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QUARTERLY REPORT NO. 5

STUDY OF THE HINGE POINTS OF THE HUMAN BODY

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ABSTRACT

A critical study of the axes of rotation of the major joints of the upper and lower limbs has had a basic importance in our work on human hinge points. Earlier anatomical approaches have made it clear that functional axes must be understood. To this end, two methods have been developed. One deals with the movement of a cadaver limb segment relative to the adjacent link, held fixed; the other involves the location in the sagittal plane of joint centers for a living individual during a stereotyped movement in which the links of a limb are all in simultaneous movement. These methods are described and illustrated.

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THE GENERAL PROBLEM

The research effort under the present contract seeks fundamental information relating to body mechanics, especially that concerned with the functioning of the upper and lower limb segments. To this end, the extremity link systems and joints of both cadavers and living subjects are being studied so that the basis for a kinematic analysis of the body during various activities, including those of the pilot cockpit, may be realized. Joint centers are to be located and link dimensions determined. Samples of living subjects are rigorously selected according to somatotype techniques so that data applicable to a range of body types may be available. Cadaver information relating to mass, density, centers of gravity, moments of inertia of body segments, and techniques for accurately estimating these mechanical constants on living subjects will facilitate kinetic analysis of body movements. Practical applications relating to manikin design and to problems of the body geometry of the fighter pilot in his cockpit are under study.

TECHNIQUES USED FOR DETERMINING JOINT CENTERS

This report will direct attention to a more or less crucial aspect of the present investigation, the location of functional joint centers and the methods underway for its solution.

The construction of a manikin with joints which function in such a manner that action patterns and segment dimensions correspond with those of the living body demands a detailed knowledge of the character and locations of the centers of rotation at each of the major joints of the limbs.

A practical problem of this sort is basically synthetic; to be successful in its solution, one must know the nature of the elements involved in the synthesis. The available literature on joints, however, does not now provide a sufficient background to permit either accurate manikin design or the layout of action patterns on paper. Information is needed on (1) the location of centers of rotation for the major joints, (2) the relations of these centers to the skeletal landmarks, and (3) the ratio of the dimensions of the links between centers to body dimensions as they vary with physique.

The above problems have been a knotty aspect of this research since its inception, and Quarterly Reports No. 2 and especially No. 4 have dealt with aspects of our efforts on joint centers. The previously reported work has dealt in detail with the character of joint surfaces. The joint contacts have been shown to be noncongruent and the axes of rotation relating to the contact surfaces have been shown to be shifting their locations from instant to instant. The radii of curvature, for successive points on joint contours, increase or decrease in patterns unique to the various types of joint concerned. Moreover, the joint contours and their instantaneous centers of rotation are somewhat variable from individual to individual. In other words, no joints appear to operate as pin-centered mechanisms; the axis shifts systematically for a given individual and one individual may differ from another somewhat. The work reported has mentioned the pertinent literature and has brought forth observations important to an understanding of the "hinge point" problem. We have still been, however, short in the reports of the essential data needed for the practical synthesis which is one of the aims for the current investigations.

This report will outline methods which have developed from our continuing study of joints and which at present appear to be gaining access to the required fundamentals in the localizing of functional joint centers. One method deals with cadaver joints; although only certain joints have been studied so far, we believe that the approach with minor modifications is applicable to each of the six major limb joints under study (i.e., shoulder, elbow, wrist, hip, knee, and ankle). The advantages of the approach on cadaver joints are: (1) that the elements involved in joint contact are continually under observation during joint movement while records are made, and (2) that bony landmarks may be laid off accurately relative to the pattern of instantaneous joint centers. The relation of landmarks to joint centers is an important consideration when it becomes necessary to locate joint centers in a living individual, where only anthropometric landmarks are available for reference.

The second method, and its application to both the lower and upper limb, relate to the living subject. It purports both to locate the effective instantaneous centers and to indicate the intervening link dimensions for a given subject during a phase of functional movement. With this method, special attention is directed to the location of the instantaneous axes during a phase of movement when the links are in the mid-position of the range of joint movement. The principal advantages from measurements on living subjects should be: (1) a correlated set of links for both the upper and lower limbs will be measured, (2) link dimensions can be correlated with general body anthropometry and body type data, and (3) differences, if any, between joint centers and effective centers for the links may be determined.

LOCATING FUNCTIONAL AXES OF LIMB JOINTS ON CADAVER MATERIAL

Since Quarterly Report No. 4 presents detailed data on the axes of the ankle and the contour of the joint surfaces of the talus and the tibia, as well as data on the areas of joint congruence for the midrange, flexed, and extended positions, the ankle joint will again serve to illustrate the present method. Material for study consists of joint preparations dissected so that the bony members and the essential ligaments are clear. For the ankle joint, a specimen of the leg and foot is separated from the body at the knee; then, the leg muscles are removed cleanly from the tibia and fibula, and the ankle ligaments are dissected. Next, the talus is separated at the subtalic joint from the remainder of the foot (which is saved for reference purposes as indicated below). The capsule of the talo-tibial joint is removed except for the essential collateral ligaments. Now the test preparation consists of the stripped down, tibia, fibula, and talus, and the essential ligaments of the ankle and the tibio-fibular joints. If the talus slides freely and smoothly on the tibio-fibular contacts and if there are no signs of arthritic changes, the preparation is used for study.

The talus rotates relative to the tibia and fibula in a movement which is predominately of the flexion-extension sort. There are, however, associated deviations in the movement toward flexion which involve eversion (toeing outward) and pronation (medial side of foot turned plantar-ward). Extension involves also the reversed pattern of inversion plus supination. Our problem is to determine the location of the major flexion-extension axis (or axes) of the joints in the sagittal plane without the complication of movements about other axes.

Our method involves fixation of the talus on an axis corresponding to the length of the foot, but the fixation on this one axis still allows the talus to rotate to execute pronation-supination movements. In practice, a 1/4-inch drill hole is made in an antero-posterior direction through the body of the talus just clear of the cartilaginous articular face of the bone. A 1/4-inch steel rod is passed through the drill hole and each end of the rod is supported by ball bearings, so that the rod may rotate freely. The bearings are alligned coaxially and are supported at the edge of the work table on small vises (Fig. 1). The position of the talus on the rod is held fixed so that the bone cannot slide along the rod. When the talus is fixed as indicated, the tibia and fibula together may flex and extend relative to the talus and the talus adjusts to its tibio-fibular contacts by rotating slightly on its steel axis as required to compensate. The rod and talus are free to rotate only on the antero-posterior axis and the amount of talus rotation (pronation-supination) is measurable with a protractor. (A pointer attached to the talus is a reference guide for bone rotation relative to the protractor.)

At the proximal end of the tibia, a 1/4-inch drill hole is made at the medial part of the lateral articulation for the femeral condyle and the drill is directed along the length of the tibia so that its axis intersects the rod through the talus. Then a steel rod is inserted several inches into the drill hole and its free end is supported on ball bearings which in turn are supported by a bench vise attached to a mobile carriage. The carriage slides on the table surface on ball bearings and the height is such that the tibial steel rod is at exactly the same height from the table top as that through the talus. Now, as the leg bones are moved in a flexion-extension arc about their talus contacts, the tibia and fibula rotate axially in a movement corresponding to the eversion-inversion movements that are conditioned by the ankle contacts. These movements are measured by a protractor set on the carriage that supports the tibial rod.

The setup illustrated now allows the leg to make flexion-extension movements about the talus; the leg moves in a plane parallel to the table top, and it moves about an axis at the ankle perpendicular to the table top. Concurrently, the talus rotates about an axis parallel to the table top and the leg bones rotate about another axis also parallel to the table top. The latter axis, however, is perpendicular to the former when the leg and footsole are adjusted to a right angle. With this arrangement, there is no limitation that will restrain any movement in the three cardinal planes permitted by the ankle. Flexion and extension movements are made by moving the leg bones manually and the angular deviations due to pronation-supination and inversion-eversion are recorded for each 5° of the flexion-extension arc. When the arrangement is adjusted for operation, a large paper is placed on the table top and a pencil point fixed to the carriage describes an arc that represents the path of the flexion-extension movements in the plane of the two steel rods. During the movement a firm pressure is maintained between the talus and legbone contacts.

The penciled arc (Fig. 2) represents the basic data of the experiment. Chords are struck off with a compass and perpendiculars are laid out in pencil (in the figure, these are the fine dashed lines); these converge toward the talus region, but it has been found that they do not converge to

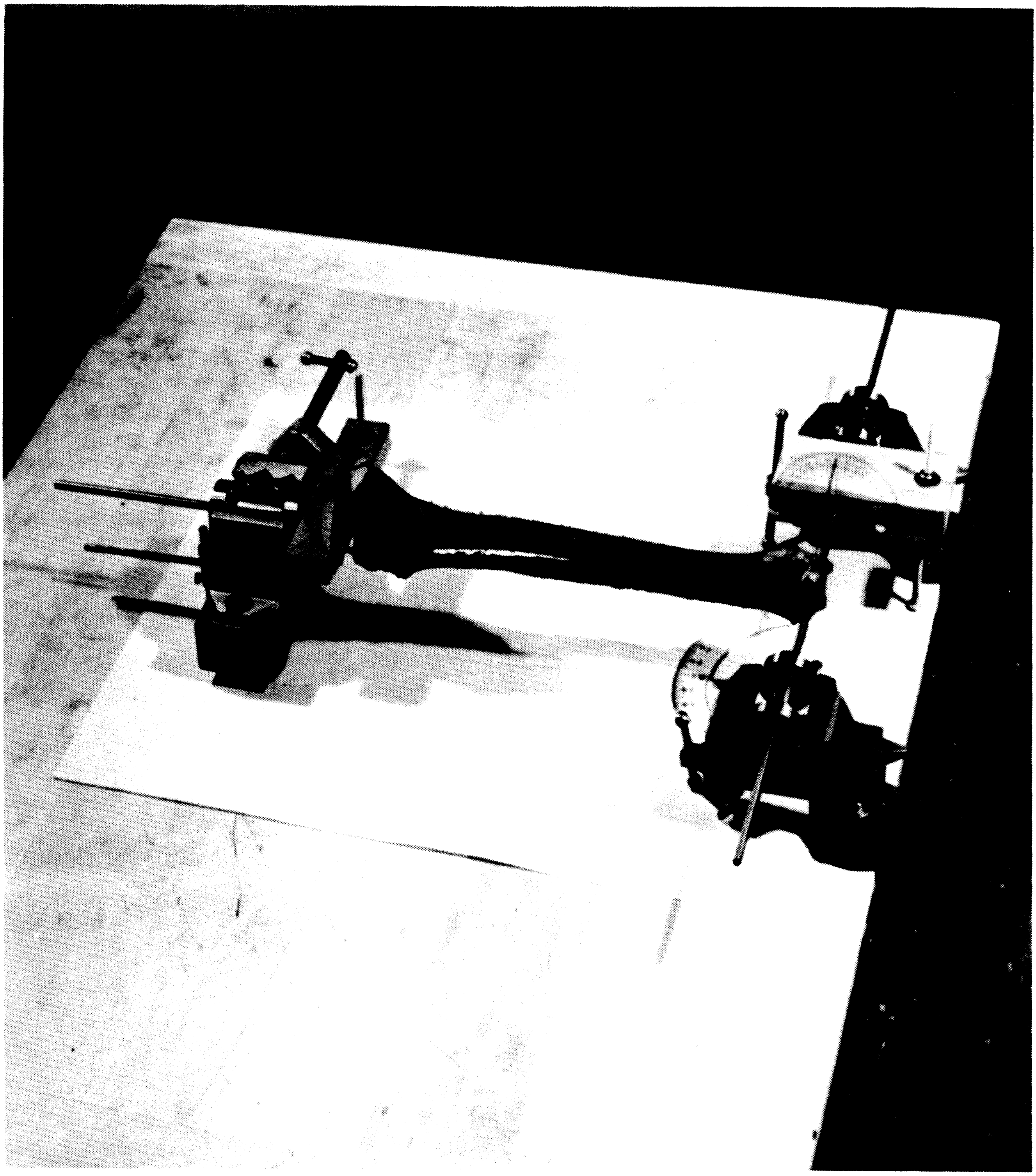

Fig. 1. The method for locating the functional axes for flexion-extension movements of the ankle joint. The bones are supported on metal rods which rotate axially on bearings held in the jaws of the three vises. The vise and bearing at the left are mounted on a carriage which moves through an arc as the leg bones are flexed or extended relative to the talus bone, which is impaled by the rod between the two vises at the right. The three protractors shown indicate angular rotations in three planes which resolve the ankle movement into movements of flexion-extension, pronation-supination, and inversion-eversion.

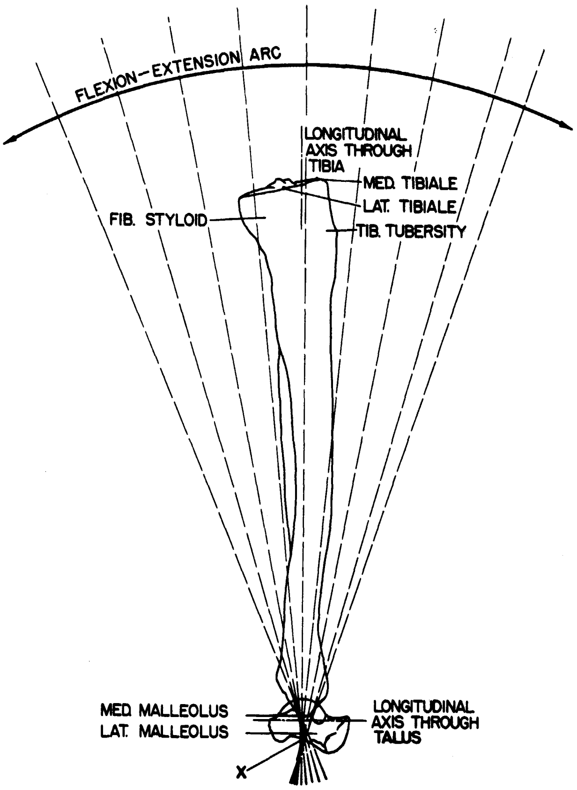

Fig. 2. The contour of the talus bone and tibia (with part of the fibular shaft) are shown; the longitudinal axes used for the talus and leg bones are shown by dashes. The vertical locations of anthropometric landmarks are indicated. Special attention is directed to the flexion-extension arc and the perpendicular chord-bisectors which converge toward an evolute curve shown at "x". This evolute represents the path of successive instantaneous axes of rotation for the flexion-extension movement.

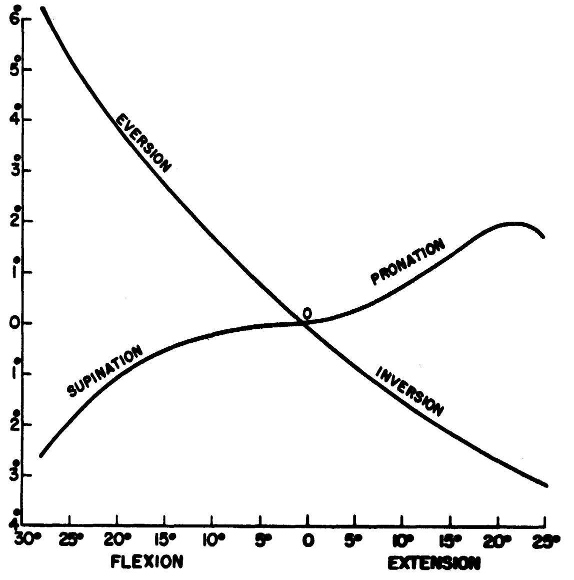

Fig. 3. A plot showing the number of degrees of eversion and supination at the talo-tibial joint associated with various degrees of ankle flexion; the degree of inversion and pronation associated with extension is also shown.

a point that would imply a "pin-centered" axis for flexion and extension. Instead, an evolute pattern (curved line at "x") may be laid out over the radii of the arc. This indicates that the radii of curvature are instantaneously changing their lengths, and that the axis of rotation changes position with each increment of movement. Figure 2 indicates a common pattern of the evolute for flexion and extension and its position is shown in relation to the contour of the talus bone.

The figure shows a single arc-like evolute with a convexity directed forward toward the head of the talus. The part of the evolute corresponding to the mid-position of the ankle between flexion and extension is just above the lower edge of the talus at approximately the level of the lateral malleolar point. The upper part of the evolute indicates that the path of the joint center comes to a higher level during ankle extension. In flexion, the path of the instantaneous axis of ankle movement drops well below the talus into the region of the calcaneus.

Figure 3 shows a graph indicating the amount of ankle pronation-supination and inversion-eversion that is contingent, because of joint contours, on flexion and extension movements. From measurements we have made elsewhere on living subjects, 4° of extension of the ankle joint (i.e., plantar flexion) is taken as the average mid-range position of the flexion-extension arc. This angle is measured with a protractor as the angle between the footsole and the long axis of the tibia. (The severed foot, saved for reference, is now placed against the talus for measurement of the angle.) The 4° extension angle is considered as a zero point for flexion versus extension movements.

Anthropometric landmarks from the tibia and fibula are laid off on the paper for the 4° extension position (Fig. 2). Landmarks used are: tibial tuberosity, medial and lateral tibiale, upper tip of fibula, and the tibial and fibular malleolar points. The linear distances of these from the 4° point on the evolute may be measured.

The above method outlines the location of instantaneous centers of rotation for the basic flexion-extension movements and it shows the functional pattern based on joint contacts. With minor modifications, the method is applicable to other joints.

EFFECTIVE LENGTHS OF LOWER LIMB SEGMENTS

The purposes of this study are (1) the location of the effective joint axes for sagittal plane movements of the lower limb and (2) the determination of the effective lengths of the proximal and distal links of the lower limb in various positions.

Figure 4 illustrates the apparatus employed for the lower limb in this experiment. The right foot of a live model is subjected to a passive motion along a straight line. The model sits upright in the chair in such a way that the position of the hip-joint is held constant, while the thigh and leg movement in a vertical plane are unimpaired. The motion of the entire limb is held somewhat in the same plane by means of the board B. The model is photographed in a darkened room using a double exposure:

(1) a flash exposure showing the whole body with the limb in some position of the movement under consideration, and

(2) a time exposure while the leg is moved through a range of movement corresponding to the voluntary range of the motion under study. Lights, fastened to each segment of the limb, are flashed at a predetermined uniform rate; these flashes are recorded as arcs of curves, as shown in Fig. 4.

This first attempt at analysis is based on the following idealizing hypotheses:

(1) The hip, knee, and ankle are all pin-centered joints.

(2) These joints lie in a plane perpendicular to the axis of the optical system of the camera throughout the movement under study.

(3) The distances between hip and knee joints, knee and ankle joints, and ankle joint and floor (measured along a normal to the floor passing through the ankle joint), are constant.

Since the various lights are flashed simultaneously, corresponding positions of the lights can be determined for a number of phases of the movement of the entire leg.

The effective lengths of the links of the thigh and leg are determined by the following procedure:

(1) Assuming the hip pivot is stationary, the three lights attached to the thigh describe arcs of circles whose centers lie at the pivot point of the hip. Choose two points on one of these arcs and erect the perpendicular bisector of the chord determined by these two points. Repeat this procedure for each of the two remaining lights using the points which

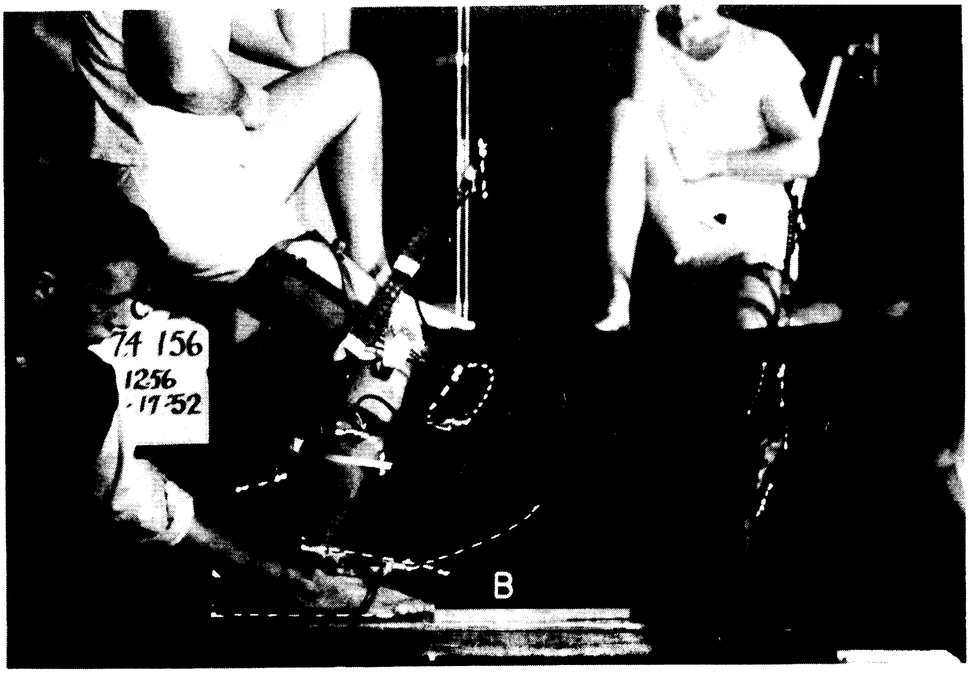

Fig. 4. The subject (and his 45° mirror image to the right) is shown with groups of one to four neon lights on metal units attached to the thigh, leg and foot. As the assistant (lower left) moves the otherwise passive foot forward or backward on the board-track "B", the lights attached to the limb segments describe patterns of arcs which form the basis for the analysis outlined in the text.

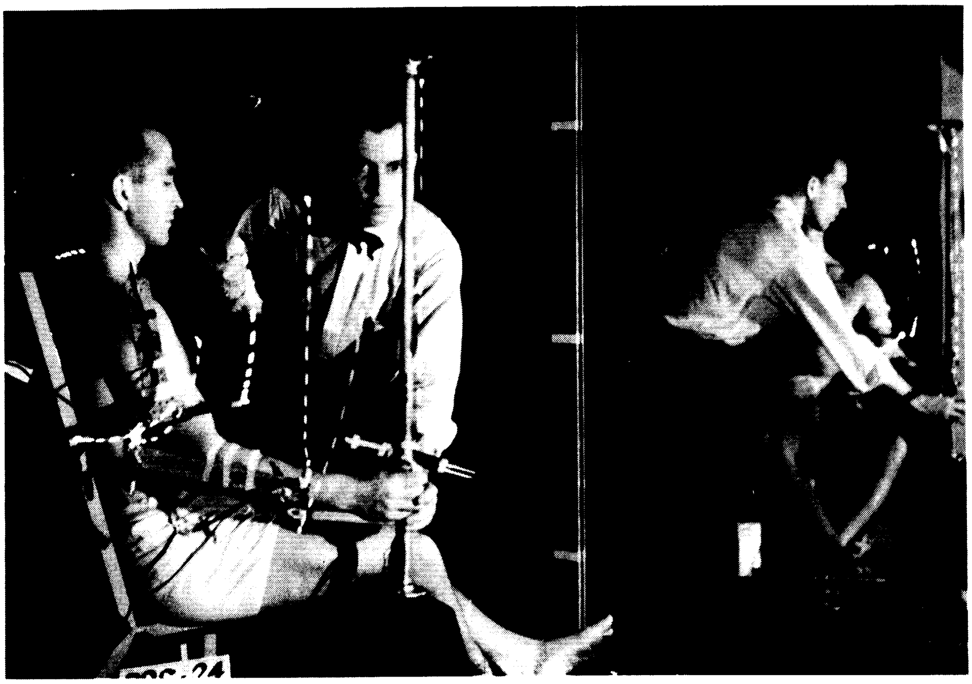

Fig. 7. This figure, showing the path of flashes of neon lights attached to the hand, forearm, and arm, is comparable to Fig. 4 for the lower limb. As the subject's hand is moved up or down relative to the vertical pipe, the angular relations of the passive limb segments change at each joint. The pattern of segment movement as indicated by light paths provides data for analysis of axes and distances between axes.

correspond to those selected previously. The intersection of these three perpendicular bisectors determines the approximate location of the hip pivot point at a given instantaneous position.

(2) When the lights on the thigh have reached their maximum elevation, the knee pivot is directly over the ankle pivot. Now, for each of the paths described by the various lights, let us designate the points corresponding to maximum elevation of the thigh by a. At each of the points a, for the lights of the lower leg, construct the normal to the curve. The intersection of these normals determines the position of the knee pivot at the time of maximum elevation of the thigh. Thus, the effective length of the thigh has been determined.

(3) The perpendicular distance from the knee pivot position corresponding to a and the floor will be designated by d. This distance may be thought of as the sum of the distance between the knee pivot and the ankle, denoted by a, and the elevation, x, of the ankle pivot above the floor at time t(a) (Fig. 5). That is,

$$d = a + x \quad ,$$

or,

$$x = d - a \quad . \tag{1}$$

Now at some later time t(e) (Fig. 6), the angle θ between the floor and a line joining the knee and ankle pivots can be easily ascertained. Consider any two of the lights attached to the lower limb; θ is equal to the angle between a line joining these two lights at time t(a) and a similar line at time t(e).

Now at time t(e), the distance d' between the knee pivot and the floor measured along the line joining the knee pivot and the ankle pivot is given by

$$d' = a + y \quad ,$$

where

$$y = \frac{x}{\sin \theta} \quad ;$$

thus

$$d' = a + \frac{x}{\sin \theta} \quad ,$$

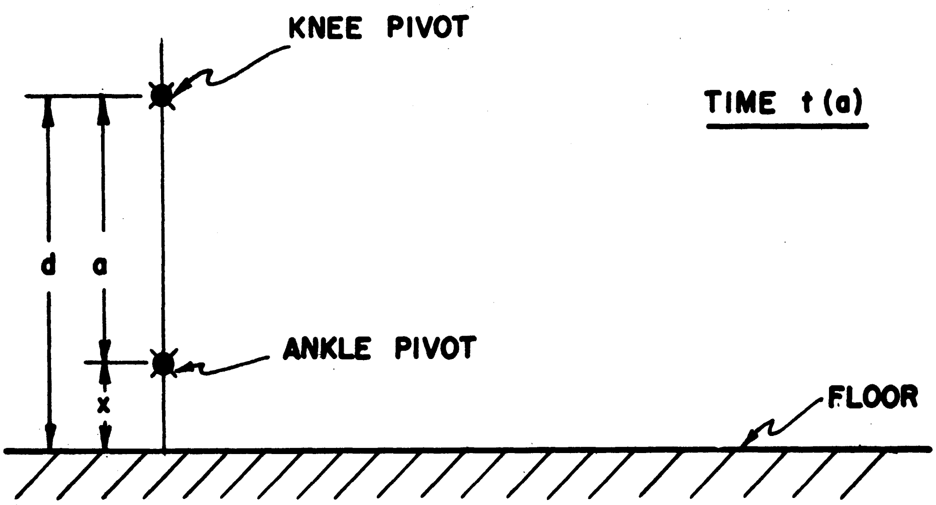

Fig. 5

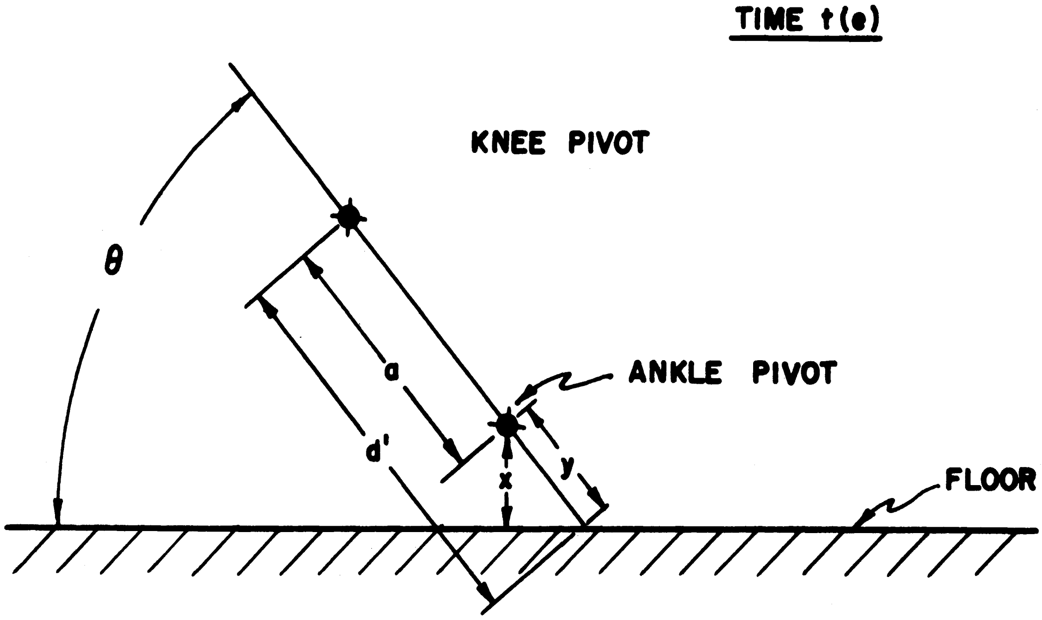

Fig. 6

Figs. 5 and 6. Diagrams of factors involved in the analysis of the movement pattern of the lower-limb; see text for explanation.

or

$$x = (d' - a) \sin \theta \quad . \tag{2}$$

Now substituting the value of x of Eq 1 into Eq 2, we have,

$$d - a = (d' - a) \sin \theta \quad ,$$

$$a(1 - \sin \theta) = d - d' \sin \theta \quad ,$$

$$a = \frac{d - d' \sin \theta}{1 - \sin \theta} \quad .$$

Thus, we have obtained the effective length of the leg. Furthermore, with x and a known, the ankle pivot is localized.

EFFECTIVE LENGTHS OF UPPER LIMB LINKS

The method for locating axes and determining link dimensions for the upper limb is identical to that used for the lower limb except that the path of the hand is vertical, whereas that for the foot was horizontal. Figure 7 shows the experimental setup. Shoulder, elbow, and wrist are placed in the picture plane of the camera as near as possible and the hand, clenched to a hand grip that slides freely on the vertical metal pipe, is passively raised or lowered. This results in movements of the arm-forearm about pivots at the shoulder, elbow and wrist. Attached lights describe arcs, which on analysis as for the lower limb system serve to determine the effective pivot axes and link lengths.