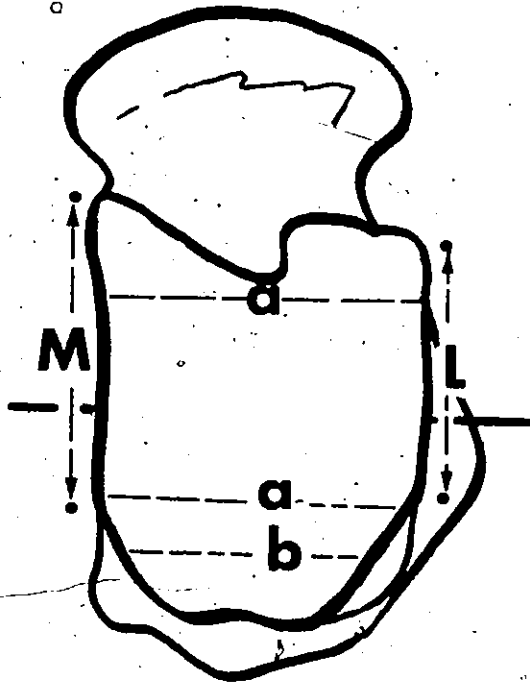
The medial and lateral edges of the trochlea are parallel to each other throughout only part of their lengths, being distance 'a' apart for this portion. Posteriorly both edges veer towards the midline of the trochlea, 'b'.

Fig. 40b.

Completion of the arc of the lateral edge is slightly inaccurate in determining an axis point.

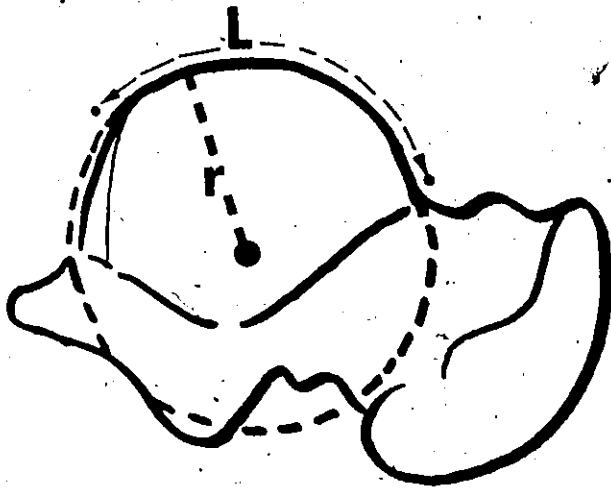
Fig. 40c.

Completion of the arc of the medial edge is also inaccurate in determining an axis point.



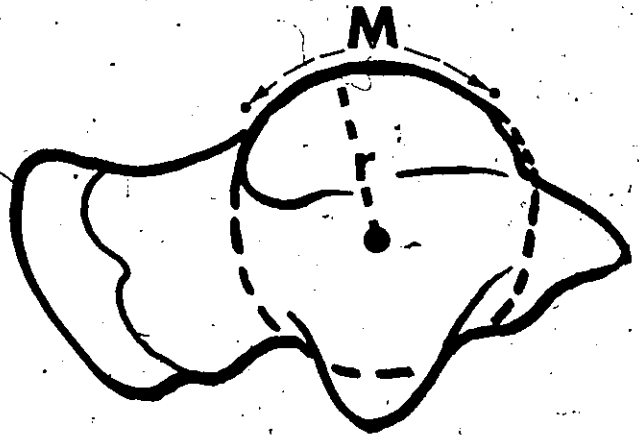
**Fig 40 a**

**r=20 mm**



**Fig 40 b**

**r=15 mm**



**Fig 40 c**

Fig. 40d.

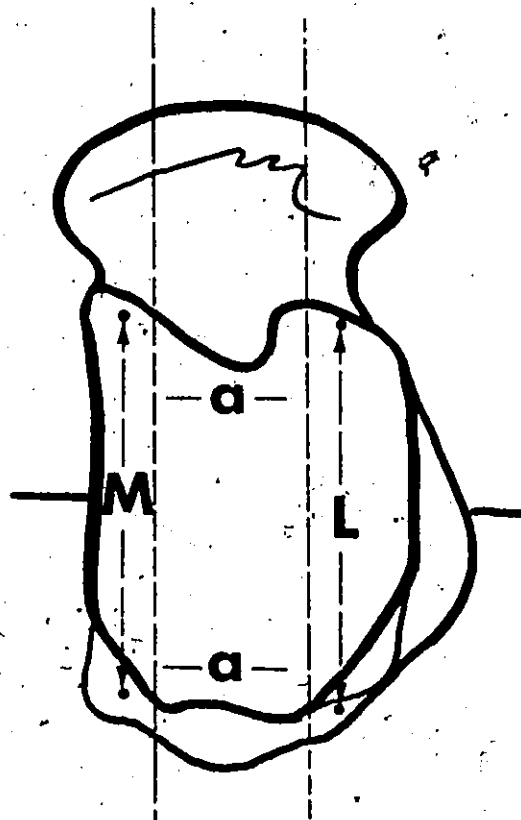
The posterior oblique sections are eliminated by cutting each edge in such a way that the new medial and lateral edges are parallel to each other and are the same distance apart from each other throughout their entire lengths.

Fig. 40e.

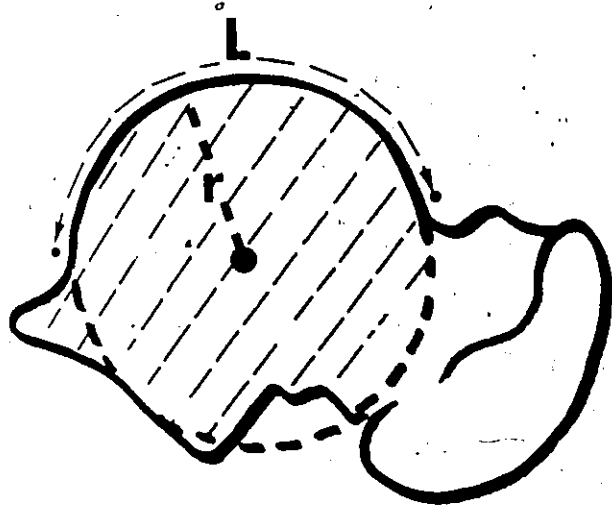
The new lateral edge is now an arc of a circle whose center is an axis point.

Fig. 40f.

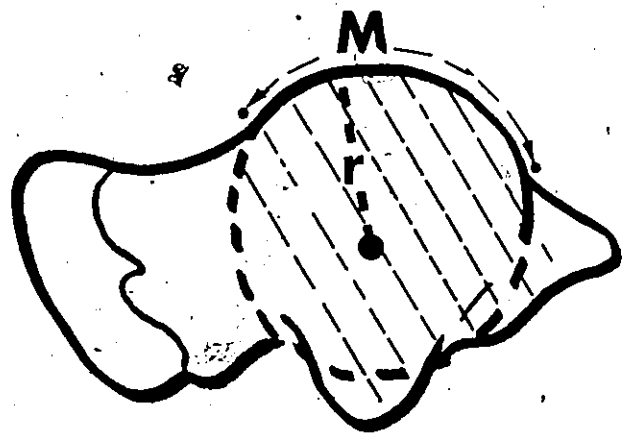
The new medial edge is an arc of a circle of a different radius whose center represents an axis point.



**Fig 40 d**



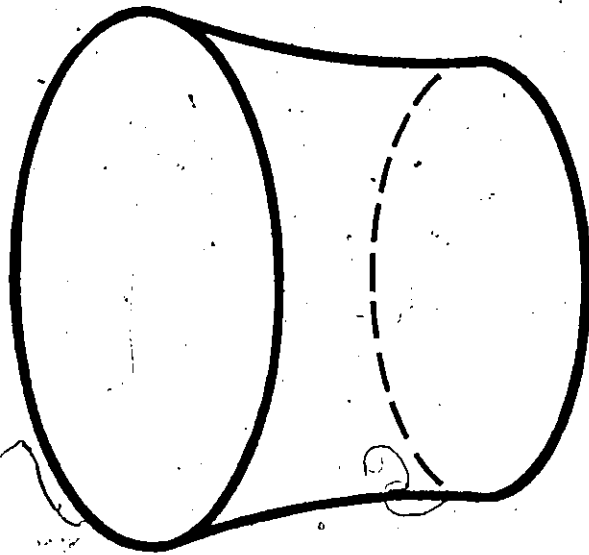
**Fig 40 e**



**Fig 40 f**



**Fig 41**



**Fig 42**

to a longitudinal section of a cone-shaped pulley.

The trochlea of the talus shown in fig. 38 can now be more accurately described as a section of a cone-shaped pulley whose articular edges are parallel. The articular edges are arcs of circles and can therefore be used to determine the axis points. A trochlea conforming to those geometrical standards illustrated in fig. 38 will

now be called a conical pulley-shaped trochlea with a circular and parallel base and truncated end.

The trochlea of the talus shown in fig. 39 can be more accurately described as a section of a cone-shaped pulley having one articular edge oblique to the other

circular end and therefore not perpendicular to the axis. A trochlea conforming to those geometrical standards shown in fig. 39 will now be called a

conical pulley-shaped trochlea with either a noncircular oblique base or a noncircular oblique truncated end.

Similarly, the trochlea of the talus shown in fig. 40 may be more accurately described as a section of a pulley

having only part of its articular edges parallel to each other. Posteriorly there is an oblique section missing from each edge so that these portions of the

edges are no longer parallel to each other and may not therefore be used in geometrical analysis. A trochlea

conforming to those standards illustrated in fig. 40 will now be called a conical pulley-shaped trochlea with circular and parallel base and truncated end, but with oblique sections missing posteriorly from each edge.

In theory therefore, trochleae of tali may be described and classified according to their geometrical shape. In general, they may be described as being similar in shape to either a cylindrical pulley or a conical pulley depending upon the shape of their bases. More specifically, they may be called cylindrical pulley-shaped trochleae with circular and parallel bases (fig. 23), cylindrical pulley-shaped trochleae with one noncircular oblique base (fig. 24), cylindrical pulley-shaped trochleae with circular and parallel bases, but with an oblique section or sections missing posteriorly from the edge or edges (fig. 25), conical pulley-shaped trochleae with a circular and parallel base and truncated end (fig. 38), conical pulley-shaped trochleae with either a noncircular oblique base or a noncircular oblique truncated end (fig. 39) or conical pulley-shaped trochleae with circular and parallel base and truncated end, but with an oblique section or sections missing posteriorly from the edge or edges (fig. 40).

With these geometrical descriptions clearly in mind, their application to the study of the talus and its axis may now be undertaken.

3. Feasibility Study for the Application of the Theoretical Properties of Cylinders and Cones to a Study of the Talus and its Axis:

Before applying the geometry of cylinders and cones to a study of the talus and its axis, it is worthwhile reiterating a very important point. Since it is only the upper surface of the trochlea, and not the surfaces of the sides (bases), which governs movement about the axis during plantar and dorsiflexion (see fig. 26 and fig. 41), it is only this surface which must be studied. The present study therefore involves the upper surface of the trochlea at its junction with its lateral and medial surfaces, that is, the lateral and medial articular edges.

With the above points in mind, twenty tali were randomly removed from embalmed cadaver ankles and were analyzed to determine if all or any of the previous geometrical descriptions could be applied to their trochleae. This study would determine the feasibility of using geometrical methods to determine an axis and would give some idea of the value of previous studies.

However, in order to study the talus accurately by geometrical methods several refinements in the type of study performed by Barnett and Napier (1952) were needed. Such refinements involved methods of clearly marking the lateral and medial articular edges of the trochleae. Since it was the upper surface of the trochlea which governed movement during plantar and dorsiflexion, it was this surface, at its junction with its lateral and medial sides, which needed demarcation. In order to find these edges of the trochleae the upper surfaces of the tali were rolled on black carbon covered paper (fig. 43a, b and c). Such a procedure resulted in carbon lines which varied in width from talus to talus. In the present investigation the outer edge of the carbon lines was considered to be the articular edge because this represented that line on the upper surface which met with the lateral or medial surface of the edge. This was the case even in trochleae which had rounded edges. Such a method ensured a standard by which tali could be compared with each other.

Each carbon marked trochlea was photographed from superior, posterior, lateral and medial aspects, and 4x5 prints were made from each photograph (fig. 44a, b, c and d).

Figure 43

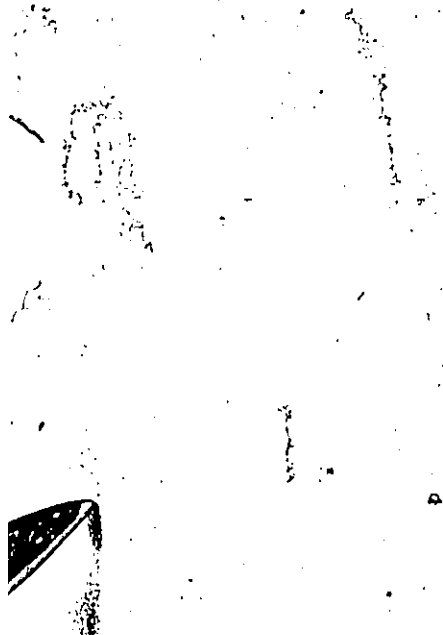


Fig. 43a. Upper surface of the talus was rolled on black carbon covered paper in order to find the uppermost surface of the trochlea.




Fig. 43b. Treating the talus in the above manner resulted in carbon lines which varied in width among tali.

Fig. 43c. The outer edge of the carbon lines (arrows) was considered to be the articular edge.

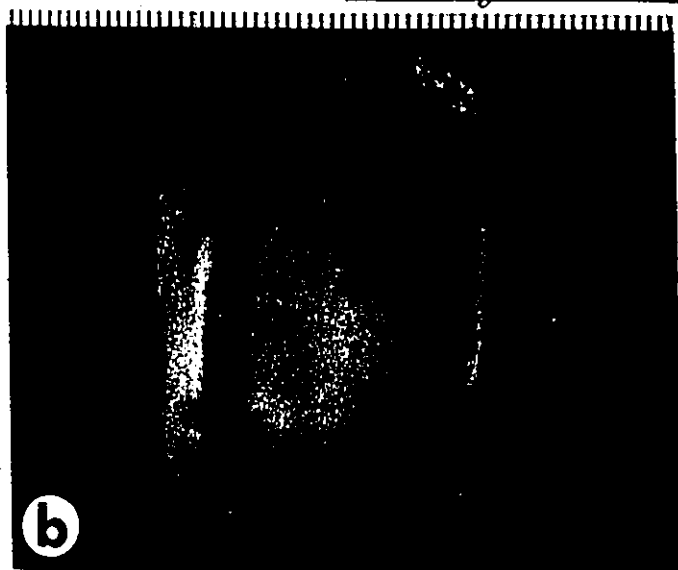


Figure 44

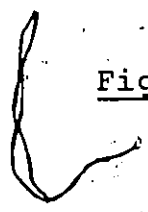


Fig. 44a. Superior aspect of carbon-treated right trochlea tali. The anterior portion of the lateral side (L) reveals a double edge: one edge which is indicated by the carbon line, and a second edge at the junction of the superior and lateral surfaces of the trochlea (arrows).




Fig. 44b. Posterior aspect of same trochlea reveals a bevelled portion posteriorly due to articulation with the transverse tibiofibular ligament (ttl). The bevelled surface causes the lateral carbon line to slope obliquely towards the midline posteriorly.

Fig. 44c. Lateral aspect of trochlea clearly showing bevelled surface posteriorly (ttl). The carbon-treated lateral articular edge is plainly visible.

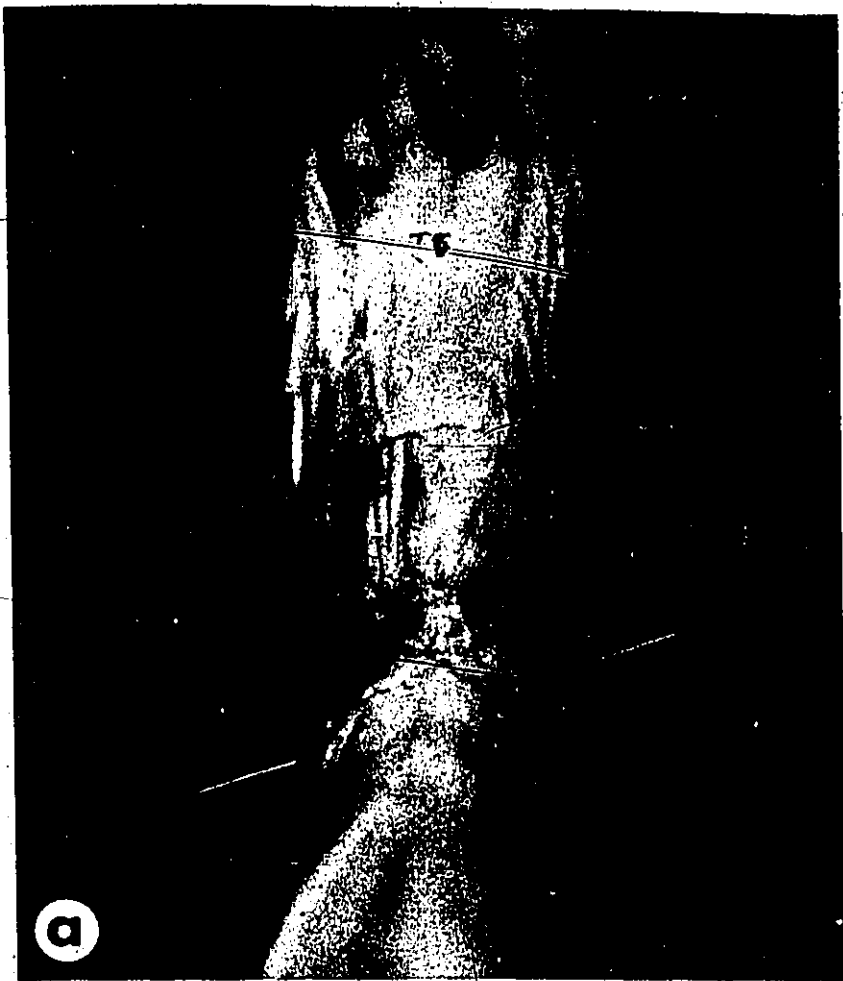
Fig. 44d. Medial aspect of trochlea showing carbon-treated medial articular edge.

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Figure 63

Fig. 63a. Superior aspect of articulated foot showing relationship of metal axis rod to leg and foot.

Fig. 63b. Superior aspect of foot after disarticulation of the ankle. A clear and unobstructed view of the relationship of the axis rod to the foot is obtained.



axes were observed to be transverse, lying oblique to the coronal plane in such a way that the lateral axis point was always located posteriorly to the medial axis point. It was not practical, nor even possible, to measure the exact angle of obliquity with reference to the coronal plane because the coronal plane of the lower limb has never been described accurately enough to permit such measurements.

Wood Jones (1949) described the axis of movement in relation to the axis of the third toe. He stated that "... movement takes place about an axis at right angles to the direction of the third toe." This, however, is not an accurate standard since the direction of the third toe obviously varies with the movements of inversion/adduction and eversion/abduction. Indeed, the "neutral" positions of the joints involved in these movements have not been defined.

Suffice it to say that the position of the axis is certainly oblique to the coronal plane, the lateral axis point lying on a level with the tip of the lateral malleolus and the medial axis point lying well below the tip of the medial malleolus.

The problem of describing any vertical obliquity of the axis remains. In the present series of experiments the subtalar joints had been immobilized with screws. Movements of inversion/adduction and eversion/abduction had, to a large extent, thus been eliminated. Nevertheless, the sole of the foot is not a flat surface, and it is once again neither practical nor possible to attempt to describe variations of only a few degrees in vertical obliquity. For all practical purposes, however, it was noted that the metal axis rods were virtually horizontal in each of the fifteen ankles.

The observations by the dynamic method showed that during normal range of movement a single fixed axis existed in the ankle joint. This axis could be represented by a rod, and its stability during movement could be noted by the naked eye, by cinematography and by radiography. The axis was horizontal but was oblique to the coronal plane, the lateral axis point being level with the tip of the lateral malleolus and the medial axis point lying well below the tip of the medial malleolus.

B. REFINED STATIC METHOD OF ESTIMATION OF THE ANKLE JOINT AXIS

After having successfully determined by cinematography that a single fixed ankle joint axis existed in each of the fifteen ankles, the present study then attempted to determine if it were possible to obtain such results by geometric study of the trochlea tali. The inherent theoretical difficulties involved in such a study have been previously discussed in detail. It was the purpose of this aspect of the study therefore to move out of the realm of theory to its application. To this end, the twenty carbon treated tali of the feasibility study were examined.

1. Observations on the Feasibility Study for the Application of Geometry to the Study of the Axis of the Talus:

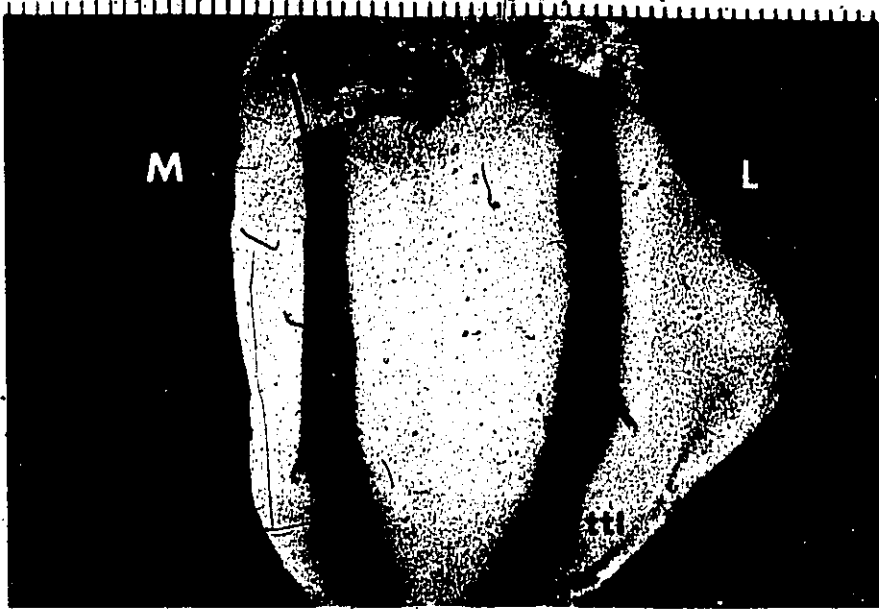
Examination of the photographs of the superior aspect of the twenty tali revealed that the anterior portions of the lateral and medial carbon lines of each trochlea were parallel to each other. These portions of the carbon lines were demarcated by pins, as in fig. 64. The posterior bevelled surface on the lateral aspect of the trochlea, contacting the transverse tibiofibular ligament of the distal tibiofibular

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Figure 64



Fig. 64. Superior aspect of right trochlea tali showing pin-demarkated parallel portions of carbon-treated articular edges. The transverse tibiofibular ligament contacts the posterior bevelled surface on the lateral aspect (ttl) and causes the lateral carbon line to slope obliquely towards the midline. The posterior portion of the medial carbon line also slopes obliquely towards the midline.



joint, caused the lateral carbon line to slope towards the midline (fig. 64). This sloping of the lateral carbon line occurred in each of the twenty tali.

In addition, there was some degree of midline sloping of the posterior part of the medial carbon line in seventeen of the twenty tali examined (fig. 64).

Therefore only the nonsloping portions of the lateral and medial carbon lines which were parallel to each other were delineated by pins.

Examination of photographs of the pin-demarcated portion of the lateral carbon line was conducted by constructing three chords with their perpendicular bisectors in order to determine whether or not the carbon lines were arcs of circles. In each case the three perpendicular bisectors met at a single point (fig. 65), indicating that the carbon arc was therefore an arc of a circle whose center was the lateral axis point. The radii of the circles were measured, and the results are shown in Table I. (The radius of the lateral arc of each trochlea is shown in the first column. The wide range in radii (17.5 mm. to 27 mm., with an average value of 23.4 mm.) indicated that a large amount of individual variation in size of tali existed.

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Figure 65

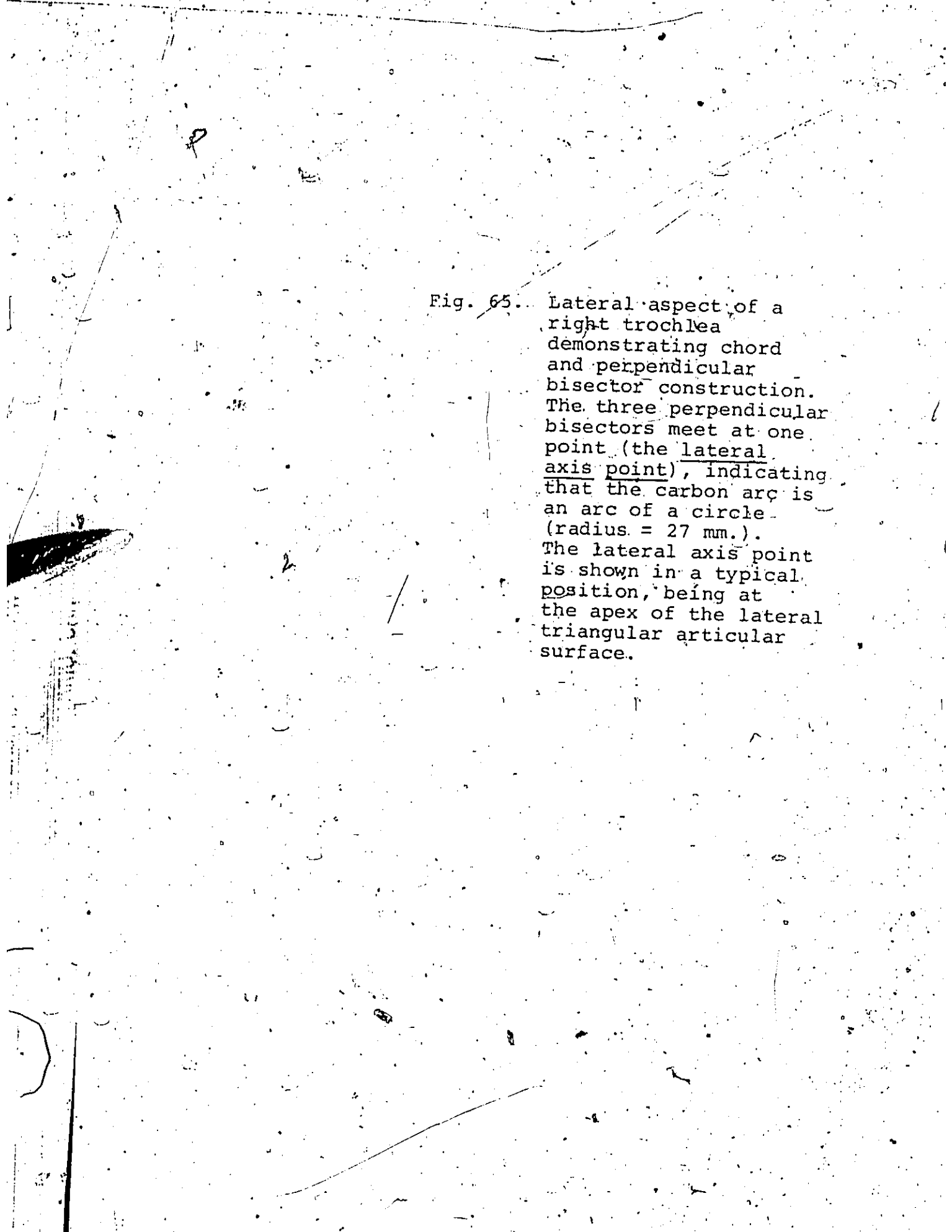
The diagram, which is very faint, shows a curved line representing the lateral aspect of a right trochlea. A straight line (the chord) is drawn across it. A perpendicular bisector is drawn from the midpoint of the chord to the curve. Two other perpendicular bisectors are shown, one for each of the two segments of the chord, and they all intersect at a single point labeled as the lateral axis point. This point is located at the apex of a triangular articular surface.

Fig. 65. Lateral aspect of a right trochlea demonstrating chord and perpendicular bisector construction. The three perpendicular bisectors meet at one point (the lateral axis point), indicating that the carbon arc is an arc of a circle (radius = 27 mm.). The lateral axis point is shown in a typical position, being at the apex of the lateral triangular articular surface.

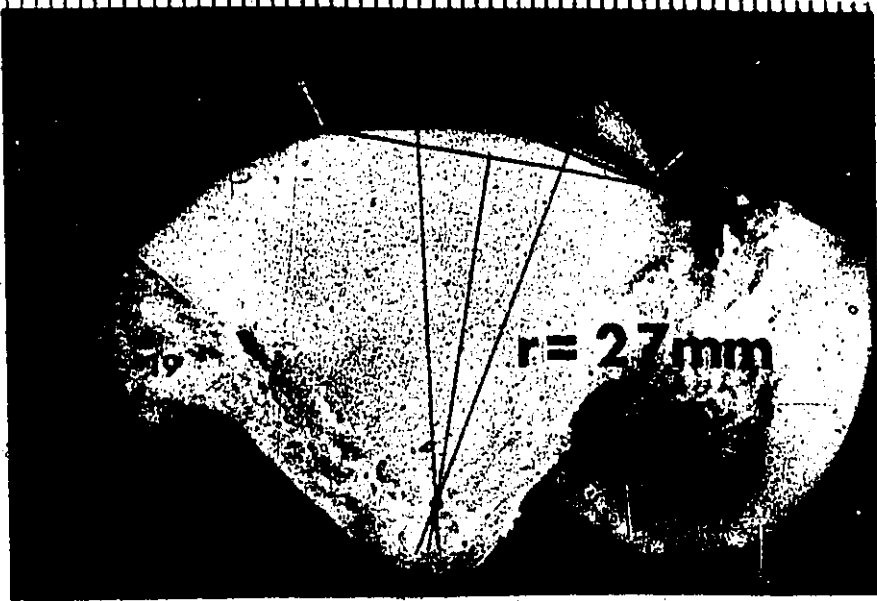


TABLE I

Geometrical Data for 20 Randomly Selected Tails Used in Feasibility Study

Tails No.	Radius (lat.) in millimeters	Radius (med.) in millimeters	Geometrical Shape
1 (left)	22.0	20.5	Conical pulley (L>M)
2 (right)	26.5	16.5	" " "
3 (left)	21.5	18.0	" " "
4 (left)	25.5	21.0	" " "
5 (left)	22.0	17.0	" " "
6 (left)	24.5	13.5	" " "
7 (right)	26.0	21.0	" " "
8 (left)	25.5	14.0	" " "
9 (left)	23.5	18.0	" " "
10 (right)	25.5	22.0	" " "
11 (right)	21.0	16.5	" " "
12 (left)	26.0	23.0	" " "
13 (left)	23.5	26.5	Conical pulley (M>L)
14 (right)	17.5	13.5	Conical pulley (L>M)
15 (right)	25.5	22.0	" " "
16 (left)	18.0	11.0	" " "
17 (left)	21.5	19.0	" " "
18 (right)	26.0	19.0	" " "
19 (right)	27.0	27.0	Cylindrical pulley (L=M)
20 (left)	19.0	12.0	Conical pulley (L>M)

Radius range: 17.5-27.0 11.0-27.0

Average radius: 23.4 18.6

Conical pulley (L>M): 18  
 Conical pulley (M>L): 1  
 Cylindrical pulley (L=M): 1

However, the position of the lateral axis point was observed to vary only slightly among the tali. It was located at the most inferior border (apex) of the lateral triangular articular surface in nine tali, as in fig. 65. It was this surface which articulated with the lateral malleolus. In ten tali the lateral axis point was located within three millimeters above the apex of the triangular articular surface. In only one talus was the lateral axis point more than three millimeters above the apex of the triangular surface.

Examination of photographs of the medial pin-demarcated carbon line was performed in the same way as for the lateral carbon line. For each talus the three perpendicular bisectors met at a single point (fig. 66), indicating that the medial carbon arc was also an arc of a circle whose center represented the medial axis point. The radii of the circles were measured and the measurements are shown in the second column of Table I. A wider range in the radii (11 mm. to 27 mm., with an average value of 18.6 mm.) existed for the medial aide of the trochlea than for the lateral side. The position of the medial axis point, however, was observed to be fairly constant in its location. In eighteen of the twenty tali it was

Figure 66

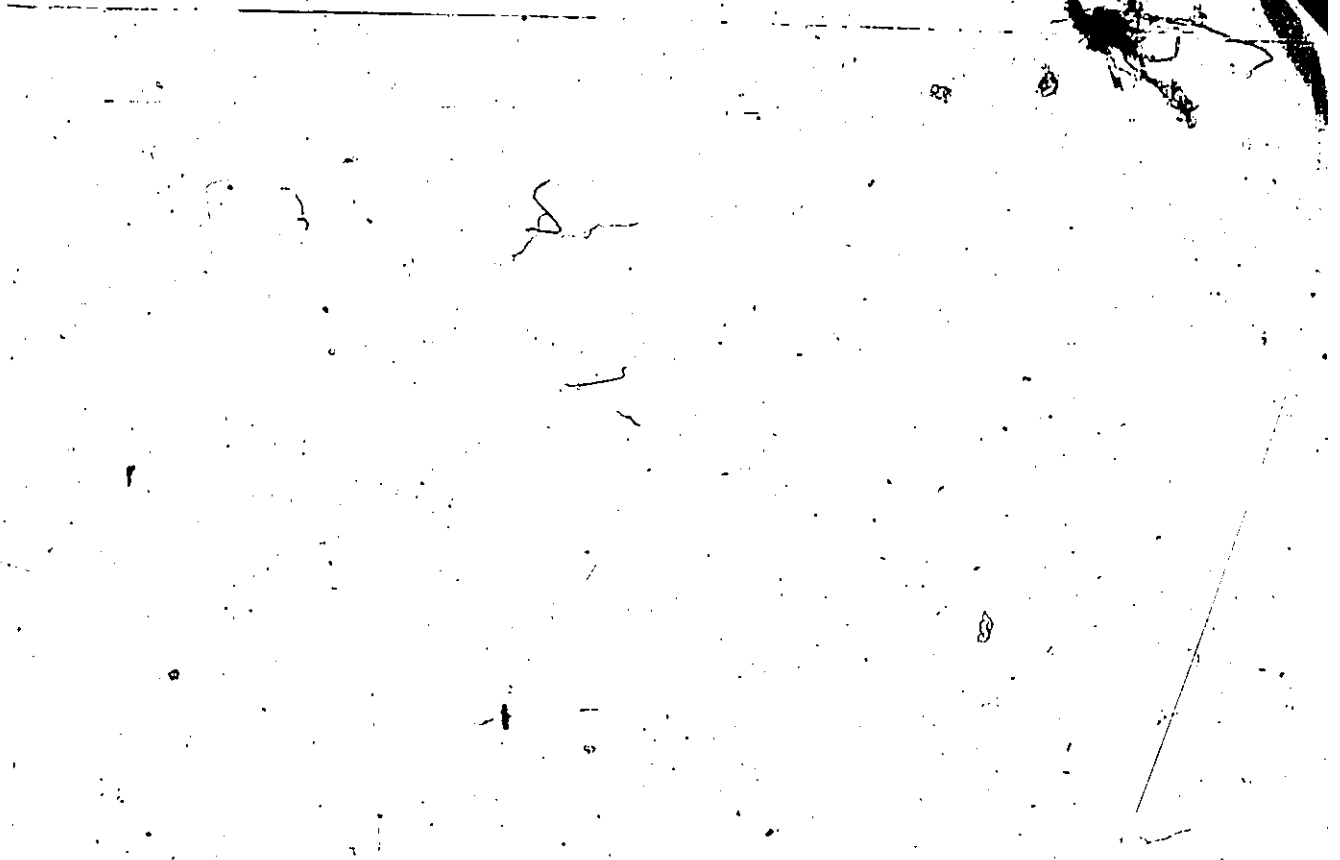
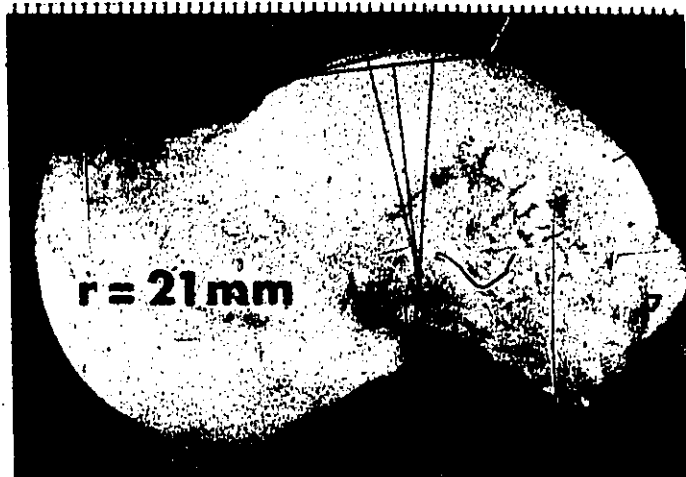


Fig. 66. Medial aspect of a right trochlea showing pin-demarcated medial articular edge. Three chords with perpendicular bisectors have been constructed. Since the three perpendicular bisectors meet at one point (the medial axis point), the arc from which they are constructed is an arc of a circle (radius = 21 mm.). The medial axis point is shown in its typical position, being located a few millimeters posterior to and a few millimeters inferior to the head of the comma-shaped medial articular surface.



located a few millimeters posterior to and a few millimeters inferior to the head of the comma-shaped medial articular surface, in the position shown in fig. 66. It was this surface which articulated with the medial malleolus. In two tali, however, the medial axis point was located well below this point (fig. 67).

The lateral and medial radii of each talar arc were compared with each other in order to determine whether or not any of the previously mentioned geometrical descriptions could be applied to the trochleae. It is evident from Table I that only one of the twenty trochleae examined (number 19) was cylindrical; that is, the radius of the lateral arc was equal to the radius of the medial arc. The remaining nineteen trochleae were conical; that is, the radius of one arc was greater than the radius of the other arc. Only one of the conical trochleae (number 13) had a medial radius larger than the lateral, while the remaining eighteen had a lateral radius larger than the medial. Therefore, only the trochlea of talus number 19 could be called a cylindrical pulley-shaped trochlea with circular and parallel bases.

Figure 67.


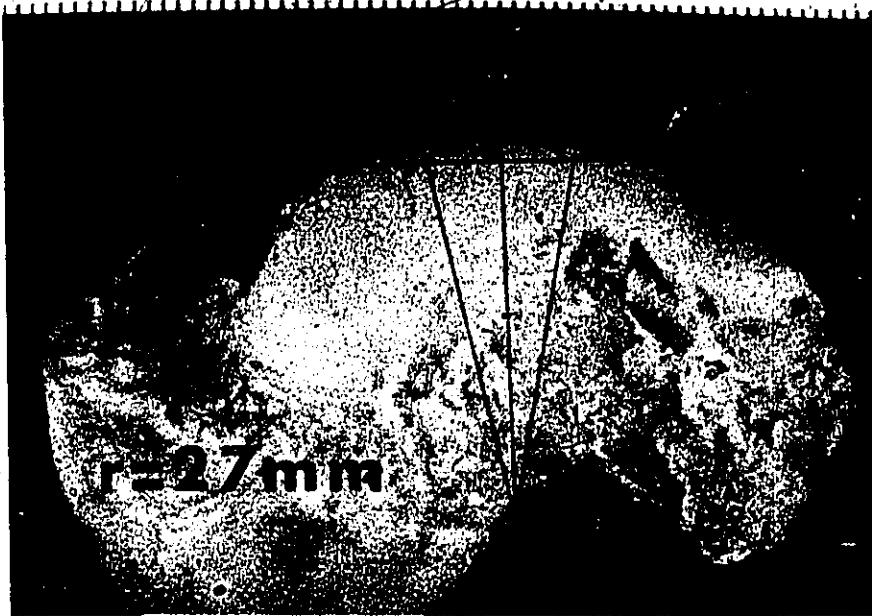


Fig. 67. Medial aspect of a right trochlea showing the atypical location of the medial axis point found in two tali. The medial axis point is located well below the typical location shown in fig. 66.



r=27mm



The remaining trochleae were therefore conical pulley-shaped trochleae with circular and parallel bases and truncated ends. The other descriptions of possible shapes of trochleae summarized previously must remain theoretical in nature for they were found to have no counterparts in the twenty tali studied.

It has thus been shown that among the twenty randomly selected tali it was possible to apply some of the previously mentioned theoretical descriptions. It also follows that an axis of the trochlea may be determined by joining the centers of the circles formed by completion of the arcs of the lateral and medial articular edges. It remains to be proved, however, if this is an accurate and useful exercise and whether or not the position of the trochlear axis determined by such a geometrical study coincides with the position of the ankle joint axis determined by the dynamic method.

2.. Observations on the Geometry of the Tali and Mortices of the Fifteen Ankles Used in the Dynamic Study and Geometric Determination of the Ankle Joint Axis:

In order to determine whether or not the geometrical axis of the trochlea was, in fact, the axis of movement of the ankle joint, the refined static method was applied to the fifteen ankles whose axes had

been determined by the dynamic method. Since the ankle joint was composed of two articulating surfaces, however, the tibiofibular mortice of each joint was also analyzed geometrically. The results of the mortice analysis were compared with the results of the trochlea analysis in order to determine whether or not the two surfaces were circular and congruent. This gave some indication of both the nature and position of the joint axis.

Refined static method of estimation of the trochlear axis

Following disarticulation, the refined static method was used to determine the geometrical axes of the fifteen trochleae used in the dynamic method by exactly the same procedure used to determine the axes of the twenty trochleae studied previously.

Examination of the photographs of the superior aspect of the fifteen tali revealed that, as before, the anterior portions of the lateral and medial carbon lines of each trochlea were parallel to each other. These portions of the carbon lines were demarcated by pins, as in fig. 68. The posterior bevelled surface on the lateral aspects of the trochleae caused the lateral carbon lines of each trochlea to

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Figure 68.


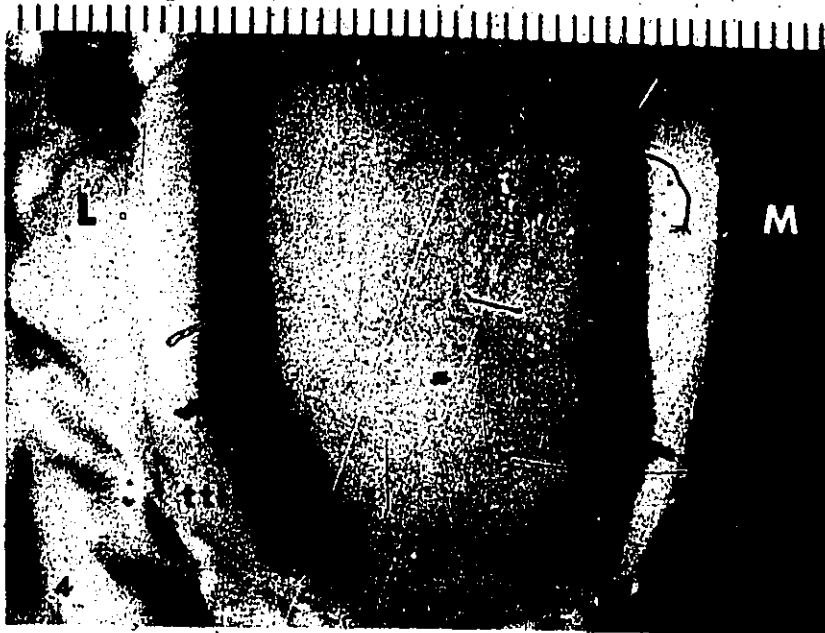


Fig. 68. Superior aspect of a carbon-treated left trochlea tali. The anterior portions of the carbon lines are parallel to each other and have been demarcated with pins. The posterior portion of the lateral articular edge reveals a bevelled surface which comes into contact with the transverse tibiofibular ligament (ttl). The bevelled surface caused the lateral carbon line to slope towards the midline of the trochlea posteriorly. Midline sloping of the posterior part of the medial carbon line also occurs.



slope towards the midline posteriorly (fig. 68). In addition, there was at least a slight degree of midline sloping of the posterior part of the medial carbon line in fourteen of the fifteen tali examined (fig. 68). The nonsloping portions of the lateral and medial carbon lines which were parallel to each other were therefore delineated by pins.

The previously described method of chord construction was used to determine whether or not the pin-demarcated lateral carbon lines were arcs of circles. For each of the fifteen trochleae the three perpendicular bisectors met at a single point (fig. 69), indicating that the lateral carbon line was the arc of a circle whose center represented the lateral axis point. The radius of the lateral arc of each trochlea was measured, and these are shown in Table II. The average value of the radii was 23.7 mm. with a range from 21 mm. to 27 mm. These values compared with an average of 23.4 mm. and a range from 17.5 mm. to 27 mm. in the values obtained from the twenty randomly selected tali.

The position of the lateral axis point for these fifteen tali was similar to the position found for the twenty tali used in the feasibility study.

Figure 69

Fig. 69. Determination of lateral axis point by chord and perpendicular bisector construction. The axis point is shown in its typical location at the inferior border (apex) of the lateral triangular articular surface. Arrow indicates axis, whose position had been determined by the dynamic method.



TABLE II

Geometrical Data for 15 Tali From Ankles  
Used in Dynamic Method

Talus No.	Radius (lat.) in mil- limeters	Radius (med.) in mil- limeters	Geometrical Shape
1 (left)	26.5	17.5	Conical pulley (L>M)
2 (right)	24.5	17.0	" " "
3 (left)	22.5	18.5	" " "
4 (left)	25.0	16.5	" " "
5 (right)	21.0	21.0	Cylindrical pulley (L=M)
6 (left)	23.5	14.0	Conical pulley (L>M)
7 (left)	24.0	16.0	" " "
8 (right)	24.5	18.5	" " "
9 (right)	27.0	23.0	" " "
10 (right)	22.5	14.5	" " "
11 (left)	25.5	20.0	" " "
12 (right)	23.5	21.0	" " "
13 (left)	21.0	17.0	" " "
14 (right)	22.5	14.0	" " "
15 (right)	22.0	19.5	" " "

Radius range: 21.0-27.0 14.0-23.0

Average radius: 23.7 17.9

Conical pulley (L>M): 14  
Conical pulley (M>L): 0  
Cylindrical pulley (L=M): 1

The lateral axis point was located at the most inferior border (apex) of the lateral triangular articular surface in eleven of the fifteen tali, as in fig. 69.

In two tali the axis point was located within two millimeters above the apex of the articular surface, while in two tali the axis point was within two millimeters below the apex.

Examination of the medial pin-demarcated carbon line was performed in the same way as for the lateral side. For each of the fifteen trochlea the three perpendicular bisectors met at a single point (fig. 70) which thus represented the medial axis point. The radius of the medial arc of each trochlea was measured and was recorded in Table II. The average value of the radii was found to be 17.9 mm. with a range from 14 mm. to 23 mm. These values compared with an average of 18.6 mm. and a range from 11 mm. to 27 mm. for the twenty randomly selected tali.

The medial axis point was again observed to be fairly constant in its location. Its position compared favorably to that found for the previous twenty tali, being consistently located a few millimeters posterior to and a few millimeters inferior to the head

Figure 70

5

2




Fig. 70. Determination of medial axis point by chord and perpendicular bisector construction. The axis point is shown in its typical location, being located a few millimeters posterior to and a few millimeters inferior to the head of the comma-shaped articular surface. Arrow indicates axis, whose position had been determined by the dynamic method.



of the comma-shaped medial articular surface as in fig. 70.

The lateral and medial radius of each of the fifteen talar arcs were then compared to each other in order to determine whether or not any of the previously mentioned geometrical descriptions could be applied to the trochleae. It is seen from Table II that only one of the fifteen examined trochleae (number 5) could be described as a cylinder; that is, the radius of the lateral arc was equal to the radius of the medial arc. The remaining fourteen trochleae were conical; that is, the radius of one arc was greater than the radius of the other arc. All of the conical trochleae, in fact, had lateral radii larger than the medial radii. Therefore, only the trochlea of talus number 5 could be called a cylindrical pulley-shaped trochlea with circular and parallel bases. The remaining trochleae were thus conical pulley-shaped trochleae with circular and parallel bases and truncated ends. Once again, other theoretical geometrical types were not found. A summary of the geometrical results which have been presented thus far is given in Table III.

TABLE III

Summary of Geometrical Results

	<u>Data from TABLE I</u>	<u>Data from TABLE II</u>
	20 randomly selected tali used in Feasibility Study	15 tali from ankles used in Dynamic Method
<u>Size (in mm):</u>		
lateral radii range	17.5-27.0	21.0-27.0
average lateral radius	23.4	23.7
medial radii range	11.0-27.0	14.0-23.0
average medial radius	18.6	17.9
<u>Geometrical Shape:</u>		
conical pulley (L>M)	18	14
conical pulley (M>L)	1	0
cylindrical pulley (L=M)	1	1

Refined static method of estimation of  
the tibiofibular mold axis.

The refined static method was used to determine the geometrical axes of the tibiofibular molds corresponding to the fifteen tali just examined. The anterior portions of the lateral and medial carbon lines on the plaster molds were examined from the photographs of their superior aspects and were found to be parallel to each other in all fifteen cases. These portions of the carbon lines were demarcated by pins, as in fig. 71. The posterior portion of the lateral carbon line of each mold sloped towards the midline (fig. 71). This was caused by its articulation with the corresponding surface of the trochlea and with the transverse tibiofibular ligament of the distal tibiofibular joint. In addition, there was at least a slight amount of midline sloping of the posterior part of the medial carbon line in fourteen of the fifteen molds examined (fig. 71). It was the nonsloping portions of the lateral and medial carbon lines which were parallel to each other which were thus delineated by pins.

The previously described method of chord

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Figure 71

Fig. 71. Superior aspect of a carbon-treated right tibiofibular mortice mold. The anterior portions of the carbon lines are parallel to each other and have been demarcated with pins. The posterior portion of the lateral carbon line slopes towards the midline (arrow) due to its articulation with the corresponding surface of its trochlea and with the transverse tibiofibular ligament. A slight amount of midline sloping of the posterior part of the medial carbon line also occurs.



construction was used on the photographs of the lateral aspects of the molds to evaluate the pin-demarcated lateral carbon lines. Fourteen of the fifteen lines were found to be arcs of circles whose centers represented axis points. The pin-marked arc of the remaining mold (number 14) was deemed too short in its extent to accurately construct three chords with their perpendicular bisectors. It was not therefore included in any measurement. The radius of the lateral arc of the other fourteen molds is shown in Table IV and may easily be compared with the corresponding radius of its trochlea.

Examination of photographs of the medial pin-demarcated carbon lines was performed as above, and fourteen of the fifteen medial lines were found to be arcs of circles. The arc of mold number 14 was again found to be too short to permit accurate analysis and was not therefore included in any measurement. The values of the radii of the medial arcs of the other fourteen molds is shown in Table IV and may again be compared with the corresponding radii of their trochlae.

TABLE IV

Geometrical Data for 15 Tali and Their Corresponding Tibiofibular Mold

Ankle No.	Radius of lateral arc of trochlea (in mm)	Radius of lateral arc of mold (in mm)	Difference (in mm)	Radius of medial arc of trochlea (in mm)	Radius of medial arc of mold (in mm)	Difference (in mm)
1 (left)	26.5	27.0	0.5	17.5	18.5	1.0
2 (right)	24.5	24.5	0.0	17.0	24.0	7.0
3 (left)	22.5	24.5	2.0	18.5	18.5	0.0
4 (left)	25.0	26.0	1.0	16.5	17.5	1.0
5 (right)	21.0	22.0	1.0	21.0	22.0	1.0
6 (left)	23.5	25.0	1.5	14.0	17.5	3.5
7 (left)	24.0	25.0	1.0	16.0	17.0	1.0
8 (right)	24.5	25.0	0.5	18.5	21.5	3.0
9 (right)	27.0	27.0	0.0	23.0	26.0	3.0
10 (right)	22.5	26.0	3.5	14.5	16.5	2.0
11 (left)	25.5	25.5	0.0	20.0	22.5	2.5
12 (right)	23.5	27.5	4.0	21.0	23.5	2.5
13 (left)	21.0	24.0	3.0	17.0	19.0	2.0
14 (right)	22.5	----	---	14.0	----	---
15 (right)	22.0	23.0	1.0	19.5	21.5	2.0
Average:	23.7	25.1	1.4	17.9	20.4	2.3

Table IV also presents a more detailed look at the above data by comparing the difference in millimeters between the radius of the lateral arc of each mold and the radius of the lateral arc of the corresponding trochlea. The greatest distance by which these two values differed was 4 mm. with an average difference of 1.4 mm. The same data is also presented for the medial arc of each mold and corresponding trochlea. It is noted that a slightly larger average difference of 2.3 mm. existed for the medial side.

The above results indicate that the lateral and medial pin-demarcated edges of both the trochlea and their corresponding tibiofibular mortice are arcs of circles. This is one factor necessary for a single fixed axis.

A more difficult problem involves the interpretation of congruency. Congruency is the other factor necessary for a single fixed axis. Table IV shows that the radius of each trochlear arc and its corresponding mortice differ by an average of 1.4 mm. for the lateral edge and 2.3 mm. for the medial edge. With a resulting "joint space" of 1.4 mm. to 2.3 mm. it could be argued that the ankle joint would belong

to the category of articulating surfaces shown in fig. 53b on page 79 (male and female surfaces are circular but are not congruent). In such a case there would be a slight variation in the axis during movement, the extent of which would depend upon the thickness of the synovial fluid between the articulating surfaces. These results might even be interpreted as supporting MacConaill's theory of joint lubrication (see page 80). On the other hand, if one considers the inherent errors involved in using geometrical methods to study the ankle joint, it is remarkable that the joint space distance arrived at is so small!

The above arguments will be dealt with later in the discussion. However, in order to get some idea of the accuracy of the positions of the geometrically determined axis points they may be compared with those obtained by the dynamic method.

C. COMPARISON OF OBSERVATIONS

Table V shows the distance between the position of the lateral axis point determined by the dynamic method and the position of the lateral axis point determined by the refined static method. It is observed that these distances range from between 0 mm. and 4 mm. with an average value of 1.7 mm. Furthermore, the distance was 2 mm. or less for twelve of the fifteen tali.

Table V reveals that the variation is somewhat greater for the medial side than for the lateral side. The range is from 0 mm. to 10 mm. with an average value of 4.4 mm., and only four of the fifteen tali show a distance of 2 mm. or less between the centers. In general, the position of the statically determined medial axis point was located posterosuperiorly to the position of the dynamically-determined point (fig. 72).

TABLE V

Comparison of Data From Refined Static Method  
and Dynamic Method

Ankle No.	Distance between <u>lateral</u> geometric and dynamic axis points (in mm)	Distance between <u>medial</u> geometric and dynamic axis points (in mm)
1 (left)	2.0	8.5
2 (right)	1.0	8.5
3 (left)	1.5	8.5
4 (left)	2.5	5.0
5 (right)	1.0	6.0
6 (left)	1.0	2.5
7 (left)	2.0	3.0
8 (right)	2.0	7.5
9 (right)	1.0	4.5
10 (right)	0.0	0.0
11 (left)	2.0	10.0
12 (right)	3.5	0.5
13 (left)	4.0	3.0
14 (right)	0.5	2.0
15 (right)	1.5	3.0
		2.0
Average:	1.7	4.4

Figure 72

Fig. 72. Medial aspect of a right talus (number 8 of dynamic study) showing the statically determined medial axis point being typically located postero-superiorly to the dynamically determined axis point (represented by a metal axis rod-arrow).



PART IV

DISCUSSION AND CONCLUSIONS

Although descriptions of the ankle joint axis have appeared in textbooks and in monographs for more than one hundred years, many of these descriptions seem to have been based upon unrecorded experiments. It was not until 1952 that a description complete with recorded experimental observations first appeared in the literature (Barnett and Napier, 1952). Barnett and Napier, who based their conclusions upon geometrical analysis of tali, described a variable axis of movement at the ankle joint. This in itself was contrary to much that had been written previously. Their work has had a tremendous impact upon subsequent descriptions of the ankle joint axis, and references to their study may be found today in many standard texts and articles. Despite the recognition afforded Barnett and Napier's work, the present study does not lend support to their conclusions.

Barnett and Napier examined the lateral and medial trochlear profiles and found that the

lateral profile was "almost always an arc of a [single] circle" while the medial profile was "compounded of the arcs of two circles of differing radii." Therefore, the lateral profile had a single axis point while the medial profile had two axis points. The anterior one third of the medial profile was an arc of a circle whose radius was less than that of the lateral profile while the posterior two thirds of the medial profile was an arc of a circle whose radius was greater than that of the lateral profile. This, they claimed, resulted in two axes: a downwards and laterally inclined "dorsiflexion axis" and a downwards and medially inclined "plantar-flexion axis." In examining the trochlea of tali, however, Barnett and Napier presented no photographs to support their conclusions. Indeed, the very method by which the tali were examined - whether by naked eye estimation, by photographs or by X-rays - was not stated.

Part of the present investigation was a feasibility study aimed at determining whether or not a geometrical analysis of the type performed by Barnett and Napier was possible.

This study revealed several very significant and important inherent difficulties which, if not taken into consideration, could easily invalidate geometrical conclusions. It was observed, for example, that the identification of the true articular edge was always difficult when the talus was viewed in profile. Indeed, what appeared to be the articular edge was seen to vary depending upon the angle at which the talus was viewed. This was especially true of the medial edge which was always more rounded than the lateral. In an attempt to solve this problem and define the edges the trochleae used in the present study were treated with carbon in order to mark the highest points on the lateral and medial sides. The lines so produced were then considered to be the articular edges. Although such a decision was somewhat arbitrary, it at least permitted a standard by which the trochleae of different tali could be compared with each other. Barnett and Napier made no provision for such a standard in their investigation.

Barnett and Napier described the medial profile as being noncircular. They accounted for this by postulating that the profile was, instead, composed of the arc of two circles. It was solely upon this

premise that they concluded the existence of a double axis of movement. The present theoretical dissertation on pulley-shaped cylinders and cones, however, has shown that a noncircular profile does not in itself necessarily imply a double axis of movement. Rather, it may indicate that (a) part of the articular edge is oblique, rather than perpendicular, to the axis of movement (Property 2 of cylinders and cones), (b) the entire edge is oblique to the axis or (c) the whole estimate, if done with the naked eye, could be an "optical illusion" (fig. 73a). To avoid this latter pitfall the anterior limits of the articular edges were pin-demarcated and photographed (fig. 73b). Remarkably, Barnett and Napier did neither of these two procedures. In all but four of the thirty-five tali examined in the present study the posterior portion of the medial articular edge was oblique to the axis and sloped towards the midline of the trochlea. The present study also showed that in each of the thirty-five tali the posterior portion of the lateral articular edge was oblique to the axis of movement and sloped obliquely towards the midline of the trochlea.

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Figure 73


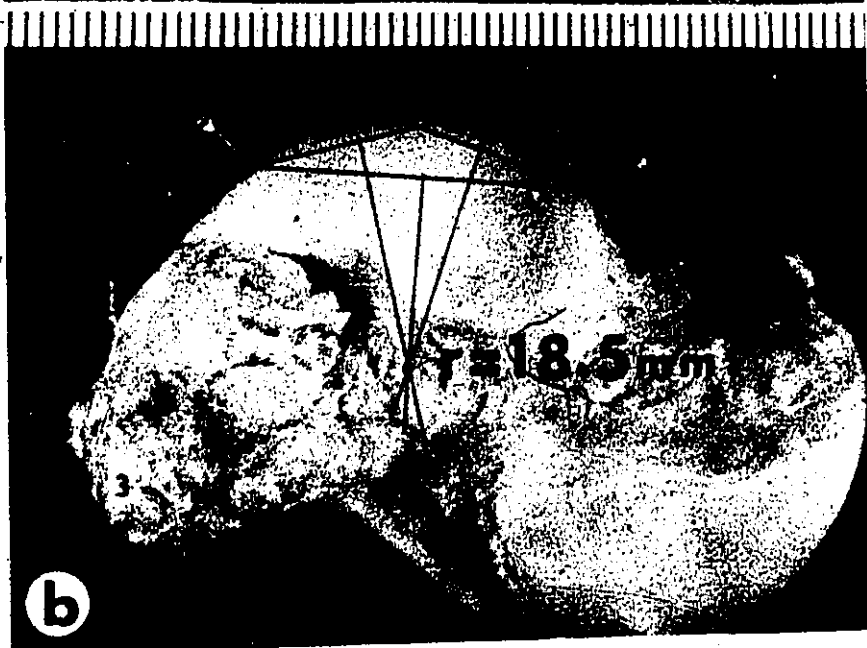
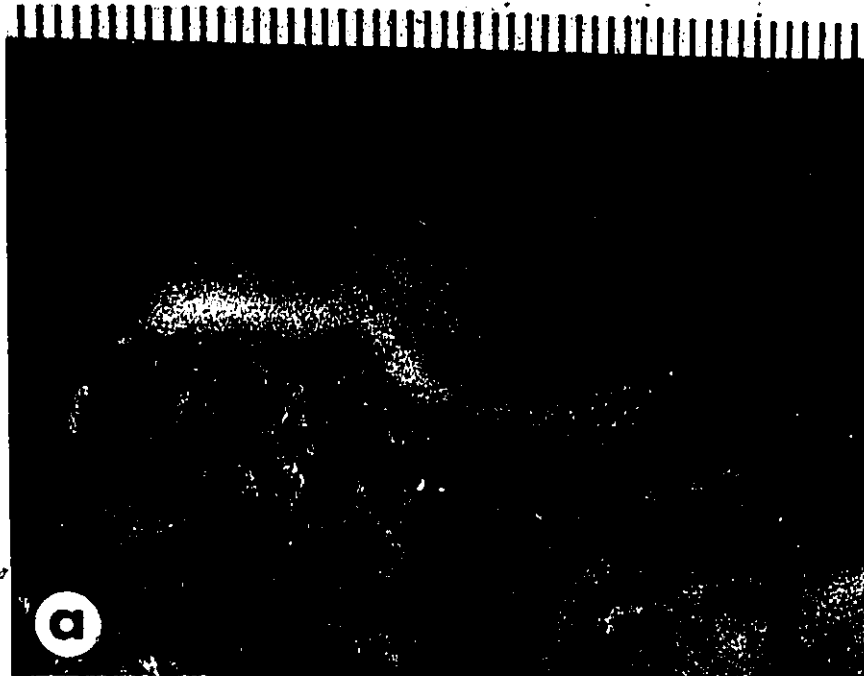


Fig. 73a. The anterior limit of the medial articular edge appears to be more extensive than it actually is because of the "comma" shape of the medial articular surface. This gives the medial articular edge the illusion of appearing elliptical rather than circular.

Fig. 73b. To avoid the above pitfall the true anterior and posterior limits were pin-demarcated and re-photographed. Chord and perpendicular bisector construction reveals that the true articular edge is the arc of a circle rather than an ellipse.



The anterior portions of both articular edges, on the other hand, were always found to be parallel to each other and arcs of circles and were therefore perpendicular to the axis of movement. It was thus only the anterior circular parts of the edges which were marked and used in the present study. Barnett and Napier failed to note this fact and used instead the entire edge in their analysis. Since the entire edge appeared elliptical in profile (as in fig. 24a), Barnett and Napier concluded that it was composed of the arc of two circles.

It should be emphasized that Barnett and Napier's study was nothing more than a poorly documented and superficial study of the geometry of the talus. The ankle joint, however, is composed of two surfaces and, since Barnett and Napier studied only one of these, the axis they determined can hardly be considered to be that of the ankle joint as they claimed. In addition they made no attempt to show whether or not the geometrical axis was, in fact, the actual axis of movement.

A different type of experiment, supporting Barnett and Napier's view of two axes of movement, was performed by Hicks in 1953. In a series of crudely

performed experiments, based entirely upon trial and error, Hicks inserted a small spike into the talus and into the tibia. A rod was attached to one spike and two pointers to the other spike. After placing the rod near the supposed line of the joint axis, one pointer was placed near each end of the rod.

The pointers and rod were adjusted by trial and error until movement of the pointers around the ends of the rod during ankle movement was at a minimum. The position of the rod was then assumed to represent the position of the ankle joint axes. Besides being inserted into bone, however, the spikes also pierced skin, fascia and muscle. Movement of these tissues, even when the bone remained stationary, caused spike and rod movement and therefore resulted in gross inaccuracy.

It is thus obvious that Hicks' experiments reflect more the nature of the muscles and other transfixed tissue than the nature of the joint itself. In addition, the experiments were performed upon undissected ankles. The nature and degree of the movement permitted in such ankles is only a matter of a few degrees. It is surprising that Hicks claimed accuracy to within 1 cm. in placing the axes!

Isman and Inman (1969) conducted a study of the ankle joint axis involving a method similar to that used in the dynamic method of the present investigation. They observed the lateral and medial sides of the talus under cross hairs during simulated plantar and dorsiflexion and located a point of minimum rotation on each side. A hole was then drilled between the lateral and medial points of minimum rotation, and a steel pin was inserted through the hole. The steel pin thus represented the axis of the ankle joint. Isman and Inman concluded that, "The measurements obtained from this sample indicate that the talocrural [ankle] ... joints can be considered single-axis joints for purposes of bracing ..." They did not however show whether or not the axis points were, in fact, points of minimum rotation. The present study, on the other hand, confirmed by cinematography and radiography that the estimated axis points were indeed the points of no rotation and that a stationary axis existed.

In addition Isman and Inman's study reflected the nature of only the articulating surfaces of the

joint since they had previously removed all surrounding tissues. The present study, on the other hand, kept capsular and ligamentous structures intact as far as possible; only those small portions of the ligaments and capsules which restricted observation of the talar pins were resected. The results of the present study therefore reflect not only the nature of the articulating surfaces, but also the relationship of axis points to capsular and ligamentous structures. The capsule and ligaments were also allowed to limit the extremes of movement as they do under normal circumstances.

In their results Isman and Inman attempted to establish the location of the ankle joint axis in relation to anatomical landmarks. Some of the landmarks used by these authors were: the distal tip of the lateral malleolus, the most lateral point of the lateral malleolus, the distal tip of the medial malleolus, and the most medial point of the medial malleolus. The present study revealed that it was not practical to measure the distance from the ankle joint axis to such anatomical landmarks because the location of such landmarks was found to vary.

tremendously from ankle to ankle. It did, however, reveal constant relationships to the ankle ligaments (fig. 74a and b) and the talus, through which the axis always passed (fig. 74c).

In a kinematic study of cinerentgenograms in living subjects Sammarco, Burstein and Frankel (1973) concluded that a series of instantaneous centers of rotation existed during movement of the ankle joint. Their study consisted of geometrical drawings made directly upon X-ray films. From their complex drawings Sammarco, Burstein and Frankel arrived at a different point of no rotation for each position of the joint during the normal range of movement. These points of no rotation, considered together, constituted a series of instantaneous centers of rotation. The accuracy of their drawings and measurements, however, is questionable since they were performed directly on X-rays. Two dimensional X-rays of three dimensional moving objects are extremely difficult to work with since there are always problems of parallax and image magnification. Often it is not known exactly which plane of the ankle is being examined unless a tomogram is performed. Also, according to the theoretical considerations of the present geometrical

Figure 74







Fig. 74a. Lateral aspect of a left ankle (ankle number 7 of dynamic study) showing constant relationships of the axis (arrow) to the lateral ligament and to the lateral malleolus. The axis was always located anteriorly to the calcaneofibular ligament (cf), posteriorly to the anterior talofibular ligament (atf), and level with the tip of the lateral malleolus (lm).

Fig. 74b. Medial aspect of a left ankle (number 7 of dynamic study) showing constant relationships of the axis (arrow), to the deltoid ligament and to the medial malleolus. The relationship of the axis to the anterior fibers of the deltoid ligament (adl) and to the posterior fibers of the deltoid ligament (pdl) is evident. The axis is located well below the tip of the medial malleolus (mm).

Fig. 74c. Superior aspect of foot with axis rod in place.



investigation, it is clear that accurate tomographical measurements could be performed only if the tomograms were made perpendicular to the axis of movement! This type of investigation is as full of pitfalls as normal geometrical estimations.

The present investigation has therefore examined the ankle joint from two points of view, the principal of which was a dynamic method. Such a method offered the advantages of considering the dynamic nature of both surfaces of the ankle joint. In addition, such a study reflected the nature and function of the capsule and ligaments in the joint in their control of movement. The axis points determined by the dynamic method were then confirmed both by cinematography and by radiography. Cinematography demonstrated that the lateral and medial axis points in each ankle had, in fact, remained stationary during plantar and dorsiflexion. Anteroposterior X-rays of the ankle joint axis in both plantar and dorsiflexion confirmed that the axis retained its stability throughout movement. The use of cinematography and radiography thus presented conclusive proof of the existence of a single, fixed axis of

movement at the ankle joint.

A secondary method used in the present study was that of static geometrical analysis. Such a method was not theoretically thought to be ideal, and a feasibility study of such an analysis was first performed. With drawbacks and ideas clear in mind the trochlea tali and the corresponding tibiofibular mortices of the ankles used in the dynamic study were then studied geometrically. The positions of the axis points obtained from the geometrical study were then compared with those obtained from the dynamic study to see if any correlation existed between the two. It was noted that a good correlation existed for the lateral axis point, the average difference between the points obtained by the two methods being 1.7 mm. A somewhat larger difference of 4.4 mm. was measured on the medial side of the ankles.

Geometrical analysis, however, was not the principal method used in the present investigation because of its inherent limitations. The rounded appearance of the medial articular edge and the double-edged lateral profile necessitated marking the articular edges with carbon. Because of the oblique sloping

posterior portions of these edges only the short anterior portions were useful in the geometrical study. Such short delineated portions of the edges were studied geometrically. Where the extent of the pin-demarcated carbon arc was long enough to permit accurate construction of chords and perpendicular bisectors, a fairly accurate estimation of the axis point could be expected. However, where the pin-demarcated carbon arc was short, as in the tibio-fibular mold of ankle number fourteen (see Table IV), an accurate estimation was not possible. In two tali, moreover, the length of the lateral carbon arc was further reduced because the articular cartilage of a portion of the carbon arc was eroded. The accuracy of using geometry to determine axis points therefore also varied directly with the length of the carbon arc being analyzed.

A further source of error involved the very orientation of the talus or mold during the photographing of the articular edges. Tilting of the talus or mold could, to some extent, affect the appearance of the carbon line from which measurements were to be made. This could therefore affect the values obtained for

the radii of the articular edges.

It was because of all of the above limitations of the geometrical method that the dynamic method was the principal one used in the present investigation. Taking into account all of the above limitations it is, nevertheless, remarkable that the average distance between the lateral geometric axis points and the lateral dynamic axis points was only 1.7 mm. (see Table V) - the size of a mere pin head. This distance was greater for the medial side (4.4 mm. - two and one half pin head diameters) because the medial articular edge was much more rounded and less distinct than the lateral articular edge. Therefore even after treating the medial edge with carbon it gave, nevertheless, a more inaccurate geometrical estimation than did the lateral edge.

It must be concluded therefore that a truly accurate determination of the ankle joint axis can be obtained only by the dynamic method as used in the present study. Such a method demonstrated conclusively that a single fixed axis existed in the ankle joint. This axis was horizontal, but oblique to the coronal plane, the obliquity being from anteromedial to posterolateral aspects of the ankle. Measurement of

angles of obliquity of the axis to the coronal plane were deemed both impractical and inaccurate. The axis was not, from any practical point of view, found to be vertically oblique. The lateral axis point was level with the tip of the lateral malleolus, and the medial axis point was well below the tip of the medial malleolus. A constant relationship of the axis to the ligaments of the ankle was the most important functional relationship since tension in various parts of the ligament depends upon the position and stability of the axis.

SUMMARY

1. A dynamic study was the principal method used in the present investigation to determine the ankle joint axis. Fifteen cadaver ankles were used in the study.

2. The subtalar joint of each ankle was immobilized with screws, and the lateral and medial sides of each ankle were carefully dissected, leaving capsular and ligamentous structures intact. Malleolar reference pins and talar pins were inserted into the lateral and medial sides of each ankle, and the axis point on each side was estimated by naked eye observations and with the aid of a dissecting microscope.

3. The estimated axis points were then checked by filming each side of the ankle during a normal range of simulated movement. Every fortieth frame was printed and enlarged, and the axis points were then checked by locating the talar pin which remained stationary in each print.

4. A hole was drilled between each lateral and medial axis point, and a metal rod was passed through the hole. Anteroposterior X-rays of each

ankle were taken both in plantar and dorsiflexion, and the two X-rays were superimposed upon each other to check the stability of the axis during movement.

5. The geometrical properties of cylinders and cones were discussed in detail in order to analyze the feasibility of previous types of geometrical studies, and a refined static method of analysis was evolved. Geometrical descriptions of various theoretical types of trochleae were subsequently formulated.

6. A feasibility study was performed on twenty randomly selected tali in order to determine whether or not any of the previous theoretical geometrical descriptions had real counterparts. It was found that the only theoretical descriptions which had counterparts in the present series were: cylindrical pulley-shaped trochleae with circular and parallel bases and conical pulley-shaped trochleae with circular and parallel bases and truncated ends.

7. The ~~fifteen~~ ankles used in the dynamic method were disarticulated, and a plaster mold of each tibio-fibular mortice was made. The refined static method

of geometrical analysis was then applied to the fifteen tali and corresponding molds in order to determine whether or not the geometrical axis of the trochlea was, in fact, the axis of movement of the ankle joint.

8. A good correlation was obtained for the lateral axis points determined by each of the two methods. A fairly good correlation was also found for the medial axis points calculated by each of the two methods, but this was less than that found on the lateral sides. This was because the medial articular edge did not lend itself to geometrical analysis as easily as the lateral edge.

9. The drawbacks of the geometrical method were discussed, and the advantages of the dynamic method were noted. It was concluded that a truly accurate determination of the ankle joint axis could be obtained only by the dynamic method. The refined geometric method did, however, show that previous geometrical descriptions and analyses were inaccurate and poorly conceived.

10. It was thus concluded that a single fixed axis existed in the ankle joint. The axis was

horizontal, but oblique to the coronal plane, the obliquity being from anteromedial to posterolateral aspects of the ankle. Measurement of angles of obliquity of the axis to the coronal plane were deemed both impractical and inaccurate. The axis was not, from any practical point of view, found to be vertically oblique. The lateral axis point was level with the tip of the lateral malleolus, and the medial axis point was well below the tip of the medial malleolus. A constant relationship of the axis to the ligaments of the ankle was the most important functional relationship since tension in various parts of the ligaments depends upon the position and stability of the axis.

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### ABSTRACT

Two methods of analysis were employed in determining the axis of the ankle joint. The principal method was a dynamic one involving observation and filming of cadaver ankles during plantar and dorsiflexion. Fourteen embalmed legs and one freshly amputated leg were dissected so that only the capsule and ligaments of the ankle joint remained. Pins were inserted into the exposed lateral and medial surfaces of the tali and malleoli, and each ankle was filmed during simulated plantar and dorsiflexion. The film was examined, and a single stationary axis point was found on each side of the talus for all fifteen ankles. A hole was drilled between the lateral and medial axis points, and a metal rod was inserted through the hole to represent the axis. Radiography of the ankles in plantar and dorsiflexion was used to confirm the stability of the axis. For each ankle a single fixed axis was found. This axis was horizontal but was oblique to the coronal plane, the obliquity being from the anteromedial to the posterolateral aspect of the ankle. The lateral

axis point was level with the tip of the lateral malleolus, and the medial axis point was well below the tip of the medial malleolus. The position of the axis points in relation to the lateral and medial ligaments was noted, and the functional importance of this position was discussed.

The second method used was a static one involving geometrical analysis of both the talus and the tibiofibular mortice. A feasibility study was performed on twenty randomly selected tali in order to determine whether or not a geometrical study of the talus was possible. It was concluded that such a study was possible. Both articulating surfaces of the fifteen ankles used in the dynamic method were then analyzed geometrically. Lateral and medial geometric axis points were found for each of these fifteen tali, and their locations were compared with the location of the lateral and medial axis points determined by the dynamic method. A good correlation was found between the positions of the lateral geometric and dynamic axis points. The correlation was not quite as good on the medial side. Plaster molds of the fifteen tibiofibular mortices were made and were analyzed in the same way as their

corresponding tali. Results obtained from each mold analysis were compared with those from analysis of their corresponding talus. It was found that the two articulating surfaces of the ankle joint were both circular and congruent and thus fulfilled the conditions necessary for a single fixed ankle joint axis.