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STUDY OF THE HINGE POINTS OF THE HUMAN BODY

(First Summary Report)

JOINT AXES AND CONTOURS OF THE MAJOR EXTREMITY JOINTS

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ABSTRACT

A major objective of the current research program is to determine the anatomical location of the rotational axes of the major limb segments. The problem is approached in this report by an intensive study of sections through articular contours. The articular surfaces of 6 major joints - wrist, elbow, shoulder, hip, knee, and ankle - were sectioned in each of 6 cadavers along critical planes so that 26 sections of each individual were available for study. The contours of each articular surface considered as involute curves were analyzed by the evolute method and the systems of curvature for each section were determined. The instantaneous centers of curvature and the radii of curvature for the contours are illustrated.

Although contours are in general similar, distinctive variations in contour curvature are present in many specimens. In no instance did the opposed contours at a joint have the same system of curvature; thus the surfaces cannot be congruent. Accordingly, the extremity links cannot be considered as functionally pin-centered mechanisms. Instead, the axis of rotation shifts its position relative to the bones in some systematic fashion as the joint moves. Incongruent joint contacts provide resilient low-friction mechanisms.

An overall view of the ankle joint articulations shows a variable pattern of contacts for the standing, the flexed, and the extended position and shows that, for this joint, stability varies according to the angular position of the joint.

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THE GENERAL PROBLEM

Research under the current contract is directed primarily to a study of fundamental information relating to the link systems of the upper and lower limbs. The aim of the study is to determine the geometrical relationships and kinematics of the limbs of a seated subject as he executes movements in the area within his reach. Both cadaver material and living subjects selected according to somatotyping techniques are being studied in terms of possible limb movements. In addition to the generalized picture of possible postures and movements of the limb segments, the study is oriented to a special problem, the body geometry of the fighter pilot in his cockpit, and to problems of manikin design. The kinematic analysis is augmented by deriving information on the mechanical constants of the body so that kinetic analyses of motions may be approached.

SUMMARY OF WORK ON JOINT AXES AND CONTOURS OF THE MAJOR EXTREMITY JOINTS

The Problem

The assigned topic "Hinge Points of the Body" implies a recognition of both the changing spatial relationships of body segments and the rotational character of the movements involved. Accordingly, a group of major extremity joints has been studied to determine the specific mechanical features operative at each joint. The approach has been anatomical and mechanical and the viewpoint has been functional.

Each joint consists of a characteristically shaped convex and concave bony member with the contact surfaces covered with a thickness of articular cartilage. The articular surfaces of two members at a joint bear on one another and the contact is made firm by muscles and ligaments as tension members spanning the joint; in addition, in certain postures superimposed weight may be transmitted from an upper to a lower bone across the joint. Similarly, impact forces may be transmitted from a lower to an upper member (or vice versa) across a joint. In rotational movements, the convex member of a joint may roll on the articular face of the other member at a point of contact. More usually, however, the typically convex articular surface of the one member glides in the concave mould of the other member and the center of rotation lies at a distance from the surfaces within the convex curvature of the first member.

The general features of joint contacts and joint shapes have been dealt with theoretically by such authors as O. Fischer,[1], Fick,[2] and Strasser.[3] What is of special interest here is that the center or axis of rotation at a joint is basically determined by the shape and contour of the contacting joint surfaces. Furthermore, collateral ligaments, as tension members across certain joints, may function as links (viz. knee joint, Zuppinger,[4] Fisher[1] and Strasser[3]) and this link mechanism may displace the point of joint contact of the convex member forward or backward relative to the opposed joint surface. This, in turn, may also displace the centers of rotation relative to the contacting members. It is, accordingly, essential that one recognize that body joints are not "pin-centered" joints such as those common in engineering designs and there is no a priori reason to assume that they function as such.

If joints are not structurally pin-centered mechanisms, the centers or axes of rotation can have fixed spatial positions only where the male and female surfaces have a constant curvature and wherethe surfaces are in constant contact. Even a superficial view of the anatomy of the major extremity joints, however, shows that they do not have surfaces of constant curvature, this is particularly evident for the convex surfaces of the humeral head, wrist, knee, and ankle. A constant curvature for the capitulum and trochlea of the humerus would appear questionable; and measurements of the femoral head show that it is a spheroid with slightly different major and minor diameters. It would appear, accordingly, that fixed axes of rotation are not to be expected, but rather changing axes of rotation which shift positions from instant to instant during movement. But, what is the path of the instantaneous centers and what is its extent? What is the range of position of instantaneous axes and what is the importance of this range in relation to the kinematics of the body-segment links? These are problems that require answers in this investigation.

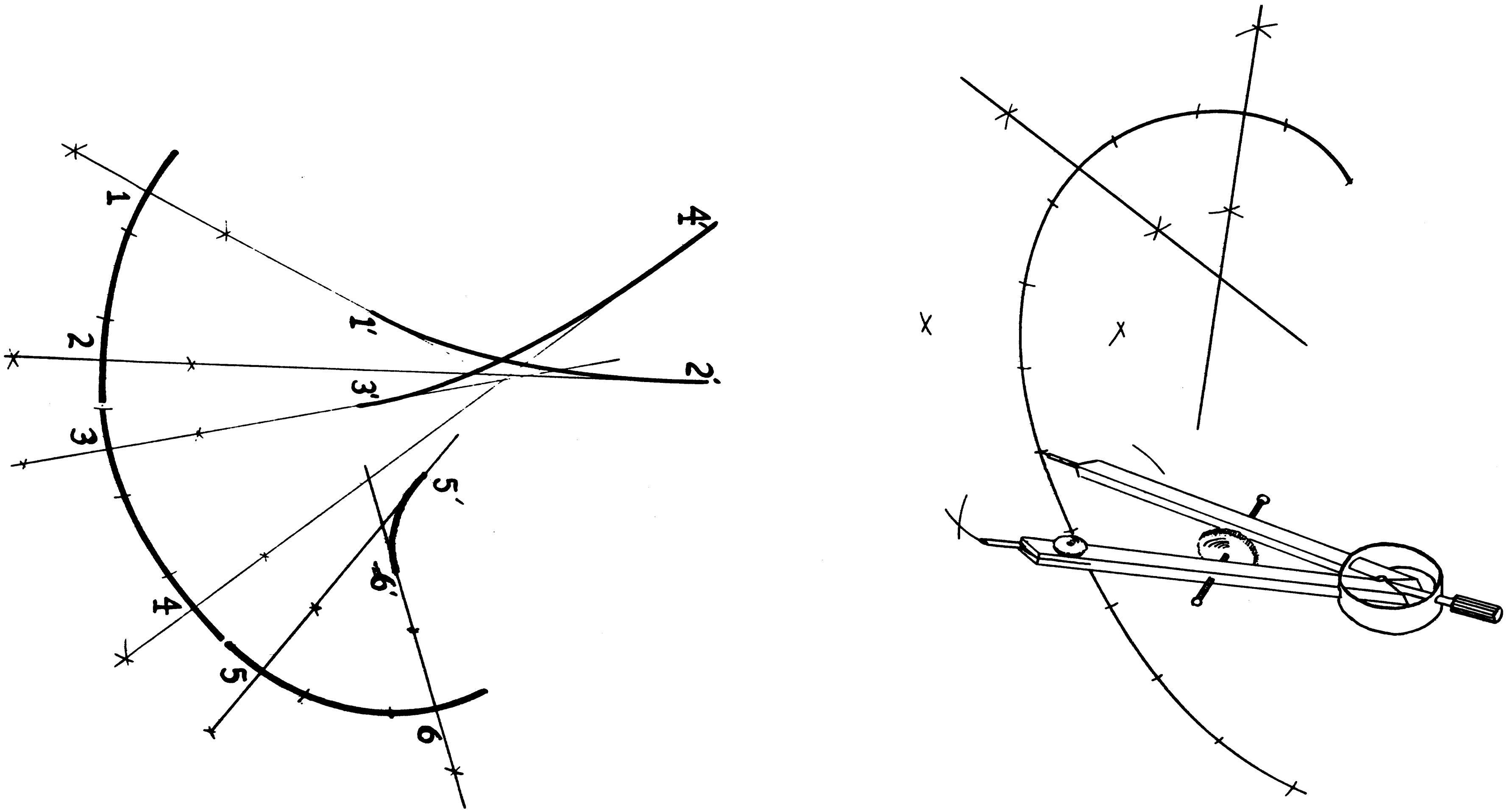
This report has been prepared to show the pattern of instantaneous axes as shown by a study of sections through cadaveric joints. Nearly 100 years ago Langer[5] showed a path of instantaneous axes for the knee joint. Bugnion[6] extended the study of the joint, using the x-ray, and Zuppinger[4] by a use of geometry on the living subject, by the use of x-rays, and through a study of knee ligaments further amplified our information. Other authors such as Fischer,[1] Strasser,[3] Braus,[7] Mollier,[8] Lanz and Wachsmuth[9] and Elftman[10] presented interpretations of the path of the instantaneous axes of the knee but these appear to be largely secondary efforts involving single generalized illustrations. Braune and Fischer[11] developed a method relative to the living knee. Fischer[12] applied a similar method involving x, y, and z coordinates for various angles of flexion for the elbow joint on two cadaver joints. No other literature, however, has been located relating to rotational axes of other joints. The whole topic of axes for the different major extremity joints has been approached in the present study and both patterns and variability have been investigated.

Methods

The present report will present results based on the intensive study of the knee, ankle, hip, shoulder, elbow, and wrist joints from six preserved cadavers. Earlier approaches (Quarterly Report No. 2), based on plaster casts of joint surfaces and end-on measurements of the radius of curvature of many bony and cadaver joints, have provided information which is now regarded as supplementary and secondary to information derived by the present method. Consequently, the earlier work will not be stressed here. For each of six cadavers, the male and female members of the joints of the left side were sectioned longitudinally along a primary plane of joint movement. For the shoulder and hip joint, additional sections from right-side joints were made perpendicular to the direction of sections on the left side.

Photographic enlargements were made of the joint contours shown in the sections and ordinarily 10 to 20 pairs of arcs were struck off on these by a compass with its needle point at equal intervals along the joint contour. Lines were then drawn through the intersections of adjacent arcs to establish normals to the contour (Fig. 1). Normals constructed in this way intersected at various distances within the concavity of the contour of the joint surfaces and formed a pattern that could be interpreted in terms of instantaneous centers of rotation.

The method of establishing a path of instantaneous centers and determining the instantaneous radii of curvature is based on a theorem in differential geometry. Any regular curve (involute) may be defined in terms of a second curve called an evolute. The evolute is the locus of the centers of curvature of the involute; it is the envelope of the normals of



Analysis of a composite curve consisting of three involutes showing an evolute corresponding with each involute. Numbers show short and long radii of curvature for each system of curvature.

Fig. 2

the involute. The relation may be illustrated in this manner: If a taut cord is wound or unwound about a finger, a point on the moving end of the cord describes a second curve which is the involute. Thus, a taut cord unwound from a rod of circular cross section (evolute) describes a spiral path which is an involute curve. Any point on the spiral is also the locus of a perpendicular which is tangent to some point on the contour of the rod. Because of this, it becomes possible to locate an evolute curve for any curve considered as an involute. Accordingly, a series of normals to a given involute curve, such as a joint contour, may be constructed; tangents to these normals form an evolute curve. When the normals are constructed for a joint contour, using the compass method, the best fitting curve which is tangent to all of the straight-line normals may be fitted by eye or may be found by placing a suitable curvature of a French curve in tangent contact with the normals. Points on the evolute curve are instantaneous centers of rotation and the distance from any one such point to a corresponding point on the joint contour is the instantaneous radius of curvature. It will be seen, now, that the instantaneous radii of curvature will be of increasing length as the instantaneous centers are further away on the evolute curve. Each evolute, thus, has one extremity near and the other extremity farther from the involute.

If a joint contour is a single system of curvature, the corresponding evolute will be a simple curve. The near end of the evolute indicates a short radius of curvature for one region of the joint contour and the instantaneous radii of curvature of adjacent regions of the joint contour increase more and more as corresponding points on an evolute are farther from the joint contour. When a joint contour is formed of two or more systems of curvature, there will be a separate evolute for each separate curvature. These may form separate lines or they may join or cross in a V, X, A or star-like pattern. The general technique of analysis may be illustrated by constructing a composite curve with French curves oriented one way or another (Fig. 2). The test curve of the figure was constructed of three different curved lines: for the left and middle sections, the more curved region of the French curves was toward the left; for the right section, the more curved region was directed toward the right. The whole test line shows no apparent break in contour, yet each part of the curvature as constructed has a separate evolute. The correspondence between evolute and an arc of the constructed curve clearly indicates the compounded characteristics of the test curve. The method applied in this way to joint surfaces of unknown systems of curvature will (1) point out different systems of curvature, (2) locate instantaneous radii of curvature, and (3) define instantaneous centers of rotation.

The following sections will show the analyses of joint curvatures joint by joint together with an indication of the contour variability for each. Points for general discussion will be included in a later section.

The Knee Joint

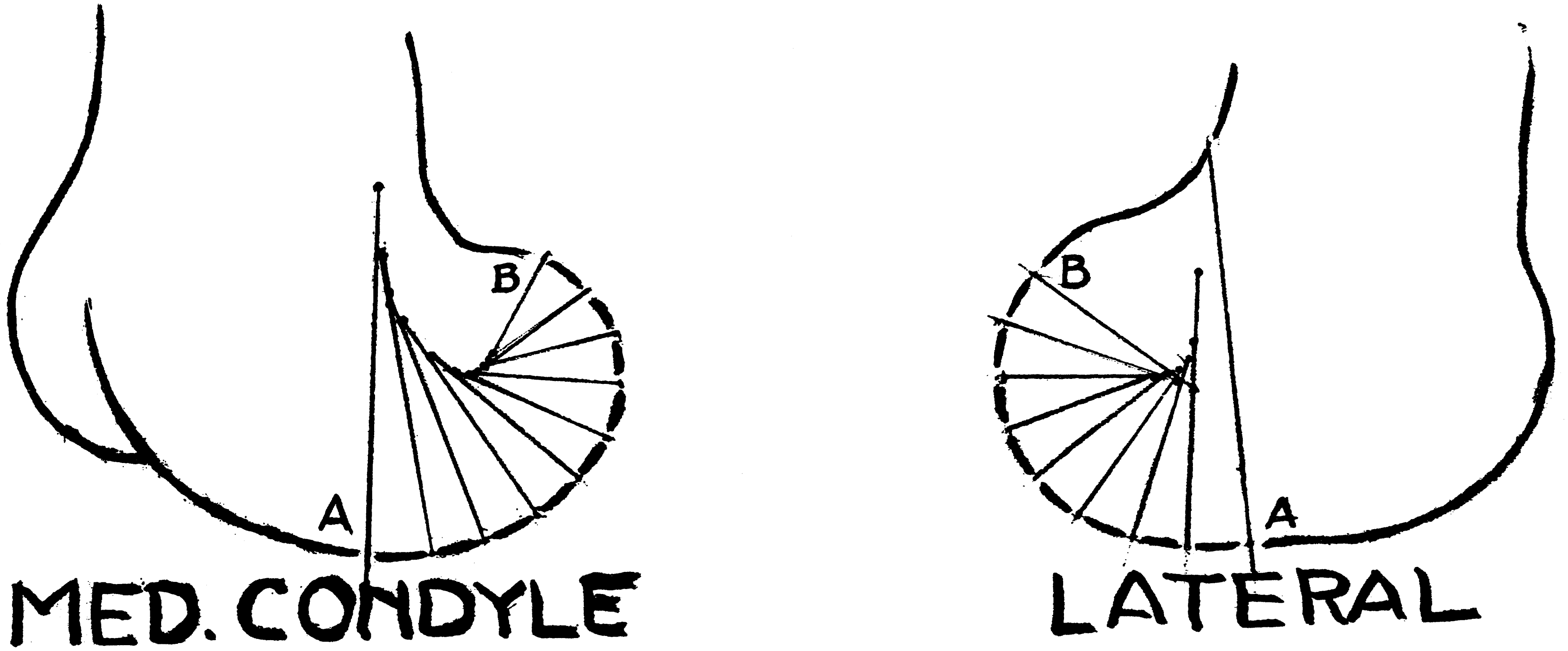
Although the medial and lateral articular surfaces of the tibia are not plane surfaces, the specific regions on which the femoral condyles move would appear to function as such. Menisci of fibrocartilage are, of course, present, but they do not intervene at the principal bearing points of the joint, and thus they are secondary to the present concern. The femoral condyles roll and slide on the tibial surfaces as they would on the surface of a table. Accordingly, the precise contours of the tibial articular surfaces were not determined.

The planes for sections through the femoral condyles were defined by rolling both condyles of a femur over a chalked plane surface so that contact lines were marked on the contours. A saw cut was then made through each condyle so that the plane of the section coincided with the plane defined by the chalk line. Section contours prepared in this way accordingly defined the functional contours.

Enlarged photographic prints were made of the cut faces of the condyles, and these showed the contours of the surface of the articular cartilage in functionally significant planes. Figure 3 shows the functional curvature of the medial and lateral condyles from the same femur. The span from A to B relates to flexion movements involving tibial contacts; more anteriorally, the contour is a region for patellar contacts and is of no concern here.

Analysis of the flexion-to-extension contours by the evolute method shows that normals to the surface (as shown in the figure) form a characteristic fan-like pattern. The evolute curve tangent to each of the normals (i.e., the line of dots at the ends of the normals for the medial condyle) is a single curved line, and this indicates that the articular curve is a single system of curvature. The evolute curve for the lateral condyle shows a generally comparable evolute to that for the medial condyle. It will be noted, however, that the evolute is more vertical and J-shaped than the obliquely lying evolute of the medial condyle.

Moreover, the two highest normals on the curvature (as shown in the figure) are not tangent to the evolute; instead, a second evolute or spur, directed downward and forward, can be constructed tangent to the last three normals. This indicates that the upper half of the rear part of the condylar curvature represents a second system of curvature. As shown by the main evolute, the instantaneous radii of curvature become shorter and shorter as the radii rotate through about 90°. Then, as shown by the second spur-like evolute, the radii elongate from the rear of the condyle to the highest flexion position of the articular surface.



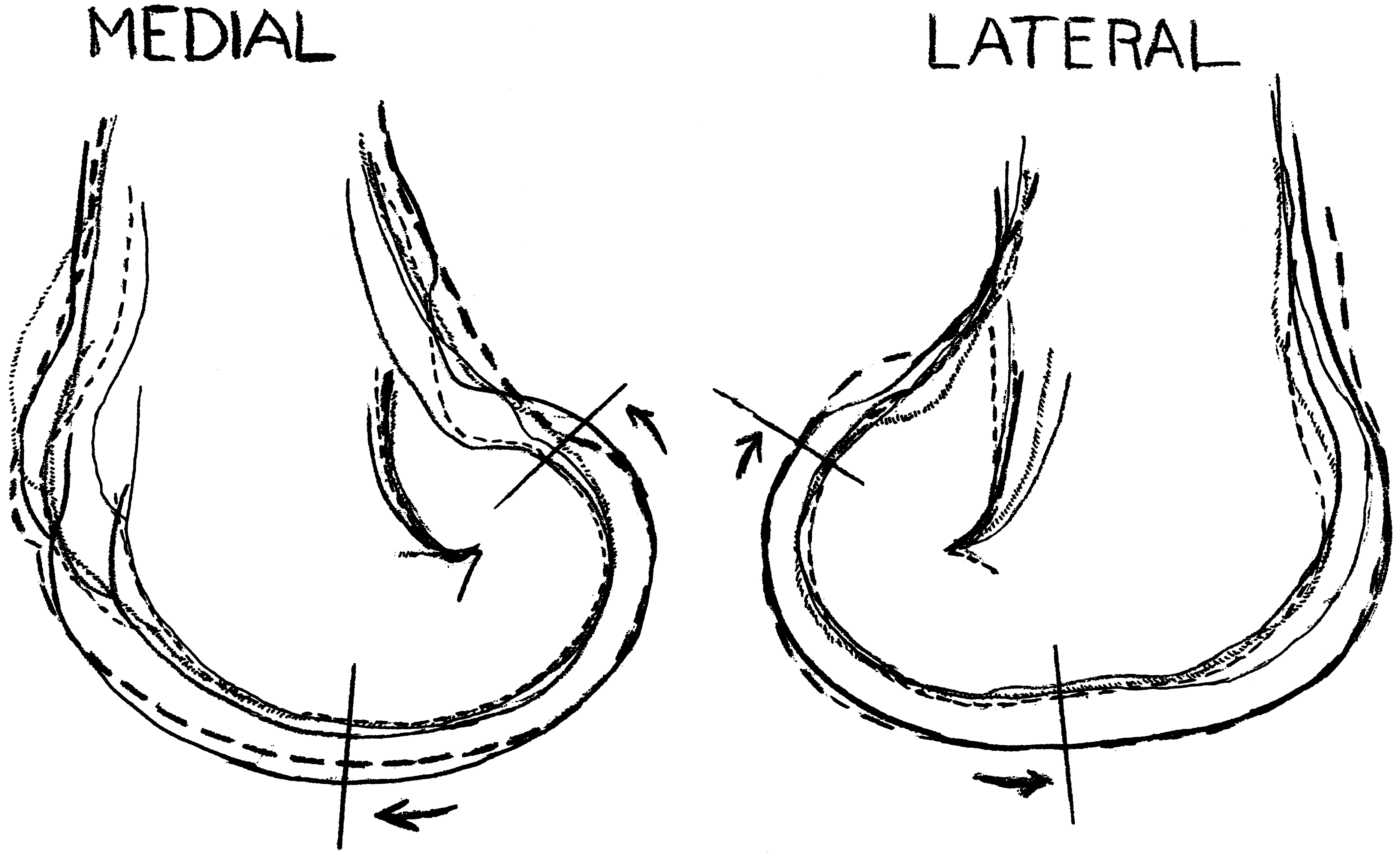
Functional sections through the femoral condyles of the same specimen. Radii of curvature for the contour from A to B are shown. The lines of dots representing instantaneous axes of rotation are aligned on an evolute curve. The medial condyle shows one evolute and the lateral condyle shows two.

Fig. 3.

This two-evolute system of curvature has been shown in figures by some authors (Elftman[10]). It is not the usual condition, however, but is a variant pattern which may be encountered in either the medial or the lateral condyle. Figure 4 shows superimposed tracings of involute and evolute curves for six medial and six lateral condyles. The general variability of the joint contours is suggested. Large joints and small ones have the same type of evolutes; evolute spurs corresponding to the upper half of the rear condyle surface are shown in two of the medial and in one of the lateral condyles. The evolute curves have been superimposed with the posterior extremity of each primary evolute at a common point and with the femoral axes (line connecting with the center of the femoral head) aligned. The curvatures of the evolutes correspond more or less, but there are differences in slant and sharpness of curvature which suggest an individual variability in contours of the involute surfaces. Apart from deviations indicated by spurs, the lengths and locations of the evolutes from specimen to specimen were, in general, similar. The instantaneous radii for the medial condyles decreased from 42 mm (large bone) and 34 mm (small bone) in the extension position to 18 to 13 mm in the flexed position. The radii of the lateral condyle correspondingly decreased from 45-37 mm to 20-16 mm.

Figure 5 shows a fully extended knee, a knee at a half-range position (63°) of flexion, and a fully flexed knee (to about 125° voluntary flexion). The general relations of the bones were checked by x-rays on a living subject; the evolutes are from the lateral condyle of a cadaver. The left-hand illustration shows a long radius of curvature (46 mm) between the tibial contact and the upper extremity of the evolute; the middle illustration shows a much shorter radius (23 mm) from the convexity of the hook of the "J" to the tibial surface; and the third sketch shows a still shorter radius (16 mm).

It will be obvious that if the distance from the tibial contact to the rotation center on the evolute changes systematically, the femoral link distance, from the center of the femoral head to the center of instantaneous rotation at a point on the evolute, increases in length as the knee is flexed. Conversely, the length from the rotational axis at the knee evolute comes closer to the talus bone at the ankle with increased knee flexion. The change in the length of the radii of curvature is great for approximately the first 20° of flexion, and is less and less for further degrees of flexion. The mid-range position (60 - 65°) of the knee is a convenient position for reference. The equivalent functional position is on the convexity of the "J". The evolute span posterior to this point corresponds to the range from mid- to full-flexion; an equal span anteriorly corresponds to a range of nearly 45° toward extension; and the remaining more or less vertical limb of the evolute relates to the approximately 20° of flexion short of full extension. According to the measurements quoted relative to Fig. 5, the decrease in radius of curvature from



Six medial and six lateral-condyle contours are superimposed to show variability. The evolutes for each contour are shown with the posterior ends of the primary evolutes superimposed.

Fig. 4.

The knee joint is shown in full extension, in mid-range flexion and in full (voluntary) flexion. The evolute of the internal condyle is shown in each figure together with the instantaneous radius of curvature which is directed to the bearing point.

Fig. 5

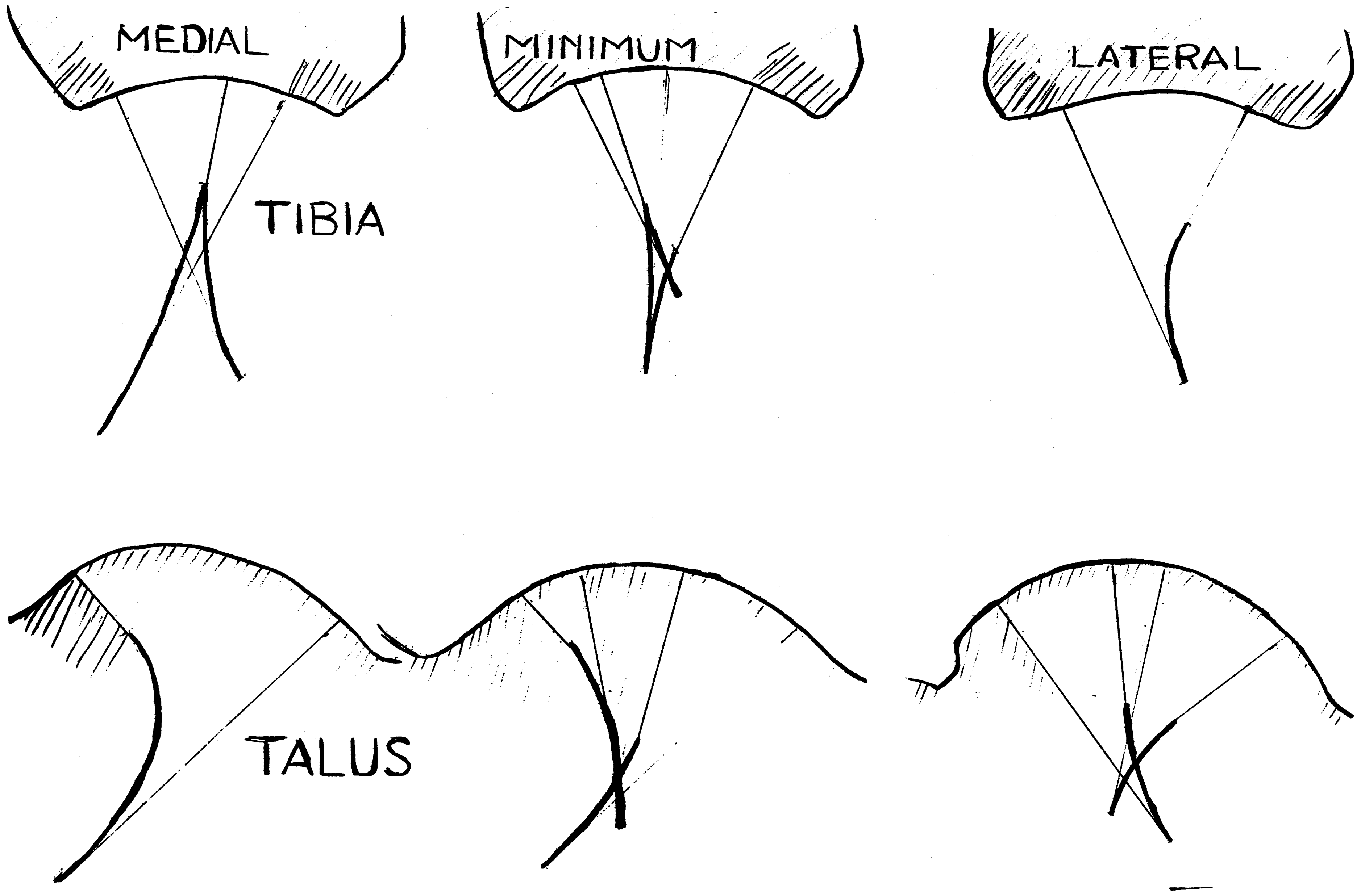
23 mm to 16 mm should decrease the tibial link length 7 mm in the change from mid- to full-flexion. A 45° extension should increase the link about the same amount. Conversely, the femoral link should increase as the lengths from femoral head to instantaneous centers increase along the evolute.

Zuppinger[4] and later Strasser[3] have pointed out that in the final phases of knee straightening, the cruciate and collateral ligaments bind and limit further rotation on the evolute. Accordingly, the upper span of the evolute is no longer a functional location for rotational axes. Rather the true rotational axes are displaced much closer to the region of tibial contact. An attempt to locate such aberrent axes of rotation is at present under way. The functional deviations of rotational axes from the evolute curve relate, it should be borne in mind, to only the first few degrees of flexion beyond the extended position of the joint. It is in this range also that axial rotations involving the medial condyle have a function in locking the joint in the extended position.

The Ankle Joint

The talus bone and the tibia form the main bearing surfaces at the ankle joint. Saw cuts were made through the talus along its medial and lateral elevation after the bone had been rolled over a chalked plane surface. A third (intermediate) saw cut was then made longitudinally through the depressed central region of the articular surface of the bone (minimum radius of curvature). The tibia was sectioned along equivalent regions of its articular face, and the planes of section were made parallel to those through the talus. Figure 6 shows the contours of the tibia and those of the talus for the same joint preparation. It also shows the evolutes which corresponded to the tibial and talus contours. It will be seen that for the talus in this specimen, only the medial ridge may be defined by a single evolute. In this curvature, the anterior extremity of the contour has a short radius of curvature, and the instantaneous radii of curvature gradually become longer and longer to the lower end of the evolute.

The equivalent section through the tibia is defined by two evolutes. In each region of curvature, the instantaneous radii of curvature are long for the anterior and posterior extremities of the articular contour, but they become short where they correspond to a point just behind the mid region of the contour. Since, in this specimen, the tibia has two systems of curvature and the talus one - and since the talus evolute does not correspond to either of the tibial evolutes - it is impossible to visualize a flush contact between the opposed surfaces of the two bones. Instead, there must be a bearing contact either at one or at two locations and the positions of these loci will differ with each differing degree of ankle flexion or extension.



The lower three illustrations show longitudinal sections through the medial, intermediate and lateral regions of the talus. The upper figures relate to equivalent tibial sections. Evolutes correlated with the articular contours are shown.

Fig. 6

Sketches at the right of Fig. 6 show the lateral ridge of the talus and the equivalent section through the tibial articulation from the same specimen. The contour of the latter section is defined by a single evolute which indicates a shorter radius of curvature for the posterior part of the articulation and a longer one for the anterior regions. In contrast, the lateral ridge of the talus shows an evolute of X-like pattern. The front half of the talus has a long radius of curvature anteriorly and the radii become shorter toward the mid-talus region. Still more posteriorly, as indicated by the second evolute, the radius of curvature is relatively long and it gets progressively shorter toward the posterior part of the articulation. The two evolutes thus locate two regions (bumps) of marked convexity.

From the lateral talus-tibia articulation, it is again seen that the male and female members of the ankle joint have different patterns of curvature and that these cannot fit together to provide an even contact for joint movements and force transmission.

The intermediate sections through the tibia and talus show evolutes respectively of A-like and X-like patterns. One limb of the X ends close to the involute surface and implies a short radius of curvature here (marked convexity); the curvature for the other limb is more gentle. Contact between the two opposed surfaces at the region of the joint must again be limited to small regions.

An overall view of Fig. 6 shows that the evolutes of the medial, tibial and talus sections are longer than those of the other sections. This implies a more gradual sweep of curvature for the medial sections than for the lateral and intermediate contours.

The smaller evolutes imply a closer approach to point-centered circular contours. In the medial and intermediate sections the relative closeness of an extremity of the talus evolute to the tibia implies bump-like convexities in the anterior region of the medial and intermediate sections; such convexities could bear at any point on the opposing tibial contour because the minimum radii of curvature for the tibial contours are greater than those for the talus.

The system of joint curvature represented for three regions of one joint preparation shows that the joint surfaces cannot fit congruently. Instead, the bearing surfaces of the joint for a given angular alignment of the ankle must be restricted to a limited area of contact. This would, in turn, imply that no part of an evolute in itself is a locus for the true functional axes of joint rotation. This, rather, would be a resultant which would vary depending upon whether there were two, three or more regions for simultaneous contact for a given joint angle. The location of a functional axis must lie in the general region of the talus occupied by our evolute lines. Moreover, if functional axes are resultants, they should lie within a much smaller region than the range demarcated by merely superimposing all the evolutes of the two opposed surfaces. The range still remains to be delineated more accurately.

Figure 7 shows the type of evolute pattern found in the medial and lateral sections of the talus from four additional specimens. Evolutes for the intermediate cut, although not shown in the figure, show generally comparable patterns of X's, A's, and stars. A considerable variability is shown in evolute and involute pattern. Three medial tibiae are similar to the pattern of Fig. 6; one differs markedly. Two medial-talus sections are similar and two have X-like evolute patterns. One lateral tibial section is like Fig. 6; three are different, though two of these are similar to one another. Minor differences in lateral talus sections are shown in the five sections of Fig. 6 and Fig. 7. Even though joint contours show variability, it will be seen again that in no instance do the male and female members of a joint have a similar pattern. Contacts between the opposed joint surfaces must be incongruent.

The Hip Joint

At the hip joint, both acetabular and femoral contours are interrupted by the acetabular fossa and fovea capitis (the ligamentum teres attachments). Figure 8 shows the involute curvatures of a vertical section through an acetabulum above and below the acetabular fossa and the corresponding evolutes. The right-side illustration shows the equivalent articular curvatures for the femur above and below the fovea capitis. The lower curvature is defined by one evolute; the upper by two. When the sketches are superimposed, the evolutes do not correspond. (In a true ball and socket mechanism, point centers would correspond.) Moreover, the curvatures of the specimen shown would not correspond for any position of hip joint rotation in the plane of the figure. The ends of the femoral evolutes nearest the involute surface correspond with potential bearing points of the femoral surface. These may bear upon any region of an acetabular contour which has a greater radius of curvature. Since the female contours are variable, the prominent femoral convexities will ride over the acetabulum in joint rotations and the common functional axis of the femur will shift toward or away from the common acetabular surface. The mean axis for femoral rotation will be a resultant depending on the number and locations of the femur-acetabular contacts. Such momentary functional axes will fluctuate as contacts vary. It should be borne in mind that the opposed surfaces will be in contact somewhere at all times and that the joint movement will be smooth, but the functional axis will shift position slightly as one set of contacts gives way to another. Similarly, the link distance from acetabulum to knee will vary in minute amounts due to axis movements at the hip joint. The amount of fluctuation at the hip joint should vary only a millimeter or so.

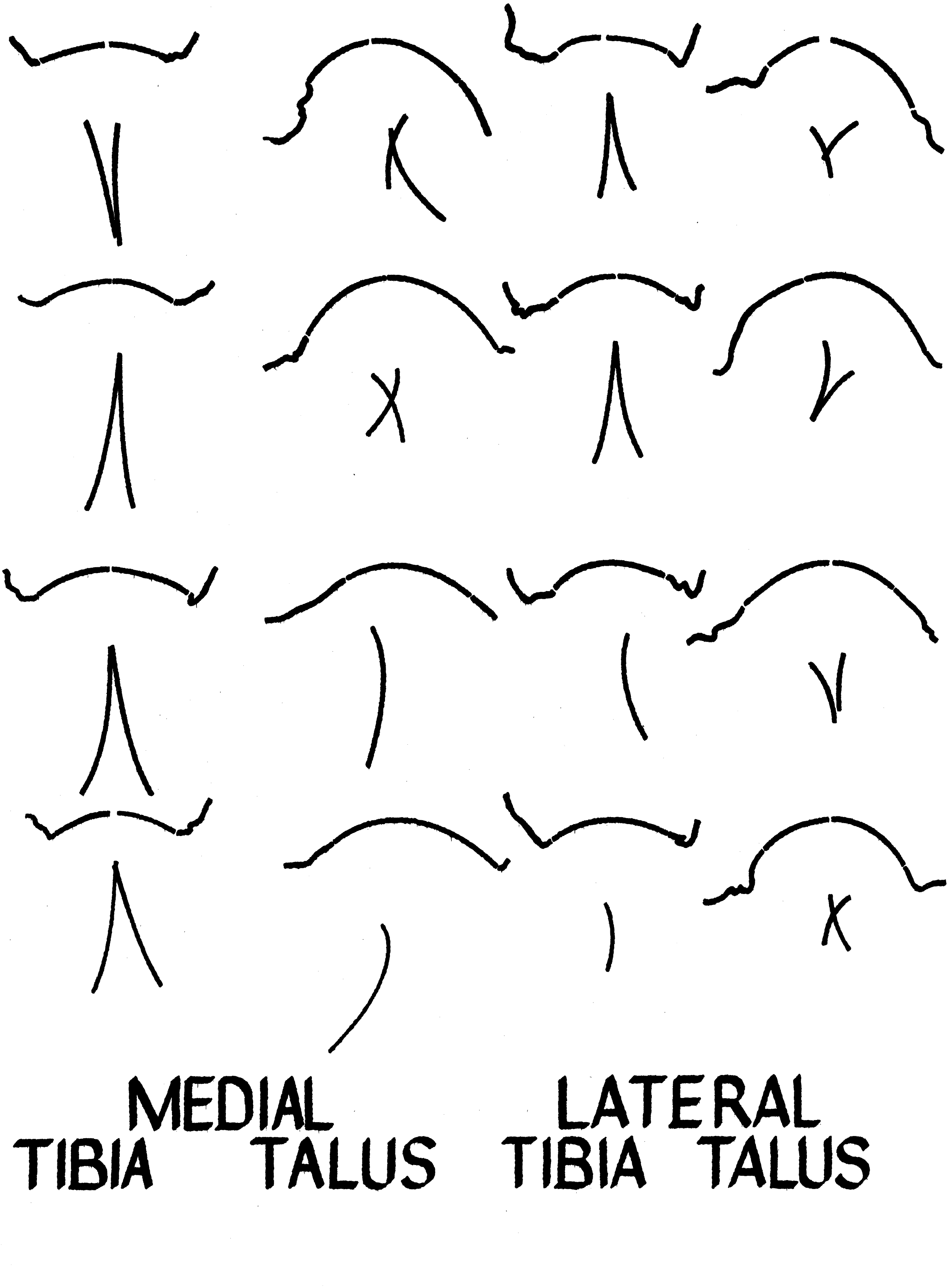
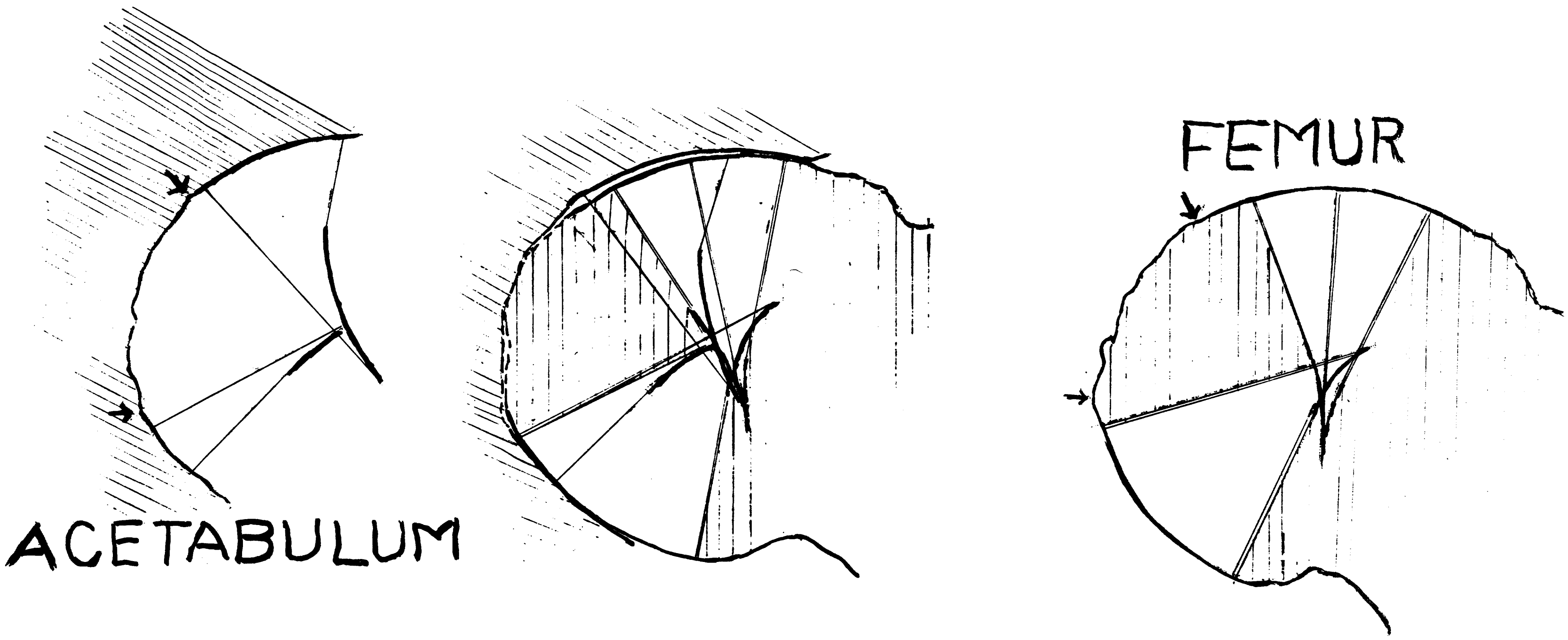


Fig. 7. In four vertical rows, the articular contours and equivalent evolutes are shown for four individual joints. Each transverse row relates to the same specimen.



Articular contours and equivalent evolutes are shown for the acetabulum and femur. The middle figure shows a superpositioning of the two separate figures.

Fig. 8.

Figure 9 shows superimposed tracings of six acetabula and six femoral heads in coronal section and also the evolutes which correspond to the various tracings. Evolutes corresponding with the region below the acetabular fossa or below the fovea capitis femoris are shown in heavy lines. Variability of the acetabular curvature is shown by the different pattern of V's, X's, and A's. For the femur, the A and star-like lines show differences in pattern and the dot-ends of the evolutes, directed toward the articular curvature, suggest the number and relative orientation of bump-like convexities (i.e., regions of small radius of curvature) in the contour of the section. In the various joints sectioned, incongruity of contact between the convex and concave members of the hip joint is again indicated.

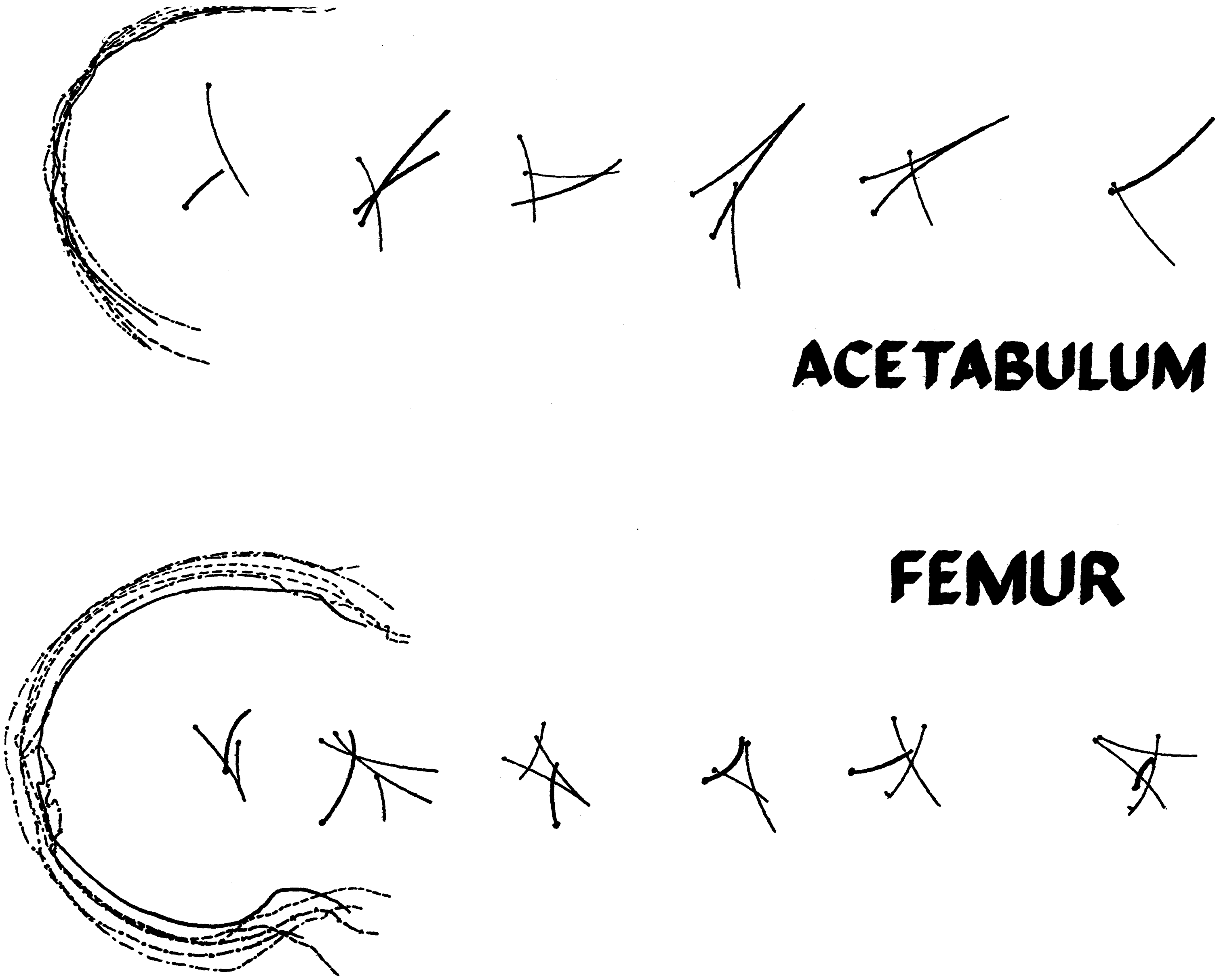
Transverse sections through the acetabulum and femoral head (not shown) indicate a similar variability. They also show a lack of congruence for the male and female articular surfaces.

The Shoulder Joint

Figure 10 shows both vertical sections through the glenoid fossa of the scapula (perpendicular to the fossa) and parallel sections through the humeral head. Like the previous hip joint figure, contours are superimposed at the left; evolutes are shown in two rows for six scapular (above) and six humeral curvatures (below). The scapular evolutes from the joint of a given cadaver are vertically above those shown for the humeral curvature from the same specimen. The differences between the scapular evolutes imply a variability in curvature for the glenoid fossa. The V's indicate a small radius of curvature for the central region of two specimens. The separated pairs of evolutes show the opposite, and the single evolutes indicate a gradation in curvature from one extremity of the fossa to the other. In all instances, the smallest radii of curvature for the glenoid fossa are further from the glenoid surface than those of the opposed humeral face. Accordingly, the humerus should have only a single contact with the relatively flatter glenoid fossa. The resilent glenoid labrum (not shown) projects beyond the surface of the fossa and this may simultaneously bear at one or more regions on the humeral head.

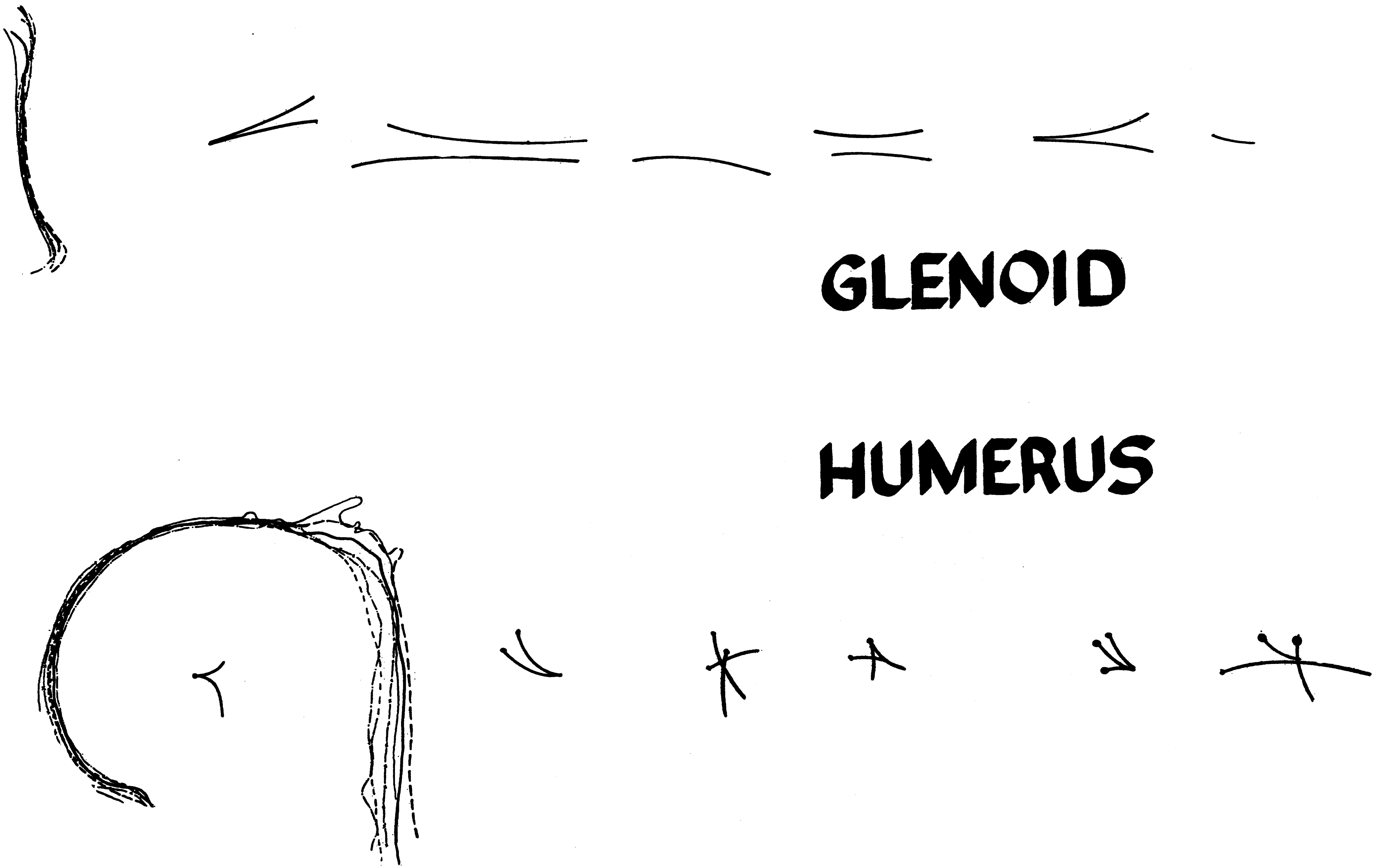
The V, A, and star patterns of the evolutes of the humeral head indicate differences in involute pattern. There may be one or more points of small radius of curvature on the surface. Depending on the angulation of the humerus to the glenoid fossa, one or more of these may bear upon the glenoid fossa for a given degree of humeral angulation.

In movements, the humeral surface slides over the surface of the glenoid fossa as the bone rotates. There should be but one or two bearing points in the plane of section. The resultant instantaneous centers of



Superimposed contour tracings of acetabular sections are shown to the left; separate evolute patterns for six acetabula are to the right. Below, superimposed contours and separate evolute patterns are shown. Dots at the ends of evolutes directed toward the contours indicate the axes for short radii of curvature.

Fig. 9.



Glenoid fossa contours are superimposed at the left; individual evolute patterns for six specimens are shown to the right. Below, humeral contours are superimposed and evolute patterns are shown individually.

Fig. 10.

rotation will shift position relative to the glenoid surface in accordance with humeral contour curvature much as the rotation centers in the condyles of the knee shift relative to the tibial contact. The humeral contours, however, are of several systems and the instantaneous centers of rotation shift and shuttle about in accord with curvature. The amount of shift may amount to 10 mm, more or less. As shown, evolutes indicate that there are individualistic patterns of curvature for the articular surfaces. The centers thus may shift position more in one individual than in another.

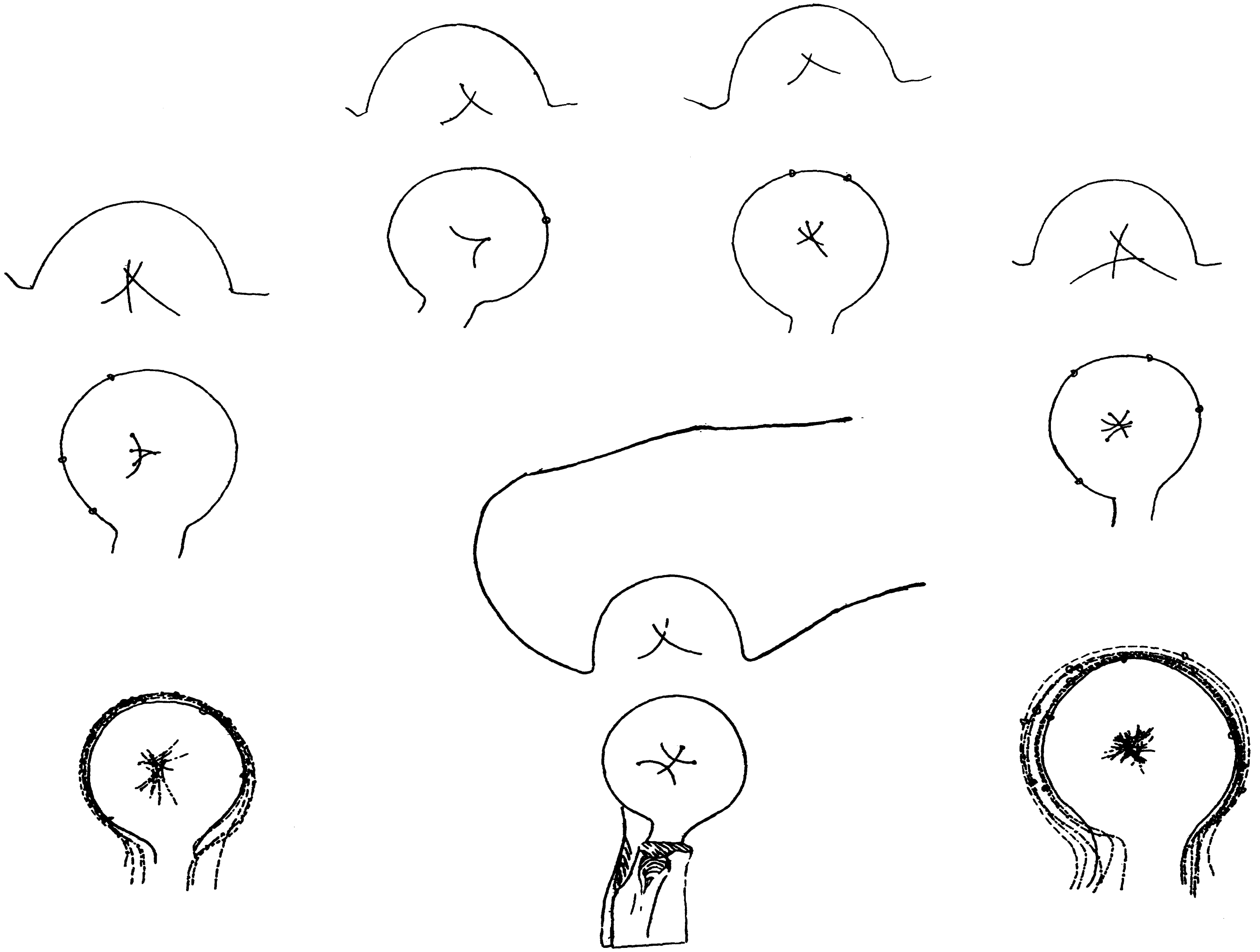
The Elbow Joint

The trochlea (ulnar articulation) of the humerus was sectioned through its medial and lateral ridges and also through its minimal section. A longitudinal section through the semilunar fossa of the ulna, along its crest, was also made; this region corresponds with the minimal section through the trochlea. Figure 11 shows a composite tracing of six medial-trochlea contours at the upper left. The evolutes corresponding with the articular curvatures form star-like and A-like patterns that vary somewhat from specimen to specimen. The whole section contour, therefore, is a composite of several systems of curvature. In the illustration, regions of the articular contour having a relatively marked convexity (i.e., regions of minimal curvature) are marked with tiny circles. Actually, convex regions are of two sorts: in one, the short radii of two systems of curvature are adjacent and the instantaneous radii become larger in directions away from the small circles; in the other, indicated by half circles, the short radius of one system of curvature is adjacent to the long radii of the adjacent system of curvature. In either instance, convexities marking a change in contour form potential bearing points.

Comparable sections through the semilunar fossa cannot be made, since the region of contact is interrupted by irregularities of the margin of the fossa. The same is true of the most lateral region of the fossa.

A composite illustration of the lateral ridge of the trochlea is shown at the upper right of Fig. 11. No special comment is necessary other than calling attention to general similarities with the figure of the medial ridge (upper left). Small circles and half circles on the contour have the same significance in pointing to relatively convex regions.

The upper central figures show the intermediate section of the trochlea and the comparable section through the sigmoid fossa of the ulna from the same specimen. The small circles and half circles again call attention to the convexities of the trochlear surface indicated by the near ends of the evolutes (dots).



The three figures at the top show: (1) The superimposed contours and evolutes of six medial condyles of the humeral trochlea; (2) an intermediate section through a trochlea together with a longitudinal section through the semilunar fossa of the ulna; and (3) a superposition of tracings of contours and evolutes relating to the lateral ridge of the trochlea. Small circles and half circles on the contour lines indicate regions having short radii of curvature. The lower four figures, like the upper middle illustration, show individual intermediate-trochlear and semilunar-fossa sections. In all sections the posterior aspect of the elbow region is toward the right.

Fig. 11.

The number of evolutes shows that either two, three, or four systems of curvature describe the section.

Evolutes relating to the sigmoid fossa of five specimens are shown and these indicate either two or three regions of marked concavity separated by regions of more gentle (relatively flat) curvature; it is the regions of gradual curvature rather than the more concave regions which provide contact points of the ulna.

A second look at Fig. 11 shows that the regions of marked convexity (bearing points) tend to fall in common regions of the contours for different specimens. The systems of curvature, however, are somewhat variable in the different specimens and the number of potential bearing points is not the same. Fisher[12] analyzed two elbow joints for the locus of instantaneous axes of rotation, and these two showed differences. Such differences should result from the variable pattern of contact points shown in the study of sections through elbow bones.

Figure 12 shows composite tracings of sagittal sections through the capitulum of the humerus and through the fovea capitis of the radius (the radius was oriented in the semiprone position so that the fovea was cut from lateral to medial). In the figure, the posterior part of the capitulum is directed to the left; the lateral part of the fovea is directed to the right.

Evolutes of the capitulum are comparable to those for the sections through the trochlea. Regions of greater convexity are shown by small circles and half circles as in the trochlea sections. As for the trochlea, these distinctive regions tend to group themselves; they are shown predominantly in the anterodistal and the posterodistal regions of the different capitulum contours.

The medial third of the fovea in most of the sections shows a convexity with a concavity at the junction with the middle third. The curvature slopes gently with a single system of curvature from this depression toward the lateral margin of the fovea. The single evolutes corresponding with the sloping concavity of the contour show a similarity from specimen to specimen that is remarkable. Since the radius rotates in pronation and supination relative to the ulna and to the capitulum, different curvatures of the fovea would face the capitulum for different degrees of pronation. Flexion and extension of the elbow cause different parts of the capitulum to face either the concavity or the convexity of the fovea of the radius. Consequently, contact points cannot readily be assessed for this part of the elbow joint.

Contours of the proximal and distal radioulnar joints involved in pronation and supination movements have not been studied.

Six superimposed tracings of the capitulum of the humerus and of the fovea capitis of the radius are shown together with corresponding evolutes. Small circles and half circles relate to regions of small radius of curvature.

Fig. 12.

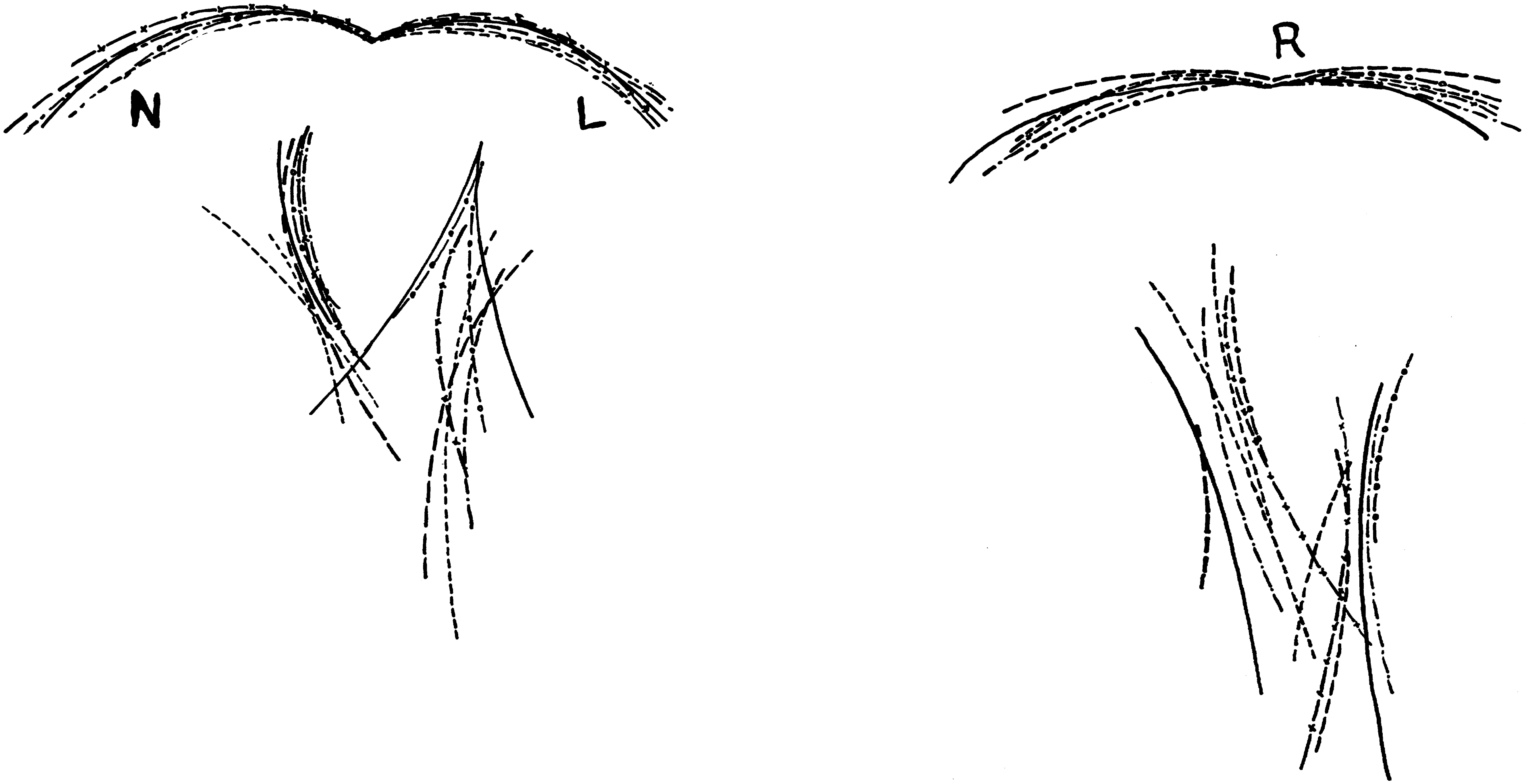
The Wrist Joint

Figure 13 shows a composite of tracings of the articular faces of the distal end of the radius sectioned from its lateral to its medial border. It also shows a composite of frontal-plane tracings through the navicular and lunate bones of the intact carpus for six specimens (the navicular bone is toward the left), and the corresponding articular contour of the radius for the same specimens (the lateral border of the radius i.e., radial styloid is directed toward the left). The pattern of evolutes as in other joints studied, shows that the wrist joint is no exception to our generalization that articular contours vary to some extent from individual to individual. The evolute patterns of the navicular, of the lunate, and of the two parts of the radius in the plane of the section are ordinarily simple systems although there are exceptional X's and V's.

The navicular typically has a sharper curvature than the lunate. Its evolute characteristically slopes obliquely toward the central (capitate) region of the carpus. In addition, the evolute curve is so directed that longer radii of curvature are toward the thumb side and the more convex part of the articular contour is toward the ulnar side. The curvature of the lunate ordinarily has the same orientation but the change in curvature is more gentle. The radius has a still greater average radius of curvature than the two carpal bones (i.e., the evolutes are longer and the nearest part of the curves is farther from the articular surface). The curvature, however, changes in the same sense as in the two carpal bones. Contacts with the two carpal bones, because of curvature differences, should be incongruent as in other joints studied.

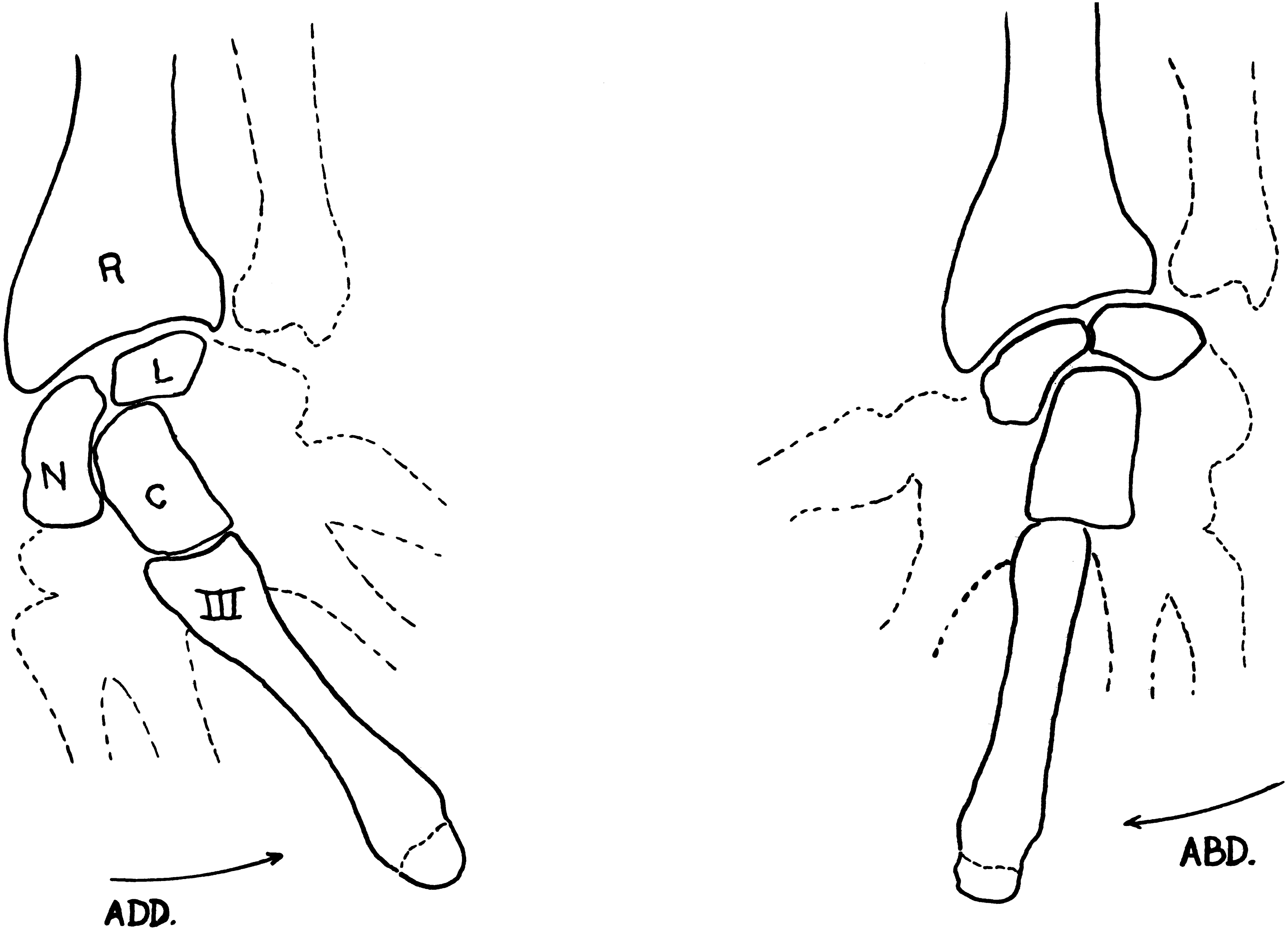
The wrist joint is structurally complex and it is beyond the present scope to deal with movements in general. Our work on contours, however, does warrant comment on one factor. The proximal two carpal bones mentioned, since they are tied together by interosseous and other intercarpal ligaments, more or less move together as they slide on the radial articulation. They should have some effect on the character of wrist rotation.

In wrist abduction, the carpal bones slide toward the ulnar side of the radius, and due to such movement the navicular articulation will bear more and the lunate will bear less on the radial surface. This shift in position is illustrated in a tracing of x-rays of the wrist in adduction and abduction (Fig. 14). The displacement of the navicular and lunate bones causes contour regions with long radii of curvature to bear on the radius, instead of those with short radii. The shift of the bones bodily, together with the change in bearing points, results in a rotation of the whole carpis about a probably moving axis in the capitate bone.



At the left superimposed contour tracings and evolutes are shown for the carpal bones of the hand which articulate with the radius; the convexity to the left relates to the navicular bone (N), that to the right is the lunate (L). The figure to the right shows an equivalent section through the carpal articulation of the radius (R); **contours and evolutes** are shown.

Fig. 13.



A tracing of two x-rays of the wrist and hand in adduction and in abduction. The radius (R), navicular (N), lunate (L), capitate (C) and third metacarpal (III) bones are emphasized.

Fig. 14

This account is obviously too great a simplification, ignoring the articular ridge of the radius, the capitate bone and its articulations, the shuttling intercarpal movements, and the role of ligaments, but it does show that the sense of curvatures at the proximal wrist articulation is in accord with known wrist mechanics.

Resumé on Joint Surfaces

There are, of course, obvious differences in the size of bones and in the size of joint surfaces that are correlated with body size and sex. Superficially, however, the joint surfaces appear fairly comparable. Actually, however, the study on joint sections reported above emphasizes that joint contours of a given type also vary. Often the contours of a given joint show a similar system of curvatures in different specimens, but in almost every group of joints studied one or more joints showed distinctive patterns of curvature. Regions of small radius of curvature i.e., (regions of prominent convexity), for instance, may be located anatomically at one locus in some specimens, whereas in others such regions might appear in a different place.

Such differences in contour imply differences in the positions of instantaneous centers of rotation as the joint members are moved. On the whole, the differences from one individual to another in the position of momentary axes relate to only certain parts of the arc (i.e., of flexion - extension, etc.) of joint movement, and the deviations are not large. Thus the study of sections suggests a type of variation in addition to the more obvious ones based on sex and body size.

More important, it should be noted from the above account on over 150 sections of the major extremity joints from 6 bodies that in no instance did matched male and female contours have the same curvature. None had a constant circular contour, and none a pattern that would allow a flush contact between the opposed section contours.

It is true that slight differences in the angulation or normality of a saw cut between one section and another would show slight differences in contour; thus, a section through a cylinder cut obliquely would appear more elliptical than circular. But the differences in evolute pattern were ordinarily of a systematically different type, and the conclusion from our data is inescapable: that complete congruity of the opposed joint surfaces does not occur.

Joint surfaces covered with resilient articular cartilage will compress to some extent (Fisher[1]) according to the load borne. This will momentarily increase the degree of congruity, but it will also result in fluctuating positions of instantaneous axes.

In entirely congruent rigid-surface articular contacts, the axis of rotation of one member against another will be in a fixed position, as in the machined shafts and bearings of engineers. Where the surfaces have contact at only certain points, where the contact points may vary from moment to moment with joint angulation, and where different systems of curvature are involved in a joint contour, the position of the rotational axis will not be constant. Instead, it will shift in accord with the number of contacts and the curvatures; that is, the position of the instantaneous rotational axis is the resultant of a distinctive group of factors.

Physiologically, the type of joint contact shown would appear to have two advantages: (1) The space between incongruent areas next to regions of momentary contact will be filled with synovial fluid. Each movement of a contact point or each shift to a new contact will involve a freshly lubricated region. This, in turn, should assure low friction value between joint surfaces. (2) Regional (or hillock) contacts of one articular surface with another will assure an especially resilient bearing in which contact regions will vary in area with varying loads.

The Ankle Joint Seen in Three Dimensions

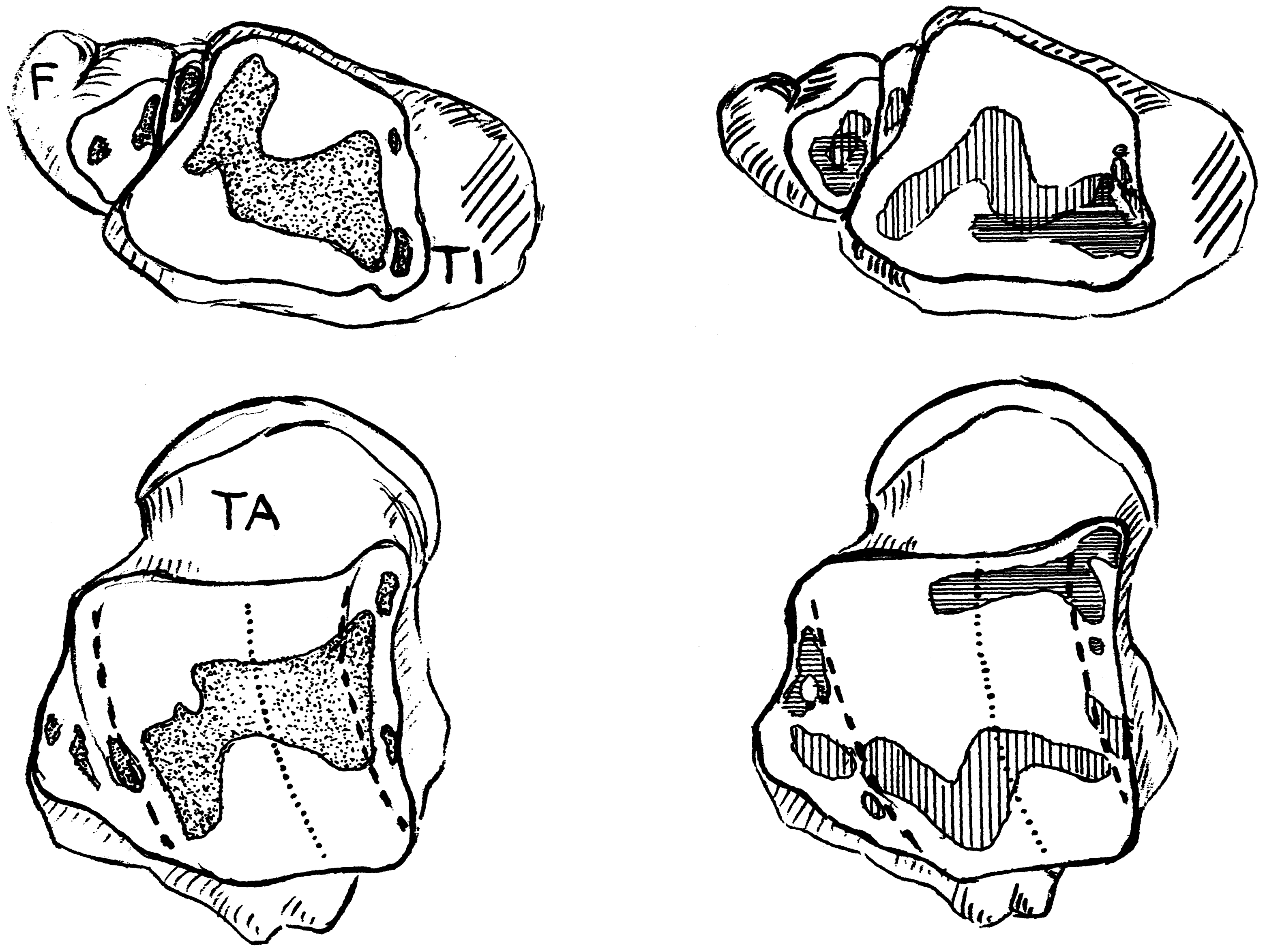
The foregoing account deals with sections through articular surfaces; the following paragraphs, though dealing illustratively with but one joint, show in another way the nature of joint contacts. A group of stripped-down ankle-joint dissections were made with the essential ligaments in place. The medial (talo-tibial) ligaments were cut so that the bones could be hinged apart and the tibia and fibula were clamped vertically in a vise with the talus surface uppermost. The foot and leg bones were adjusted to a mid-range position of 4° extension and the fore and aft margins of the tibia were marked with an indelible pencil on the articular surface of the talus. Then a second set of marks was made on the talus for 30° of further extension. Finally, a third set of marks was made to indicate the tibial contact with the talus at 30° of flexion beyond mid-range. A colored paste of casein paint (direct from the tube) was smeared thinly over the articular surface of the talus and was worked evenly over the whole surface until it was of an appropriate consistency. The talus was then gently superimposed on the tibiofibular contacts so that the tibial marks made on the talus representing the mid-range position exactly corresponded with the tibial margins. Then pressure applied from talus to tibia transferred some of the pigment to the leg bones at points of articular contact. After the articular surfaces had been wiped clean of pigment, a thin coating of the paint was then applied to the tibiofibular surfaces. When the talus was in place and pressure was applied, the pigment was transferred to contact points of the talus. The pattern of contact for each impression was recorded on plaster casts of the joint surfaces and repeated impressions of pigment were made until a constant average pattern was certain.

Figure 15 shows the tibial and fibular articular surfaces and the surface of the talus of one specimen; the average contact of articular surfaces, after many repetitions of the pigment transfer technique, are shown in stipple at the left for the mid-range (4° extension) position of the ankle. The illustrations to the right show the contact regions when the ankle is flexed 30° beyond mid-position (horizontal shading) and when it is extended to 30° beyond mid-range (vertical shading). Clearly, different bearing contact regions are involved in the three ankle positions. The pattern of contact shows a certain similarity from joint to joint, but there are differences in detail which, however, are consistent with expectations based on information from sections. The contacts for the mid-range position of the ankle as shown are broader than for the other two positions, which suggests a position of relatively greater stability for the mid-range (standing) posture than for more extreme flexion and extension.

The changing position of contacts shown bears out the conclusions derived from tibial and talus sections. Since the tibial surface is relatively flat, contacts are determined primarily by talus convexities. The lines of dashes in the figure were obtained by rolling the talus over a chalked plane; these indicate the planes of saw cuts for sections through the talus. The intermediate cut lies between at the minimum average curvature (line of dots). It will be seen from the figure that the bearing contacts for a given ankle angulation may simultaneously involve all three section contours, only two, or but one at a time. The common functional axis of rotation for any given degree of flexion or extension (i.e., plantar flexion) should lie obliquely, and its position will vary with changes in the flexion-extension angle.

Further Work on Joints

This phase of the problem deals basically only with sections through joint surfaces. The talo-tibial joint study based on pigment impression is illustrative of a companion study that will be reserved for a later report. Further work on joints involving the location of mid-range positions of joint axes is at present under way, and it is planned to summarize this at a later time along with work dealing with localization relative to anthropometric landmarks. The eventual defining of link dimensions for the extremities will carry this phase of our study relating to joints as far as has been intended.



To the left the lower articulation of the fibula (F) and tibia (TI) are shown above the superior surface of the talus (TA). The anterior extremity of the talus is directed upward; that of the tibio-fibular surface is directed downward. The stippled areas represent contact areas of the leg bones and talus for the mid range position of the ankle. To the right, horizontal shading demarcates contact areas for a 30° flexion position and vertical shading indicates contact areas for a 30° extension position of the ankle joint.

Fig. 15.

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