ENGINEERING RESEARCH INSTITUTE
UNIVERSITY OF MICHIGAN
ANN ARBOR

QUARTERLY REPORT NO. 1

STUDY OF HINGE POINTS OF THE HUMAN BODY

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Project M996

WRIGHT AIR DEVELOPMENT CENTER, U. S. AIR FORCE
CONTRACT NO. AF 18(600)-43, E. O. NO. R695-70 PO-12j
DAYTON, OHIO

March, 1952

ABSTRACT

The first phase of the work reviewed in this report is a general evaluation of the component structures of the major segments of the upper and lower extremity from the standpoint of their masses and centers of gravity. This work, planned as a background for defining what is meant by an "extremity segment", shows that bones and to some extent skin indicate segmental characteristics, but that intervening tissues do not. Muscle centers of gravity, however, cluster within segments rather than fall across joints--exceptions are rare--and muscular movements should not greatly add to or detract from the mass of a limb segment if it is so defined that intersegmental boundary planes divide clusters of muscle centers of gravity.

The second phase of work outlined deals with the location of joint axes on the basis of the radius of curvature of articular surfaces. Axes so determined are localized in relation to standard extremity anthropometric points.

This report, in addition, shows aspects of the nature of project equipment and approaches. It also outlines items of research under way at the date of writing and in prospect for the immediate future.

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THE GENERAL PROBLEM

Considerable information is in the literature on measurements showing the size and proportions of the living body and its general subdivisions. Lengths and circumferences have been measured on adults conforming with various special populations and on children, both sexes, and on numerous racial groups. Such measurements have contributed fundamental data on such topics as growth, body build, clothing sizes, and the sizing of extremity prostheses. In addition to civilians, military personnel (USA) of both world wars have been measured. Probably the most recent survey, and an elaborate one too, is the 1951 Anthropometric Survey of Air Force personnel by the Antioch College group, which involved some 135 measurements on over 4000 men. All these studies give heavy emphasis to standardized linear dimensions of an arbitrary nature such as stature, height from the ground to specific bony landmarks, measurements between palpable bony landmarks and maximum or minimum circumferences. Important as the anthropometric information has shown itself to be the few stereotyped postures assumed by subjects during measurements necessarily imposed limiting conditions on the application of data to practical situations. Accordingly, special studies such as those upon seating, catwalk dimensions, and cockpit design, which again involved more or less sterotyped postures, have been made. Each of these studies may solve a specific problem in an empirical way, but the solutions are not readily transferred to other situations.

Details aside, the fundamental problem of the present investigation is an attempt to derive supplementary types of information on the body which, in relation to routine anthropometric data, will permit broader functional application of information. The approaches of this study seek data on body geometry, on body masses, and on mechanical factors such as centers of gravity and moments of inertia of parts. It is planned to develop information relative to four standard male somatotypes. Primary emphasis will be upon the upper and lower extremity segments. As the work develops, certain situations of a practical nature will be considered.

WORK TO DATE

Of several leads now under investigation, two are selected here for synoptic treatment. The first is directed to a critical review of what is understood by the term "extremity segment". The second is a closer view of the major extremity bones, in an attempt to locate axes of movement, or "hinge points", and relate them to the standard anthropometric landmarks of the extremities.

Extremity Segments

A child soon learns to recognize such body segments as head, hand, forearm, and thigh. These parts are distinguished by their general constancy of form, by the spanning distances between joints, and by relations to adjacent segments and the body as a whole. The parts, however, change form and dimension as they are modified by muscular actions and by external contacts. Body forms have a constantly changing plastic character not to be found in simple manikins. A critical treatment of body mechanics cannot ignore the plastic changes in form, since these may alter mass distribution significantly.

A general view of extremity structure is shown by Fig. 1, the right hind leg of a dog. General subdivisions are recognizable, but precise and logical lines of separation between segments are not obvious. Skin, fascia, muscles, and blood vessels are continuous from one segment to the next. The bones alone show discrete units, but even here segments may be regarded anatomically as separable at articulations or functionally as separable at hinge axes. If hinge axes alone are utilized in defining segments in a functional-mechanical treatment, it becomes necessary to analyze how other masses are placed in relation to interpivotal spans.

Since skin and fascias in the dog may be loose and highly elastic, these integumentary layers continue more or less smoothly from segment to segment. The haunch and thigh above the stifle (knee) are against the trunk and are covered by skin that is confluent over the loin and belly.

Accordingly, skin is of little value in demarcating segments. Furthermore, since extremity muscles--according to the fundamental tetrapod plain--either span from one bone to the next in sequence across a joint, or extend over two or more joints in sequence but have no attachment in the intermediate segments, an obvious way of apportioning muscles into gross extremity segments is not clear.

Fig. 2 shows an approach to handling this problem of muscle anatomy. The X's show where the centers of gravity of the individual muscles lie in relation to the bones of the hind limb (horizontal shading); solid lines show the distance from the farthest point of the muscle origins, and the dashed lines show the distance to the farthest insertion points of the muscles. The centers of gravity of muscles cluster typically about the bone segments. With the possible exception of small axis rotating muscles about the hip and stifle, the centers of gravity clearly fall into one segment or the next. (In the dog's forelimb, however, the deltoid center of gravity overrides the joint, but an equal contraction of each end would not alter segmental masses greatly.) Moreover, a shortening of a muscle belly by half would not appear to shift any muscle center of gravity into the adjacent segment. Accordingly, it should be possible to separate segments across muscles in such a way that the muscular masses on either side of separating planes should be more or less constant irrespective of the posture assumed by an extremity.

In the human, the pattern is more clear-cut except for the shoulder girdle mechanism; the thigh and buttock are more separated from the trunk, and borders of the external face of the pelvis are subcutaneous. Three upper extremities and two lowers of preserved cadavers have been analysed in the same way as those of the dog. The muscles' centers of gravity are more readily separated into limb segments. Moreover, when a joint is flexed actively, the flexing muscle fibers shorten and the centers of gravity of the muscles shift upward in the segment; conversely, extensor centers of gravity shift lower. To what extent this mechanism is an automatic compensating system cannot be inferred, however, since finer intramuscular anatomy, fasciculus lengths, fiber obliquity, and intramuscular tendonous anatomy are not known accurately. To a degree, however, some compensation may be assumed to exist. A consequence should be either that the composite-segment center of gravity retains its relative position irrespective of muscular activity or that the segment center of gravity shifts but slightly. Certainly, lengths of tendon slip into or out of an extremity segment during hinge movements at an adjacent joint, but the mass of these tendon lengths is small and the alteration of extremity mass will be of relatively low magnitude.

The above information should provide an operational background for a later phase of this investigation, when extremity segments must be separated in order to derive data on whole segment mass, center of gravity, and moment of inertia.

Of similar significance is a check on the location of skin creases. Flexion movements compress the skin on the acute side of the bent extremity, and creases appear. To what extent are creases superficial marks of extremity segments? For the complex patterns of flexure lines on the palmar surface of the hand and fingers, Wood-Jones (The Principles of Anatomy as Seen in the Hand, Blakiston, Philadelphia, 1920, 319) has emphasized that the lines typically do not correspond with joint positions. Creases that appear near the larger extremity joints may have more significance in superficially defining segments. The creases that appear in all possible joint positions may be short partial-flexure lines and they may be multiple (Fig. 3). It is only in the wrist that an approach to encircling crease lines may be found. Various types of body physiques are to be studied to determine the significance of creases as surface clues to precise defining of extremity segments.

The above approaches clearly show that a naive appreciation of extremity segments is of limited application in analyzing functional mechanics of the body. The dissection of one extremity segment from another for analysis will require critical judgment and a determinable range of error.

These studies were conducted as follows: Human extremities were dissected after they had been anchored to a reference board with an arbitrary marker, from which linear plus or minus measurements (i.e., more superior or more inferior) could be made. Anthropometric calipers were used to measure: (a) the highest point of a muscle origin relative to the zero level of the reference board, (b) the lowest point of an insertion, and (c) the muscle-belly tendon junction. The entire muscle and its tendon were carefully removed together and the position of the center of gravity was located on a balance plate (Fig. 5) and marked by a pin. Then the muscle was carefully replaced on the cadaver with origin and insertion in proper location; the locus of the center-of-gravity pin relative to the zero level was measured with calipers. The procedure was repeated for each muscle of an extremity except for the intrinsic hand and foot groups. The dog extremities were handled in the same way, except that the reference board had both an X and a Y scale and origins, insertions, muscle-tendon junctions, and centers of gravity of muscles were plotted in two dimensions.

Major-Extremity Hinge Axes

The second problem relates to localizing the major-extremity hinge axes. As indicated earlier, numerous anthropometric studies have been made, and they record dimensional magnitudes of parts or of the whole body. The information, however, is largely conditioned by both the arbitrary character of the measurements and by the sterotyped postures in which the body is held during measurement; thus many of the standard measurements have little value in predicting dimensions in the more mobile regions of the body. For instance, the difference between supine body length and stature would be unpredictable from routine measurements; chest expansion must involve separate before and after measurements; belly girth in trunk bending is an unknown relative to erect posture measurements; shoulder measurements such as bi-deltoid and those relating to the acromion are meaningless when the arms are upraised. In fact, in all mobile regions such as jaw, neck, shoulder, chest, belly, hip, and hand, the standard measurements fail completely in prediction value for a variety of functional positions.

What is needed is a different class of information. Furthermore, if this type of information can be dove-tailed with anthropometric approaches, the increased scope should at least be vitalizing.

Hinge axes are functional and mechanical entities. Moreover, they have a structural basis which consists of the abutting faces of bone articulations as compression members, and ligaments and muscles as tension members. Joints differ structurally; the heavy ligaments of the hip and knee may be contrasted with the muscle-surrounded humero-scapular joint. Collateral ligaments at the knee, ankle, elbow, and wrist certainly plan an important role in hinge movements. More obvious conditioners of the type of movement at joints, however, are the articular faces of the bones and covering articular cartilages. Certain joints like the hip, shoulder, and elbow superficially appear to be surfaces of rotation, in which instance the axis of rotation would be a point or a line fixed in space. In other places, like the knee or wrist, the location of the axis changes with either the extent or type of movement. There is, thus, a path of instantaneous positions of the axis. If articular faces are in continuous contact during movements or for any static position, the curvature of the more convex member at any point should determine the instantaneous axis for the next phase of rotation. Atmospheric pressure has long been indicated as a cause for maintaining joint integrity. Muscles across joints are so placed that tension assures contact. Walmsley and MacConail have described congruous positions of certain joints where considerable areas of joint contact exist and form stabilizing mechanisms.

A detailed modern study of the contour of articular surfaces is warranted. This contour is best expressed in terms of the instantaneous radius of curvature, that is, the distance from a tangent at a point on the surface of a joint to the axis-center of curvature (or movement).

This study on both upper and lower extremity hinge joints for the present is limited to determining the instantaneous radius of curvature of the principal (convex) articular faces measured on a line corresponding approximately with the vertical axis through the extended extremity. Since this is the principal position measured in anthropometry, the axis of rotation located from instantaneous radii of curvature may then be located relative to nearby anthropometric landmarks (Fig. 4). Conversely, distances equal to average radii of curvature as approximate plus or minus corrections can be measured from standard anthropometric landmarks. These should not only permit good estimates of the position of hinge axes and the determining of interpivotal distances in extremities, but should provide a background for graphically handling problems of position for different-sized bodies in unusual postures. A further treatment of instantaneous radii of curvature for other positions on articular faces would allow further refinement. Subsequent to this report, it is intended to make at least an exploratory study of the major-extremity joints in terms of changing articular curvature and the corresponding change in the position of the hinge axis as the joint is moved.

The method of determining an instantaneous axis from radius of curvature may be compared with an alternate method applicable to living individuals. A dentist, Luce, in 1880 attached a plate to the lower jaw. The plate had a face bow attached which recurved laterally over the side of the face. Several tiny lights were attached to the bow. When photographed in the dark, the lights traced curved paths on a photographic plate. Perpendicular lines from the tangents to each path intersected along an instantaneous path which defined condylar movement. This technique has been applied by several authors to studies of jaw movement. The technique is applicable to extremity movements, and it will be used in later studies on living subjects. Frame-by-frame tracings of motion picture records will be another technique to be utilized.

The tools used in this study were an osteometric board (Fig. 7), a dial-gage depth measurer (Fig. 8), and spreading calipers. Total bone lengths and tandem lengths of combined arm and forearm and thigh and leg bones were determined on the osteometic board. All measurements on the lower extremity were made with the femoral condyles or tibial condyles at 90° to the length of the board. The humerus long axis was aligned with the length of the board and the ulna and radius were measured in the articulating position, showing the carrying angle. The axis of the measuring board was treated as the vertical whole-extremity axis. The calipers were used in measurements of the lengths of concave-ended bones and for width measurements.

The dial-gage head had a rigid plate attached transversely, and this carried two projecting pins set exactly 10 mm apart (or alternately 20 mm apart or 30 mm apart, according to the size of the articular surfaces measured). Midway between was the dial-gage foot pin. Each of the three projecting pins was pointed. All three pins were adjusted to the same height so that when they all touched a glass surface plane, the dial-gage read zero. When set against a convex surface, as along a great-circle section of a joint, the depression of the middle pin gave a dial reading in hundredths of a mm that corresponded with the depth of the arc defined by the three contact points.

The linear distance between the two contact points defined the chord of the arc. Through a geometrical construction, where the depth of arc and half chord were known (Fig. 6), the diameter minus the arc depth was determined. From this the diameter could be obtained and then the radius of curvature.

Two series of bones were treated: one consisted of humerus, ulna, radius, and lunate from 20 male cadaver upper extremities, and femur, tibia, and talus from 20 male cadaver lower extremities; the other series consisted of 20 random sets of cleaned dry skeletal bones (same type and number). The cadaver bones were moist and had articular cartilages. None of the specimens had accompanying records on age, stature, etc.

The lunate was selected for measurement after x-rays of a living hand in various phases of movement showed its profile curvature to be a good index of a center of wrist movement in the head of the capitate bone. The dial-gage pins were set on articular faces of the cartilages or bones in both an A-P and lateral direction, for the humeral and femoral heads, for the humeral capitulum, and for the radial face of the lunate bone. The ulnar trochlea and the talus were measured for three circumferences: medial, intermediate, and lateral. All measurements were made end-on relative to the above-defined method of determining a vertical axis through the extremity.

Radius-of-curvature data were plotted relative to bone lengths. Frequency distribution curves and standard deviations were computed. Joint radius of curvature in general correlated with bone length, but body weight and physical type may also be influencing factors.

Polyaxial joints (upper humerus and femur) showed consistent differences of nearly 1 mm between radius of curvature of A-P and lateral great circles. Uniaxial joints (elbow and talus) showed an approximate straight-line axis. The axis of the elbow deviated from the humeral longitudinal axis by the carrying angle.

For the femur and humerus, the interpivotal length equals total bone length minus the radii of curvature at the two ends; for the humerus, the carrying angle causes this length to be longer for the ulnar articulation than for the radius. The interpivotal distance for the forearm is radius length (measured between concave ends of bone) plus capitulum radius of curvature plus lunate radius of curvature. The tibial length plus the femoral condylar and talic radii of curvature gives the interpivotal length.

For each instantaneous axis in both extremities, the cluster of neighboring anthropometric points was measured (Fig. 4) and the distance from the axis (as determined in the study) to each landmark was measured. Averages and variability were considered.

WORK BEGUN AND IN PROGRESS

A. Main-Line Problems

1. The pelvis and hip joint of skeletal and cadaveric material are being studied with a view to locating the axes of hip rotation relative to pelvic landmarks. This is an extension of the problem outlined in the section immediately above. The approaches, at least initially, involve measurements in three dimensions, and the techniques are similar to those used in locating other extremity hinge points relative to landmarks.

2. A further extension of the hinge-point study on cadavers involves the location relative to landmarks of the pivotal attachments of collateral ligaments at the elbow, wrist, knee, and ankle. These ligaments form the principal hinge supports for bending movements.

3. The literature on the range of joint movement is being read. A stripped-joint preparation of a whole cadaver (i.e., a skeleton with approximately natural movements) has been made. With the pelvis fixed in a rigid support, femoral movements, vertebral column movements, and movements of the other major members will be studied. Many photographs on strip film will be made showing the extreme movement possible at each joint. When the range of knee movement relative to the hip has been mapped by frame-by-frame projection of records, the range of all possible ankle-joint positions relative to the pelvis will be determined. Similarly, the possible positions of the other major joints will be determined relative to the pelvis. The location of joints in space, the types of joint movement, and the range of movement will be recorded. This is intended as background for movement studies on living subjects of different builds.

4. Several preserved cadavers have been sawed, after freezing, from head to foot into approximately inch-thick transverse sections. The mass and center of gravity of each section has been determined and plotted relative to height. This gives a picture of the distribution of body mass in the vertical body. In one instance, sections were dissected to determine the mass of bone, of muscle, of organ, and of skin and subcutaneous tissue for each level. When techniques have been perfected, and if means for protecting the research team from possibly infective body sawdust can be developed, it is planned to make similar studies on unpreserved bodies.

B. Supplementary Problems

1. Preliminary work in preparing somatotype photos of living subjects and in measuring them has begun. Pending delivery of a lens, a

setup that will permit duplication of the Dupertuis' technique of somatotype photography is at hand.

2. Somatotype photographs of living subjects are being measured according to the Weinbach technique so that cross-sectional areas (computed as ellipses) may be approximated for different levels of height. This technique will supply data for comparison with section A-4 above.

3. An exploratory study of skin mobility and skin elasticity on the young adult male has begun.

4. An exploratory study of the intramuscular anatomy of some of the more complex muscles has begun. This will deal with faciculus length, fiber obliquity, and the arrangement of intramuscular tendon patterns.

Certain of the problems above involve periodic teamwork activity of the research personnel; others are interim problems assigned to one or another individual.

WORK IN PROSPECT

1. As work progresses, the cadaver emphasis will shift to a study of an analysis of masses, centers of gravity, and moments of inertia of body segments.

2. Work on living subjects, selected by the somatotype techniques, will involve measurements of volumes by segments and levels so that data will allow a comparison with cadaver information on the mechanical properties of parts.

3. Along with the above, a photographic study of natural body movements (using motion pictures and strobe-light records) will be made upon selected living subjects. This will entail movements of the standing body and movements in a seat conforming with the "fighter" pilot's cockpit (Fig. 9).

EQUIPMENT ON HAND FOR RESEARCH

A. New Equipment and Construction

1. Anthopometric Instruments: standard anthropometer sliding caliper, spreading caliper, and steel tape, for measurement of the living

body, cadavers, and bones are available.

2. Osteometric Board: shown in Fig. 7, this is for measurement of bones in standardized positions.

3. Balance Plate (Fig. 5): this was made from a square of sheet metal scored with cross lines from corner to corner and having two opposite corners turned down to form balance points. The balance points rest upon elevated base plates. The sheet metal was bowed down until the center of gravity of the whole sheet was just below the level of the balance points. When a muscle or section is shifted about on the plate until it balances, the center of gravity lies immediately over the scored line between balance points. This position can be marked with a pin and then when the test specimen is rotated 90°, the pin may be readjusted laterally as required to locate the intersecting balancing line.

4. Dial-Gage Depth Measurer (Fig. 8): two fixed pins, a set distance apart, and a middle gage pin may be set against a curved surface and the dial reading indicates the depth of arc. From this and the half-chord, the radius of curvature may be computed geometrically (Fig. 6).

5. Equipment for Somatotype Photography: a subject-stand with turntable (Figs. 10 and 11), a projection-screen background, and a 5 x 7 view camera with triple and single back and strobe light (Fig. 12) are available. Both camera and projecting screen will do double duty in photographing movement patterns or in studying photographic records.

6. Black Photographic Background Screens: these are for photography of movement patterns of subjects having neon glow-lamps attached to extremity parts.

7. Large Mirror: set at 45° for simultaneous photography of a side view of a subject along with a direct view (Fig. 9), it can also be used to reflect projected images to a tracing table.

8. Tracing Table: the tracing table is glass-topped with underslung 45° mirror, projector stand and projector for frame-by-frame analysis of motion picture records (Fig. 13).

9. Mock-Up Pilot Cockpit (Fig. 9): this is used as a reference base for subjects when studied in the seated posture.

B. Auxiliary Equipment Previously Available

The following equipment was already available:

1. Motion picture camera.

2. A 20 kilogram balance with 1-gram sensitivity.

3. Control mechanism for adjusting flashing rates of tiny neon glow-lamps to be attached to body segments in studying movement patterns.

Most construction is now complete but two or three further items are under construction or in prospect; chief of these is equipment for measurement of living-body volumes.

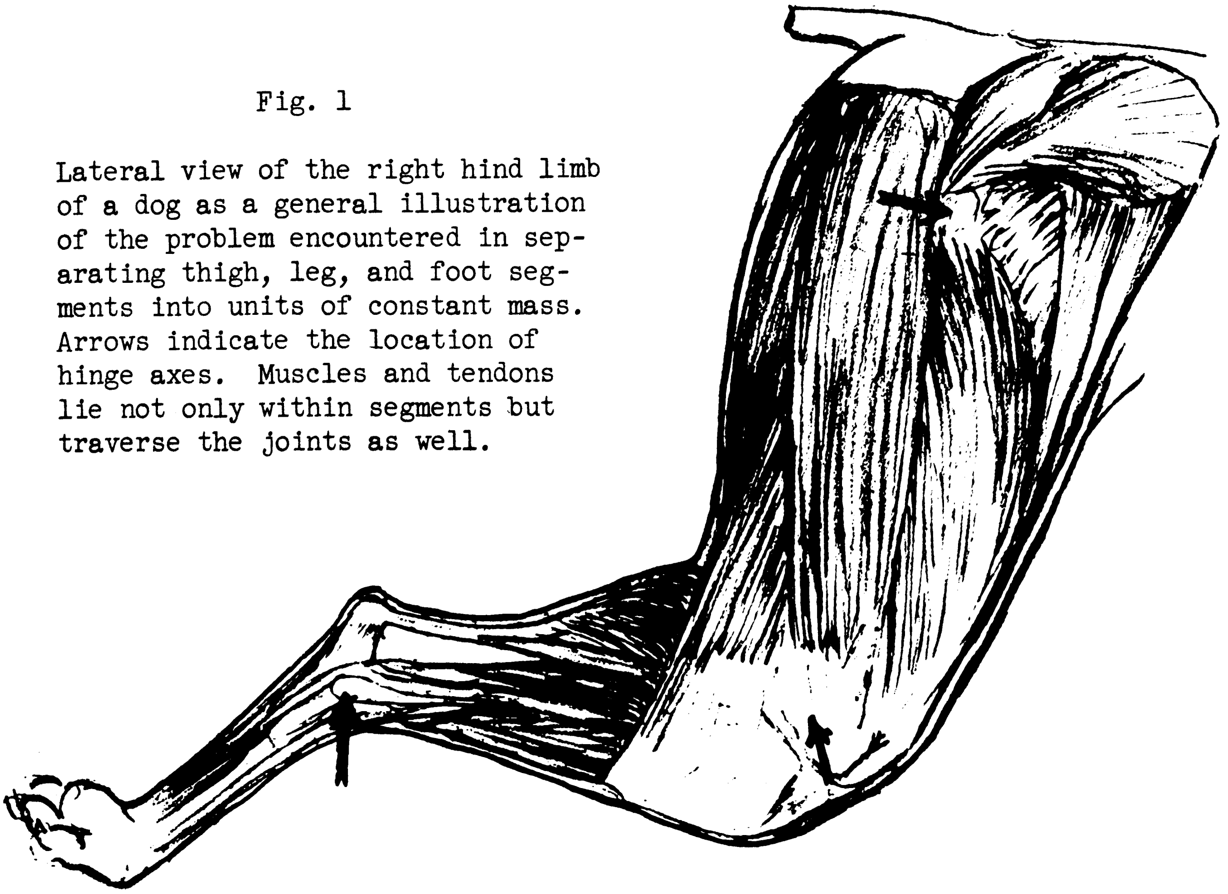

Fig. 1

Lateral view of the right hind limb of a dog as a general illustration of the problem encountered in separating thigh, leg, and foot segments into units of constant mass. Arrows indicate the location of hinge axes. Muscles and tendons lie not only within segments but traverse the joints as well.

Fig. 2

X's represent on a plane the location of the centers of gravity of the individual muscles (+ tendons) in a dog's hind leg. The straight line distances from origin to center of gravity is shown by solid lines; dashed lines indicate distances between centers of gravity and insertion points. The light horizontal shading represents bony units; arrows indicate hinge axes. Segments must be dissected across hinge axes and across tendons in such a way that segmental masses remain approximately constant irrespective of joint posture.

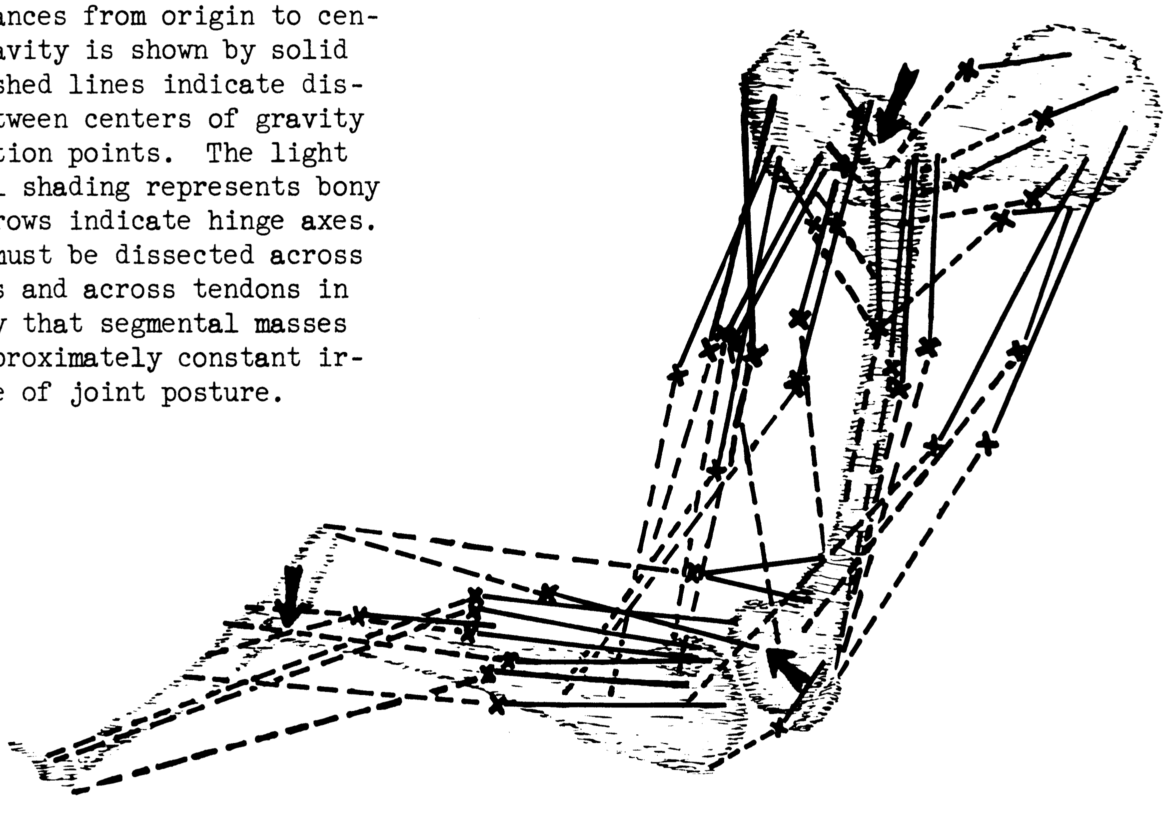

Fig. 3

Rear-oblique and front-oblique views of the left side of a study subject. The subject systematically made all possible joint movements at each joint or joint-system -- from small movements to the maximum possible -- and skin flexure lines were marked with skin pencil as they appeared. For this illustration, the skin-pencil marks on the photograph were inked for more contrast.

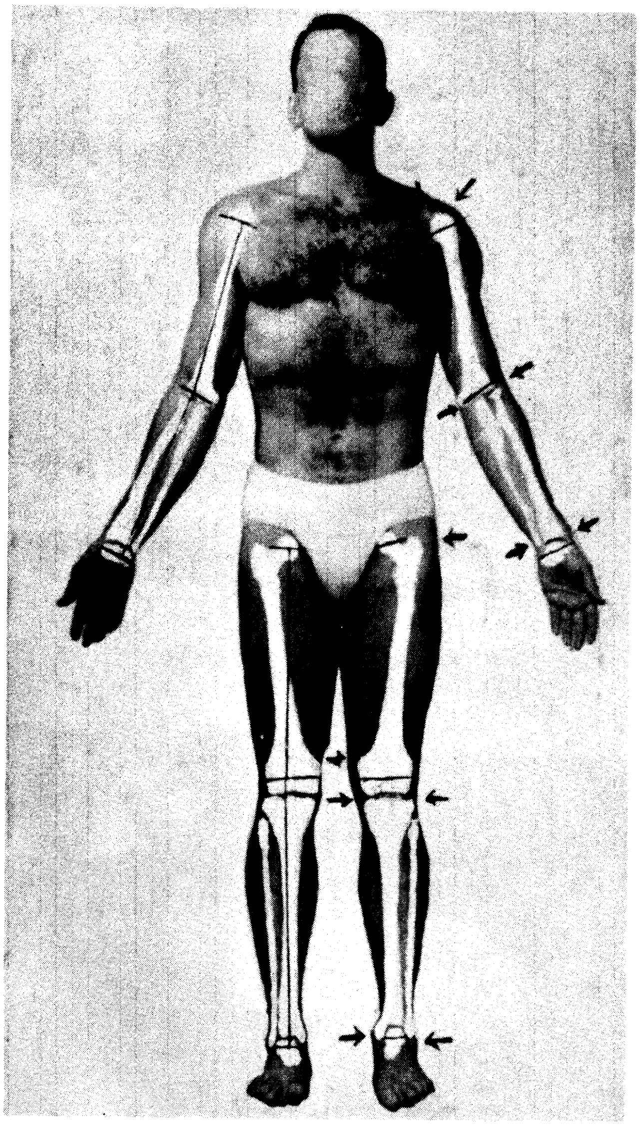

Fig. 4

The major extremity bones were drawn in white in this photograph. Arrows indicate the locations of the standard anthropometric landmarks. The approximate levels of hinge axes as determined from the radii of curvature of articular surfaces are shown on both sides. The more-or-less vertical black lines on the left represent interpivotal distances.

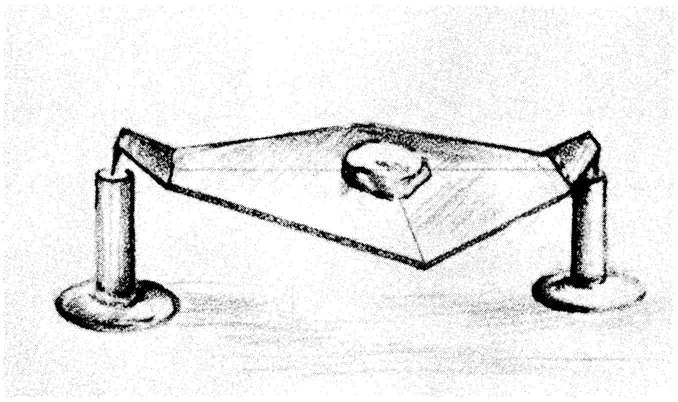

Fig. 5.

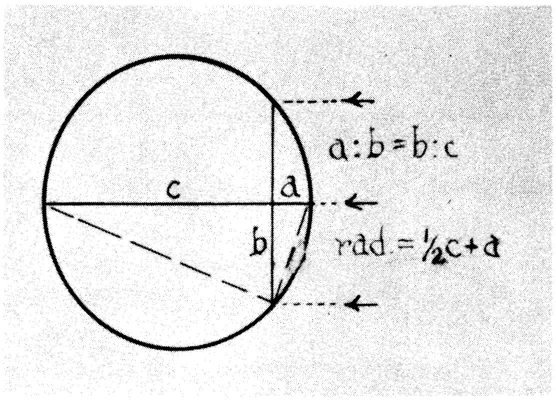

Fig. 6.

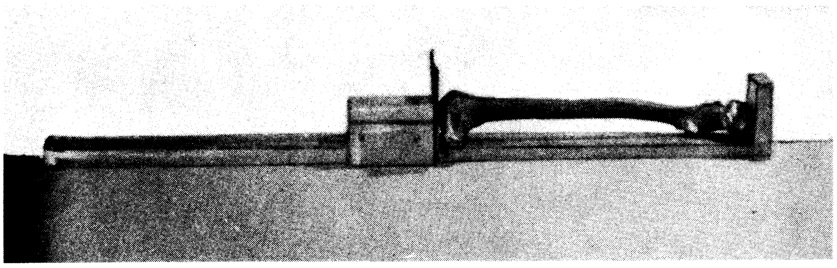

Fig. 7.

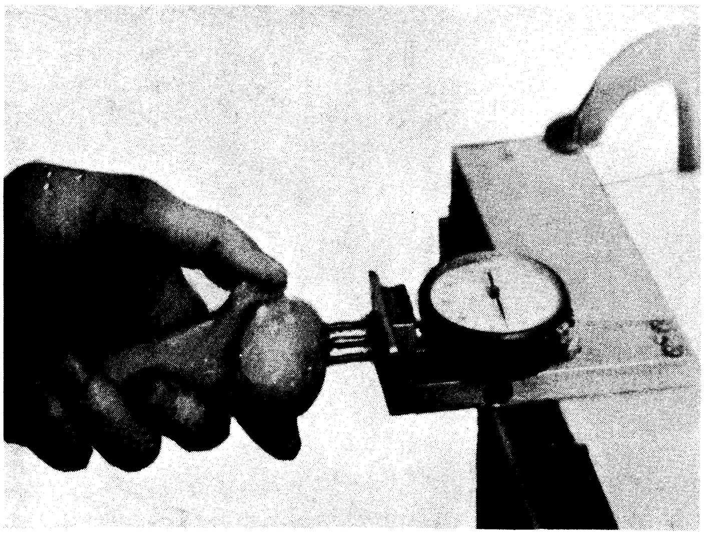

Fig. 8.

Fig. 5. Balance plate for locating the center of gravity of sections of the body and of muscles.

Fig. 6. Geometrical construction involving similar triangles as a way of determining the radius of curvature of a circular arc. The two outer arrows corresponding with fixed pins on the measuring device define the length of the chord of the circle; the middle arrow represents the depth-gage pin. Depth of arc through displacement of the middle pin is measured on a dial gage.

Fig. 7. Osteometric board. When bones are oriented in standardized positions, the overall length is measured on a metric scale set in the base of the board.

Fig. 8. Depth-measuring gage. The articular surface of a humerus is placed against the three pins of the instrument in measuring position.

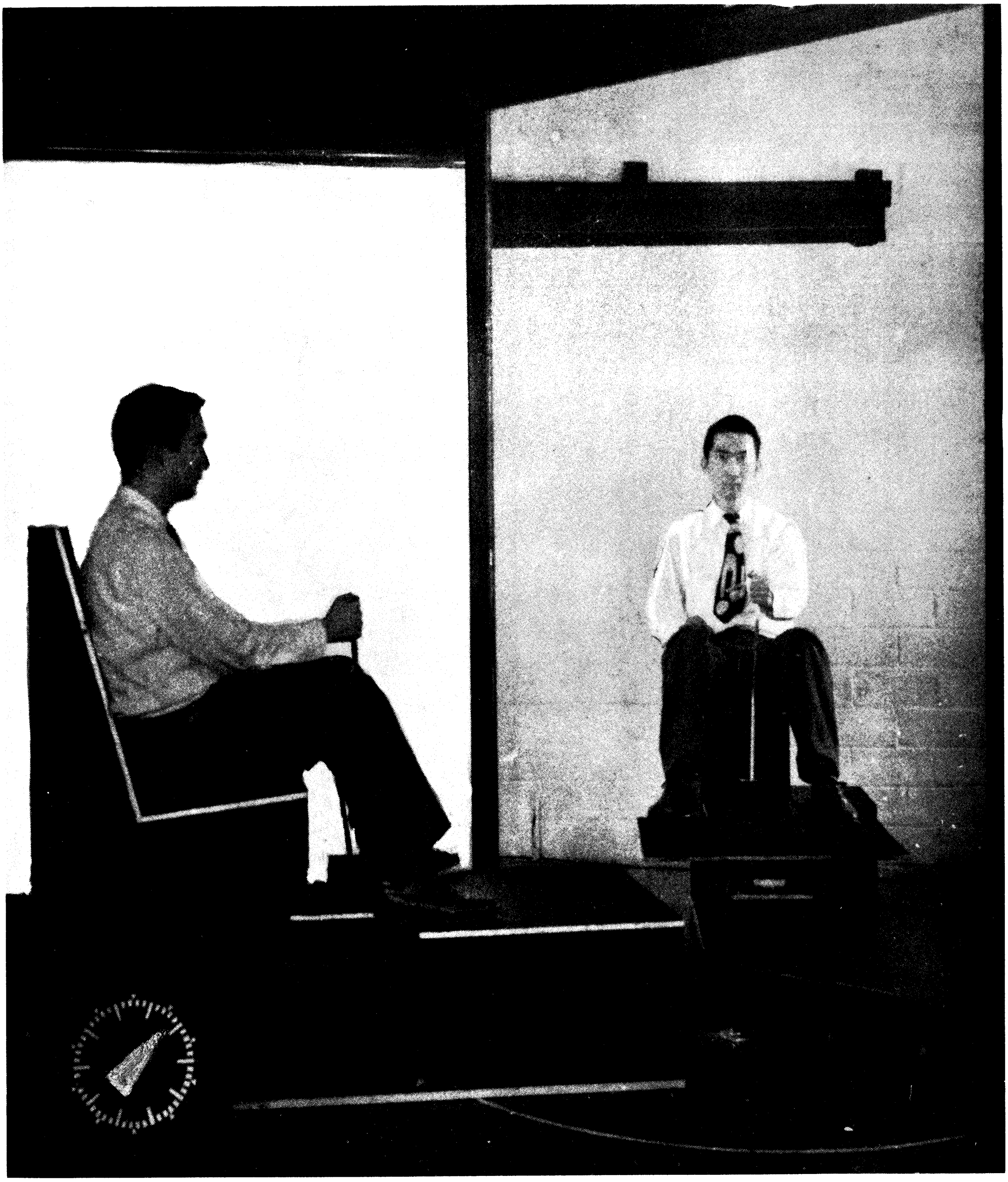

Fig. 9. Mock-up of a seat for study of body movements. The seat, which has the profile dimensions of the "fighter" cockpit, is shown from the right side and the front view is reflected by the large 45° vertical mirror.

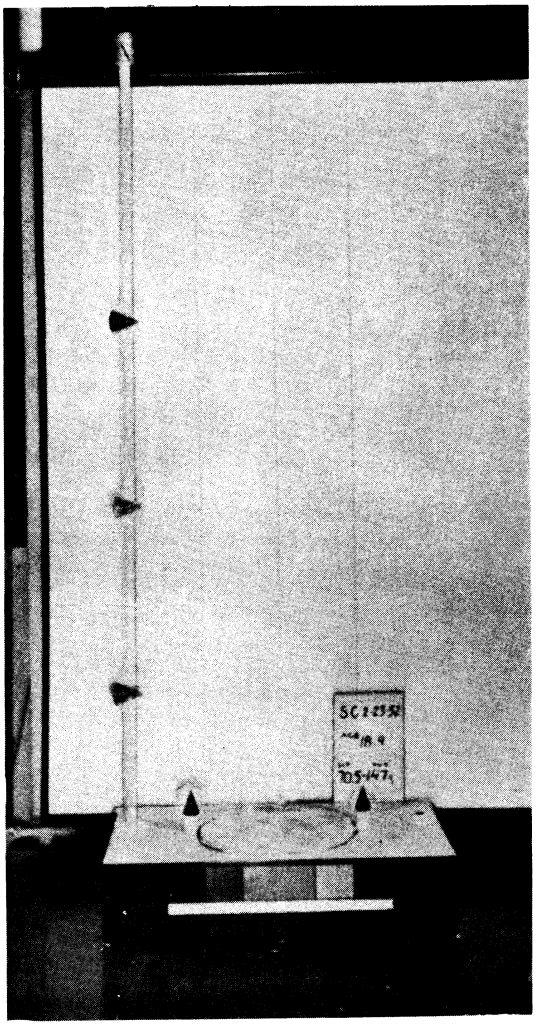

Fig. 10.

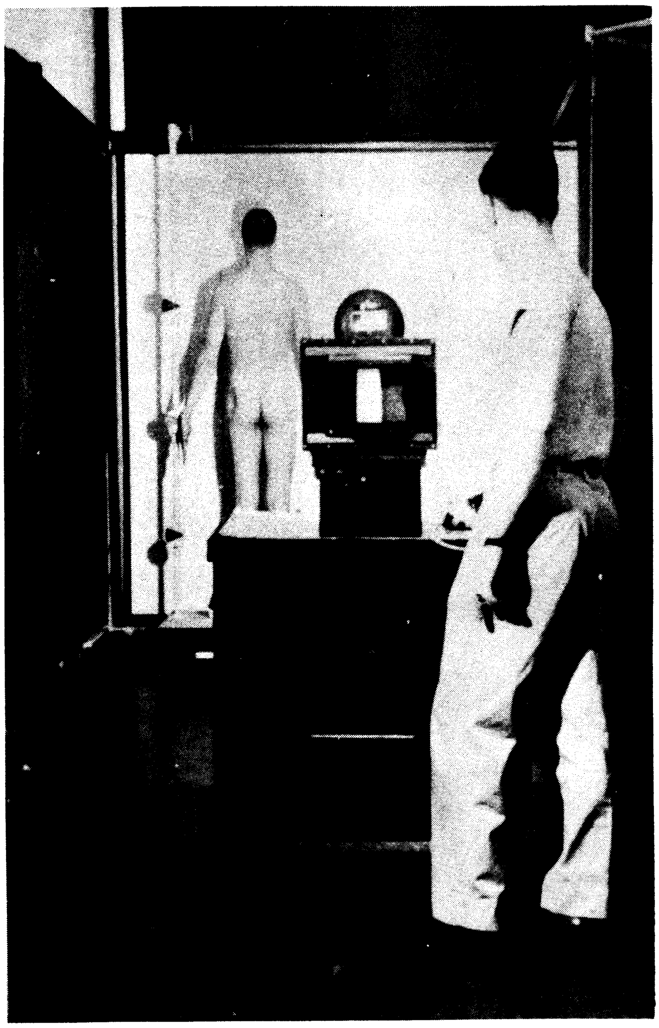

Fig. 11.

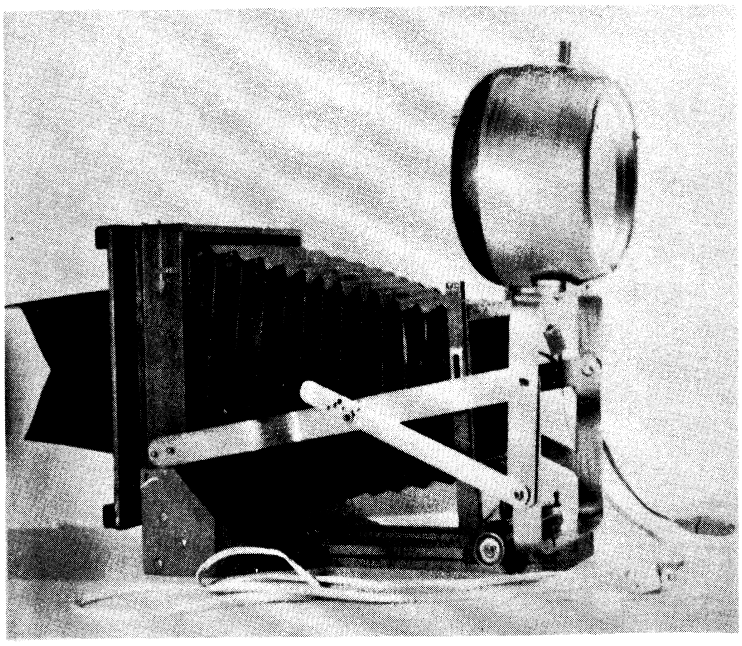

Fig. 12.

Fig. 10. Posing stand with turntable for standard somatotype photography. Black triangles at 50-cm distances for checking calipers.

Fig. 11. Arrangement for taking somatotype photographs.

Fig. 12. View camera for 5 x 7 film with triple-exposure back and speedlight.

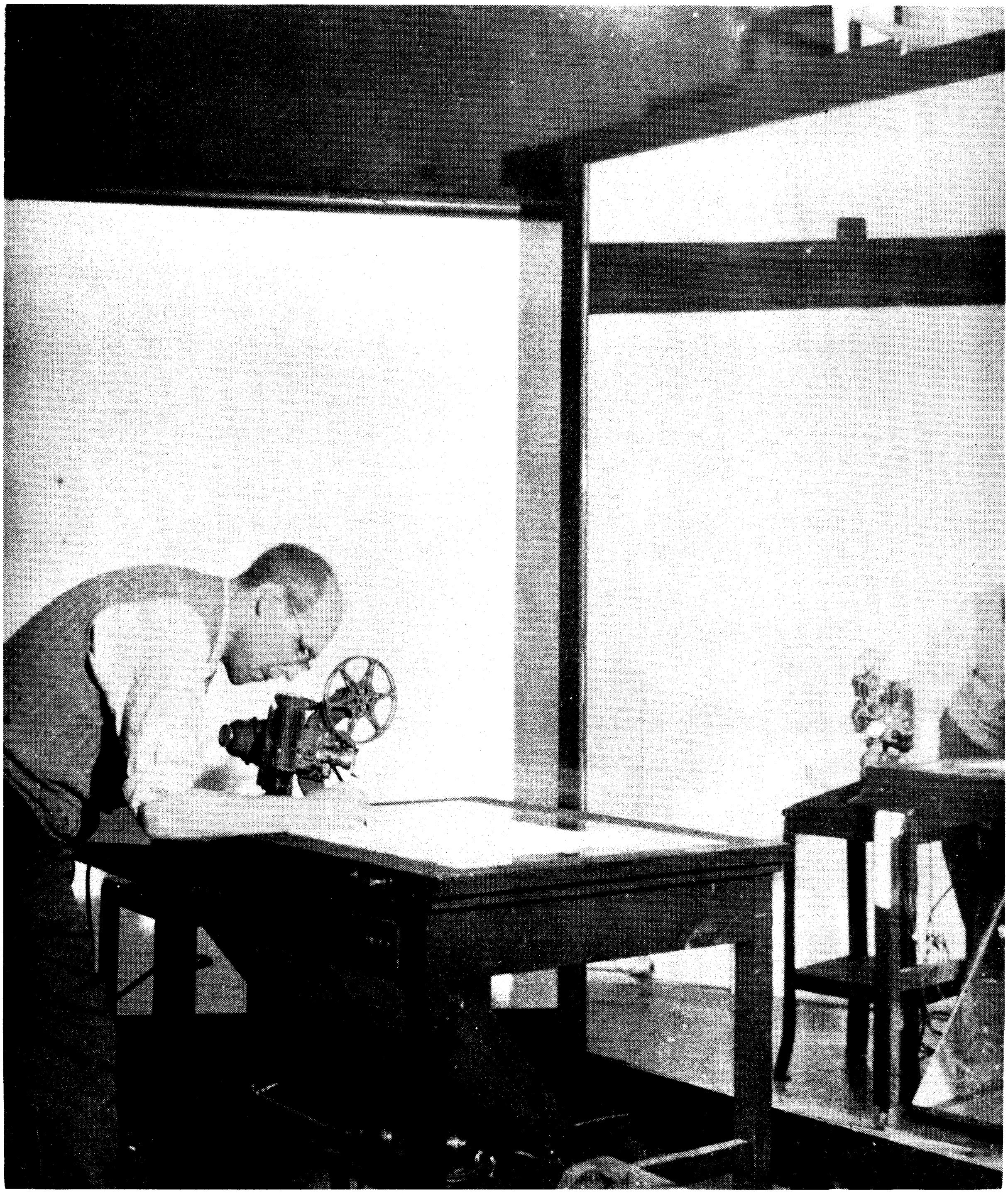

Fig. 13. Tracing table with glass top and underslung 45° mirror. The image of a frame of motion picture film is projected to the large vertical mirror, thence to the 45° mirror, and to the table top, where the image may be traced on paper.