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SPACE REQUIREMENTS OF THE SEATED OPERATOR

Geometrical, Kinematic, and Mechanical Aspects of the Body With Special Reference to the Limbs

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FOREWORD

This report was prepared under Contract No. AF 18(600)43 between the Wright Air Development Center and the Regents of the University of Michigan. The research was carried on in the Engineering Research Institute of the University of Michigan as Project No. 1996. Professor Wilfred T. Dempster served as the principal investigator for the University while Capt. F. D. Van Wart and Mr. H. T. E. Hertzberg monitored the contract for the Aero Medical Laboratory under Project No. 7214, "Physical Anthropology," Task No. 71727, Biokinematics of the Human Body In Flight."

Over the three-year period of the contract many persons, including more than thirty part-time student assistants, aided in one or another phase of the research effort. Special mention should be given Dr. George Gaughran who carried on much of the work presented in Chapter IX, and Dr. William Felts, Dr. George Suzuki, and Mr. Creighton Gabel, who contributed extensively to various phases of the work. This report reflects also the effective contribution of Mrs. Berta Duey, project illustrator.

Professor B. M. Patten, Chairman of the Department of Anatomy and Professor R. T. Woodburne, Professor of Gross Anatomy, have aided immeasurably by making available the facilities of the Department of Anatomy for this project.

ABSTRACT

The structure of the limb joints and the range and type of their motions were studied on cadaver material, with supplementary work on living subjects, in order to clarify geometric, kinematic and engineering aspects of the limb mechanism. Plans for the construction of manikin joints which showed normal ranges of limb movement were developed from this information. Specifications were also worked out for drafting board manikins which show correct limb ranges for seated postures. Subjects comparable to the model physique of Air Force flying personnel and highly selected small samples of muscular, thin, and rotund builds supplied information on the range of possible hand and foot movements which was consistent with the seated posture. Maximum dimensions of the work space for seated individuals were determined; a study of the kinematic factors involved permitted an evaluation of the potential utility of different regions within reach. Eight cadavers were dismembered to provide data on such physical constants as mass of parts, segment centers of gravity, density and moments of inertia. This work was supplemented by data on the distribution of body bulk in the living subjects studied. Applications of the above information to analyses of horizontal push and pull forces in terms of couples permitted an evaluation of the effectiveness of body mass, leverages and support areas.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

JACK BOLLERUD
Colonel, USAF (MC)
Chief, Aero Medical Laboratory
Directorate of Research

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GLOSSARY OF UNUSUAL AND NEW TECHNICAL TERMS

ANGIOCARDIOGRAPH--A technique for making multiple x-ray exposures of a region in sequence and at intervals of a second, more or less; designed for following the course through the heart of radiopaque materials added to the blood—here used for making sequential x-rays of wrist movement.

ANGULAR MOTION--Movement of a body in rotating about some center of reference; two points on the moving body change their angular positions relative to one another during the motion (cf. translatory motion).

ASTHENIC--Characterized by weakness, feebleness or loss of strength; here used to refer to the thin, linear type of body physique.

AXIS OF ROTATION--For angular movements of one body relative to another in a plane, all points in the moving member describe arcs about a center axis, this is the axis of rotation; it may have a stable position or may shift from moment to moment relative to the non-moving body.

CARDINAL PLANES--In anatomical descriptions the body is conventionally considered as if it were in the upright standing posture, and positions and shapes of parts are differentiated as up vs. down, fore vs. aft and mid-plane vs. lateral; three classes of mutually perpendicular cardinal planes related to the standing posture are: (1) sagittal (front-to-back and up-and-down), (2) transverse or horizontal (front-to-back and side-to-side), and (3) coronal (up-and-down and side-to-side).

CENTER OF CURVATURE--The center or focus of a radius which moves to describe a curve; there is one center for a circle and a changing pattern of instantaneous centers for other curvatures for which the radial length changes.

CENTER OF GRAVITY--The point or center of mass through which, for all orientations of a body, the resultant of the gravitational forces acting upon particles in the body pass.

CENTROID--A point in any geometrical figure (volume, area, line) analogous to the center of gravity of a body with weight; the moments of the figure (the product of minute segments multiplied by their distance from the centroid) are in balance relative to the centroid.

CINEFLOUROSCOPIC TECHNIQUE--A technique of making motion pictures of x-ray images by photographing a fluoroscopic screen.

CLAVISCAPULAR JOINT (Orig. term)--The functional composite consisting of acromioclavicular joint plus coracoclavicular joint (i.e., coracoclavicular ligaments or trapezoid plus conoid ligaments).

CLOSED CHAIN--A sequence of several links so interconnected by joint elements with limited degrees of freedom that only determinate or predictable movements of the parts are possible.

COMPONENTS--According to Sheldon's system of typing body build each individual physique shows in different degree characteristics of softness, roundness, fullness, and breadth (called component I), of muscularity (component II) and of linearity (component III); the amount of each of the three components may be graded by inspection and measurements of photographs on a seven-point scale (or on a 13-point scale counting half points).

CONGRUENCE--If the opposed articular faces of a joint were in simultaneous contact with no areas that did not coincide the joint would be congruent; congruent position—a position of a joint where the contacts are congruent.

CONTINGENT MOVEMENTS (Orig. term)--In joints of one degree of freedom of motion (viz. elbow; ankle) the relative movement of bones forming the joint do not move exclusively in a plane on one axis of rotation alone, rather the contacting curvatures of the joint induce secondary, concomitant motions on axes perpendicular to that for the principle movement; these accessory and invariate motions are called contingent movements.

COUPLE--A pair of equal forces acting in parallel but opposite directions, not in the same line, and tending to produce rotation.

DEGREE OF FREEDOM (OF MOVEMENT)--A free body may rotate in any angular direction about a point, i.e., it rotates in any of the three dimensions of space; thus it has three degrees of freedom. When its motion is so restrained that it may rotate about two perpendicular axes only, it has two degrees of freedom. When it is limited to movement about one axis only it has one degree of freedom.

DEGREE OF RESTRAINT (OF MOVEMENT)--When an unrestrained rotating body moves about a point in any of its three degrees of freedom there is a zero degree of restraint. When it may rotate about any two axes, movement about the third axis is restrained, i.e., one degree of restraint. With two degrees of restraint, movement is limited to rotation in one plane only, i.e., it has one degree of restraint. With three degrees of restraint all angular motion is prevented.

DESMO-ARTHROSES (Orig. term)--A functional joint system consisting of a gliding joint (arthrosis) with, at an appreciable distance, a ligamentous binding together (desmoses) of the bones concerned; examples: sternoclavicular joint, claviscapular joint.

DETERMINATE--With but one solution; predictable on the basis of the defined conditions.

EFFECTIVE JOINT CENTER (Orig. term)--In a composite chain of three or more links with interconnecting joints, the rotation of a distal link over two or more joints may be related to some point in space as center of rotation; this is the effective joint center.

EFFECTIVE SEAT CONTACT (Orig. term)--The mean reaction vector at a seat (or foot rest) which opposes the gravity vector of a seated individual to form a couple; its position in the sagittal plane is located by balancing moments involving forces which act at the front and rear of the supporting surface.

END MEMBER--The terminal segment, such as the hand, foot, head or finger, beyond the last joint in a body joint chain.

ERGOSPHERE (Orig. term)--The total work space available to the end member of a link system, i.e.. to a hand or foot, relative to some fixed point of reference; the term may in addition include the whole body of the individual and the augmented space required for facilitating movements of other body parts.

EVOLUTE--For every system of curvature, called involute, a second curve, called evolute, may be constructed; tangents to the latter are normal to points on the involute curve; the evolute is the focus of the center of curvature of the involute arc.

EXCURSION CONE OF A JOINT (same as joint sinus)--The total range of angular motion permitted a moving member of a joint when the other member is rigidly fixed.

GLOBOGRAPHIC PRESENTATION (OR RECORD, ETC.)--A method of showing the angular range of joint movement upon a globe with meridians and parallels; one member of a joint is regarded as rigidly fixed with the functional center of the joint at the center of the globe while a point on the other member describes a circuit upon the surface of the globe which encloses all possible positions of the moving part.

GRAVITY LINE (LINE OF GRAVITY)--A downward vertical force vector through the center of gravity of a body.

GREAT CIRCLE--The intersections with the surface of a sphere of a plane which passes through the center of the sphere.

INCONGRUENCE--When the opposed surfaces of the members of a joint articulate in partial or ill-fitting contacts, the joint is incongruent.

INDETERMINATE--Having an indefinite number of values.

INSTANTANEOUS AXIS OF MOVEMENT--When two points on a body in motion, relative to another body or to the space of the observer, change their angular relations during the motion, this angular change for any instant occurs in a plane and the movement for that instant may be described as a rotation about a stationary perpendicular axis called an instantaneous axis.

INSTANTANEOUS JOINT CENTER--The momentary center about which a body moves in rotating on a plane; a point on an instantaneous axis of rotation. In a circular motion the center has a constant position, for other angular motion in a plane it shifts to a new locus; successive loci describe a path of instantaneous centers.

INVOLUTE--A curve traced by a point on a taut thread as it winds upon a fixed curve called an evolute; perpendiculars to an involute curve are tangent to points on the evolute curve.

JOINT SINUS--When one member of a joint permitting at least two degrees of freedom of movement is held fast and the other member link is rotated to its limits in all directions, the moving member sweeps out a conical concavity which includes within its range all possible movements allowed by the joint structures.

KINEMATICS (N), IC (Adj.)--The science which is concerned with the motions of bodies and systems without regard to forces producing them; the geometry of moving systems.

KINETOSPHERE (Orig. term)--The space or space envelope which encloses all possible translatory movements of the end segment of a link system held in some constant orientation; it is defined relative to some fixed reference point of the body or contact point in the environment (seat "R" point, etc.).

LEVERAGE--The straight line distance from the center of rotation of a body to the point of application of a perpendicularly acting force which tends to rotate the body, cf. lever arm; moment arm.

LINK--The straight line which interconnects two adjacent joint centers; the axial core line of a body segment between two joints or between a terminal joint and the center of gravity of the end member (or between the terminal joint center and an external body contact).

MEAN DEVIATION--A measure of the variability about an average; the deviations on either side of an average, all considered as positive values, are summated and divided by 4.

MOMENT--The effectiveness of a force in tending to twist or cause motion around a central point.

MOMENT OF INERTIA--A measure of the effectiveness of a mass in rotation. The change in angular velocity in a rigid body which rotates through the action of a given torque depends upon both the mass of the body and the distribution of that mass about the axis of rotation. Moment of inertia is the summation of the point masses of a body times the square of their radial distance from the axis of rotation.

MOMENT OF ROTATIONS--See TORQUE.

PERCENTILE--Any of the points which may be used to divide a series of quantities or values arranged in order of magnitude into 100 equal groups; thus the 50th percentile divides the sample equally while the 95th divides the upper five percent from the remainder.

PYKNIC--The thick set, short, stocky body build.

"R" POINT--Fixed reference point; as seat "R" point, the midpoint of the junction of the seat back and the seating surface.

RADIUS OF CURVATURE--The radius of a circle drawn through three or more consecutive points in a curve at the region of reference.

REULEAUX METHOD--A method developed by the German engineer Reuleaux in 1875, for locating instantaneous centers of rotation; when any body moves in an arc, instantaneous centers for a short phase of the motion are located at the intersections of normals to midpoints on the mean paths of two points on a rotating body.

SEAT "R" POINT--The fixed reference point in considerations of hand and foot movements, etc.; the midpoint of the junction of a seating surface and the back of the seat.

SIGMA, OR σ --Symbol for standard deviation.

SINUS--(See joint sinus or excursion cone).

SOMATOTYPE--An overall classification of an individual's physique based upon an evaluation of the relative rotundity, muscularity, and linearity shown; these three components are separately evaluated on a seven-point scale (frequently half-points are used also). The evaluations of an individual are designated by a formula indicating the quantity of each components as 1-2-7 (e.g., 1 - low in rotundity; 2 - slight development of muscularity; 7 - extreme linearity).

SPIROMETER--An instrument for measuring the air capacity of the lungs.

STANDARD DEVIATION--A measure, calculated by statistical methods, of the dispersion of values about their mean; one standard deviation (symbol: sigma) includes about 68 percent of the observations above or below mean, two standard deviations include about 95-1/2 percent.

STROPHOSPHERE (Orig. term)--The space which encloses the total range of movement of a point on a terminal link segment through all possible translatory movements and for the possible end member positions as the part rotates about one axis only of the terminal joint; the space envelope for the movement is related to coordinates through a fixed reference point in space.

TORQUE--A measure of the effectiveness of a twisting force or couple; force times the distance from a perpendicular to the line of action of the force to the center of rotation. Alternate term: moment of rotation.

TRANSLATION--TRANSLATORY MOTION--Straight or curved motion in which all points of a moving body have at each instant the same direction and velocity. Contrast with rotation.

CHAPTER I

INTRODUCTION

The function of this report is to present work on certain anatomical, geometrical, and mechanical features of the male physique which are essential (1) for the synthesizing of manikins capable of realistic movements, (2) for an understanding of the body kinematics of a seated operator (or pilot) in his work space (cockpit), and (3) for the defining of work-place dimensions.

The investigation had its inception in conferences and correspondence with members of the Anthropology Section of the Aero Medical Laboratory at Wright Field during the spring and summer of 1951. Practical requirements for knowledge about the pilot in relation to the cockpit space clearly called for special categories of information.

The complexity of controls and the split-second timing which may be required of pilots for certain maneuvers in the operation of high-speed aircraft demand that the cockpit, controls, and pilot form an efficient man-machine system. The man, of course, can be trained but he cannot be physically modified. The limitations of his muscles and joints and of his physiology and psychology are built-in and immutable. Only the cockpit and its controls may be changed in the hope that efficiency will be increased. It is ordinarily assumed that if each control is to be placed at just the right position in space relative to the reach, strength, and convenience of an operator, increased efficiency should ensue. The unanswered question is, "What is the right position in the operator's work space?" Kinematic data on the seated person, however, are far too incomplete for much help with the problem. It is a complex one, too. The fact that an operator is ordinarily faced with multiple controls imposes special problems.

It is important that the placement of one control does not hinder the operation of another, that controls are effectively placed for operational sequence, and that routine and rarely used controls are not confused. In addition, it is essential, particularly for operation over long periods, that the conditions for body comfort be as near optimum as possible. The designer of such work places as the airplane cockpit, must also plan with concern for emergency and safety factors. Obviously, much information about the body and its limitations must be known if the operator is to be well integrated with the machine.

The consideration and balancing of these factors are the domain of the design engineer. Problems, however, involving the dimensions, functioning, and psychology of the machine operator require special knowledge, and for better data additional research is invariably necessary. The design engineer requires working references of various sorts. The aim here is to provide and interpret information on the kinematic mechanism that the body of the seated subject represents.

Several technical and scientific fields quite apart from that of the design engineer also require equivalent information on kinematic aspects of the body.

Pertinent data in many instances, however, simply have not been available. Consequently, arbitrary assumptions and working approximations have been used in certain instances for practical designs or for the devising of research procedures directed to the solution of problems involving overall body functioning. In this respect, one may mention the artificial limb designer (Anglesworth, Ed., 1952), who must often adopt rule of thumb tests of workability, viz., the joints of an upper limb prosthesis should be adjusted so that the hand may reach the mouth. Important recent work (Klopsteg and Wilson, 1954) should contribute much to this field.

Workers concerned with the analysis of time and motion film strips (Barnes, 1949; Raphael and Clapper, 1952; and Raphael, 1953) and students of locomotor kinematics (Marey, 1895; Fischer, 1904; Bernstein, 1935; Elftman, 1939, 1943, 1951; National Research Council Committee on Artificial Limbs, 1947; and Eberhardt and Inman, 1951) need to analyze records of movement. Analysts of athletic performance (Cureton, 1939) deal with patterns of movement. Various arbitrary simplifications as to joint mechanisms and linkages must be made. If these approximations are to be fully realistic, much detailed study on the mechanical nature of the body anatomy still remains to be done. Artists' manikins and the teaching of figure construction and movement for students of drawing and sculpture (Bridgman, 1920) are actually based on rather crude assumptions of body structure. Military manikins such as "Sierra Sam" of the Air Force, "Elmer" (Swearingen, 1951) and "Mark III" (Alderson Research Laboratory, 1954) meet certain technical requirements, but arbitrary approximations have been used in numerous instances. One cannot discount these efforts, however, as long as they are practically effective. Nevertheless, improvements should always be welcome. It is obvious in each of the instances above that bones and joints, and their movements, form the basis for operational patterns. These should be clearly understood if practical applications are to be effective. However, there is still no statement of underlying kinematic theory applicable to all these fields.

NATURE AND SCOPE OF THIS RESEARCH

A technical literature, largely prior to World War I and mostly German, gave some basis for an understanding of body mechanics and locomotion, but when some specific problem is posed, like the mechanics of the seated subject, the background work appears to be inadequate. Contract AF 18 (600)-43 and its supplementary extensions set out the basic objectives of this study and provided the opportunity both for the development of further data and for an evaluation of earlier efforts. Technical report AF 5501 (Randall, et al., 1946) and plans HIAD 1, 2, and 3 had provided specifications for an effective seat for the airplane cockpit; a 39-1/4-inch (practically one meter) heel-to-eye-level height had been selected as standard, and seat adjustments had been devised to provide this operating height for pilots of any size or build.

When a pilot occupies such a seat in a cockpit he must operate hand and foot controls placed in the space about him. Knobs, levers, crank handles, and pedals, whether placed well or poorly, must have some spatial or geometrical relation to the seat or to some reference point on it. Since airplanes have been operated predominantly by push or pull movements of the hand and feet in the sagittal plane, one assumption in discussions between technical personnel at Wright Field and the author was that a profile design-manikin--a flat, metal or plastic, articulated scale model of the average pilot, which would be laid on a designer's drawing board—would aid in the placement of controls.

A manikin is a reduced or simplified scale model. To be of value, a design manikin must be constructed with concern for all pertinent features of the body geometry. It is important that each feature of the manikin parallels features found in the body. A manikin is no better than the background of analytical work that is assembled for its construction. To serve the cockpit designer it should (1) be comparable to the mean pilot build or to specified larger or smaller physiques, (2) represent relations of the seated figure correctly, (3) have correct joint and segment relations, and (4) allow movements comparable to those of actual individuals. Such a manikin will distinguish between regions beyond and within reach of the seated pilot and it should be of service in the placement of controls. The manikin, however, is a tool and like all tools, its uses and limitations should be understood. Even if a suitable manikin were at hand, the adjustment of its parts by the fingers would be an entirely different problem from the adjustment of limb positions by the body itself. How is one to know if manikin postures correctly represent functioning body postures? What allowances should be made for heavy or light builds? A consideration of such problems makes it clear that various levels of information are pertinent.

The hand and foot, as the important operational end members of the limb systems, acquire special significance in this connection. First, the purely dimensional aspects of the limbs demand functionally significant measurements rather than merely convenient measurements based upon the common anthropometric, nonfunctional, body landmarks. These have not been available before. Functional joint centers and their changing relationships with joint movement must also be known. The literature, however, has given little more than clues on the mode of operation of two or three joints. The range of joint movement, the orientation of joint hinge axes, and the operation of stops at joints, such as ligaments, or bony processes as at the elbow, must be understood. Again the literature presents information which falls short of the synthesis represented by an accurate manikin. All these features represent a type or level of information that is nothing more than body geometry.

Such a geometrical system is basic, but it is also pertinent to know how the body mechanism operates it. We are continually directed back to the actual body system. One readily recognizes that physiological factors, such as nutritional status, oxygen level, exercise or fatigue, and psychological factors involving motivation, habit, boredom, etc., influence behavior; yet all behavior involves space, body postures, movements, and time.

A second level beyond the geometrical relates properly to body kinematics. How does the range and character of movement at one joint affect the next member and particularly the effective end member? Little in the literature has contributed to the specific problem of the seated individual or to the kinematic aspects of his hand and foot movements. Information in this area becomes an essential when problems of the work space are to be explored. Attention in this study has been largely limited to the resultant range and position of the end members alone and to the space envelope needed to encompass their movements. It is at this level that the body system and the manikin begin to show differences.

A third level of concern, relating to how the body handles itself, depends upon the fact that the body parts have weight. For 24 hours a day the body members are continually subjected to gravity and possibly to other accelerations. The body mechanism must always work in harmony with this fact in both its static and dynamic activities. Because of the structural complexities of the body and because many physical constants are as yet unknown or poorly known, generalized or engineering treatments of the statics and dynamics of machinery are of limited help in providing a basis for understanding body mechanics. Mechanically, the body may be considered as a group of lever systems, and, as in other such systems, the only movements possible between adjacent members are rotatory in nature. Through chains of articulating bony units the trunk and limbs become mechanisms capable both of executing motion patterns and transmitting forces in different and definite ways. These mechanisms provide a machinery powered by muscles. Muscle tensions, however, operate against contrary forces, such as inertia of body mass, opposing muscular forces, or external resistances. Many factors, thus, must be known before the machine problems of the body are clear.

APPROACHES TO THE BODY MECHANISM

A solution to practical problems such as those of the pilot cockpit or any other operational system calls for an understanding of the body machinery in the sense of its mechanism. The principal task of this project has been the clarification of features of this mechanism. Naturally, a study of this nature could not, in a limited time, attempt to cover more than a fraction of the pertinent material. Since instructions from technical colleagues at Wright Field pointed primarily to the upper and lower limbs, these parts were emphasized, and very secondary attention was given the trunk mechanisms.

Although the approaches of our research on geometrical, kinematic, and mechanical levels were oriented to the body mechanism itself, the cockpit problems were kept in mind constantly. At times, critical observations leading to the understanding of a mode of operation sufficed; on other occasions, considerable quantitative data were required. The approaches involved data gathered both on cadavers and from living subjects to provide classes of information which would supplement one another. Since cadaver data relate to defunct individuals and living functional processes cannot be followed with such subjects, a primary attempt was made to acquire data from living subjects. Where the necessary data could be obtained only from cadavers, methods of transfer were developed, so that reasonable estimates relating to a specific living subject could be made. In the work on living subjects, a small sample of male college students who matched the fighter pilot physique formed our baseline study group, but equal study was given groups of extremely thin, rotund, and muscular subjects to see if there were any important trends based on body build.

Even though this investigation was oriented toward the airplane cockpit and its operation, it will contribute useful data only within the framework of its methods and the levels of data relevance. Information from this investigation, which should have practical value, falls into three categories.

First, factual data are presented, and these may be interpreted in terms of the design of cockpits or other installations for the seated subject.

Secondly, an interpretation of the organic mechanism involving kinematics and mechanics has been presented. Body problems call for an understanding of many classes of operational factors. Our concern with a functioning body mechanism should underscore its complexity and limitations. Dimensions, kinematics, and mechanical aspects of the body are first level concerns in body operations. The design engineer who must concern himself with human factors must be a compromiser, but if he gives way too far at this level the operator may be encumbered or inconvenienced in an unwarranted fashion. This report may give the engineer some suggestions for his designs; but more important, it may make him wary of quick answers to body problems and conscious that much investigative effort must be made at the level of body mechanics before he may work with full confidence.

Thirdly, a series of new or little used research methods has been presented. Perhaps the investigative methods used here will suggest adaptations to new problems. Further research in body problems may be stimulated also by the gaps and arbitrary limitations inherent in the present investigation.

CHAPTER II

MATERIAL AND METHODS

The following pages outline the general methods used in this research. They are presented as numbered reference items, which may be consulted as required in reading the later text. It will be necessary simply to locate in this chapter the item number referred to in the text. In addition, a general perusal of the chapter will indicate the nature and scope of the techniques employed.

The study material included skeletal material, joints, preserved and unpreserved cadaver material, and a group of male college students. According to purpose a variety of procedures was followed. The aim was the development of coordinated information based on both living subjects and anatomical material.

(1) SKELETAL MATERIAL

The University of Michigan osteological collection was available for study. Each of the principal bones of the skeleton was available in numbers up to 400 or more. No data, however, accompanied the material so that sex, age, and physical status were unknown. The distribution and range of dimensions in cadaver bones certainly did not correspond with those of the young, white, American male population for which information had special interest; the cadaver population had too many small individuals in it. Some bones appropriate to the dimensions of the military population, however, could always be found. Only undamaged bones free from obvious gross pathology were selected for use.

(2) BONE LENGTH TO STATURE DATA

For some qualitative uses no special selection was required; for other purposes it was necessary to measure and select material from the collection, so that it matched dimensions characteristic of the other population. Anthropometric data from Wright Field were available on flying personnel (Hertzberg, Daniels, and Churchill, 1954) and on male Air Force basic trainees (Daniels, Meyers, and Churchill, 1953); these data defined the populations of special interest and broke them down further into size groups that corresponded with percentile bands. Data such as the old Manouvrier tables (Manouvrier, 1892; Martin, 1914; and Hrdlička, 1947), which correlated stature and limb bone lengths, were recently extended (Telkkä, 1950); Dupertuis and Hadden, 1951; Trotter and Gleser, 1952); the last-named study was especially notable, since it related to living stature measurements of known Army inductees and the measurements of skeletal bones from the same subjects after their demise and before interment. For purposes of this investigation, the formulae and graphs of the

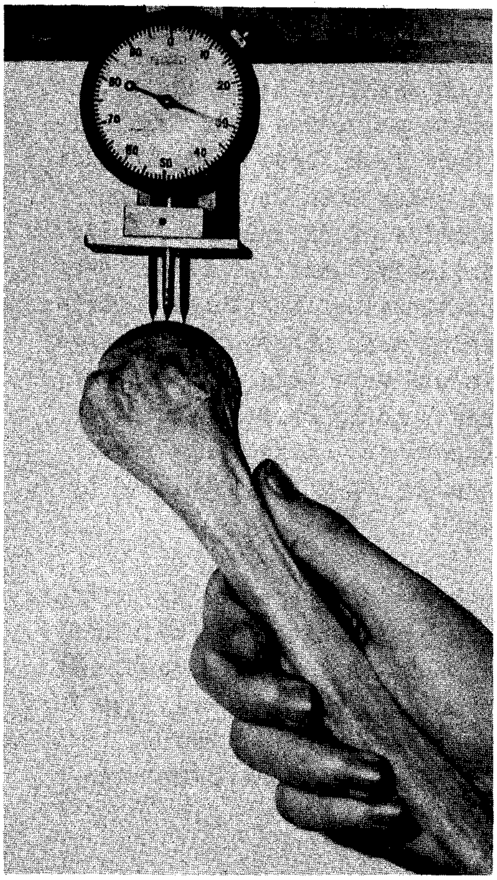


Figure 1. Dial Gauge (Lensometer) Method of Determining Average Radius of Curvature.

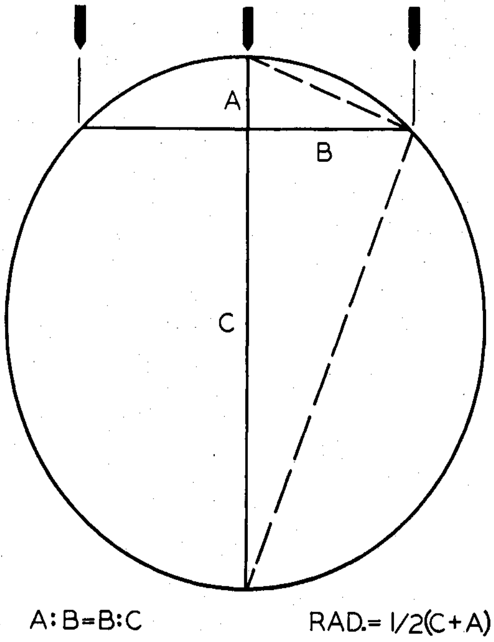


Figure 2. Method of Calculating Radius of Curvature. Geometrical construction for determining average radius of curvature (using lensometer dial gauge) for the arc between the heavy arrows, right and left. Equations below are involved. A and B are known or measured values.

the average radius of curvature was determined. Ordinarily, the foot pins were placed so that they spanned several different regions of a joint curvature and an average measure of radius of curvature was recorded. For a concave articular surface the middle pin was adjusted so that it projected well beyond the other pins; the difference between a positive reading from a concave joint and a still larger reading, when the pins were against a plane glass surface, represented the depth of the arc.

(5) ANALYSIS OF ARTICULAR CURVATURE: EVOLUTE METHOD

The second method for determining the shape of the contour of a section through a joint indicated the changing radius of curvature from point to point along a curvature rather than an overall average radius. A circular arc has a constant radius of curvature and a single center of curvature. The gauge method treated the articular surface as if it were circular and gave one value for the radius of curvature, but it is questionable whether any joint surface presents a perfectly circular contour. Any regular curve other than the circular is characterized by radii of curvature, which increase or decrease in length systematically; the centers of curvature move from instant to instant and one may speak of a path of instantaneous centers.

published works were inadequate.

Through the kindness of Professor Mildred Trotter of Washington University, St. Louis, a tabulated transcript of the raw data on 711 white males was made available for this study. Plots of stature to bone length were made from these data; in addition, means of bone lengths and standard deviation were calculated for those individuals whose statures corresponded with the 50th percentile of the Air Force pilot's stature. The 5th and 95th percentiles were treated similarly. Additional plots of the length of one bone to that of another from each individual of the three percentile groups showed ratios which were of use in determining mean proportions of segments for functional applications. Useful confirming plots were made from data on the Western Reserve series of cadaver measures (data measured by Professor Wingate Todd), which were kindly supplied by Professor C. W. Dupertuis. Since only post-mortem statures had been recorded, these data were secondary to those tabulated by Professor Trotter.

With known bone lengths for the 5th, 50th, and 95th stature percentiles (statures of 185-6 cm, 175-6 cm, and 165-6 cm) samples of matching bone length were obtained from the Michigan collection. Care was taken to insure that the selected samples included a range of specimens of various lengths comparable to the range of size for each selected percentile class. The principal limb bones used were: humerus, radius (ulna), femur, and tibia. From the selected samples of bones additional measurements of articular size and bone proportions could be taken.

(3) INSTRUMENTS USED

Overall lengths of the limb bones were measured on osteometric boards; sliding calipers or bow calipers were used for other dimensions. Long bone lengths were measured according to the standard techniques recorded by Hrdlička, 1947; Dupertuis and Hadden, 1951; and Trotter and Gleser, 1952.

(4) DETERMINATION OF ARTICULAR CURVATURES: DIAL GAUGE METHOD

Articular curvatures were measured in two ways: for a general measurement a dial gauge was used (Figure 1); a mathematical method (infra) involving evolute curves was more detailed. On either side of the foot pin of the dial gauge (lensometer type gauge) two parallel reference pins were mounted 10 mm (or alternately 20 mm) apart. Initially, the three pins were adjusted to the same height by placing them against a flat plate of glass; when adjusted the gauge read zero. Then the pins were placed in contact with a convex articular contour along a great circle section (Figure 1); the amount of depression in hundredths of millimeters of the middle gauge pin represented the depth of the arc defined by the three contact pins.

The chord of the arc between the two outer pins was a known dimension and the depth was indicated by the gauge. From the gauge value, the geometrical construction, and the formula shown in Figure 2, the diameter minus the arc depth was determined. The latter value plus the arc depth equaled the diameter, and from this

According to a theorem of differential geometry any regular curve, called an involute curve, may be defined in terms of a second curve, termed an evolute. The evolute is the locus of the centers of curvature of the involute; it is the envelope of the normals of the involute. If a system of normals to an involute curve is constructed, a second curve which is tangent to points on these normals is the evolute. If a taut cord is wound or unwound about a circular rod, a point at the moving end of the cord describes a spiral curve. The latter is the involute and the surface curvature (or cross section) of the circular rod, the evolute. The rod, however, may have an elliptical or other curved section. The taut cord is at all times tangent to the evolute and normal to the spiral path; at each instant the straightline part of the cord is the radius of curvature. Because of this relation it becomes possible to locate an evolute curve for any curve considered as an involute.

If, as in Figure 3A, compass arcs are used to construct normals to a test curve, it will then be possible to fit a second curve by placing a suitable curvature of a French curve in tangent contact with the normals (Figure 3-B). Points in sequence along the evolute curve are successive, instantaneous centers of rotation for the involute curve; the distance from any one such point on the evolute to a corresponding point on the test (involute) curve is the instantaneous radius of curvature for that point of the test curve. The instantaneous radii of curvature increase in length as the instantaneous centers are farther away on the evolute curve. Each evolute thus has one extremity near while the other extremity is farther from the evolute.

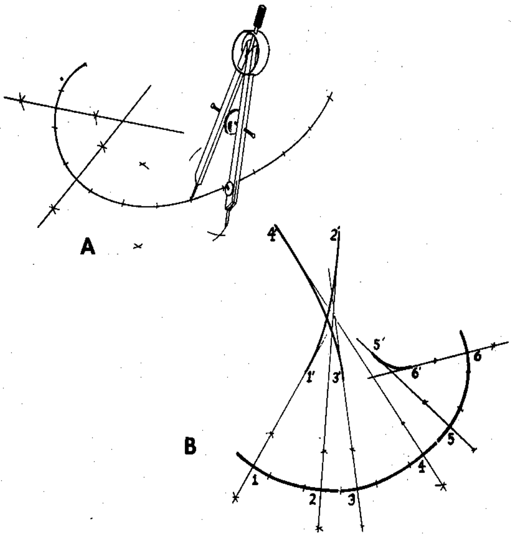


Figure 3. Curves Explanatory of Evolute Analysis.
A. Constructions of normals to a test curve through use of compass arcs.
B. A composite curve is broken into component involute curvatures 1-2, 3-4, and 5-6 by the evolute analysis; normals to the involutes are tangent to evolute curves designated by primes.

As presented in Figure 3B, the analysis of a composite of several systems of curvature shows that there is a separate evolute corresponding with each type of curvature. Even though there is no visible break in the contour of a composite curvature, its component curvatures are clearly separated by the evolute method.

(6) APPLICATION TO BONES

This mathematical technique was applied to articular surfaces in the following way: The convex articular end of a bone was held against a chalked surface as the shaft was rotated through an arc, and a chalk mark was transferred to the articular face along a line of contact. A straight saw cut was then made through the bone in the plane of the chalk line, and the cut faces of the two parts showed contours that provided study material. Photographic enlargements of the contours were used; on these, normals to the contours were constructed, using compass arcs. Tangent curves, which were the best fit to a sequence of several normals, were drawn in as evolutes. Where more than one evolute was drawn, the contour was a composite of more than one simple curvature; each evolute defined the character of only a portion of the whole curvature. The method applied in this way to articular surfaces of unknown systems of curvature by (1) pointing out the different systems of joint curvature, if the curve were composite, (2) locating instantaneous radii of curvature, and (3) defining the path of instantaneous centers of rotation.

(7) JOINT SPECIMENS: MATERIAL

Dissected joint preparations were used for various purposes. Since the routine dissection procedure in one of the courses in gross anatomy at the University of Michigan did not cover the limbs, some 40 embalmed upper and lower limbs were available as joint material. Only joints from white male specimens were selected. The specimens represented an older segment of the population, commonly 50-90 years of age. In all work on joints, specimens showing obvious arthritic changes were excluded. Routine attention was given to hip, knee, ankle, shoulder, and elbow joints. Supplementary work was also done upon specimens of the wrist, sternoclavicular joints, and the coraco-acromioclavicular joint complex.

Ordinarily, the entire proximal and distal bones entering into the construction of a given joint were separated from the rest of the limb. The joint preparation was then carefully dissected, so that ligaments were not injured. To be acceptable for use, a joint had to be both free from pathology and capable of showing a complete "normal" range of movement under manipulation. Although careful checks were made of the overall structure of joints, the degrees of freedom of movement, the relative orientation of adjacent joints, and the range of movement, chief attention in this work regarding joints was focused on the problem of locating the axes for "hinge points" of the various joints.

(8) METHODS OF JOINT STUDY

Each of the major joints of the cadaver material was studied by four primary methods: (1) direct observation during manipulation, (2) determinations of curvatures of articular contours based on sections, i.e., evolute methods, (3) analyses of joint centers (infra) involving functional movements of joints, and (4) determinations of reciprocal contact areas for different joint angulations. In addition, living joints were observed under the fluoroscope, and critical points were marked with skin pencil. Serial x-ray negatives were also made of the wrist, showing bones in various positions of joint bending.

(9) DIRECT OBSERVATION OF MANIPULATED CADAVER JOINTS

Early in this study joints of limbs still connected with the trunk as well as separated joints were systematically manipulated, and pins or nails were driven into the adjacent bones. As the bones were moved the pins described arcs about a true, functional joint center. After each movement a pin was replaced closer to the dead center until a point was reached where the marker did not appear to move. Centers marked in this way were never operative for more than a few degrees of angulation. No single center applied for the whole range of joint movement. Nevertheless, for small ranges (10-20°) of movement, a pin could be placed so that it represented a reasonably approximate center for that range of movement. A second pin would provide a better index for the next phase of the range; a third pin might be still better for an added range of movement. Several pins, thus, could be placed by trial and error so that they corresponded with axes that were momentarily active. The method, however, did not lend itself to accurate description, and there was considerable uncertainty, because an upward and backward movement might not be executed in exactly the same plane. The method did serve as a rough, practical guide.

(10) METHODS ON JOINT SECTIONS

Since the center of joint rotation is a function of the articular curvatures of the members forming the joints, an accurate knowledge of the articular curvatures was necessary. Cartilage-covered articular faces of the bones forming the major joints were rolled over chalked planes, according to the same method used for bones (Item 6, supra). Ball-like articular heads were marked by sweeping the bones through a great circle arc; other surfaces, such as the distal end of the femur or the talus, were rolled so that two condyles or two marginal rims were in contact simultaneously. Saw-cut sections were made similar to those for study of bone contours. Photographic enlargements of these contour sections were then analyzed by the involute-evolute method, mentioned above under bones (Items 5 and 6). The dial gauge method (Item 4) had use at times also.

(11) LOCATION OF JOINT CENTERS: FUNCTIONAL METHODS

The above-mentioned techniques involving sectioning of articular contours and the analysis of evolutes are methods for defining curvatures. The curvature of the articular face of only one member of a joint may be analyzed at a time. Only in the instance of a true circular contour could these methods also locate the functional center of a joint. Since male and female contours are not truly reciprocal and since the binding of ligaments may functionally change the position of joint centers, special methods were called for in the locating of functional joint centers. Ordinarily, from three to five dissections of each joint were made on preserved cadaver material for this purpose; these included gleno-humeral (shoulder) joints, humero-radio-ulnar (elbow) joints, hip joints, knee joints, and talo-tibio-fibular (ankle) joints. Flesh was removed down to the bones and ligaments. The latter were then carefully prepared so that the essential (collateral) ligaments were clear; next, the joint capsule intervening between the essential ligaments was removed. Each specimen was tested to assure that its movements were free and comparable to the range of lifelike movements. If the dissection in any way damaged the essential hinge ligaments, that specimen was discarded. Joints showing any gross pathology were also excluded. The functional method for locating joint centers involved immobilization of one member of a joint and the moving of the other through its range of movement; the center about which the moving member rotated was determined by a geometrical method (infra, Items 14 and 15) for each part of the arc of movement.

(12) JOINT CENTERS OF SPECIFIC JOINTS

The basic technique for obtaining joint-center data is shown in Figure 4B, for which the talotibial joint was arbitrarily taken for illustration. The leg and foot were separated from the body at the knee, and the talus was separated at the subtalar joints from the remainder of the foot. This latter part was saved for reference, as will be noted below.

The ankle joint is not a pure hinge joint; in addition to the major flexion-extension movement in the sagittal plane, there are small contingent movements involving (1) outward and inward movements (abduction-adduction) of the toes on a transverse plane and (2) rotation movements about a longitudinal axis through the foot; the latter movements involve pronation (medial or big toe margin of the foot downward) and the reversed movement (supination). The value of each of these movements was determined during the procedure for locating the path of instantaneous joint centers.

The method involved the impaling of the talus on an axis, i.e., on a steel rod, in line with the long axis of the foot. When the rod and talus rotated together about the common axis, a movement comparable to the pronation-supination movement was effected. In practice, a 1/4-inch drill hole was made in an anteroposterior direction through the body of the talus, just clear of the upper cartilaginous articular face of the bone. A 1/4-inch steel rod was then passed through the drill hole and each end of the rod was supported by ball bearings, so that the rod could rotate freely. The bearings were aligned coaxially and were supported at the edge of the work table, as shown in the figure. The position of the talus was fixed so that the bone could not slide along or rotate on the rod. When the talus was fixed as indicated, the tibia and fibula together could flex or extend relative to the talus, and the talus was free to adjust as required to its tibiofibular contacts by rotating slightly on its steel axis. The rod and talus were free to rotate only on the anterior-posterior axis, and the amount of talus rotation (pronation-supination) was measured with a protractor. (A pointer attached to the talus served as a reference guide for bone rotation relative to the protractor.)

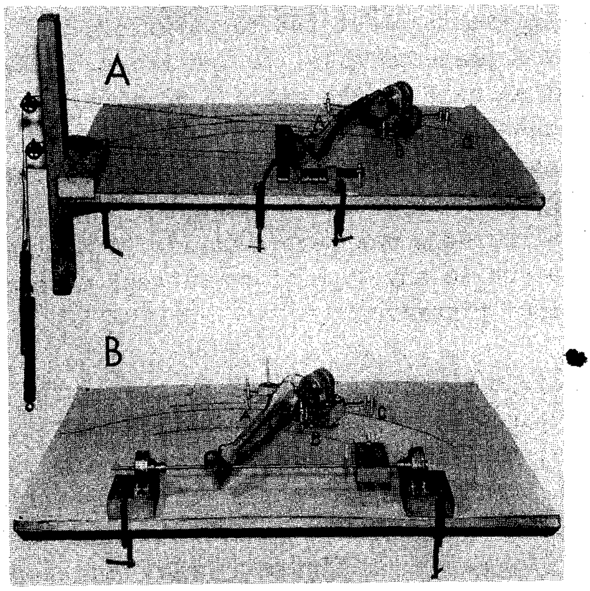


Figure 4. Methods for Determinations of Joint Centers.

A. Arrangement for gaining data pertaining to joint centers for the abduction-adduction movement at the hip. Letters A, B, and C refer to three pencil points and the arcs drawn.

B. This photograph shows the setup used to obtain flexion-extension records relating to the talotibial joint. Letters again refer to pencil points and curves drawn. Protractors that indicate concomitant bone rotations are seen on the cart above pencil B and on the block over the transverse steel rod.

Another 1/4-inch drill hole was made into the proximal end of the tibia at the medial part of the lateral articulation for the femoral condyle, and the drill was directed along the length of the tibia, so that its axis intersected that of the rod through the talus. Then a steel rod was inserted several inches into the drill hole, and its free end was supported on ball bearings, which in turn were supported by a mobile carriage. The carriage could slide over the table surface on ball-type supports, and the height was so adjusted that the tibial steel rod was at exactly the same height from the table top as that through the talus. Then as the leg bones were moved in a flexion-extension arc about the talus, the tibia and fibula were caused to rotate axially. The latter movement, corresponding to the abduction-adduction movement of the foot, was determined by the ankle contacts. This movement was also measured by a protractor set on the carriage that supported the tibial rod.

As implied earlier, the essential talotibial and talofibular ligaments were intact and the joint was fully flexible. The setup illustrated allowed the leg to make flexion-extension movements about the talus within the range permitted by ligaments. The leg moved in a plane parallel to the table top, and in so moving it flexed or extended about an axis at the ankle perpendicular to the table top. Concurrently, the talus rotated about a sagittal axis parallel to the table top (i.e., pronation-supination), and the leg bones rotated about another axis also parallel to the table top (i.e., abduction-adduction). When the leg and foot sole were adjusted at a right angle, the latter axis was perpendicular to the former. With this arrangement there was no limitation to any type of contingent movement permitted by the ankle in the three cardinal planes.

Flexion and extension movements were made by moving the leg bones manually, and the angular deviations caused by pronation-supination and inversion-eversion were shown by the protractors; the deviations were recorded for each 10° of the flexion-extension arc. When the arrangement was adjusted for operation a large paper was placed on the table top, and three pencil points attached to the carriage on outriding rods described arcs (A, B, and C; Figure 4) that represented the path of the flexion-extension movements in the plane of the two steel rods. During the movement a firm pressure was maintained between the talus and leg bone contacts.

The record, after several careful full flexions and extensions, showed three penciled arcs; when properly executed, the lines were clear and single. Simultaneous positions of the three pencils for representative angulations of the joint were carefully marked on the curves and points at 5-10° intervals from these were worked on each curve. In addition, the outlines of the bones and joints at a midrange angulation were projected vertically to the paper; the positions of bony landmarks were also indicated on these outlines. The method for analysis of the records will be shown a few pages farther on in the report.

Essentially the same arrangement was used in producing records for the elbow joint and for the knee. For the elbow, the joint was held at the mid-flexion angle of 70° and a 1/4-inch drill hole was made through the ulna perpendicular to the humeral axis and just inferior to the joint; into this hole was inserted the rod supported by the two bearings (cf. talus support). The other rod passed from the superior end of the humerus through its longitudinal axis so that its projection was directed toward the rod through the ulna. Humeral flexion or extension related to the ulna was associated with humeral rotation (medial and lateral rotation) about its long axis and also movements of the ulna (abduction-adduction) about its rod. Penciled arcs were traced during flexion and extension movements, and protractor readings of the contingent rotations were made for each 10° of flexion or extension.

For the knee joint, the rod supported by two bearings passed from front to back through the tibia just below the knee articulation, while the other rod passed through the femoral head and was directed toward the knee. As for the elbow, the knee was bent to a mid-flexion position, when the tibia was drilled; the drill hole passed obliquely through the tibia and lay in the sagittal plane at a right angle to the femoral long axis. Arcs drawn by the pencils on the carriage were made in the same way, and records of pencil positions were made for each 10° of flexion-extension.

Since the contribution of the patella was essential to a normal type of knee movement, the action of the quadriceps muscle in pressing the patella against the distal end of the femur had to be artificially simulated. This muscle tends, insofar as allowed by ligaments, to induce posterior displacement of the femur relative to the tibia when the knee is flexed. The upper part of the patella was drilled transversely and heavy rubber bands were wired to this bone; the bands passed in front of the knee and up to the anterior aspect of the midfemoral shaft, where their other ends were wired fast. In this manner, tension by the rubber bands pressed the patella against the femoral condyles in all phases of knee flexion.

The hip and shoulder joints presented a special problem because of their ball and socket relations. In these instances, the acetabulum of the hip joint or the glenoid fossa of the scapula was removed from the parent bones and set in a small box of dental stone which served as a matrix. The joint sockets (in the matrix) were accurately oriented so that the cardinal anatomical planes, sagittal, coronal, and transverse, were known relative to the joint socket. The socket and matrix were then fitted into a small vise and the head of the femur or humerus was fitted into the socket. For these instances, in contrast to other joints, it will be obvious that the ligaments had been removed entirely. When the socket was oriented parallel to the work table and record paper, the femur or humerus was weighted with a roll of sheet lead to hold the head in the socket by gravity. The steel rod of the movable carriage fitted into a hole drilled longitudinally from the distal end of the bone and directed toward the center of the head of the bone. Three, or sometimes two, penciled flexion-extension arcs were traced on the record paper in the same manner as with the other bones and the analysis was carried out as indicated shortly.

When the socket and matrix were fitted into a vise so that they were perpendicular to the paper surface, i.e., for abduction-adduction movements, a special mechanism was needed to hold the head of the bone into its socket. Drill holes were made through the necks of the bones and a pin was passed through perpendicular to the paper surface. Strings attached to each of the pins were passed over pulleys and the strings were weighted. Figure 4A illustrates the arrangement used. In this manner the head of the bone was pressed firmly into its socket; abduction-adduction movements were effected and penciled arcs made at the carriage permitted the standard analysis outlined below. The method of analysis of instantaneous joint centers will be outlined after the technique of record taking on other joints is presented (Items 14 and 15).

Figure 5 shows a graph indicating the amount of ankle pronation-supination and abduction-adduction that was contingent because of joint contours on flexion and extension movements. From measurements made elsewhere on living subjects, 3° of extension of the ankle joint, i.e., plantar flexion, was taken as the average midrange position of the flexion-extension arc. This angle was measured with a protractor as the angle beyond a perpendicular between the foot sole and the long axis of the tibia. The severed foot, saved for reference, was now placed against the talus for measurement of the angle. The 3° extension angle was considered as a zero point for flexion-extension movement in the measurement of the contingent movements in planes at right angles to the principal movement.

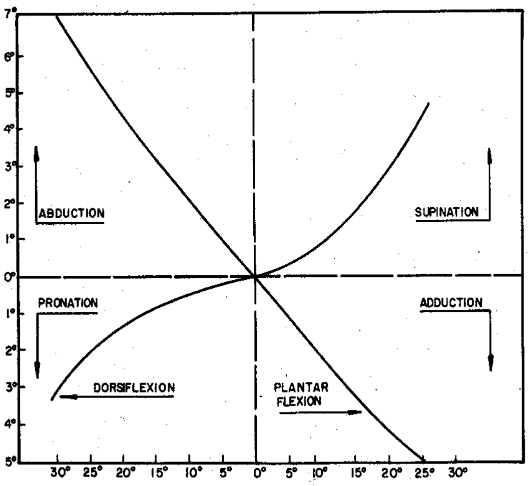


Figure 5. Amount of Contingent Movement at the Ankle. Curves showing the amount of contingent abduction and pronation found with different degrees of dorsiflexion at the talotibial joint. The amount of contingent supination and adduction associated with plantar flexion is also shown.

(13) JOINT CENTERS OF THE WRIST

Because of the number of bones entering into it, the wrist joint could not be treated like the foregoing joints. Accordingly, a method applicable to the living wrist was devised. The method, which involved successive x-rays, may be outlined in relation to Figure 6. The upper photos show (1) a hand grip with projecting rod, (2) a raised, semicircular guide on which the rod glided, and (3) a base into which the forearm was wedged. One base held the wrist flat and prone, and the other held it at 90°. The subject's forearm was wedged in place on the base, and the grip, held snugly, was supported by the rod resting on the semicircular guide. With the hand so poised, the wrist in one instance could flex or extend in a plane or in the other abduct or adduct in a plane at 90° to the first.

Actually, there are unrecognized contingent movements at the wrist—the wrist supinates slightly during extension and adduction and pronates during flexion and abduction. These pronation-supination movements occurred about the axis of the hand-grip rod in the experiment. Only the prime movements of the hand, grip, and rod in the plane of the recording film, however, need be considered here.

Three tiny lead shot were embedded in the rod and others were embedded in the base board. The supports for the hand and forearm, as described and shown in Figure 6, were placed on the table of an angiocardiographic x-ray machine with the white area of the base (cf. figure) squared over the film. As the wrist slowly swept from full extension to flexion (or abduction to adduction), 12-15 instantaneous exposures recorded the changing positions of the hand and of the shot embedded in the rod. When records of successive shot positions resulting from the instantaneous exposures were superimposed and were traced in sequence, arcs of movement of the shot were available and these data permitted the same type of analysis used for records from

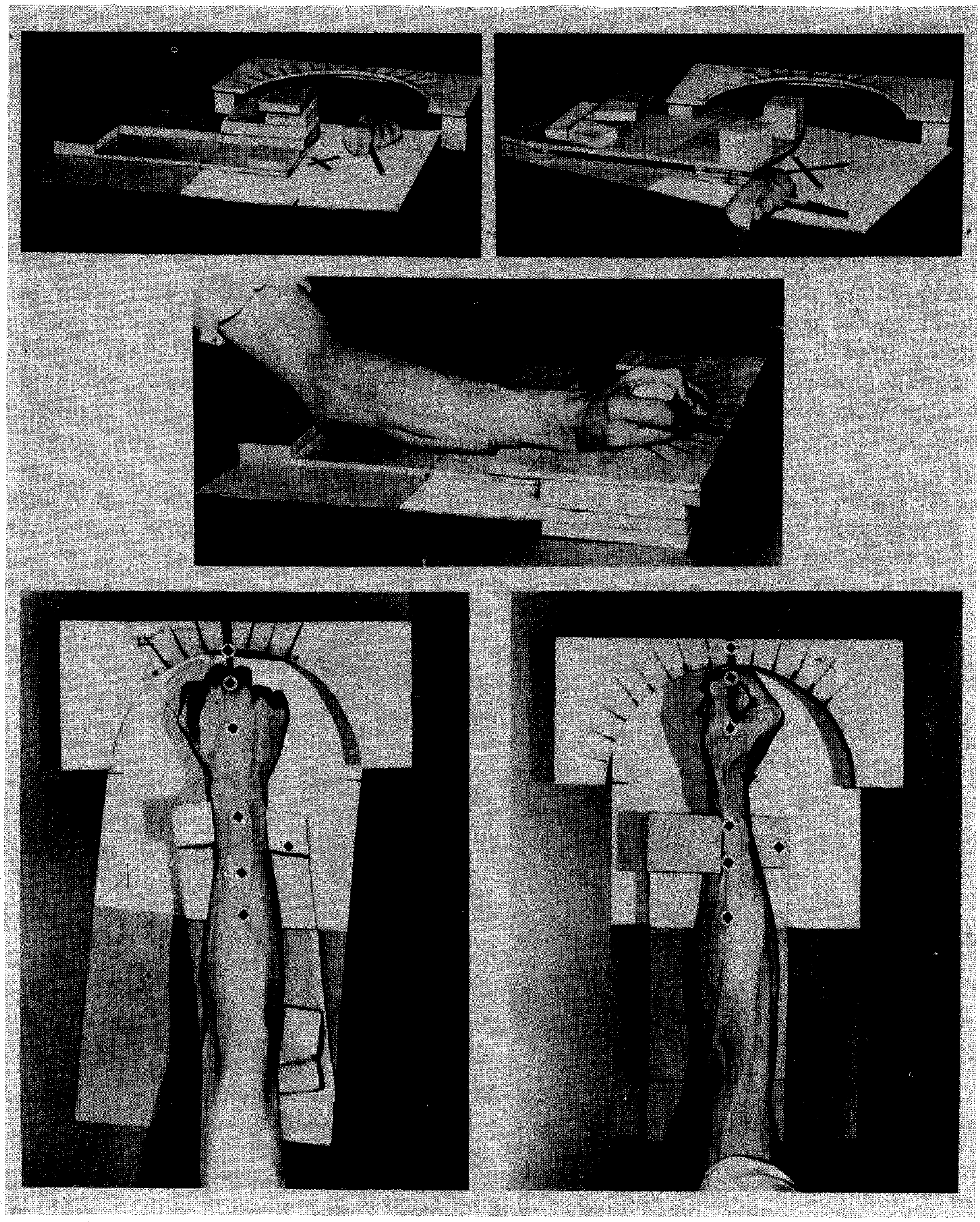


Figure 6. Special Method for Determining Wrist Centers. The upper two photos show restraining gear used for obtaining data on wrist centers by the use of angiocardiographic x-ray equipment. The other illustrations show forearm restraints, hand grip, and motion guide in use for the abduction-adduction movement (lower left) and for the flexion-extension movement (center and lower right).

cadaver joints. Images of shot embedded in the support base formed fixed points of reference.

(14) CENTERS OF ROTATION: METHOD OF ANALYSIS

Reuleaux (1875), a German engineer, devised the method of locating instantaneous centers of rotation for any body moving in a plane relative to points that are stationary on the plane. The method depends upon measurements of the relative angular motions of two points on the moving body. When the two points move the same straight-line distance in a unit time, the movement of the body is translatory; when the distances are unequal, an angular component is introduced, and the movement becomes a rotation about some momentary center of rotation. The Reuleaux technique was designed to locate this momentary center.

In Figure 7 each of the two points on part A moves to a new position at B in a short interval of time. The average path of motion of each point may be represented by the heavy, straight lines. It will be noted that perpendiculars erected from the midpoint of each line intersect at point AB. This point is a mean instantaneous center for the rotation A to B. Similarly, in the movement B to C, normals to the midpoints of the next average lines of motion intersect at point BC, the instantaneous center for the next phase of the motion. In this manner a series of points, including CD and DE, form later instantaneous centers of rotation. The curved line AB-DE accordingly represents a sequence of instantaneous centers of rotation about which the movement occurs.

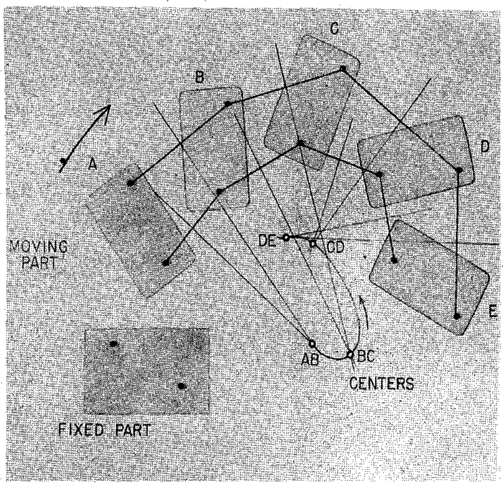


Figure 7. Method for Locating Instantaneous Centers. Reuleaux (1875) Method for locating instantaneous centers of rotation. The heavy lines representing successive phases of a movement show the relative motion of two points on the moving part. Mid-interval normals intersect at points AB, BC, etc. These points momentarily and in sequence are centers about which angular motions of the moving part occur.

(15) APPLICATION TO JOINT DATA

This type of analysis may be applied to joint movement if one member of the joint system is held stationary while the other moves. As the moving member rotates through its range, the position in the plane of movement of two (or more) points may be determined for a series of successive instants during the movement. (It is convenient to locate these instantaneous positions for equally-spaced successive intervals of, for example, 5 or 10°.) Straight lines between successive momentary positions of each moving point define an average path for short intervals of travel. Normals from the midpoints of these straight lines intersect at instantaneous centers of rotation. The path connecting successive centers is descriptive of the type of movement.

In the procedures on joints outlined above, one member in each instance was immobilized and the other member was moved. For the wrist, ankle, and elbow, where contingent movements occur, these secondary movements were ignored and the major movement in a plane of reference was alone considered. The pencils A, B, C, or the lead shot in the hand grip, moved through a succession of positions in a plane. The curves produced form the raw data for the Reuleaux method of analysis. Only two penciled arcs were actually necessary; the other, however, was confirmatory.

Since the three pencil points carried by the cart formed the apices of a triangle of constant size, it was always possible to locate equivalent points on each of the curves. Ordinarily, equivalent points were laid off at 5 or 10° intervals. Normals constructed on each of the three curves at equivalent mid-interval positions intersected at a common instantaneous center of rotation. Successive centers, when connected in series, formed a path of instantaneous centers. This path of instantaneous centers had a characteristic position in relation to the outline of the bone which had earlier been traced on the work paper. A comparison of these paths of instantaneous centers relative to fixed bone contours for different joints emphasizes distinctive peculiarities in the nature of joint functioning. Such patterns of instantaneous centers will be considered for the several joints in a later chapter of this report (Chapter IV).

(16) AREAS OF JOINT CONTACT

The several types of joints have been studied to determine how much of the reciprocal articular faces are in contact at different angular positions of the joint. The technique has been simply the severing of ligaments at a joint and the painting of one member with a paste of moist casein paint. One bone was held rigidly in a vise with its articulation uppermost and the other member was pressed in contact for a specific angulation of the joint. (Alternately, the contacting member was moved through a section of arc.) After this procedure a paint imprint was transferred to the clean member and one or more areas of contact were seen. These patterns were recorded on casts of plaster or dental stone that had been made of the articular faces prior to the paint imprint procedure. Then the paint was cleaned away and the procedure was repeated. After many repetitions of the paint application and imprint-ing on one or another face of the articulation, penciled records traced on the casts came to acquire a very constant pattern. The nature and implications of these contact areas will be discussed in Chapter IV.

(17) SKELETON-LIGAMENT PREPARATION

Early during the phase of study on joints an entire preserved cadaver (male, aged 60 years) was dissected as a joint-study preparation. The thoracic, abdominal, and pelvic contents were eviscerated, and flesh was carefully removed down to the skeleton and joints. Each of the joints of the vertebral column, thorax, and pelvis, and of the limbs to a level below the wrist and ankle was carefully dissected. All joint-capsular tissue other than the principal ligaments was removed from the freely movable joints, and each joint was manipulated as the dissection proceeded to assure that essentially normal types of movement occurred at each joint. No obvious joint pathology or abnormalities were present in this body. The joints were freely anointed with glycerin to keep the ligaments flexible and soft.

The pelvic cavity was filled with plaster of Paris to make a solid block, and heavy brass plates were bolted anteriorly and posteriorly. A pipe coupling was fastened to the posterior plate, and by this the preparation was supported on a stand with the legs dangling. The trunk collapsed, however, if not wired upright. With this preparation, movement patterns of individual joints or of any combination of lower limbs, of upper limbs, or of upper limb and trunk could be followed. Forces supplied by muscular action during life had to be simulated through manipulation by the observer. At times, obvious errors could be introduced by this manipulation. For instance, since the shoulder girdle could not be supported by a tension system comparable to that normally supplied by shoulder muscles and by the overlapping skin, certain movements of the scapula that were not realistic could be obtained. This preparation found frequent reference for over two years as a qualitative background for movement study and for miscellaneous points relating to the design of a manikin. Because of changing ligament flexibility, which varied with drying or glycerin applications, only qualitative data have been taken on this specimen.

(18) RANGE OF MOVEMENT: CADAVER JOINTS

A primary use of the ligament-skeleton preparation was the demonstration of the range of movement at individual joints and the inclusive range of a series of two or more adjacent joints. The total range of the end member of a whole limb could be demonstrated also and limitation in movement could be assigned to specific joints. An important use of this preparation, and of a number of isolated joint dissections too, was the demonstration of the total range of movement allowed and the nature of our work has been a restudy and extension of earlier work on the possible range of motion at the major limb joints. Actions at each joint have been studied qualitatively and quantitatively usually on three, four, or more joint dissections.

To study joint amplitude, one member of a joint system was clamped rigidly in a vise, and the other member was moved to the limits of its range in every direction possible. Ordinarily, at momentary positions through this range, measurements were taken so that the range could be reconstructed. By one method several multiple exposure photographs were made of the momentary positions. When superimposed images were traced (Figure 38), the range of joint movement could be visualized. Alternately, measurements of joint angles and the appropriate x, y, or z coordinates of a constant reference point on the moving bone gave usable data. The information was ordinarily referred to a spherical surface, as will be outlined in the later treatment of the globographic method of recording joint range (Chapter IV).

(19) MECHANICAL MODELS OF THE LIMBS

To clarify the relations of the limb geometry beyond what could be gained by the ligament-skeleton preparation, metal stick-figure models of the limb links were prepared (Figure 8) as an aid for study. The models were made at half life-size and all joints were point- or pin-centered. The construction of these models required attention to (1) link dimensions, (2) type of movement with consideration of degrees of freedom at each joint, and (3) data on average joint limits relative to the range of movement permitted. As construction proceeded, it was found that critical attention had to be directed to an added factor, that of (4) the angular relation of some fixed position of one joint relative to the orientation of the next bone and joint in sequences.

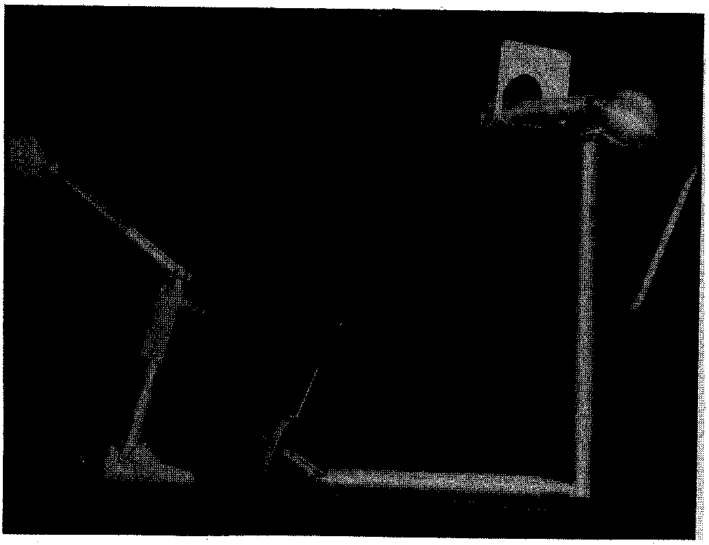


Figure 8. Models of Joint Systems of the Limbs. Aluminum models of the lower (left) and upper (right) limbs, which illustrate the general type and range of movement at each joint.

Each joint of the models was provided with metal stops, which held the range within positive limits. The pin centers and the positive ranges provided unique differences from living joints or cadaver joints such as those of the skeleton-ligament preparation. Although the models were without tension members equivalent to muscles and were not weighted as are the body segments, they contributed to an understanding of the geometry of limb movement and to the problems of manikin construction. Many problems of kinematics during this study were referred to the metal models and to the ligament-skeleton, as well as to living subjects.

Perhaps the most important function of these preliminary models was the crystallizing of a pattern, which could be compared with actual joints and corrected for details. The manikin specifications of Chapter V have profited from these preliminary models. Machined joints, which had far greater accuracy as to the range and character of joint movement than those of Figure 8, were later designed (Figure 58); these were made to clarify problems of manikin design and to provide a way of interpreting the pecularities of organic joint systems to readers trained more in engineering than in anatomy.

(20) LIVING SUBJECTS

The living subjects studied consisted both of a routine group of 39 men carefully selected on the basis of physique and a secondary, supplementary group. The latter, which included a few men from the selected group as well as several individuals of indifferent build, including members of the investigative team, were frequently used for checking and for miscellaneous observations. This group was important for both planning purposes and for filling in supplementary and largely qualitative data not obtainable from the select sample.

It should be appreciated that the aim of our study of living subjects was not so much the investigation of the range and variability of a population as such. Attention, rather, was directed to learning something about the anatomical and kinematic factors of the body mechanism. More specifically we wanted to learn how a typical seated subject handled himself kinematically. The small samples studied were merely a device which gave assurance against overemphasizing chance idiosyncracies which might be presented if only one or two subjects had been studied. Quantitative and often photographic data, of course, were necessary at almost every stage; in certain instances, according to topic, averages based on from three to five individuals sufficed; in others both averages and ranges on a larger sample were determined.

Only white male adults served as subjects. To show possible trends according to physique, individuals characteristic of four body builds (median, rotund, thin, and muscular) were studied. The Sheldon system of somatotyping (Sheldon, Stevens, and Tucker, 1940; Sheldon, Dupertuis, and McDermott, 1954) was used for the selection of types.

(21) SELECTION OF SUBJECTS

Most of the study subjects were contacted at the routine physical examination for men students that is given each fall and winter at the University of Michigan. The men were seen in the nude as they passed in sequence through examining stations; men who tentatively seemed to have the desired builds after weighing and stature measurements (and calculating of the height to cube-root-of-weight index) were approached with the prospect that if further tests confirmed our estimate of their physical types, they could be assured of some hours of employment with pay. Nearly all the selectees assented; they were then scheduled for somatotype photos.

Standard front, left side, and rear somatotype photos were made according to the technique of Dupertuis and Tanner (1950). Photographs were mailed to Professor C. W. Dupertuis of Western Reserve University for his somatotype diagnosis. He graded the somatotype on a 13-point scale. On the basis of his replies the men were selected or rejected as study subjects. To be suitable, thin subjects must have had a height-to-cube-root-of-weight index of 14.00 and a somatotype rating of 6 or 7 in Component III (thin) and 1 or 2 in Components I (rotund) and II (muscular). To enlarge the sample, two individuals with a 3 rating in Component II were included. Rotund individuals with a 6-7 rating in Component I and with a 1 or 2 in the other components were sought; actually three individuals with a 3 rating in the muscular component (II) were included. Only muscular individuals with a 6-7 rating in Component II and 1-2 in the others were included in the study sample.

The median group was selected to correspond with builds common among Air Force fighter pilots. A study of the body build of 643 student and fighter pilots from the 1950 Anthropometric Survey Sample (later published as Hertzberg, Daniels, and Churchill, 1954) had recently been made (personal communication from Edmund Churchill, 1952), and the most frequently appearing builds (462 men or 72 percent of the sample) had been designated the "inner circle" group. This group had a 2, 3, or 4 rating in Component I, a 3, 4, or 5 rating in Component II, and a 1 to 4 rating in Component III. The following tabulation indicates the body types of the "inner circle" group with the frequency of occurrence in a group of 462 men (Table 1). Thirteen body-build types were in the group, and an average type would be about 3-1/2 - 4-1/2 - 2-1/2.

TABLE 1

DISTRIBUTION OF MOST COMMON SOMATOTYPES OF PILOT BUILDS*

Somatotype	Frequency No.	Frequency %
252	22	3.4
343	70	10.9
344	49	7.6
352	61	9.5
353	38	5.9
442	59	9.2
443	62	9.6
444 and 333	18	2.8
451	21	3.3
452	47	7.3
453 and 342	15	2.3
	462	71.8 or 72% of whole pilot sample of 643

*Data from Churchill, personal communication.

Our intent was the obtaining of study samples of 10 highly selected individuals in each of the four groups. Actually, 10 thin, 11 median, 11 muscular, and 7 rotund individuals made up the sample. The following tabulation (Table 2) shows the somatotype ratings of the study sample.

Figure 9 shows the distribution of the body types in a three-dimensional model of the Sheldon triangle. The model related to a 13-point scale, ranging for each component from 1, 1-1/2, 2, and so on, to 6-1/2 and 7 points. Component I ranges from 7 points at the lower left corner of the model to 1 at its right rear side; Component II ranges from 7 at the upper apex to 1 at the base; and Component III is high at the lower right apex and grades to 1 at the opposite side.

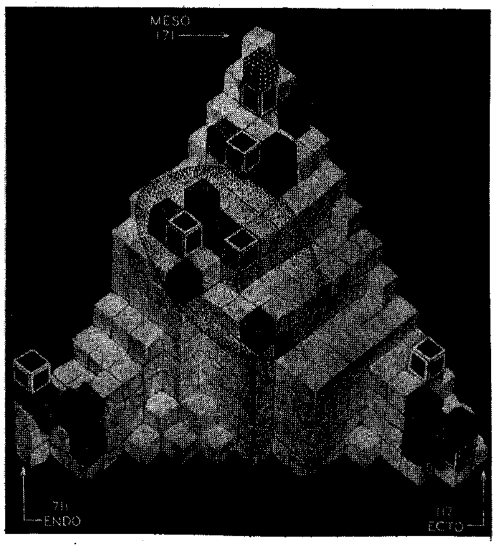


Figure 9. Distribution of Subjects on the Sheldon "Triangle." A 13-point scale is illustrated. The most centrally located gray cube is somatotype 4-4-4. The farther toward the extremes of the model, the more extreme are the body types; thus the extreme cube marked Endo refers to extreme rotundity. Meso is extreme muscularity, and Ecto is extreme thinness. Gray cubes indicate that the study sample included one individual of a given somatotype; white-edged cubes indicate two subjects of a given type; and the dotted cube includes three subjects of this build. Cubes in the central stippled area are included in the "inner circle" of pilot builds; the area includes the "median group" of study subjects.

The gray cubes represent one individual of a given somatotype build; white-outlined cubes indicate two men of the same build; and the dotted cube includes three men who had the same build. The model shows that our sample clustered in four regions. There was no overlap of types. The Air Force median group, it will be noted, fell near the muscular group; on the whole, it was moderate in Component I and low in Component III.

Sheldon's somatotyping method has been used here simply as a technique for obtaining four different groups of body build, which henceforth will be called simply thin, median, muscular, and rotund. The somatotype classifications and the measurements referred to below serve to define both the similarities and variability of physiques of the men who cooperated as subjects.

TABLE 2

SOMATOTYPE AND DIMENSIONS OF STUDY SUBJECTS

Group	Subject	Somatotype			Age	Height, in.	Weight, lb	Ht/Wt
THIN	1	1^2	2	7	20	76.8	154	14.24
	2	1^2	1^2	7	21	74.4	134	14.53
	3	1^2	1^2	7	22	71.1	114	14.68
	4	2	2	7	18	73.4	132.5	14.30
	5	2	1^2	6^2	22	73.0	128	14.35
	6	1^2	1^2	6^2	18	74.4	133	14.58
	7	2	2^2	6^2	18	73.2	140	14.09
	8	2	6		19	70.2	125	14.10
	9	1^2	3	6	26	77.8	172	13.99
	10	1^2	3	6	18	72.0	133.5	14.10
MEDIAN	1	3^2	5^2	2^2	24	67.4	156	12.56
	2	4	5	2	23	68.7	168.5	13.21
	3	3^2	5	3	19	71.3	170	12.83
	4	3^2	5	3	21	70.4	163	12.89
	5	4	5	2	26	70.7	181	12.50
	6	4	4	4	26	71.2	169	12.92
	7	4	5	1^2	24	67.0	162	12.32
	8	3^2	5^2	2	20	70.0	172	12.58
	9	3	3^2	4	24	69.0	141	13.26
	10	2	5^2	2^2	22	72.2	174	12.93
	11	2^2	5	2	33	66.6	152	12.51
MUSCULAR	1	1^2	6^2	1^2	20	67.4	153	12.60
	2	1^2	7	1^2	18	68.6	168	12.42
	3	1^2	7	2	21	71.4	186	12.51
	4	1^2	6	1^2	22	69.4	167	12.64
	5	1^2	7	1^2	21	73.6	211	12.36
	6	1	6	2	22	70.0	160	13.00
	7	2^2	6	2	26	72.0	186	12.61
	8	2^2	6	1^2	21	65.8	151	12.36
	9	2	5^2	2	19	69.7	155	12.97
	10	2^2	6	2	17	70.7	171.5	12.65
	11	2	6	2^2	18	70.0	171	12.88
ROTUND	1	7	3^2	1	19	70.7	272	10.83
	2	7	3	1	18	69.8	261	10.99
	3	7	3	1^2	19	68.6	224	11.30
	4	7	3^2	1	19	68.3	244	10.85
	5	6^2	2	1^2	19	67.0	186	11.73
	6	6^2	1^2	$2(2^2)$	18	64.6	145	12.29
	7	6^2	3	2	24	70.4	232	11.46

(22) ANTHROPOMETRY OF LIVING SUBJECTS

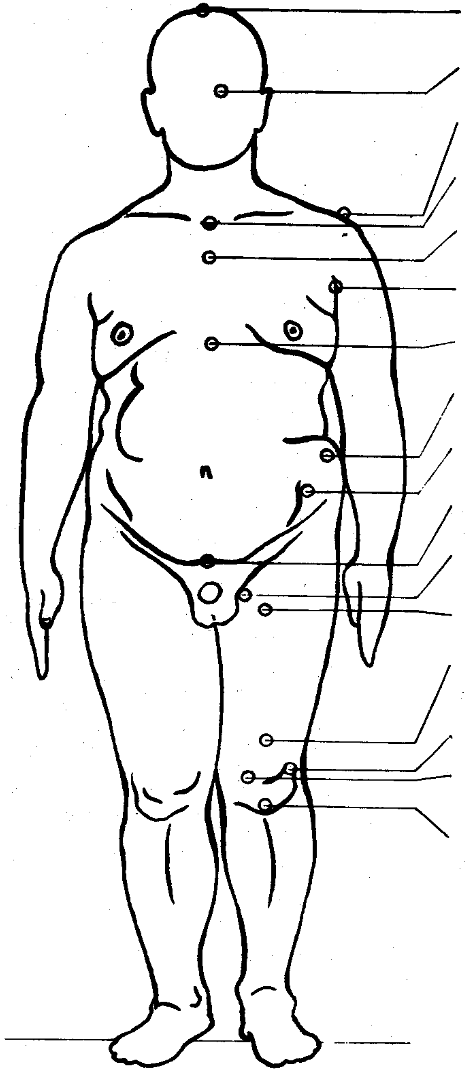
Sixty-nine anthropometric measurements were made on each man. These included 19 heights from the floor (standing), 24 circumferences at different levels, 3 supine lengths, 3 sitting heights, and 20 caliper measurements, mostly upper limb lengths and trunk widths; the only anteroposterior dimension measured was head length.

The plan for the battery of measurements was set up on consultation with members of the Wright Field anthropometric unit; a number of the measurements corresponded with those used in the Antioch College anthropometric survey of Air Force personnel (Churchill, 1951; and Hertzberg, Daniels, and Churchill, 1954). Standard anthropometers, calipers, and metal tapes were used, and measuring techniques patterned after those of the Wright Field anthropometric unit were employed. Special comment, however, may be made on several measurements. To have meaning, body measurements must be geared to some purpose. Accordingly, our measurements were made to fulfill a twofold objective. First, the measurements, like the somatotype check, were to provide a description of the character of our study sample. Figures 10 through 13 indicate the locations of measurement, the averages, and standard deviation for various study groups. The second objective was the obtaining of integrated measurements, which gave some index of body bulk and which included a minimum of "floating" values.

Heights from the floor for standing subjects are integrated by the common reference point at the floor. Most of the circumferences were taken at levels where the height was known; in measurements of girth a friction fit of the metal tape, i.e., the loosest possible fit which did not slip on the skin, was sought. The level of circumferences, apart from those of the upper limb, and trunk breadths were defined by anthropometric points or by bone landmarks. Thus, chest width at xiphoid level, shoulder width at sternal angle, and shoulder or chest width at the anterior axillary fold were more precisely located than is often done. With this approach there were few "floating" measurements. In fact, these were limited to upper limb circumferences and a few caliper measurements (viz., interspinous width, biclavicular width, the flexed arm lengths, and the supine lengths). Three supine measurements were made: these consisted of body length and two others relating to the distance between the body center of gravity and the vertex and the distince between the foot sole and center of gravity. The location of the supine body center of gravity was determined by stretching the subject, arms at side, on a board supported by knife edges on two scales. Through a balancing of moments involving the weights recorded on each scale and the distance from knife edge to center of gravity, the latter point was located.

(23) SPECIAL MEASUREMENTS

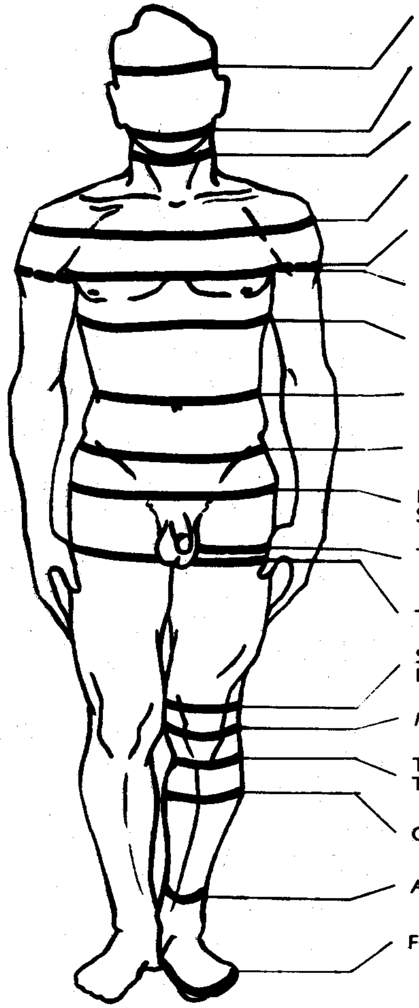
Since the objectives of this study necessitated the obtaining of information relating to body kinematics, various measurements beyond those involving linear anthropometric measurements were made. These included measurements of joint range for



HEIGHT FROM FLOOR: (in cm.)	**MEDIAN**		**ROTUND**		**MUSCULAR**		**THIN**	
	Av.(11)	**S.D.**	**Av.(7)**	**S.D.**	**Av.(11)**	**S.D.**	**Av.(10)**	**S.D.**
STATURE	175.1	4.3	173.3	5.7	176.3	5.3	186.2	5.1
INNER CANTHUS	163.1	3.8	162.4	5.1	164.5	6.8	174.4	5.2
ACROMION	143.5	3.7	144.1	4.6	144.9	5.0	153.8	4.9
SUPRASTERNALE	142.6	3.8	141.5	5.1	144.1	4.8	151.7	4.8
STERNAL ANGLE	139.4	3.8	139.4	5.0	140.8	5.2	147.8	5.1
ANT. AXILLA	132.8	3.0	133.7	5.4	133.6	5.0	143.5	4.8
XIPHISTERNUM	124.3	2.7	124.3	5.6	127.0	4.2	133.0	4.7
ILIAC CREST	105.0	2.8	103.2	4.1	105.1	2.9	111.8	3.6
ANT. SUP. SPINE	99.4	3.2	96.6	4.0	100.4	3.1	106.8	3.7
PUBIS	89.3	3.8	85.7	3.2	90.5	3.2	95.9	2.9
GLUTEAL SULCUS	79.9	3.3	78.5	2.7	80.4	3.2	87.2	2.6
CROTCH	83.2	4.2	79.2	2.5	84.0	4.1	89.6	4.0
SUPRA-PATELLARE	52.3	2.1	52.8	1.8	53.1	2.1	56.0	2.1
LATERAL TIBIALE	47.5	2.1	47.3	2.5	47.7	3.1	51.1	3.4
MEDIAL TIBIALE	47.0	2.6	45.5	2.3	46.8	2.9	49.8	3.2
TIBIAL TUBEROSITY	42.7	1.8	42.4	1.6	44.5	2.5	46.4	1.9

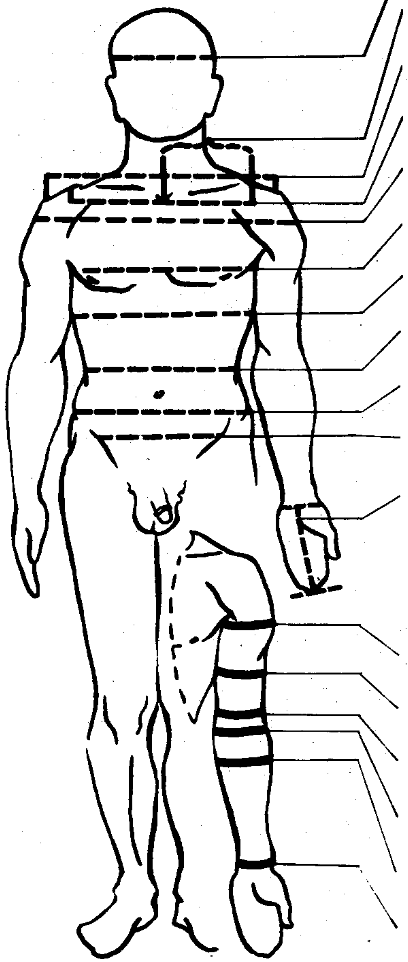
SUPINE MEASUREMENTS: (in cm.)	MEDIAN		ROTUND		MUSCULAR		THIN	
	Av.(10)	S.D.	Av.(7)	S.D.	Av.(11)	S.D.	Av.(10)	S.D.
BODY LENGTH	176.6	4.9	174.0	7.1	177.5	5.7	186.6	5.2
VERTEX TO PUBIS	85.8	2.9	86.5	5.3	86.8	2.6	90.6	5.6
VERTEX TO C.G.	76.1	5.0	76.2	4.6	78.7	3.2	84.1	3.3

Figure 10. Measurements of Study Sample.



CIRCUMFERENCES: (in cm.)	MEDIAN Av.$_{(11)}$	MEDIAN S.D.	ROTUND Av.$_{(7)}$	ROTUND S.D.	MUSCULAR Av.$_{(8)}$	MUSCULAR S.D.	THIN Av.$_{(10)}$	THIN S.D.
HEAD (euryon)	58.0	2.2	58.1	2.0	57.7	1.6	57.2	1.7
HEAD (gonion)	47.3	2.2	51.2	3.2	48.4	2.0	44.1	3.1
NECK (thyroid cartilage)	38.0	1.5	41.0	2.8	38.5	1.6	35.2	2.0
SHOULDER (sternal angle)	106.0	4.6	116.0	9.0	107.5	5.0	102.9	4.4
SHOULDER (axilla)	116.6	3.9	126.6	9.0	118.9	4.2	104.8	5.2
CHEST (axilla)	97.2	3.9	109.0	6.5	98.3	5.5	87.2	5.4
CHEST (xiphisternum)	91.3	4.0	104.7	7.4	89.8	4.2	79.3	5.2
WAIST (min.)	79.8	3.9	102.9	10.6	78.2	4.1	71.2	3.0
ILIAC CREST	83.9	6.2	112.1	10.6	82.8	5.9	77.8	2.2
PUBIC SYMPHYSIS	95.4	3.1	112.3	9.2	96.1	5.1	89.3	3.3
TRUNK (gluteal sulcus)	94.8	3.7	106.7	7.1	95.0	5.2	84.8	2.7
THIGH (crotch)	57.1	2.4	66.9	5.0	59.3	4.1	49.5	3.7
SUPRA-PATELLARE	38.8	1.5	45.9	4.1	39.7	2.4	34.8	1.6
MID-PATELLA	37.5	1.5	42.4	3.3	37.9	2.3	35.1	1.6
TIBIAL TUBEROSITY	34.0	1.2	39.6	3.2	34.7	2.1	32.0	1.7
CALF (max.)	38.3	2.0	41.9	3.9	38.6	1.9	33.7	2.1
ANKLE (min.)	23.6	1.2	25.1	2.7	23.5	1.2	21.3	1.5
FOOT AT FLOOR	62.2	2.3	62.4	3.0	63.5	3.3	63.1	3.0

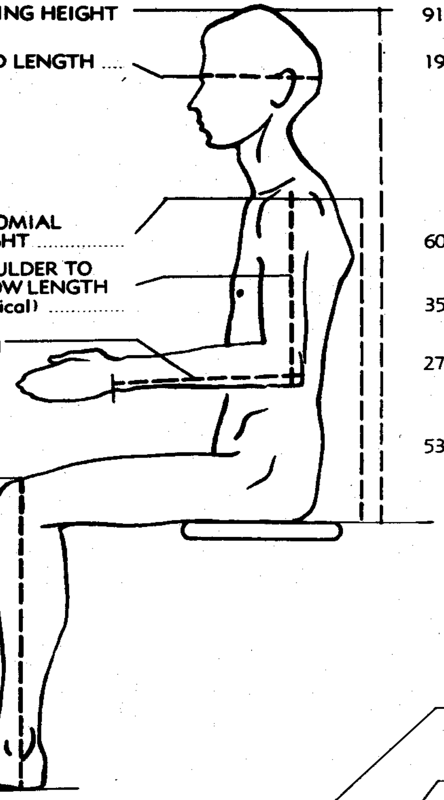
Figure 11. Measurements of Study Sample.



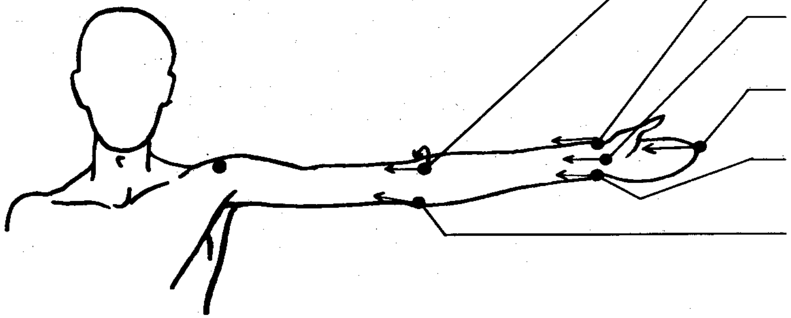
BREADTHS: (in cm.)	MEDIAN Av.(11)	S.D.	ROTUND Av.(7)	S.D.	MUSCULAR Av.(11)	S.D.	THIN Av.(10)	S.D.
HEAD	15.8	0.5	16.1	0.4	15.8	0.5	15.4	1.0
CLAVICLE LENGTH	16.8	0.6	16.7	1.3	16.6	1.1	16.1	0.9
BIACROMIAL	40.4	1.4	40.7	3.2	41.7	1.7	39.9	2.3
BICLAVICULAR WIDTH	33.4	1.0	34.1	2.4	32.9	2.0	32.4	1.7
BIDELTOID (level of sternal angle)	45.3	1.1	48.2	3.4	46.7	3.0	43.3	2.5
CHEST WIDTH (axilla)	33.0	1.8	36.6	2.7	34.1	2.1	31.5	2.3
CHEST WIDTH (xiphoid)	30.7	1.8	35.9	3.0	31.3	1.4	27.9	1.8
WAIST WIDTH	28.7	1.6	34.1	2.8	28.3	1.7	25.5	1.6
INTERCRISTAL	29.3	1.3	37.1	3.9	29.3	2.3	29.4	1.8
INTERSPINOUS	24.7	1.3	32.2	3.2	24.8	2.7	25.9	2.0
HAND LENGTH	19.1	1.0	18.9	0.6	19.7	0.8	19.5	1.1

UPPER LIMB CIRCUMFERENCES: (in cm.)	MEDIAN Av.(11)	S.D.	ROTUND Av.(7)	S.D.	MUSCULAR Av.(11)	S.D.	THIN Av.(10)	S.D.
ARM AT AXILLA	31.6	1.6	36.2	4.7	32.7	2.0	26.2	1.4
MID-ARM	28.6	1.3	32.1	4.0	29.3	1.3	24.1	1.6
ARM ABOVE MED. EPICONDYLE	25.3	0.8	29.0	2.5	26.2	1.5	22.1	1.0
FOREARM BELOW MED. EPICONDYLE	26.8	1.1	29.6	2.5	27.8	1.4	23.8	1.0
UPPER THIRD OF FOREARM	27.0	1.1	29.0	2.7	28.4	1.2	23.3	1.8
WRIST (styloids)	17.4	0.6	18.2	1.2	17.8	0.9	16.6	1.0

Figure 12. Measurements of Study Sample.



SEATED MEASUREMENTS: (in cm.)	MEDIAN Av. (11)	S.D.	ROTUND Av. (7)	S.D.	MUSCULAR Av. (11)	S.D.	THIN Av. (10)	S.D.
SITTING HEIGHT	91.5	3.3	89.3	2.3	91.4	3.1	95.0	3.7
HEAD LENGTH	19.9	0.6	19.8	0.6	20.2	0.8	19.9	0.9
ACROMIAL HEIGHT	60.8	2.7	59.3	2.3	61.2	3.5	64.1	2.9
SHOULDER TO ELBOW LENGTH (vertical)	35.3	1.7	35.7	1.1	37.0	2.4	37.3	2.0
FOREARM LENGTH (horizontal)	27.3	1.1	28.2	1.4	30.0	3.5	29.2	1.1
KNEE HEIGHT	53.6	1.6	54.5	2.7	54.6	2.0	57.8	1.9



ARM LENGTHS (in cm.) (arm supportd) ACROMION TO:	MEDIAN Av. (11)	S.D.	ROTUND Av. (7)	S.D.	MUSCULAR Av. (11)	S.D.	THIN Av. (10)	S.D.
RADIALE	29.1	2.5	29.3	1.8	29.3	1.8	32.1	2.0
RADIAL STYLOID	53.5	2.6	52.4	3.3	54.4	2.5	58.3	2.2
DISTAL FLEXURE LINE OF WRIST	55.1	3.1	52.8	3.4	55.6	2.4	58.9	2.0
END OF FINGER TIP III	73.0	2.9	71.8	3.9	74.1	2.6	77.9	2.8
ULNAR STYLOID	53.9	2.8	52.9	2.3	54.6	2.3	58.3	2.5
INFERIOR POINT OF MEDIAL EPICONDYLE	30.3	2.5	30.8	1.3	31.0	1.6	31.3	1.4

Figure 13. Measurements of Study Sample.

the limbs (Item 24), measurements relating to thoracic and pelvic positions for the seated individual (Item 25), and measurements involving limb movements (Items 28 and 29).

(24) JOINT RANGE

Earlier, in Item 18, a technique was described in which one member of a cadaver joint was immobilized in a vise, while the other member was moved about to the limits of movement in all possible directions. This method seemed impractical for the study of the joints of living subjects, because complete immobilization of one part was necessary. Standard clinical methods using the goniometer merely treat the range of movement in a plane, viz., flexion-extension or abduction-adduction, and the space range pattern is ignored. The method, however, is rapid and it is clinically useful; furthermore, it is adaptable to determination of joint range for large samples of subjects. Despite this, the literature on goniometry records very little on the statistical variability of normal joint movement. Not all joints have been studied and in some joints certain classes of movement have been ignored entirely. Consequently, a restudy was carried through here.

A photographic method, often employing double exposures, was used in the present study for recording the range of movement of the limb joints. The general method had been used earlier by Wilson and Stasch (1945). Certain angular measurements were similar to those in current use (Moore, 1949, A and B); Hellebrandt, Duvall, and Moore, 1949); that is, a proximal part was held in a fixed position and the distal part was moved to its limits in either direction. In other instances, new procedures were developed. For example, where greater certainty in measurement could be obtained for our technique, a distal part was held fixed, and the proximal part was moved.

The general procedure was as follows. The subject was questioned as to whether he was right- or left-handed. He was queried also as to the history of possible joint injury, dislocation, fracture, arthritis, or other defect. Records were taken on the side of hand preference, except that where the history suggested a joint abnormality the opposite side was photographed.

Photographs were made on 35-mm film with an Argus camera by the flash of a speed lamp. The room was darkened and black backgrounds were provided. For double exposures an initial flash exposure recorded one extreme of a joint range; the lens was then kept open following exposure until the subject assumed an opposing position; then a second flash exposure was made. Parts of the body which would otherwise present a conflicting background for the test joints were covered with black velveteen cloth.

A special work table, painted black, was employed as a support for the subject or his limb segments. Horizontals were marked on the table edge with light-reflecting tape to serve as references. Special posing techniques and procedures are outlined in Table 3.

Frames of the strip of negatives were projected as enlarged images and the best estimates of link lines interconnecting joint centers were ruled on paper; horizontal or vertical reference lines were also traced. Angles were then measured with a pro-

TABLE 3

OPERATIVE CONDITIONS FOR DATA ON JOINT RANGE

Joint and Type of Movement	Body Position and Limb	Record	Angle Measured
WRIST—Adduction	Standing, hand flat against verticle back of work table in restraining gear.	Double exposure: (1) forearm bent at wrist to extreme adduction	Angle between forearm link and line of third digit.
—Abduction	Same position relative to table.	(2) forearm in extreme abduction. Dorsal view of hand and forearm.	Same, also included adduction-abduction angle.
—Extension	Standing, palm flat on table, forearm vertical and supinated, bent to max. extension.	Single exposure, ulnar aspect.	Forearm link relative to horizontal.
—Flexion	Dorsum of hand on table, reference plate pressed against palm, supinated forearm maximally flexed.	Single exposure, ulnar aspect.	Angle between forearm link and reference plate, also included flexion-extension angle.
GRIP ANGLE	Standing, 1-1/8-inch wooden grip with projecting axial reference rods held loosely in the hand, hand and forearm hanging vertically.	Single exposure, dorsal aspect of hand and forearm.	Angle between thumb end of grip axis and a perpendicular to the forearm length.
FOREARM—Supine	Facing camera, bent forward with arm vertical and forearm on table, hand directed toward camera lens.	Double exposure: (1) extreme supination	Angle between vertical and thumb end of grip axis.
—Prone	Hand-grip axis in picture plane, forearm in supination, then pronation.	(2) extreme pronation. End view of hand and grip.	Same, also included pronation-supination angle.
ELBOW—Extension	Sitting sidewise to camera, test limb toward camera, arm horizontal on block, hand grip vertical and in picture plane, semiprone forearm.	Double exposure: (1) elbow maximally extended	Angle between forearm link and projection of arm link.
—Flexion	Forearm straight in extension, then bent in flexion.	(2) elbow maximally flexed with hand over shoulder, lateral view.	Same, also included flexion-extension angle.
SHOULDER—Medial rotation	Sitting, arm horizontal on block directed toward camera, forearm swung medially in the frontal plane.	Double exposure: (1) extreme medial rotation	Angle between the forearm link and the vertical.
—Lateral rotation	Same, arm swung laterally.	(2) extreme lateral rotation.	Same, also included medial-lateral rotation angle.

TABLE 3 (continued)

Joint and Type of Movement	Body Position and Limb	Record	Angle Measured
SHOULDER—Extension	Supine, test side toward camera, straight limb hanging in the sagittal plane over edge of table.	Double exposure: (1) extreme hyperextension	Angle between arm link and table horizontal.
—Flexion	Same position, arm swung in sagittal plane to position overhead.	(2) extreme flexion.	Same, also included flexion-extension angle.
—Abduction	Supine with head toward camera, sagittal plane of the shoulder joint in line with camera lens, straight arm hanging laterally over table edge at right angle to body axis, reference rod resting on chest.	Double exposure: (1) extreme abduction	Angle between arm link and a perpendicular to the reference rod.
—Adduction	Same position, arm swung maximally toward the opposite body side.	(2) extreme adduction.	Same, included also abduction-adduction angle.
ANKLE—Flexion	Standing sidewise on box with thigh horizontal and foot on table top with lateral side toward camera, bending leg on foot to max. flexed position.	Double exposure: (1) max. ankle flexion	Angle between leg link and vertical.
—Extension	Same position, moving trunk and other leg backward until ankle is maximally straightened.	(2) max. ankle extension.	Same, also included flexion-extension angle.
FOOT—Inversion	Standing on box facing camera, test foot on table, toeing toward camera, swinging knee and leg maximally inward with foot sole horizontal.	Double exposure: (1) max. inversion	Angle between leg link and vertical.
—Eversion	Same, swinging knee laterally.	(2) max. eversion.	Same, also included inversion-eversion angle.
KNEE—Lateral rotation	Standing, thigh about 45° to vertical, test foot resting on turntable with leg vertical and ankle above center of turntable, swinging toe and turntable outward.	No photograph, direct measurement of angle.	Angle between toe forward position and extreme lateral rotation.
—Medial rotation	Same, toe turned inward.	Same	Same, angle between toe forward and extreme medial rotation, also included medial to lateral rotation angle.

TABLE 3 (concluded)

Joint and Type of Movement	Body Position and Limb	Record	Angle Measured
KNEE—Extension (standing)	Standing, weight on opposite foot, test limb straight with foot on ground.	Side-view photograph, double exposure: (1) leg straight	Angle between thigh link and leg link.
—Flexion, voluntary (standing)	Same, thigh vertical, leg flexed slowly to max.	(2) leg in max. voluntary flexion.	Same, also included flexion-extension angle.
—Forced flexion (kneeling)	Kneeling, trunk vertical with weight of haunches forcing max. knee flexion.	Single exposure, side view.	Angle between thigh and leg links.
—Extension (prone)	Prone, test side turned to camera, suprapatellar region on block, leg hanging in max. extension.	Triple exposure: (1) max. extension	Angle between thigh link and leg link.
—Flexion, voluntary (prone)	Same, max. voluntary flexion.	(2) max. voluntary flexion	Same, also included flexion-extension angle.
—Forced flexion (prone)	Sames, grasping foot and forcing calf and leg against thigh.	(3) max. forced flexion.	Same, also included flexion-extension angle.
HIP—Medial rotation (sitting)	Sitting with thigh horizontal and knee directed toward camera, foot hanging free, swinging foot medially.	Double exposure: (1) max. medial rotation	Angle between leg link and the vertical.
—Lateral rotation (sitting)	Same, swinging foot laterally.	(2) max. lateral rotation.	Same, also included angle between medial and lateral rotation.
—Medial rotation (prone)	Prone, knee bent 90° with leg bent to vertical, reference rod placed transversely across pelvis to provide horizontal plane, turning leg inward.	Double exposure: (1) max. medial rotation	Angle between leg link and perpendicular to pelvic reference rod.
—Lateral rotation (prone)	Same, turning leg outward.	(2) max. lateral rotation.	Same, also included medial-lateral rotation angle.
—Extension	Supine, side to camera, buttock on block with thigh hanging straight, pelvic guide indicating the horizontal set on the pubis and the right and left anterior-superior spines, hip in max. extended position.	Double exposure: (1) max. hip extension	Angle between thigh link and horizontal (i.e., pelvic guide).
—Flexion	Same position, knee bent, hip maximally flexed until pelvic guide is tilted away from horizontal.	(2) max. hip flexion.	Same, also included flexion-extension angle.
—Abduction	Supine with head toward camera, camera aimed along sagittal plane of hip joint, reference rod across anterior-superior spines of pelvis, knee bent to 90°, heel in contact with table surface, turning knee outward.	Double exposure: (1) max. abduction	Angle between thigh link and perpendicular to pelvic reference rod.
—Adduction	Same, turning knee inward.	(2) max. adduction.	Same, also included abduction-adduction angle.

tractor to the nearest degree.

(25) PELVIC AND THORACIC TILT ANGLES

Since the seated subject was important in this investigation, the relative orientation of the parts of the trunk skeleton to the seat was pertinent information. Side-view photographs were made of each subject as he sat in a wooden replica of the pilot cockpit. In addition, the subject was photographed side view in the standing, in the supine, and in several seated postures. The latter included (1) the subject seated on a low block at the same level as the seat. Then, for another record (2) the seat level was raised 3 inches above the level of the heels. Next [(3), (4), etc.] the seat level was raised by 3-inch blocks until the subject, nearly standing, could no longer rest his ischia on the top block.

A pelvic and a thoracic guide were placed over skeletal landmarks for each of the side-view photos indicated in the foregoing paragraph. The pelvic guide (Figure 14) consisted of a narrow metal plate with a plane of plastic set perpendicular at its middle. At the free end of the plastic plane a rod covered with light-reflecting tape was set in place to provide a line of reference in the photographs. Three pillars, which could be adjusted in height, provided supports for the metal plate and its reference gear. One pillar (C) in the middle of the plate fit over the pubic bones at the symphysis, and the others (A and B) fit over the anterior-superior spines of the right and left ilia. The positions of each pillar could be moved sidewise and set anew to allow for any pelvic size.

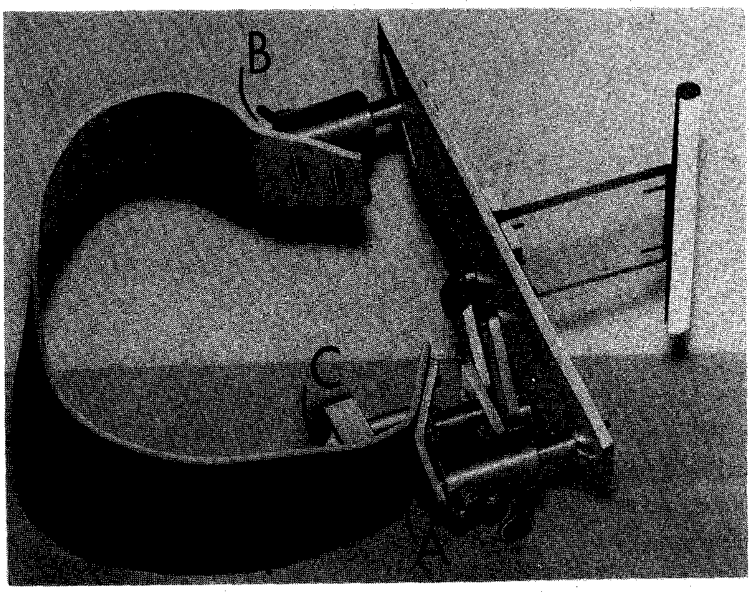


Figure 14. Device for Indicating Pelvic Tilt. Lead belt, formed individually to fit over the bony landmarks of the pelvic brim of a subject, and attached pelvic guide. Foot pieces, or pillars, of the guide, A and B, were adjusted to overlie the anterior superior iliac spines of the subject, and piece C was adjusted until the white guide at the right was vertical (0°) for the standing posture.

To support the pelvic guide in contact with the three pelvic landmarks, a heavy belt was cut from 3/16-inch sheet lead. Each man was provided with an individual form-fitting belt, and the foot pillars of the guide were screwed into lugs placed on the belt at points corresponding with the locations of the anterior-superior spines of the ilia. The belt was fashioned after a paper pattern had been moulded to the subject's form. Strips of heavy, gummed, manila paper, such as one uses in sealing packages for mailing, were pasted on the subject's skin to a thickness of three or four layers, so that the papers overlaid and girdled the upper pelvic bony landmarks. On drying and hardening, the paper was trimmed so that it in no way interfered with trunk or lower limb movements. Then it was removed to provide a pattern for the cutting of the sheet lead.

The lead belts were sufficiently heavy that they fit snugly over the upper pelvis with the guide against the three landmarks; there appeared to be virtually no shifting of the belt with changes in posture. After the belt and guide were fitted to a subject, the guide plate was tilted as needed through adjustments of pillar heights, until the light-reflecting reference line lay vertical (0°), when the subject stood squarely on both feet. Any tilting of the pelvis associated with the seated posture was thus indicated by an angulation of the reference line.

Thoracic tilting was measured by another type of guide (Figure 15). This consisted of a metal plate shaped to fit against the sternal manubrium. The metal plate had a perpendicular, sagittally directed, 30° triangle of clear plastic attached.

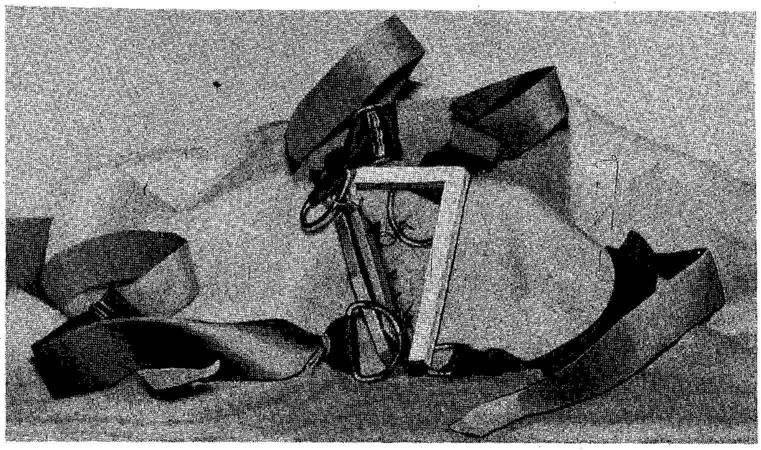


Figure 15. Index for Determining Thoracic Tilt. The manubrial guide is shown as a metal base plate and a perpendicular triangle of clear plastic with its free edges bound with light-reflecting tape. Four rings fixed to the base plate give attachment to elastic rubber tie straps.

To serve as reference lines the free borders of the plastic plane were marked with light-reflecting tape (Figure 15). The manubrial guide was strapped to the subject with elastic rubber strips passing behind the neck and around the chest, so that it fit firmly on the manubrial plane uninfluenced by any shoulder girdle and trunk movements. Unlike the pelvic guide, the manubrial guide was not adjustable. Its initial angulation of the plastic triangle, the manubrial angle was determined for the standing posture. Similar measurements of the guide angle seen in sideview photographs gave an index of thoracic orientation for other postures.

As indicated above, side-view photographs were made of each subject: standing, seated in the pilot-seat replica, and in 10 or more seated postures representing seat heights from 0 to 30 inches or more. Pelvic and manubrial angles were determined for each posture from photographic negatives; the images were enlarged, and guide angulations were measured by protractor relative to a true vertical within the field of view.

(26) STROBOSCOPIC METHODS

Stroboscopic lights attached to body parts permitted us to make photographic records of patterns of limb movement. This procedure had several uses in the investigation. Small 1/25-watt neon glow lamps, attached to and moving with the limb segments, were photographed by time exposure in a darkened room with black backgrounds. With a red filter over the lens a faint blue light provided sufficient general illumination for both the subject and photographer.

When the frequency of the alternating-current supply for the glow lamps was suitably adjusted in relation to the speed of movement the records showed a well-spaced tracing of flashes; the path of movement of the light showed as a series of dashed lines (Figure 16). Some records consisted only of the paths of limb and glow-lamp movements but more usually the additional triggering of a speed-lamp flash at some instant during the movement provided the advantage of showing the subject's position during a phase of his movement (Figure 16).

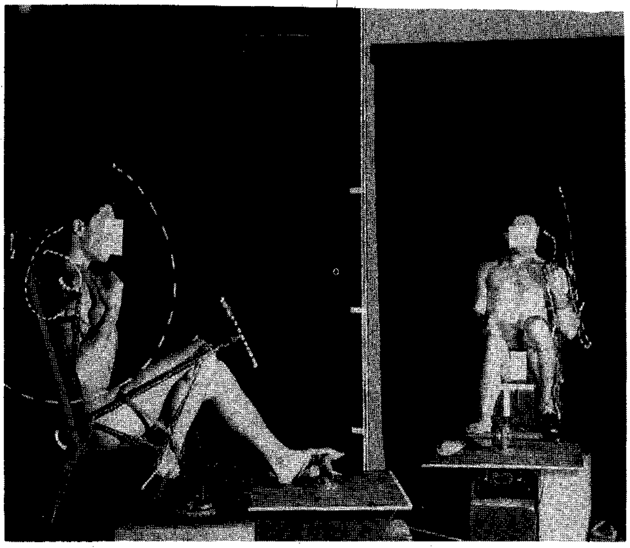


Figure 16. General View of Test Subject in Pilot Seat Mockup. The subject is shown from both the side and front as seen through a 45° mirror. Attached to the maximally-flexed upper and lower limbs are metal triangles, which bear three flashing glow lamps. In this record the subject simultaneously flexed the shoulder and hip, and flashes from the glow lamps described curves about the effective joint centers.

The neon glow lamps, when plugged into the laboratory 60-cycle ac circuit, provided 30 equally timed flashes per second. With a strobotac (General Radio Company) in the circuit also, any frequency from 1 to 200 flashes per second was possible. For very rapid movements 100-200 flashes per second had use; for other purposes 5-10 flashes per second had value.

(27) SHOULDER AND HIP CENTERS

The neon glow-lamp traces were used to locate the positions of the effective shoulder and hip axes about which movement occurred. Lightweight triangles of "erector set" strip metal (Figure 16) provided anchorage for three neon bulbs. One such triangle was bound to the maximally flexed arm and forearm by belt straps, so that the limb members and attached lights moved as one unit. The subject sat with side view to the camera and swung the test limb through a rapid sagittal-plane full flexion, a slow flexion, and a fast and a slow extension. The front view of the subject was also seen in a large vertical mirror set at 45° to the camera. This provided an index as to possible deviation in movement from the sagittal plane. Occasional records were rejected when the light traces for shoulder or hip movements deviated from the sagittal plane by more than a few degrees.

Separate enlargements were traced for photographic negatives; each showed three arclike patterns of neon flashes. By counting along each arc, simultaneous flashes were identified on each arc. With these data the Reuleaux method for locating instantaneous centers (Item 14) could be employed. Only two arcs were strictly necessary; the third gave confirmatory data. Tangent lines between equivalent pairs of adjacent flashes were constructed, and midpoint normals from each of the three arcs defined an intersection representing an instantaneous center of shoulder rotation. Similarly, normals between other successive flashes defined other centers. A continuous path could be drawn through the locations of successive instantaneous centers.

The second triangle with three lights was bound in a similar way to the maximally flexed thigh, leg, and foot of the seated subject. Initial trials showed that free whole-limb movements so displaced the body that the records could not be used. Accordingly, a milder type of supported limb activity was planned (Figure 16). The subject sat with the toe of his shoe on a platform of suitable height so that he could rock the whole limb about the hip joint through an arc of 15 or more degrees. Fast and slow sagittal-plane flexions and extensions were recorded as arcs of neon flashes, and the accompanying speed-lamp flash froze the body position at an instantaneous phase of movement. Additional exposures represented combined shoulder and hip movements in or out of flexion or extension phase. These records, when enlarged and traced, were also analyzed by the Reuleaux method indicated above.

(28) RANGE OF FOOT MOVEMENT OF SEATED SUBJECTS

The procedures outlined here were devised so that one could define the space ahead of a seat which would be required by an individual for various possible foot positions. Dimensions, fore and aft, sidewise and vertically, and the shapes of enclosures that would not restrict movement, were sought.

The basic procedure was simply that the foot was moved at floor level to its limits in all directions and that a one-fifth-scale pantograph tracing of the maximum circuit was recorded. Then the foot was moved at horizontal levels, 3 inches, 6 inches, etc., above the floor plane, and similar records of range were made for each level. When summated, the pattern of movement could be visualized in the three dimensions of space. A wooden replica of the standard aircraft type seat (pilot cockpit) provided a fixed reference for foot movements.

A test subject was seated in the standard wooden seat. The seat could be raised or lowered to different heights relative to a low reference platform (for the foot) that moved on casters over the floor. The adjustments for body size consisted of raising or lowering the seat until the height from the platform to the front edge of the seat was exactly the same as the popliteal height above the platform when the leg was vertical. The height recorded, however, was the vertical distance from the platform to the junction of the seat surface and seat back ("R" point). As the subject sat squarely on the seat, his trunk rested against the back of the seat and his buttocks were well back toward the junction of the seat and seat back. The pelvic guide, used in measurements of pelvic tilt (Figure 14), proved adequate in detecting any marked shift in the subject's position.

The platform on which the foot rested consisted of a rectangular-base plate which slid over the floor on four ball-type casters. The base plate was rigged to two link systems, right and left (Figures 17 and 18). Both linkages were pivoted also on a large plate of sheet metal resting under the seat in a fixed position. The link mechanism on the subject's right, which consisted of a drafting machine-type of linkage, kept the foot continuously oriented straight forward in a sagittal

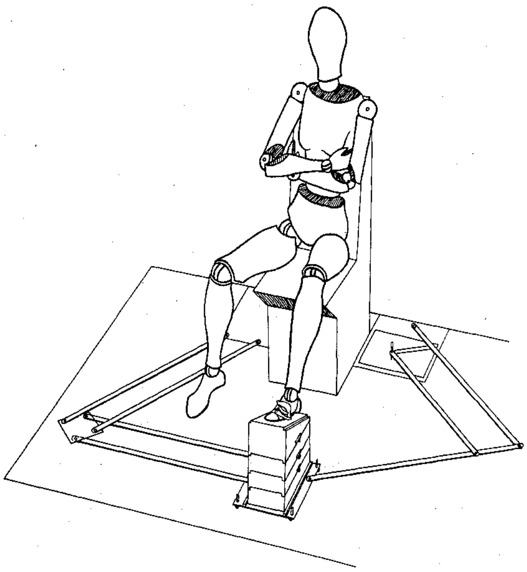


Figure 17. Setup for Determining Horizontal Foot Range. Arrangement of subject, seat, foot rest, and linkages for determining foot range at a given horizontal level relative to the floor. The linkage on the subject's right continually directs the foot forward; that on his left is a 1:5 pantograph. The blocks below the foot show that the heel is raised 9 inches and the foot is tilted 30° above horizontal.

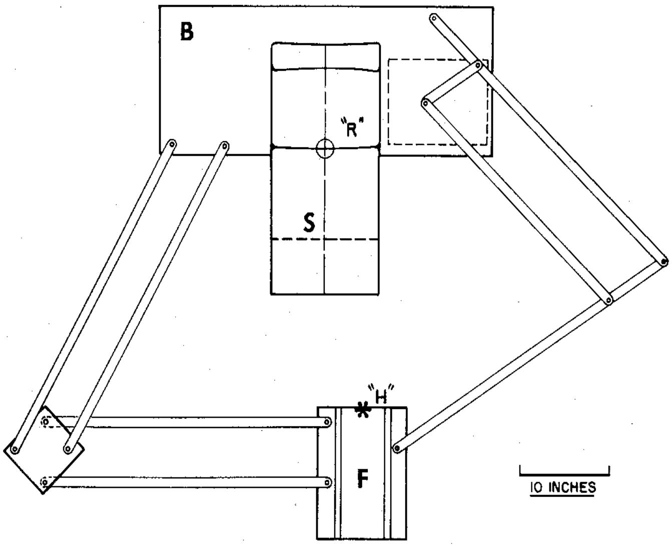


Figure 18. Floor Plan of Linkages for Foot-Range Determinations. Floor plan of base plate (B), seat (S), foot plate (F), and linkages (pantograph to the right and drafting machine linkage to the left); "R" refers to the fixed reference point at the midline point of the junction of seat and back; "H" is the heel point or moving reference.

plane. On the left the linkage was a 1:5 pantograph which traced a reduced outline of the foot excursion. A pad of 0.1-inch-scale graph paper was accurately aligned on the metal plate for the pantograph pencil.

With the pantograph, a one-fifth-size tracing was obtained of the area outlined by a foot excursion as projected to the floor level. The accuracy of the pantograph linkage was much greater than the 0.1-inch graph-paper scale which represented 1/2 inch of actual movement. These records were the source of our primary data. Throughout the work the seat provided a fixed reference while the midpoint of the posterior contour of the heel provided the moving reference point of the foot in the pantograph tracing. This point of reference will be called "heel point."

The subject's bare left foot was fitted into a metal plate with a raised heel guard and strappings for the tarsal and metatarsal regions of the foot (Figure 17). This plate fitted on to the base plate of the mobile platform. Then the foot, held passively by the subject, was moved by an assistant to the extreme limits of movement first in a clockwise and then in a counterclockwise circuit. A series of five records was made, first with the foot flat and next with the foot plate supported on wooden wedges of 30, 45, 60, and 75°. The system for foot angulation was as follows: The flat foot, with sole parallel to the ground, was 90°; the smallest (30°) wedge gave a foot position of 60°; next were the 45, 30, and 15° foot positions. The 0°, vertical foot sole, position was not used.

After clockwise and counterclockwise circuits with the heel at the floor level for each of the five foot angulations were executed, the foot level was then raised 3 inches by adding a block of 3-inch height to the base plate. For the oblique angulations, wedges were placed between the 3-inch block and the foot plate (Figure 17). Five records (90-15°) were made with the 3-inch block in position. Similarly, by additional 3-inch blocks the foot was raised by 3-inch increments. A maximum height of 30 inches could be obtained in this manner. Each pantograph tracing thus represented a vertical projection of the heel point as it moved through a clockwise and a counterclockwise circuit at a given level relative to the floor or seat height.

With each test run some 50-55 tracings (each on 8-1/2 x 11-inch graph paper) represented 10 or 11 horizontal planes and five inclination angles of the foot. The distances from the heel point to the midsagittal plane and to the front of the seat were recorded on each tracing for a standard base plate position. With these measurements a projection of the seat surface and "R" point could be added to each record.

Ordinarily, the clockwise and counterclockwise circuits on the records did not quite superimpose; a mean circuit was drawn as an area for further treatment. In some instances the contours were retraced and cut from slices of styrofoam plastic. When piled, these plastic slices provided a three-dimensional scale model of the range of position of the heel point under the conditions of the test (Figure 84). The space envelope, represented by the styrofoam model, has been called kinetosphere (see glossary).

Planimeter measurements were made of the areas of each contour. Data on area and section height, treated as moments, permitted the calculation of the height of the centroid or center of gravity of the kinetosphere. With this information appropriate sections above and below centroid level were selected, and heavy aluminum foil or cardboard cutouts were made of the tracings. When these were suspended from different points, the horizontal location of the centroid could be determined. From such information it was possible to locate the centroid of the space needed by the foot (i.e., kinetosphere) relative to the seat "R" point. Distances were measured in each of the three cardinal planes. The centroid served as the best zero point of reference for a kinetosphere in that sagittal, coronal, or horizontal planes through this point represented most fairly kinetosphere shape on a plane surface; the centroid corresponded with the most average or "midrange" heel position for a given foot orientation.

For consolidating data on individuals of a given body type and for purposes of comparison, top-, front-, and side-view graphs were made of the kinetospheres for each individual. Such graphical plots could be scaled off from the individual mean sections after sagittal and transverse measurements from the centroid to the contour boundary had been made. Thus, for each type of kinetosphere for each individual, contour plots in three mutually perpendicular planes were made. Seat and floor positions were included in these plots, which now took precedence as data over the pantograph tracings and mean contours.

Plots for individuals of the four body builds were superimposed and traced on sheets of translucent acetate plastic. Composite graphs of the several individuals were made by averaging points at equivalent horizontal levels for each physique. These composites also permitted comparison of kinetospheres representing different foot angulations.

(29) RANGE OF POSSIBLE HAND POSITION

Determinations of the shape and dimensions of the space required by the hand involved a more elaborate method than that outlined above for the foot kinetosphere. A photographic method was employed here. Neon glow lamps (Item 26) operating at a slow flashing rate of 5 or 6 seconds were used in the darkened room. In the procedure the lamp was attached to a hand grip, and its flashes indicated the hand position as it ranged over a surface in the frontal plane of the subject. The subject sat on a wooden replica of the standard pilot seat, and he moved his hand over a fixed frontal plane at arm's length so that it described a circuit at the extreme limit of movement. Then the seat and subject were advanced a measured distance relative to the plane and a new circuit was described. Additional circuits were thus described as the subject was moved forward in steps until the whole range had been explored section by section. The records obtained in this way consisted of a group of frontal serial sections, which could be combined to show the total range of hand position relative to some reference point such as the seat on which the subject sat.

In the standard test each subject sat nude, facing the camera, on a wooden mock-up of the standard pilot seat (Figure 19). A standard vertical distance between eye level and heel was made 39-1/2 inches by adjustments of the seat height relative to the floor plane.

Three or four wire grids were suspended from an overhead horizontal bar parallel to the picture plane of the camera to provide a surface over which the hand could range (Figure 19). Initially, the subject and seat were set at such a distance that he could reach forward and just touch the grid with the reference surface of his hand grip. Then, for the experimental records the subject moved his hand behind and parallel to the grid.

The hand grip consisted of a 30-mm aluminum rod about which dental moulding compound had been shaped, so that there was a good fit for the fingers and thumb of the left hand. When the hand grasped the grip firmly, it had a posture much like the position at rest, when the hand is supported horizontally in the supine position. At the thumb end of the grip an aluminum ball provided with drilled and threaded holes allowed a small rectangular reference grid to be attached at one of a number of selected angular positions in relation to the hand grip. It was important that the grip and hand be oriented carefully for each subject. The wrist and hand were initially aligned straight ahead and the grip was held vertically; the plane of the grid was then carefully adjusted so that it was upright, i.e., 0°, in the frontal plane. After the initial adjustment seven other grip positions (Figure 20) were obtained simply by screwing the grid to the ball of the hand grip at other standard angulations.

In use, the hand grip was always oriented in the frontal plane parallel to the wire screens, and the hand and grip were tilted to conform. When the grid was held in the frontal plane, the hand could assume any one of five sagittal-plane grip angulations. These were: 0° vertical, 30° forward, 60° forward, and 90° forward (in the last instance the grip was horizontal and directed forward as in Figure 20). The grip was also adjusted for three positions in the coronal plane in addition to the 0° position. These were the prone and supine positions and a vertical position with the thumb downward, called here the invert position.

A 1/25-watt neon glow lamp was adjusted to the hand grip, so that its position as photographed appeared at or near the middle of the hand grip; to this end it was adjusted over the III knuckle. Other lamps also were fitted over the acromion and radiale (radiohumeral joint) with adhesive tape.

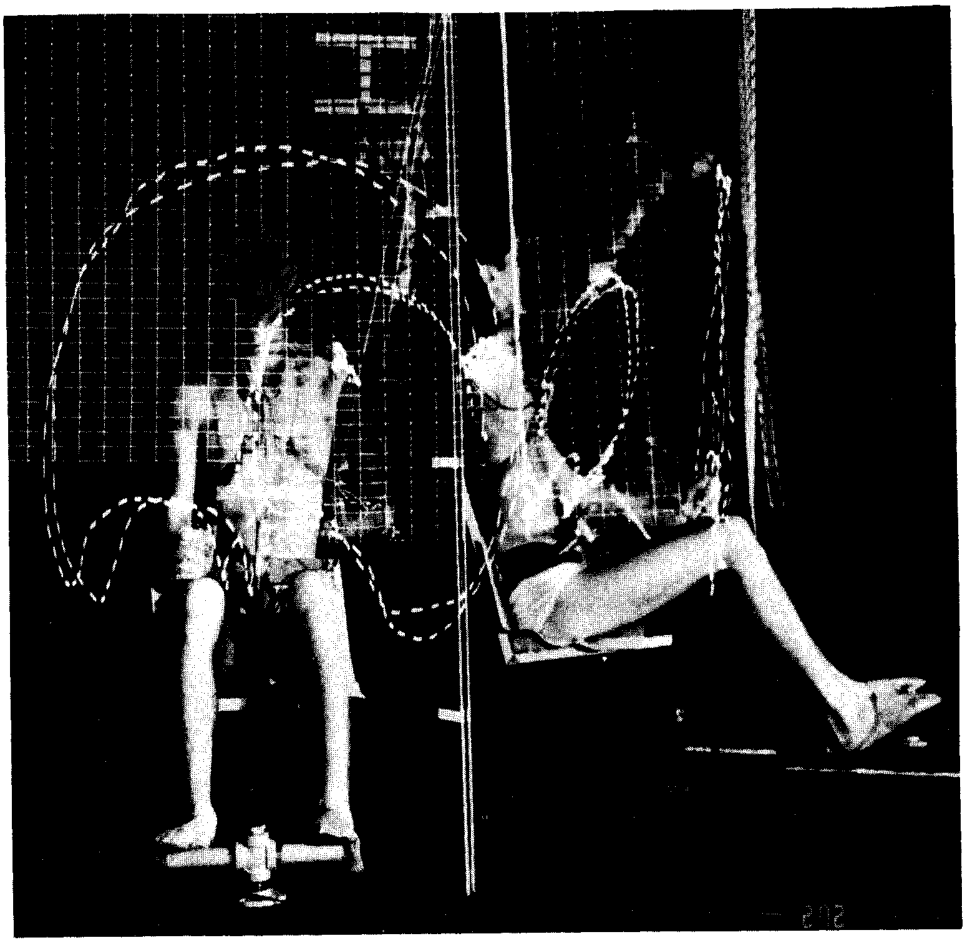


Figure 19. Arrangements for Determining Hand Range. General direct- and side-view mirror image of a subject sitting in a standard seat for the hand-range experiment. In front of the subject is a grid of three wire screens. The subject holds vertically in his left hand a hand grip (prone hand position shown) and makes the widest circuit possible parallel to and behind the grid plane. Flashing neon glow lamps are at the hand, the radiale, and the acromion; circuits of white, dashed lines indicate the paths of the glow lamps in the dark for a clockwise and counterclockwise circuit. The whole view of the subject was recorded for an instant by a speed-light flash during a much longer exposure.

A large 5 x 7-ft mirror at 45° and at the subject's left (Figure 19) showed the grid sidewise as well as the side view of the seat and subject. Records were taken with a Graflex camera at 15-ft distance from the plane of the wire screens; the camera covered a field like that shown in Figure 19. A red lens filter, transparent to neon light, was fitted to the camera, and a low-intensity blue light that did not record through the filter was used for general illumination of the otherwise darkened room. Black backgrounds were provided for both the subjects seen directly and for the mirror-image view.

The first photographic record was taken of the subject as he sat squarely seated against the seat back and head rest; he held the grid of the hand grip parallel to the reference grid; his shoulder was maximally protruded, and his arm was directed straight forward. While the neon lights flashed, the subject slowly moved his hand clockwise,

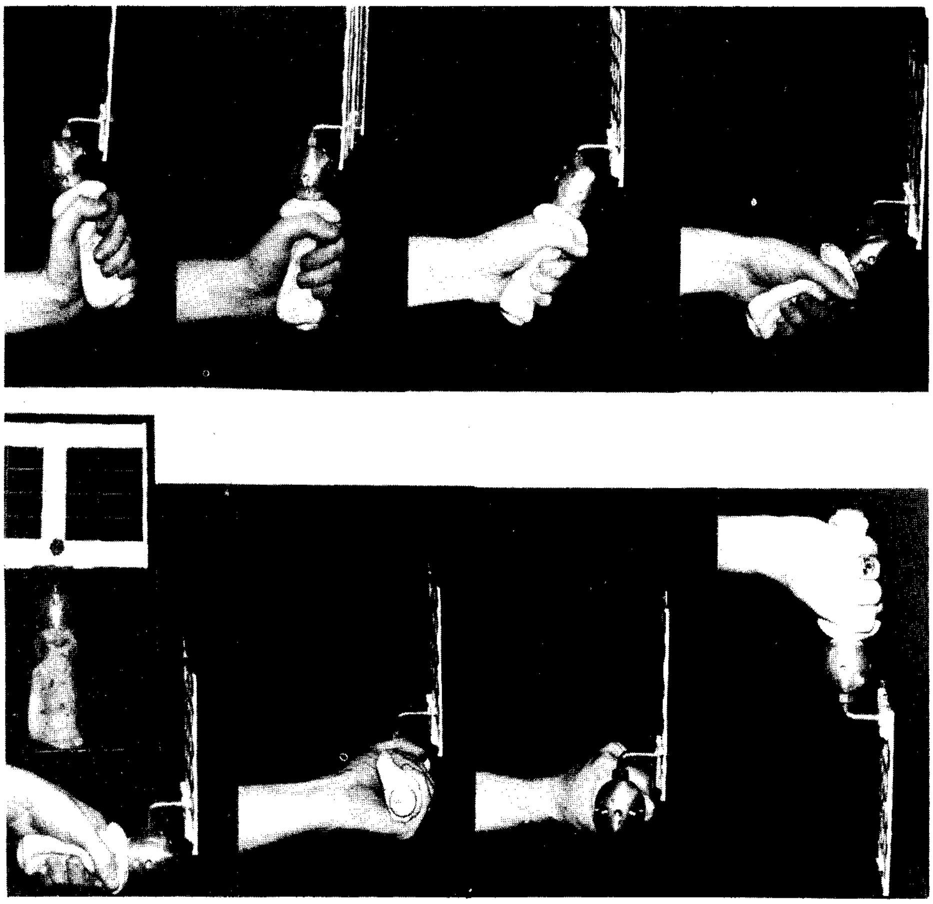


Figure 20. Various Adjustments of Hand Grip. Hand grip (inset, lower left) and orientations of the left hand used in acquiring data on the manual work space. Positions: (upper row) -30°, 0°, +30°, +60°; (lower row) 90°, supine, prone, invert. For each position the flashing neon glow lamp was adjusted so that it lay over knuckle III.

then counterclockwise, through a circuit at the very limits of his reach. This was a free, voluntary movement; in contrast, the foot (Chapter II, Item 28) was moved passively by an assistant. Throughout the movement the hand grip was held in some constant orientation (Figure 20) just behind the reference grid. The camera operator could see the hand grid directly by the faint blue light of the room, and he could correct the subject, if directions were not followed. In the mirror view, likewise, the camera operator could see the reference grid end-on; where there was any failure to keep the hand grip at the frontal plane, the subject could also be corrected. At times, the records were repeated. After practice runs in a clockwise and a counterclockwise direction the camera was opened, and the paths of the neon lamps were recorded. Sometime during one of the two circuits a speed lamp flash was used to illuminate the whole view; this provided an instantaneous image of the subject in both the direct and side views.

After the camera was closed and a new film (Super XX film pack) was in place for a second exposure, the seat and subject were moved forward a fixed distance of 3 or 6 inches, and the hand movement and photographic procedures were repeated. After each record the subject was moved forward a standard distance relative to the reference grid, until the subject could no longer move his hand behind the reference plane. Sections of the grid directly in front of the subject were raised or removed, when they would contact him; movements of the hand to the side of or behind the body level were traced over a single grid at the left of the body.

The photo negatives for each position of the subject were projected in an enlarger to exactly one-fifth natural size, and the neon light paths plus critical landmarks in the view were traced. A mean contour, which averaged clockwise and counterclockwise circuits of the hand, was then drawn in. From these tracings scale measurements of the range of movements were obtained. Planimeter measurements of the area of each mean circuit were made. These areas for different AP distances, when treated as moments, located the AP position of the centroid of the three-dimensional space bounded by the circuits. Representative sections were traced also on cardboard as in the procedures for foot kinetospheres; these were cut out and suspended from different points, to locate vertical and horizontal positions of the centroid or center of gravity. These centroids were located, as for the foot, relative to the "R" point of the seat.

Three-dimensional reconstructions of styrofoam plastic were also made from tracings of representative movement patterns. Cutouts made from the plastic and corresponding with the shapes of the sections were stacked, to provide three-dimensional reconstructions. Grid position, "R" point of the seat, and all other measurements were carefully scaled to the one-fifth size on tracings and reconstructions for all procedures involving photo records.

For each subject eight groups of photographs were made, and each group represented a standard hand orientation (Figure 20). Each group consisted of a series of frontal plane sections that measured anteroposterior levels from the most forward to the most posterior region that the individual could reach. It should be noted that in all the records on all the subjects the hand grip was continually oriented in some standard position relative to the plane of the reference grids; the hand and forearm were directed toward the rear surface of this plane.

(30) CADAVER MATERIAL

Seven unpreserved ("fresh") and three preserved male cadavers formed a special class of study material. Table 4 provides a tally of the data from death certificates plus certain measurements and notes on the eight bodies subjected to standard dismemberment and measurement procedure. One of the other bodies was sawed into transverse sections, and the remaining one was dissected as the ligament-skeleton preparation of Item 17.

A choice of cadavers was made available for this study through arrangements with Professor Russell T. Woodburne, who, as head of the Gross Anatomy unit of the Department of Anatomy served as custodian of anatomical material. Bodies were examined on receipt at the University of Michigan morgue. To be acceptable for this study, subjects must have been free from amputations or obvious defects, not autopsied, not obviously emaciated, and non-tubercular. The main-line procedures on body segments, indicated below, required periods of several successive days by a team of workers, ordinarily including several medical students; consequently, work could be scheduled only when a team could be assembled for a continuous period.

The Michigan Anatomical Law prescribes a ten-day minimum period for possible claiming of bodies before they may be used as anatomical material. Therefore, to coincide with the ten-day interval prescribed by law, bodies were examined on receipt for about two weeks prior to the ten-day period which preceded a conveniently scheduled work period. The most suitable bodies arriving during the selection period were marked for possible study. Each body that seemed usable was suspended by tongs at the ears, and front, left side, and rear somatotype photographs were made on 5 x 7 film. The supine height, body weight, and the height of the supine center of gravity was determined at this time.

Then the body was placed in the morgue's cold room for at least the ten-day period. The photos were mailed to C. W. Dupertuis, Professor of Clinical Anthropology, Western Reserve University, for somatotyping. Professor Dupertuis assessed body build according to the Sheldon system (Sheldon, Stevens, and Tucker, 1940; Sheldon, Dupertuis, and McDermott, 1954). He generally found the rigid pose of the suspended cadavers not amenable to fine discriminations, and his judgments were based on a seven-point somatotype scale rather than the thirteen-point scale used for living subjects. On receipt of the somatotype classification, a new judgment was made on whether or not to work with the cadaver. The eight bodies actually used as indicated in the table, were all of more or less medium build.

TABLE 4

TALLY OF WHITE MALE CADAVERS
DISMEMBERED FOR A STUDY OF BODY SEGMENTS

Cadaver	Somatotype	Age, yr	Supine Height cm	Weight, lb	Cause of Death	Embalmed
14815	4-5-2-1/2	67	168.9	113	unknown	yes
15059	3-5-3	52	159.8	128-1/2	cerebral hemorrhage	no
15062	4-2-4	75	169.6	128-1/2	general arteriosclerosis	no
15095	4-3-4	83	155.3	109-1/4	unknown	no
15097	4-5-3	73	176.4	159-1/2	esophageal carcinoma	no
15168	3-3-4	61	186.6	157	coronary thrombosis	no
15250	3-3-4	—	180.3	133	acute coronary occlusion	no
15251	4-4-2	—	158.5	123	chronic myocarditis	no

The embalmed specimens were tentatively selected by inspection, then they were photographed and somatotyped; if acceptable as average-type builds, the bodies were used without further delay.

It should be noted that all the available cadaver material represented individuals of the older segment of the population. The specimens were smaller than either the average white male population or the military populations of special interest, and the weights were below those of average young individuals. Physically, however, the subjects were representative specimens for their age level.

Three types of procedures were followed on the cadaver material: (1) seven unpreserved bodies and one preserved specimen were dismembered, and segment masses, centers of gravity, density, moments of inertia, etc., were determined (Items 32 to 37), (2) one preserved body was frozen and sawed into serial sections (Item 38), and (3) one body was dissected as the skeleton-ligament preparation mentioned above (Item 17). In addition, dissected bodies from the student dissecting rooms were used from time to time. As indicated earlier, many separated limbs were used in relation to the study of joint centers. No identifying information on this material was available; only white male specimens, however, were used.

(31) CADAVER MEASUREMENTS

Each body, on selection, whether preserved or unpreserved, was subjected to a routine anthropometric survey, including 24 circumferences, 19 supine measurements dealing with height from foot sole, and 21 caliper measurements (9 lengths, 10 breadths, and 2 depths). Although measurements on cadavers are not truly comparable with those on living subjects (standing and supine measurements represent different conditions), the battery of cadaver dimensions measured dealt with the same landmarks as those of living subjects. Further comments on the anthropometric measurements of living subjects were outlined earlier in Item 22. The measurements gave an indication of the physical makeup of the cadaver sample which could be compared with other populations; a more important use, however, was that of a check on further measurements made on body segments relating to joint centers and centers of gravity.

(32) CADAVER DISMEMBERMENT

The procedures relating to the gathering of data on body segments were based on a logical plan of dismemberment. Since segments are in fact continuous, any separation of segments is arbitrary. Units, however, which move *en* masse with rigid elements of the body framework are desired, but these cannot be obtained simply by disarticulating segments. A later chapter on the link system of the body (Chapter III) develops the proposition that links, i.e., the span between joint centers rather than bones, are the effective core lines of the body segments. Each link is enveloped by a certain mass of adjacent tissue, to form a mass segment. Segments, thus, must be separated at joint centers; Braune and Fischer (1890) did this on three bodies. In contrast, Harless (1860) simply dismembered limb segments on his specimens by disarticulating the joints. Meeh (1895) followed Harless' method on infant bodies.

Whereas Braune and Fischer sawed across joint centers of straightened limb segments of the supine body, after freezing, by arbitrary transverse saw cuts at joint centers, the plan here was to freeze joints at the mid-position of their movement range and to bisect the joint angles by cuts through joint centers. Our assumption was that separations across straightened joints, or across fully-flexed joints, would place a portion of the mass properly belonging to one segment more or less into the next segment. The midrange position should provide a more reasonable compromise as to the separation of segment masses.

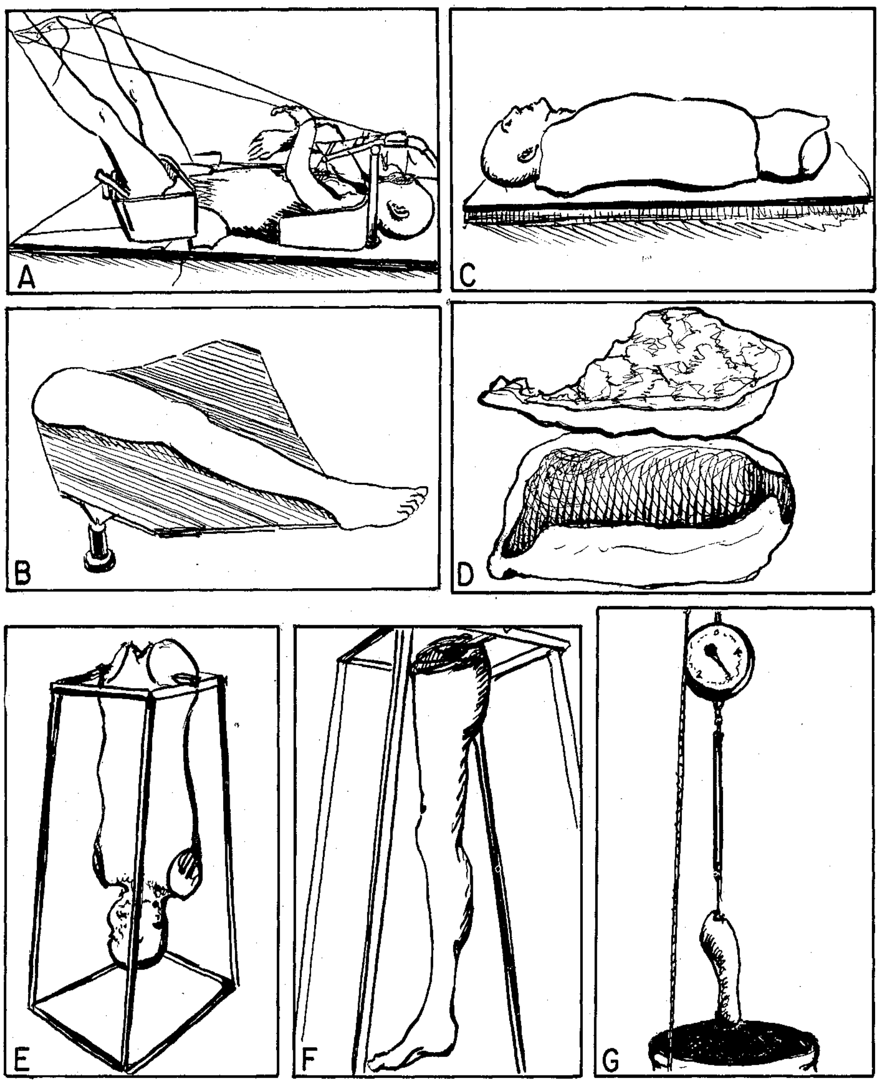


Figure 21. Procedures Associated with Cadaver Dismemberment. A—The cadaver was lashed on a work board with the hip and shoulder fixed at mid-range positions. Joints were frozen solid by dry ice in metal containers. B—Balance plate for determining the level of center of gravity of the lower limb. C—Preparation of plaster of Paris mould of the shoulder region. D—The shoulder mass, frozen solid, is shown lifted away from the plaster of Paris shoulder mould. E—Trunk, with shoulders intact, suspended at the acetabula on knife edges for determination of oscillation time, a method associated with experimental determination of moment of inertia. F—Lower limb has been supported on knife edges for determination of the moment of inertia. G—Upper limb segment suspended from a scales prior to immersion in the tank of water below — for determination of the mass of water displaced (i.e., volume).

The procedures began by lashing the cadaver to a work board and bending the hip and shoulder joints to a midrange position (Figure 21A). Thus, the humerus was flexed at the shoulder as nearly as possible to 60° (beyond the vertically downward position), abducted to 45° (beyond the sagittal plane), and medially rotated to 32°; the hip was flexed to 57°, abducted 10° beyond the sagittal plane, and laterally rotated 3°. These positions of bending were based on an early estimate of joint range angles that were later amplified, and which are dealt with in Chapter IV, Tables 5 and 6; the positions were reasonably close estimates.

PROCEDURES AND METHODS ON CADAVER PARTS

(33) Trunk and Whole Limbs

The first cuts into the cadaver were made prior to the first freezing procedure. An incision from the crease at the crotch overlying the ischiopubic ramus was continued down to the bone; then each of the muscles arising from the outer aspect of the ischium and pubis was dissected from its periosteal attachment. This made the bending of the hip joint easy. The limbs were tied in place with rope secured to posts on the work board. Dry ice was then packed about the four joints (Figure 21A). The body, trussed in this manner, was next placed in a cold room overnight.

The next morning, the joints were frozen solidly in position and were rigid, even without the guy ropes. A saw cut, which simultaneously bisected the flexion-extension and abduction-adduction angles, was made through each of the four joints. Then there were five body parts: head and trunk, right and left upper limbs, and right and left lower limbs (Figure 22).

Each of these parts was next subjected to a sequence of five procedures: (1) parts were weighed; (2) the location of the center of gravity of the straightened part was determined; (3) the period of oscillation (for moment of inertia) was determined; (4) when the frozen thigh and shoulder regions were thawed, the volume was determined by the Archimedes method; and (5) the parts were prepared for subsequent procedures.

Weighings up to 20 kg were made on a metric balance with a one-gram sensitivity; the heavier trunk segment, however, was weighed in pounds to the nearest quarter-pound and measurements then were converted to the metric system.

The linear location of segment centers of gravity was determined on a balance-plate (Figure 21B). The latter device consisted of a square sheet of stainless steel on which diagonals had been scored; the two opposing corners turned down to a right angle. The bent corners rested on short metal pillars placed on the floor; when the plate was balanced, it swung horizontally on the support pillars. Since maximum sensitivity of the balance-plate was dependent on the center of gravity of the plate and superimposed mass being just below the support points, the metal plate was bent so that its upper surface was concave from side to side. Two plates were actually used so that the depth of the concavity could be more properly adjusted to the parts; trunk, thigh, and whole lower limb parts were balanced on a larger and deeper plate than other parts. The test limb or trunk part was moved toward one end or the other of the balance-plate until the plate swung horizontally in balance (Figure 21B).

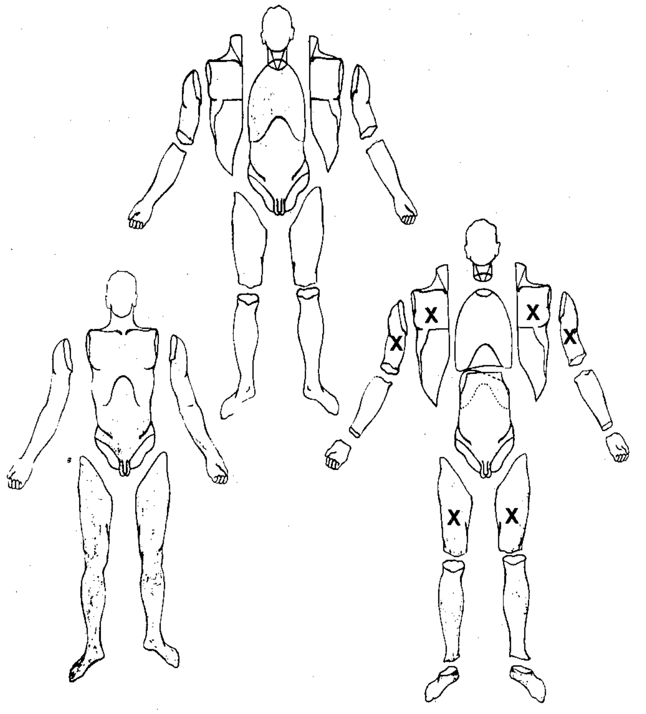


Figure 22. Plan of Dismemberment of Cadavers. As shown, the procedure made 27 parts available for various measurements. Note that the six parts marked with "X" in the sketch to the right are the same as those of the central sketch.

Then a cord, stretched above the scored diagonal from point to point, indicated the linear location of the center of gravity. Pins were inserted into the tissue at this level; then the distance from the pins to each end of the mass was measured.

For the trunk, measurements from points over the center of gravity to the vertex of the head and to the center of the hip joints were made. For the limbs, measurements from the center of the ball of the shoulder and hip joints to the pins marking the center of gravity, and from these to the distal end of the member, were made. In addition, a straight-line distance between terminal measuring points was measured for each part. Since pins over the center of gravity were on the surface, the three measurements represented sides of a scalene triangle; the sum of the two shorter measurements was greater than the hypotenuse. At a later time a simple calculation gave the location of the center of gravity relative to the hypotenuse, viz., the ratio of one of the short measurements to the sum of both was the same as that between the straight-line distance to the center of gravity relative to the hypotenuse.

The oscillation period was determined on a free-swinging pendulum system. For the trunk, a half-inch pipe was placed through a horizontal drill hole from the center of one acetabulum to the other. End plugs inserted into both of the pipe openings were provided with knife edges. The trunk then was up-ended and suspended as a pendulum on a metal framework by knife-edge contacts (Figure 21E). The body then was allowed to swing freely on the knife edges through an arc of approximately 5 degrees.

Before the trunk was suspended as a pendulum, the neck region was frozen by packing with dry ice; this allowed the whole trunk to swing en masse, without whiplash movements of the head and neck. For the limbs, a bar on knife-edge supports was screwed into the center of the cut surface of the ball of the hip and shoulder joints. Ten measurements, each of 10 periods of oscillation, were taken with a stop watch; from these an average period was determined and recorded.

The moment of inertia for a mass of irregular form was calculated from the formula:

$$I_o = \frac{WL}{4\pi^2 f^2} ,$$

where W equals mass x g (i.e., 980 cm/sec^2), L is the distance from the center of gravity to the point of suspension, and f is the frequency of oscillation. The moment of inertia at the center of gravity can then be calculated by the equation:

$$I_{CG} = I_o - \frac{W}{g} L^2 .$$

Volume was determined by totally immersing a part in a tank of water and measuring the weight of the immersed part (Figure 21G). The difference between the weight in air and the weight in water represented the weight of water displaced — or the volume equivalent. Parts with air content, as the trunk, had to be weighted, so that the part could be immersed; corrections for the additional weight were made. Prior to immersion, sufficient time was allowed so that parts which had been frozen could thaw entirely. Following the brief immersion required for the weighing, a part was lifted free of the water for draining, before subsequent procedures were begun.

(34) Limb Segments

Next, the five members originally separated (Figure 22) were prepared for further dismemberment. The elbow and knee joints were bent to mid-flexion angles of 70 degrees and 62 degrees, respectively, and the parts were placed in plywood troughs, so that the joints could be packed and frozen with dry ice. Prior to placement in the troughs, the joints were manipulated as an aid in locating the joint center; on the basis of such movement, and with knowledge of the location of joint centers from other work (Chapter IV), an estimated mean joint center was marked by scalpel cuts through the skin. Frozen joints were then bisected with saw cuts at the estimated joint centers.

Now there were eight additional limb segments for study (Figure 22): two thighs, two units consisting of the leg and foot, two upper arm sections, and two composite forearm-hand units. Each of these was subjected to weighing, center of gravity determination, measurement of oscillation time, and volume determination. The techniques were similar to those outlined above. For the determination of oscillation periods, the limb segments in these instances were suspended as pendulums, after the proximal joint centers were screwed into the bar on knife edges.

(35) Shoulder Regions

Procedures for trunk dismemberment were more elaborate. The intention relative to the shoulder masses was that the parts retain their shape during procedures involving centers of gravity location and pendulum oscillation. Accordingly, it was necessary to freeze these parts solid. To aid in this procedure, a plaster of Paris mould was made of each side of the trunk, completely overlapping the shoulder mass (Figure 21C). The shoulder section was defined as the shoulder girdle plus all muscles operating on these parts, and the overlying skin and subcutaneous tissue. So defined, the shoulder extends from the rear portion of the skull to the crest of the ilium, and from the attachment of girdle muscles to the vertebral spines and lumbodorsal aponeurosis. In front, the mass attaches to the thorax.

Accordingly, after the plaster mould was removed, incisions were made from (1) the mastoid process to (2) the suprasternal notch along the anterior edge of the sternocleidomastoid muscle, (3) along the medial border of the pectoralis major muscle, (4) to the fifth chondrosternal junction, then laterally (5) to the lateral limit of the pectoralis major muscle. Next, the incision followed (6) the digitations of the serratus anterior muscle to (7) the anterior margin of the latissimus dorsi M. Next, the incision followed to (8) the crest of the ilium following the anterior edge of the latissimus dorsi muscle. This incision then continued posteriorly along (9) the crest of the ilium to (10) the lateral border of the lumbodorsal fascia. From this point, the incision carried to (11) the twelfth thoracic spine and along (12) the spines of the thoracic and cervical vertebrae to (13) the skull. The incision was completed by following (14) the nuchal line to the mastoid process.

The trapezius and sternocleidomastoid muscles were detached from the skull; the sternoclavicular joint was disarticulated; the pectoralis major and pectoralis minor muscles were separated from the thoracic wall, as were the serratus anterior and latissimus dorsi. The latter muscle was also detached from the crest of the ilium and the lumbodorsal aponeurosis. The trapezius and rhomboid muscles were separated from the vertebral column. The levator scapulae muscle was detached from the cervical transverse processes, and the omohyoid muscle was cut at the anterior margin of the sternocleidomastoid muscle. The whole mass was then separated along shearing planes next to the thoracic and abdominal walls. The brachial plexus and axillary artery and vein were separated at the outer margin of the first rib. With these dissection procedures, the whole shoulder mass was separated from the trunk.

The mass was next laid into the concave plaster mould (Figure 21D), so that its shape was the same as when in contact with the trunk structure. Dry ice was packed into the concavity of the shoulder mass as it lay in the plaster mould, and the mass frozen solid. Now, there were three torso units: the right and left shoulder and the trunk proper, i.e., head and neck, thorax, and abdomino-pelvic complex. Each of the three parts was weighted, and before the shoulder masses thawed, the center of gravity was determined by suspension at several points. The center of gravity was located and distances were measured to (1) the sternoclavicular joint, (2) the center of the humeral head, and (3) the axillary margin of the scapula. At a later time, the position of the center of gravity relative to the scapular blade was determined; to this end, a hole was drilled through the frozen tissues and through the scapula directly opposite the center of gravity. The distance to the scapula was measured; later, when the scapula was cleaned, the locus of the scapular perforation was determined.

While the shoulder mass was still frozen, it was screwed to the knife-edge bar at the medial end of the clavicle, and the oscillation period was determined. Further procedures on the trunk section (without shoulders) were similar to those recounted earlier. To obtain data on moment of inertia, the neck section of the trunk was again frozen with dry ice and the up-ended trunk, supported through the acetabula, was oscillated so that the period could be determined. On thawing of the shoulders and trunk the volumes of the parts were determined by the Archimedes method.

(36) Trunk Segments, Distal Limb Parts, and the Head

Next, the trunk section was separated into three units (Figure 22). The head and neck were separated from the trunk by a knife-cut along the upper border of the first rib, by disarticulating the joints between vertebrae C-7 and T-1 and by severing the remaining soft tissues at the same level. The thorax was separated from the abdomino-pelvic complex by carefully separating the peritoneum from the lower surface of the diaphragm, by disarticulating the column between T-12 and L-1, and by severing the deep muscles of the back at the same level.

No further separation of the abdomino-pelvic mass was feasible. Because of visceral mobility with changes in position, the abdomino-pelvic mass was frozen prior to location of the center of gravity, weighing, and swinging as a pendulum. Volume determinations on the abdomino-pelvic mass were not ordinarily attempted; it will be remembered that some hours of manipulation had preceded—hollow viscera were variably distended with air.

The hand-forearm and leg-foot members were frozen with the wrist and ankle in midrange postures, and saw-cuts were made along planes (1) transversely through the head of the capitate bone (landmarks: mid-pisiform bone, distal wrist crease, and the dorsally palpable groove between lunate and capitate) and (2) from the upper border of calcaneus to the lower tip of the fibula and just above the talus head.

After the foregoing dismemberment procedures, there were eleven new segments: head and neck, thorax, abdomino-pelvic mass, and right and left hands, forearms, feet, and legs (Figure 22). Weights were taken, as were weights in water, pendulum oscillations, and the spans from center of gravity to joint centers or to ends of members. The procedures described above finally resulted in 17 separate body segments, plus 10 sections which were composites of limb or trunk units. On each of these, the mass, volume, location of center of gravity, and pendulum period were determined.

To locate the center of gravity of the head and neck mass, several points of suspension were tried until the head hung with its sagittal plane horizontal. Lead-headed tacks were placed into the skin on each side of the head at selected suspension points. In two instances, also, the center of gravity of the head alone was determined by the same method. The anatomical locations of the suspension points, right and left, were noted; the center of gravity fell at or near the midsagittal plane on a transverse line which connected these points. Lateral x-ray films were made of the head, and the intersection of the bony structure of the sagittal plane with the line between the lead-headed tacks was determined. Where Harless and Braune and Fischer had removed the head by a simple oblique saw cut, the head was carefully separated by dissection.

(37) Anatomical Loci of Centers of Gravity

A follow-up procedure, made on the 17 unit segments, was designed to locate the positions of centers of gravity anatomically in three dimensions. First, each of the members (except for the head, where the x-ray record served) was suspended from various points after freezing or, alternately, was balanced on the balance-plate with different surfaces uppermost. Three to four transverse drill holes were made into the frozen members, aiming toward the centers of gravity; next, pointed 1/4-inch dowel sticks were driven into the tissue toward the centers. Then saw cuts in the plane of the sticks were made, so that the center of gravity was transected.

Structures on the cut faces of the sections were carefully identified, and the location of the center of gravity was defined anatomically in terms of the bone or muscle on which it fell. After the parts had thawed they were dissected, and the loci of centers of gravity were measured relative to their distances from specific structural landmarks above and below the plane of section.

(38) CADAVER SECTIONS

The embalmed body used in this procedure was frozen in a freezing chamber and then placed horizontally on a table on casters at the side of a heavy meat-cutting bandsaw. An end guide set at 1 inch (25.4 mm) determined section thickness. Inch-thick, transverse head sections, then neck and shoulders to the axillae, were cut in sequence. The last cut detached the upper limbs. Then the sectioning was continued through the trunk to the crotch, when the lower limbs were separated. Next, the right upper and lower limbs were cut in sections of similar thickness. The left limbs were not used.

As the sections were removed in serial order, they were placed on thin sheets of plastic. Thickness at four points were measured as a check on saw-cut thickness. Then the sections were weighed. Following this procedure, the sections of the shoulder and hip regions were dissected so that trunk and limb masses in each section could be determined separately. In addition, the sections were dissected into component tissue elements; these were weighed separately, section by section, to get information on the relative distribution of the component material. Records were obtained in this way for the skin and subcutaneous tissue, the muscle, the bone and joint material, and the remaining organ tissue.

(39) BODY BULK MEASUREMENTS ON LIVING SUBJECTS: IMMERSION TECHNIQUES

The procedures on cadaver segments mentioned above involved the dismemberment of parts, the locations of segment centers of gravity, and the determination of weights and volumes. These measurements were derived from the particular defunct individuals studied. Valuable as the measurements are, they do not apply specifically to the type of young adult builds found in military personnel. It is rarely possible to obtain such physiques in a cadaver population; yet, practical applications of mechanical data on body parts would be of the greatest interest for the younger group.

Measurements of segmental masses, densities, centers of gravity, and moments of inertia of body parts require that the different units be dismembered. Volumes, however, may be obtained either in toto or in a stepwise pattern without dismemberment. Moreover, these measurements may be made on either cadavers or living subjects. Segmental volumes determined on living subjects may be compared with equivalent data on cadavers, and such comparison should make clear the order of discrepancy between the two groups. Where volumes are comparable, other cadaver values should be trustworthy estimates of living values; where there are differences, the direction and magnitude of corrections should be suggested.

In those practical situations where the order of density between segments may be disregarded, volume figures may be used directly as mass. Our work on the body bulk of living test subjects was based upon two types of volume measurement: (1) volume of whole limb segments involving water displacement and (2) stepwise measurements of cross-section areas of both the whole body and the limbs relative to vertical height (Items 40 and 41).

Figure 23 shows four specially designed tanks for the immersion of limb segments. Initially, a measuring tank was filled to its brim with water, so that any excess fluid overflowed into the catch-jacket about the tank. All overflow in the jacket was then drained off, and the petcock was closed; the subject, under guidance, immersed limb segments to predetermined boundary landmarks as the water spilled over

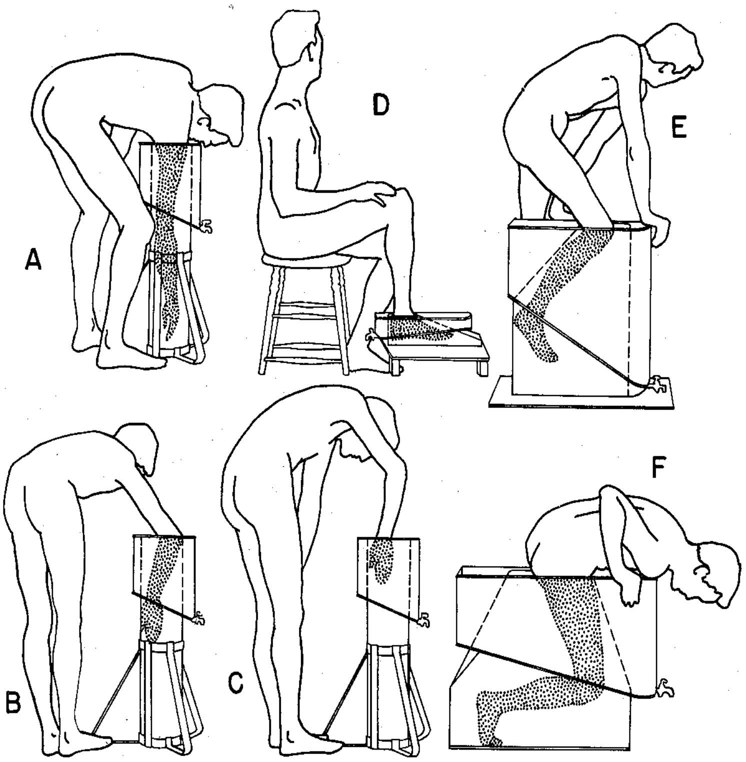


Figure 23. Segment Volume by Water Displacement. Methods of determining volumes of limb segments on living subjects by water displacement. Parts were immersed to predetermined landmarks as indicated in the text.

into the jacket. Landmarks were made with a skin pencil while the limb was bent to midrange. When the water touched the landmarks the limb was removed and the water was drained from the jacket into a tared vessel and was weighed to the nearest gram. The weight of water (in grams) was interpreted as volume (in cubic centimeters) of water displaced. When a limb was to be immersed to a given joint center, that joint was flexed to a midrange angulation (as shown in the figure) so that the water level bisected the joint angle. Thus, immersed segments were bounded by planes corresponding to saw-cuts used in the cadaver dismemberment procedures. Landmarks employed were as follows:

For the hand:	(1) mid-point of pisiform bone, (2) distal wrist crease at palmaris longus tendon (or, if the wrist crease was not clear, mid-point of palpable tubercle on volar surface of navicular bone), (3) palpable sulcus dorsally between lunate and capitate bones.
For the hand plus forearm:	(1) lower border of medial epicondyle of humerus, (2) 8 mm above radiale.
For the whole upper limb:	(1) palpable sulcus above acromioclavicular joint, (2) anterior axillary fold at the projection of thoracic contour, (3) posterior axillary fold at the projection of thoracic contour.
For the foot:	(1) superior border of calcaneus anterior to Achilles' tendon as palpated medially and laterally, (2) upper border of head of talus, (3) lower tip of fibula.
For the foot and leg:	(1) mid-point of posterior curvature of medial condyle of femur as palpated, (2) same for lateral condyle.
For the whole lower limb:	(1) anterior superior spine of test side, (2) ischiopubic sulcus between thigh and scrotum, (3) line from ischium to above femoral trochanter.

From the six volume measurements, other values were obtained by subtraction. Thus records were obtained on:

(1) Whole upper limb (measured).
(2) Upper arm (calculated).
(3) Forearm and hand (measured).
(4) Forearm (calculated).
(5) Hand (measured).

(6) Whole lower limb (measured).
(7) Gluteal and thigh segment (calculated).
(8) Leg and foot (measured).
(9) Leg (calculated).
(10) Foot (measured).

Measurements were obtained for all the standard series of study subjects (Items 20 and 21); data were grouped according to body type.

(40) WHOLE-BODY MEASUREMENTS

Body sections of cadavers (Item 38) present areas of variable size. If these were plotted relative to height, the area under the resulting curve would represent body volume, and the contour shape of the curve would show the variable distribution of bulk. Apart from density differences, this contour would be similar to the outer contour of Figure 95, based on section weight. A comparable method was used on the standard series of study subjects. Cross-sectional areas at different heights, however, were traced by pantograph.

Figure 24 suggests the method of making pantograph tracings at different body sections. Mounted on upright pillars was a movable table surface, which could be raised or lowered electrically. Sketch B shows an 18- x 24-inch cut-away area of the table top, where the subject stood; eight adjustable clamps (shown) were moved in or out to fit the body contour just below the table level. Two pantographs, right and left, were mounted on a common pillar; the short pencil arm of each pantograph could be hinged out of the way to provide clearance for the other. Each pantograph was constructed so that one inch of movement of the long arm (at the skin surface) represented exactly 10 mm of movement of the pencil.

When the table height was raised until the pantograph-tracing arm was at the height of a selected body landmark, the clamp rods were adjusted to prevent body sway. An operator at one side traced the body contour—just touching the skin surface—and a 1:2.54 pencil tracing of the half contour was recorded on paper. Then a second operator traced the other side of the body and completed the pencil contour. The height of the tracing was recorded, and a new record sheet was placed for the next tracing. Then the clamps were released, and the table height was set to a new landmark at a different height; another pantograph tracing was then made. To keep the table level at a convenient height for the operators, the subject stood on a box for tracings from foot to knee level, and he sat for tracings of the head contour.

A complete record of a subject consisted of 20 contour tracings together with records of section height to the nearest 0.1 inch; total body height to vertex represented a twenty-first measurement. The 20 landmarks for height were selected from a much larger number of levels used in trial measurements; these are presented as the minimum number of levels which will reasonably show the distribution of bulk relative to height. The selected landmarks were as follows:

(1) left foot sole (1 cm above the floor level),
(2) left medial malleolus (tip),
(3) left minimum ankle,

(4) left maximum calf,
(5) upper edge of left tibial tuberosity,
(6) left mid-patella,
(7) left supra-patellare,
(8) left thigh at crotch,
(9) trunk at gluteal crease,
(10) upper margin of pubic symphysis,
(11) uppermost part of iliac crest,
(12) minimum waist circumference,
(13) junction of xiphisternum and sternal body
(14) trunk at anterior axillary margin,
(15) trunk plus shoulder at same level,
(16) shoulder at sternal angle,
(17) acromial height,
(18) thyroid cartilage,
(19) gonion,
(20) euryon.

Total height formed a twenty-first level of zero area.

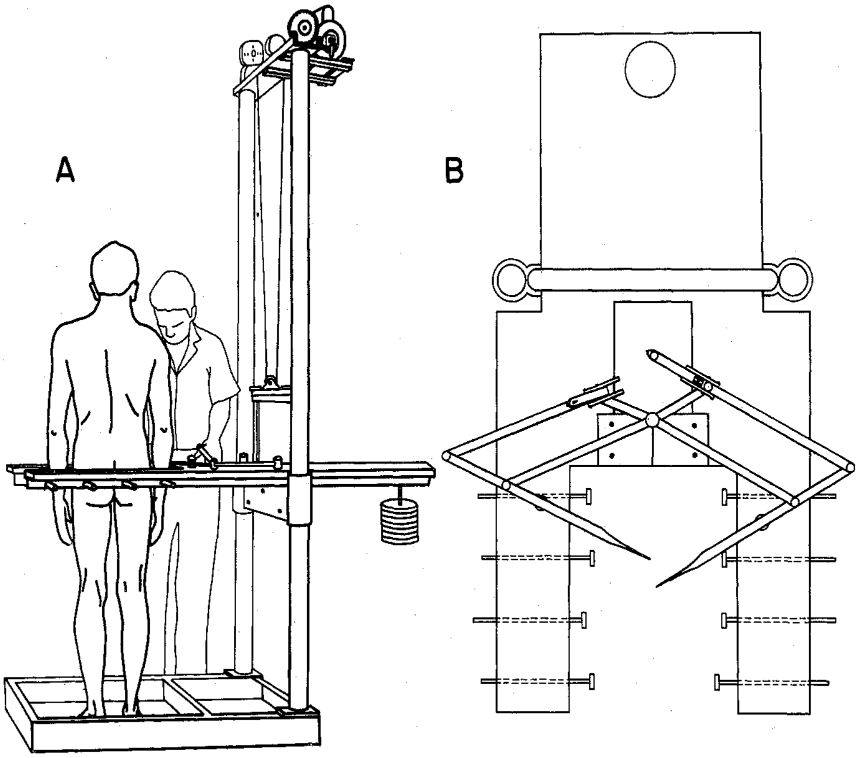


Figure 24. Equipment Used for Body Volume Determinations. Double planimeter mechanism for obtaining area-to-height data. A—The adjustable table surface is shown as set for a lower trunk level; the operator traced the body contour at this level with the pantograph tracer arm. B—Plan of table top and two pantographs on a common post.

Since the pantograph ratio converted inches to centimeters, the heights between actual tracings were likewise treated in the metric scale. Accordingly, when section contours were measured by a planimeter set for the metric scale, the areas needed only to be recorded as square inches (instead of square centimeters) to represent the full body scale. When planimeter measurements of sections were plotted relative to height, a body-contour plot resulted. The area of this contour, measured in turn by planimeter, represented the body volume.

Since the free upper limbs could not be stabilized well, they were not traced in our routine series of subjects. As another simplification, only the left lower limb was traced. The left lower limb area was simply doubled to present a nominal value for both lower limbs at a given height. This method ignores limb asymmetries; checks on a few subjects, however, showed the error to be relatively small. An additional technique (Item 41) supplied data on the upper limb and supplemented data on the lower.

When body volume estimates multiplied by average values for specific gravity (Boyd, 1933) were compared with body weights, discrepancies due to volume were less than 5 percent. The error of the pantograph-planimeter system, when applied to rigid blocks and cylinders, where volume could be computed from dimensional data and where the pantograph tracing arm could ride on a rigid surface, was nearly 2 percent. Body sway and irregularities in tracings, due to the soft skin contour, accounted for the additional error. The error in volume was comparable to weighing on a scales with an error up to 5 percent; assuming that the error was reasonably distributed in the various sections, the relative distribution of bulk along a body height contour should be fairly accurate.

(41) LINEAR DISTRIBUTION OF LIMB VOLUME

To supplement the method outlined above, the upper and lower limbs were immersed in water and successive levels of water were withdrawn and measured. A plot of the volume of water-withdrawn-per-inch height gave a contour representing limb volume.

For the upper limb, the subject lay prone on a table with his left upper limb hanging into a glass tank of constant diameter. The limb was immersed to the acromial level; the limb also was stabilized by adjusting the legs on a hand grip until they just met the floor of the tank. Successive one-inch levels of water were aspirated off into separate, tared collecting bottles. These were weighed and the tare was subtracted. When the weight of water displaced was plotted relative to height on a graph representing tank volume, the limb contour was shown. Since only one limb was measured in this way, nominal values for both limbs were taken as: 2 x left limb volume.

The lower-limb volume-to-height curves were obtained in a similar way. The test lower limb (right) was immersed in a tank to crotch level. An adjustable foot rest was set at such a height that the subject could stand with his right foot on the platform within the water tank and the crotch level would be just at the tank brim. Successive 2-inch heights of water were siphoned into collecting bottles and weighed, as for the upper limb. Plots of these data, when made to an appropriate scale, were comparable to those from the pantograph-planimeter method for the whole body.

(42) EFFECT OF BODY DEAD WEIGHT ON HORIZONTAL PUSHES AND PULLS

Since a pilot or other seated operator must work with hand controls involving pushes, pulls, or twisting motions, some understanding of the mechanics of forces and torques should contribute to design problems of the work space. Knowledge along this line should aid in the placement of controls for efficient operation. The following study relates to horizontal pushes and pulls exerted in the midsagittal plane; action in the midplane necessarily called for symmetrical two-handed pushes and pulls.

Sagittal pulls to the side of the median plane and oblique force vectors were not considered here; Item 43, following, directs attention to certain aspects of one-handed pulls. The procedures were designed to determine how body dead weight, involving downward force vectors, contributed to hand forces in the horizontal plane. To this end all pertinent action and reaction forces were measured and equated for a limited series of actions.

The general method involved a nude subject sitting on a seat platform and pushing or pulling horizontally at shoulder level (Figure 25). Horizontal forces at the seat and at the hand, as well as vertical forces at the seat, were measured with pressure gauges or dynamometers. To assure that forces were mid-sagittal, balanced two-handed pushes or pulls were used.

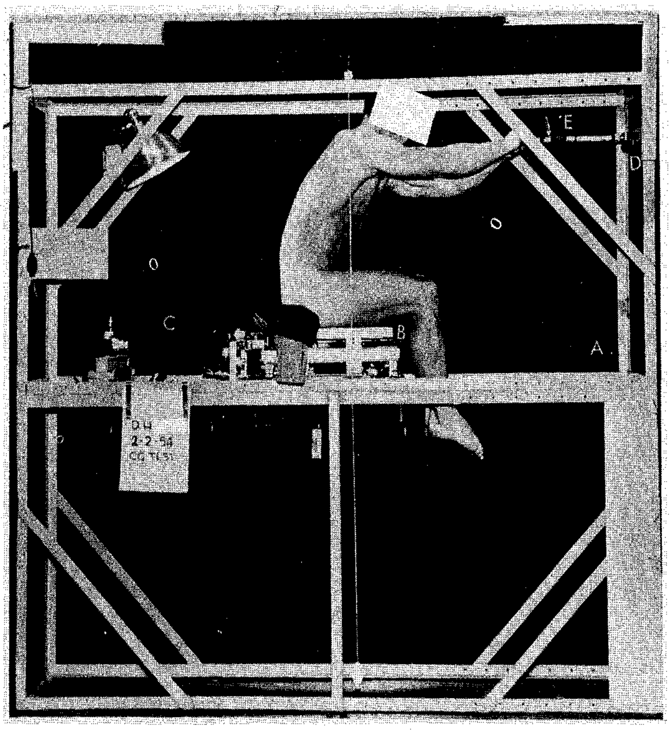


Figure 25. General Arrangements for a Hand-Push Test. Lettered par welded support framework; B—seat supported by pressure gauges; C—cameras for recording seat forces; D—hand dynamometer for recording horizontal thrust; and E—hand grip with mirror and spirit level for assuring horizontality.

Figure 26 shows the basic apparatus. At its right end, upper section, a horizontal bar, which could be set at different heights, supported a 200-lb tension dynamometer, or, alternately, a 100-kg compression gauge (D). These recorded hand pushes or pulls. Horizontal members at the mid-height of the frame supported a rectangular base-plate, which was the bottom lamina of the seat. Above this, a rectangular metal seat frame (B) was supported near its corners by four Dillon pressure gauges (100-kg capacity). These gauges collectively recorded the weight of whatever mass was superimposed; different readings implied an asymmetrical distribution of mass.

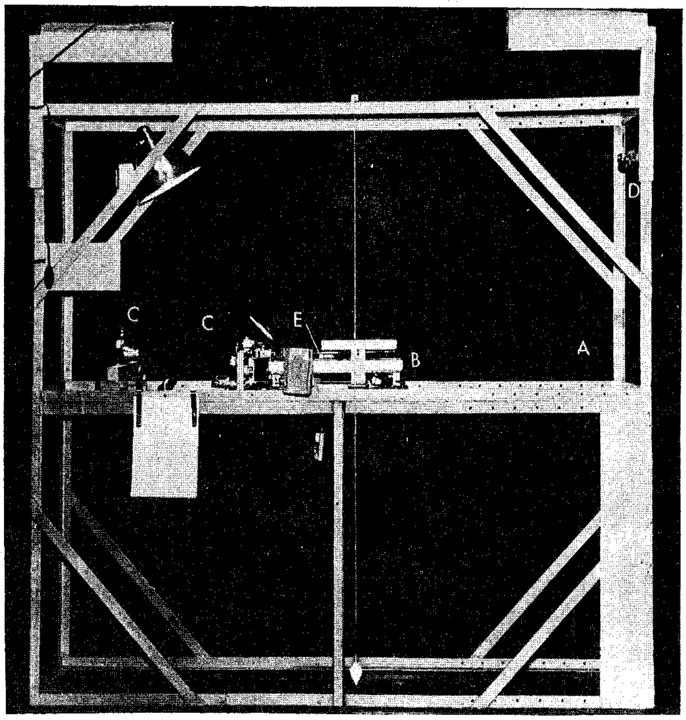


Figure 26. Apparatus Used in Study of Horizontal Mid-Sagittal Pushes and Pulls. A—welded support; B—seat and front right pressure gauge; C—camera for recording seat gauges; D—pressure gauge for recording hand push forces (the support for this could be set at various heights); and E—ball bearings on which seat moves forward or backward.

Figure 27 (right) shows the four gauges near the corners of the seat frame, which they support. (The seating surface has been lifted away to show this view.) At the upper sagittal margins of the metal frame, right and left, metal channels carried several 1/2-inch ball bearings. The seat board, which also had metal channels on its undersurface at its sagittal edges, rested upon the ball bearings. These permitted the seat to slide freely in a fore-and-aft direction on the metal seat frame. Free fore-and-aft movement, however, was entirely eliminated by horizontally-mounted Dillon gauges (100 kg capacity), which were set between the seat frame and the seat. Forces tending to displace the seating surface forward were recorded on the front gauge; backward displacing forces were recorded on the rear gauge.

The top surface of the seat board was covered by a rubber friction mat. Some 80 lb of lead weighting were attached to the seat surface near its rear edge, to prevent seat tilting in certain subject postures. Readings on the six gauges were recorded directly or through 45-degree mirrors by two 35-mm Argus cameras, which were activated by solenoids. Camera No. 3 of Figure 27 photographed a frame counter, two dials registering vertical components at the rear of the seat and, through a mirror, the dial that registered horizontal thrust. The other camera registered the remaining gauges and additional counter.

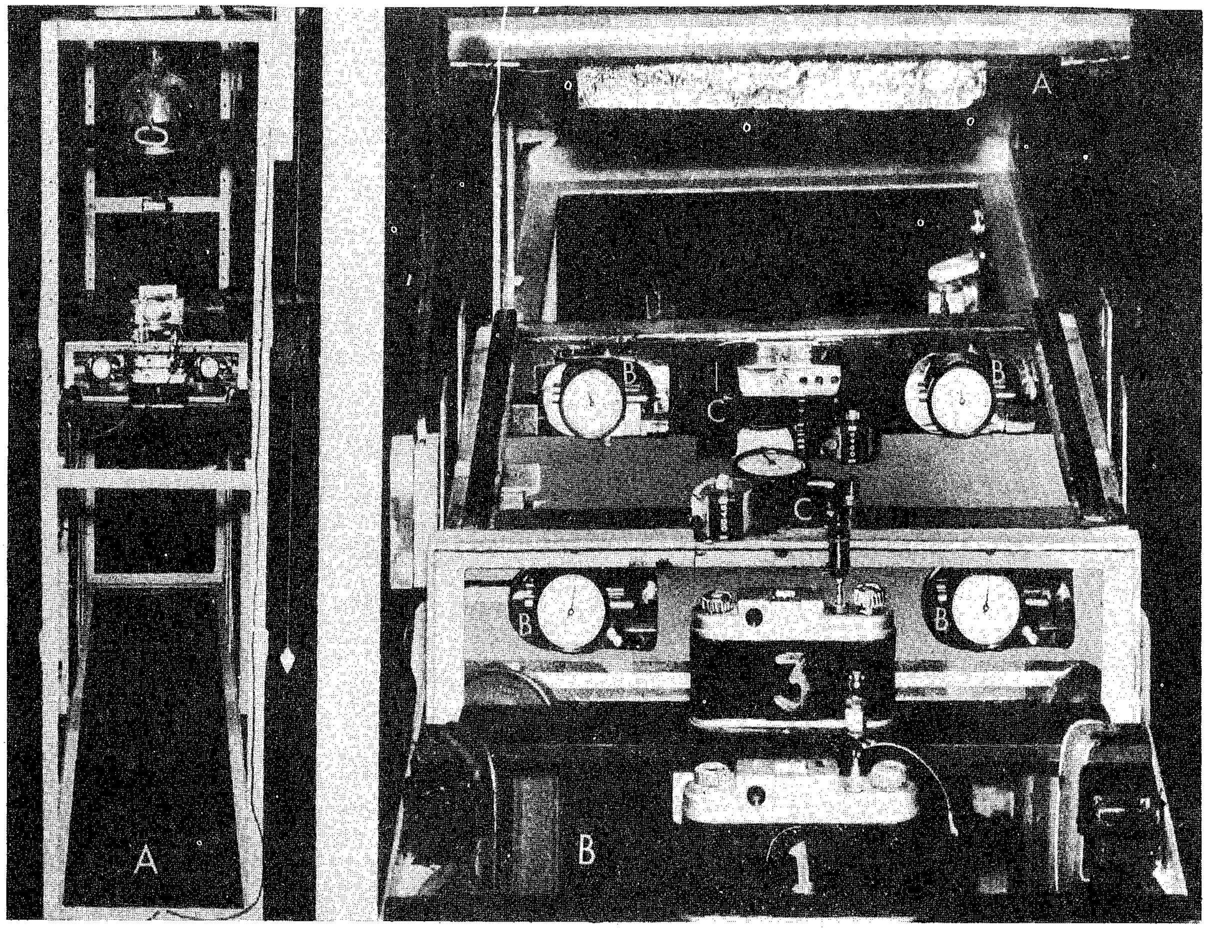


Figure 27. End and Detail Views of Hand-Force Apparatus. A—View of left hand end of welded support, pressure gauges, and camera. B—The seat (A) has been lifted to show a more detailed view of four pressure gauges (B) which bear the weight of the seat; in the middle of the area below the seat are gauges (C) which record fore-and-aft seat forces. Solenoid-operated cameras marked No. 3 and No. 1 are shown below. Note that a counter appears in the view of each camera.

A subject was required to sit on the seat, and for each man the hand-dynamometer height was adjusted to shoulder level. Six push and six pull positions were planned for each subject. In certain postures, the hands were far from the body toward the dynamometer, in others they were closer to the body. To this end, a series of 6- and 3-inch lengths of pipe was coupled to a T-shaped grip for the application of push and pull forces; a spirit level and mirror were mounted on the bar, so that the subject could be certain of a truly horizontal force.

The six pull positions of the standard test are shown in Figure 28. Push positions are shown in Figure 29. In all instances the subject exerted all the force of which he was capable. At least 10 records for each posture were required for a full

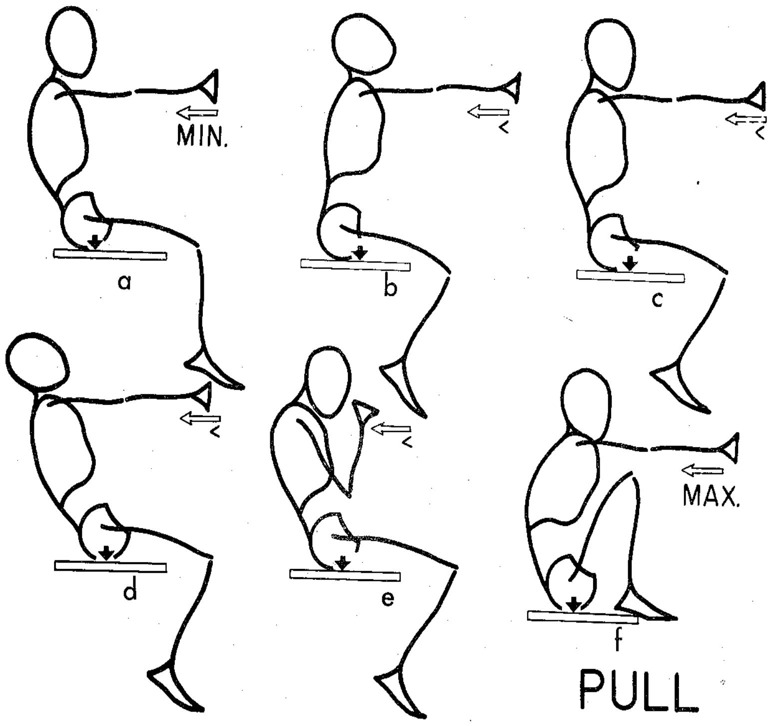


Figure 28. Six Standard Postures Used in Pull Experiments. Postures from "a" to "f" are arranged in order of increased magnitude of horizontal force applications.

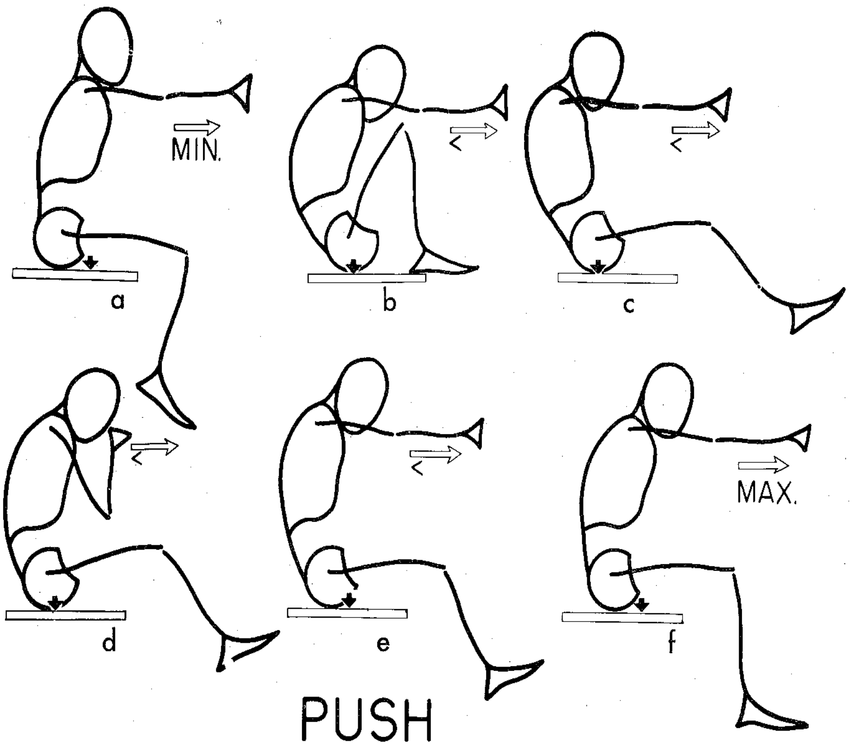


Figure 29. Six standard push postures arranged in order of magnitude of horizontal force produced.

routine; to avoid fatigue effects, repetitions were limited to two at any appointment. Thus, 120 records, or more, were available for each subject. Three subjects were used in this work.

When the subject was in position for a maximum effort for whatever posture, an observer watched the hand dynamometer dial. When the gauge reached a maximum, the operator took an overall side-view photograph of the body position (like that of Figure 25), and through the solenoids he made simultaneous records of the six gauges at the seat. A 120-mm Ciroflex camera was used for the overall views. Thus, for each test there were records on: (1) the hand push or pull force, (2) the horizontal counterforce at the seat, (3) the distribution of the subject's weight at the front and rear of the seat, and (4) a side-view record of the subject's posture.

The data for 10 repetitions of each posture were averaged to provide the generalizations outlined later. The side-view photographs were enlarged and traced on translucent sheet plastic. By superimposing such tracings for a given posture, the variation in position and an average position could be determined.

Data analysis necessitated a determination of the subject's center of gravity and of its reciprocal force—the reaction at the point of effective seat contact. The former was calculated by considering the sum of the moments about the seat contact at the rear gauges, using the average data derived from 10 repetitions for a given posture. Figure 30 shows the pertinent relations. The effective point of seat contact was calculated from the relation:

$$F_1X = F_2(d - x);$$

the force system in this study was in equilibrium; hence, the sum of the clockwise and counterclockwise moments about any point should equal zero. Further, the forces in our system form a vertical and horizontal couple, as will be illustrated later, and by multiplying the perpendicular distances between two parallel forces by the magnitude of either of the two forces, the moment and sense of the couple could be determined, and the accuracy of our derived data could be confirmed. Locations of the body center of gravity were checked through the use of cadaver data on the locations of segment center of gravity, and of measures of body bulk made on the three test subjects of this experiment, using immersion and pantograph-planimeter techniques.

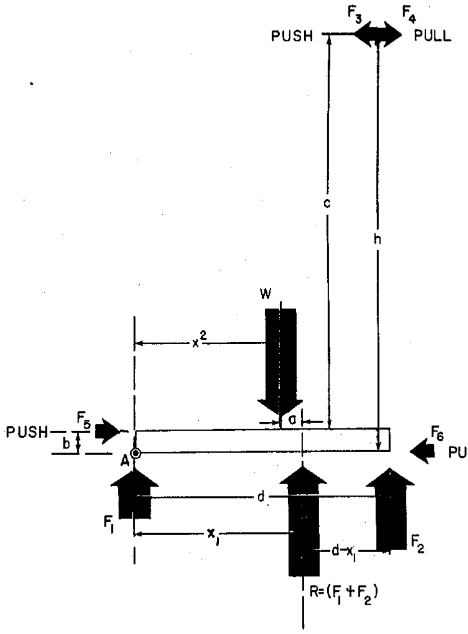


Figure 30. Diagram of force vectors and distances for moment analyses involving the location of whole body centers of gravity and points of effective seat contact.

The locations of centers of gravity in body segments were known. Equivalent points could be located on the overall side-view photographs of the test subjects. Values for section bulk based on volume measurements of the test subjects were assumed to be located at these points on the photograph. Thus, points at the arm, forearm, hand, thigh, leg, foot, and trunk minus limbs in the photographs were considered to represent concentrations of mass. Horizontal distances of these points from some zero point were measured. The whole body center of gravity represented a balance point in clockwise and counterclockwise moments of these segment centers. Results of the two methods of checking the location of body center of gravity were ordinarily within a few millimeters. A further treatment of the different postures is reserved for Chapter IX.

(43) HAND GRIP ORIENTATIONS FOR MAXIMUM PULLS

Procedures outlined in Item 29 showed the shape and dimension of the minimum space required by the hand. Regions beyond reach in contrast with those within, were clearly defined. Regions within reach, however, are of special significance to the design engineer. Further data than those supplied by aforementioned methods are desirable. It would aid him to know which regions within reach are better than others for the placement of gear and controls. Data on locations preferred by workers, on locations which permit greater speed of operation, and on locations permitting unobstructed vision are pertinent also. Psychologists have contributed importantly here. Present procedures were designed to give supplementary information on the relative importance of different regions within reach, insofar as pull forces are concerned. Likewise, they were designed to determine which hand orientations were preferred.

Figure 31 shows the apparatus which was employed. The method depended on photographic records of subject postures, in addition to dynamometer measurements. An inch-thick, well-supported panel, 6-1/2 feet long and 8 feet high, set crosswise in the work room, was oriented to a large 45-degree mirror, so that a direct side view and mirror-image end views could be photographed. Central areas had been cut away before installation, so that a subject sitting in the plane of the panel could move his limbs in an unhindered fashion. His right side was directed toward the recording camera.

A box-like support for a seat was set transverse to the panel. On this a seat with a backrest, having the pitch of a standard pilot seat, could be set at various positions, either right or left of the panel. It could be set with the panel at the midline of the seat, or it could be set so that the panel was 6, 12, 18, or 24 inches to the right or left of the seat midline. The panel was marked with a grid of vertical and norizontal lines of light-reflecting tape, as shown in the figure; in addition, small pulley wheels were set about the margins of the cut-out area and at several other points on the panel. A 200-lb tension dynamometer, shown in the figure, could be attached about any of the pulley wheels by either a short or long, or intermediate loop.

The seat was adjusted to one of six positions relative to the panel: (1) panel at midline, (2) panel 6 inches left, (3) panel 6 inches right, (4) panel 12 inches right, (5) panel 18 inches right, or (6) panel 24 inches right. The subject sat on the seat; the head rest and the foot stirrups were adjusted so that forward or backward pulls would be well-braced. A wire or rope loop from the dynamometer was hung over some pulley wheel at random. As the man pulled, the axis of the dynamometer assumed some optimum alignment, cf. dashed line of the figure. This alignment angle will be shown to have some importance in the later analysis of pull functions.

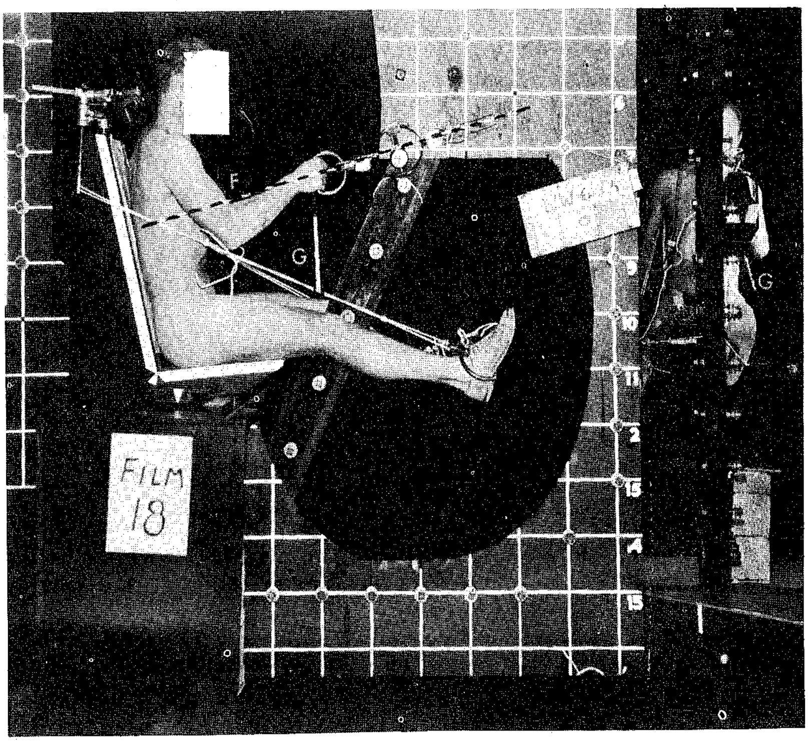


Figure 31. Sample Record for Hand-Pull Force-Vector Analyses. Side-view and a mirror-image front view of a subject pulling on a hand dynamometer in the force vector procedure. The vertical panel with a grid of 6-inch squares and with pulleys for dynamometer attachment is shown; foot stirrups and rope provide a bracing for the body.

To the subject's end of the dynamometer, a small pulley block was attached. Through this ran the steel ring of the stirrup-like support for the hand grip (Figure 31). The ring of the stirrup ran freely on the pulley wheel. As the subject pulled, the stirrup ring found an equilibrium position relative to the pulley at some point consistent with the subject's grip angle. In addition, the dynamometer and grip were free to rotate on the pull axis.

This system permitted two degrees of rotational freedom for the hand grip in the line of the pull. Accordingly, as the subject pulled, his hand assumed some position of preference; a 10-inch projecting rod covered with reflective tape gave an index of the grip angle. The direct photograph, the 45-degree mirror ahead of the subject, and a second, smaller, 45-degree mirror mounted overhead gave three simultaneous views of the index rod. Depending on hand grip orientation, the angle of the rod could be measured in one, in two, or in all three views. A trigonometric check of the apparent lengths from the photographs permitted more accurate assessment of grip angles in the three planes of space.

The experimental subject in an hour-long appointment could pull perhaps 30 times without undue fatigue. The dynamometer was zeroed and looped over a pulley, which was selected at random. Then the subject was instructed to pull his maximum in a plane parallel to the panel. As the dynamometer reached a maximum, a photograph of the direct and mirror-view images was made. Our 120-mm Ciroflex camera was used. The pull force was recorded, and a second random selection of a pulley as a dynamometer attachment was made.

Perhaps a dozen right-handed pulls—forward, backward, up, or down—were made in random sequence at a given seat-panel position; then, for another seat panel relationship, another random set of pulls was recorded. Altogether, nearly 250 records were made of our chief subject. A smaller number of tests—largely checks—were made on two additional subjects. Enlarged tracings were made to scale of each record, showing the posture for the pull and the orientation of the grip, as seen directly and in the mirrors (Figure 108). Force vector lines, such as the dashed line of pull in Figure 31 and the foot-stirrup vectors, were drawn in. Joint center positions for the wrist, elbow, and glenohumeral joint were added, and upper and lower arm links were drawn to interconnect these centers.

With a protractor several angles were measured; these included angulation to the vertical of the pull vector, the counterthrust at the foot, and the hand-grip index, as seen in the direct view; in addition, two mirror-view angulations of the hand-grip index were determined. Data available from each test thus consisted of (1) hand dynamometer values, (2) a record of the subject's body and upper limb posture, (3) force vector angulations for the hand and for the foot, and (4) angulation data on the hand grip. Data, accordingly, were available for every pull, for different angulations of pull, and for pulls in sagittal planes at different distances from the body midplane.

CHAPTER III

THE LINK SYSTEM OF THE BODY

ORIENTATION

As intimated earlier, there is an extensive literature on the anthropometry of military personnel as well as on other populations. Recent examples of military pertinence are: Randall, Damon, Benton, and others (1946); Kennedy (1949); Morant (1947, 1951); Newman and White (1951); Daniels, Meyers, and Churchill (1953 a and b); Hertzberg, Daniels, and Churchill (1954); and McFarland, et al. (1953). Such measurements, it should be borne in mind, relate to linear dimensions and to the body surface. They consist of heights of body landmarks, widths, circumferences, and spans between certain surface points. In general, a fairly standardized series of measurements involving specific landmarks and specified body postures have been used. Where special objectives, such as the sizing of clothing or the design of seating have been anticipated, the range of measurements has often been extended.

These measurements have both scientific and practical value. Different populations, for instance, may be compared where similar measurements have been used; the numbers of individuals having a measurement in common can also be learned. Nevertheless, it should be appreciated that anthropometric measurements are by their very nature superficial, and that arbitrary landmarks are involved. It is readily recognized that measurements made on one population are relevant only for similar population samples. It is less commonly understood, however, that the applicability is also strictly limited to the same conditions that applied when the measurements were taken. That is, the measurements are not functional. They may not be transferred indiscriminately to other body postures. For instance, arm span cannot be obtained by adding measurements of (1) acromion to finger tip and (2) bi-acromial width.

A functional system of measurements or a system of corrections for standard measurements is required to solve problems involving a variety of postural and kinematic positions. A main-line interest in the present investigation was the seeking of certain fundamentals concerning the geometry of the functioning body. To this end, the skeletal structures and joints have been studied in a functional context, and a concept of body links has been developed. In addition, the distinctive anatomical features of the body which are basic to the link idea have been explored.

Although such a system should have pertinence for a variety of body situations, the principal applications here have related to the seated subject—to the pilot in the cockpit of a plane. Various students of locomotion (Marey, 1895; Fischer, 1893, 1904, 1906; Elftman, 1939, 1943) and workers in the time-and-motion field (Barnes, 1949) utilized simplified presentations of skeletal segments, but apparently no one has systematically developed a concept of the kinematically significant units that are involved. Differences between a man-made machine and the peculiarities found in the body system have not been explored.

GENERAL FEATURES

A mechanical and kinematic treatment of the body demands an interpretation of the anatomy in the language of physics. Thus, rather than bones and muscles, one must think of masses, levers, and forces, of compression and tension systems. It is the purpose of the present chapter to present an interpretation which has developed from experiments in the present project.

Bones, like other structural materials, are actually not rigid bodies; under stress they are subject to the strains associated with bending, compression, torsion, shear, etc. (Dempster and Liddicoat, 1952; Evans, 1953). Nevertheless, within a framework of routine operation, they may be treated as rigid bodies. Forces may be transmitted along or across a bone or from one bony member to another across joints. This is true for static conditions as well as for situations involving movement. There are a number of equilibrium positions which the units may assume relative to one another. The active tension forces of muscles may be involved in static support, or the dead weight of parts may be supported passively by ligaments or by external contacts. Such positions may be maintained either by low forces across joints or by opposing muscles under considerable tension.

The bony members, moreover, are surrounded by non-rigid tissues, which move en masse with the bones. Body segments, such as the forearm, thigh, chest, and head, are thus composite units with both rigid and soft tissue components. Such segments are most readily recognized in the limbs, where the segments have a changing angular relation to one another. Skin flexure lines may suggest boundaries in some instances; in others, the establishment of precise boundaries is not easy, since muscles and other structures cross from one region to the next, so that only the most arbitrary boundary line can be drawn. One may still recognize, however, that the limb masses move on deep-lying level systems and hinges. Clarification can come only with the development of a rational system.

Limb bones present certain features of a mechanical nature, which lead to profitable ideas. Parallel bones, such as the radius and ulna, or bones like the femur or clavicle, with their spiraling patterns or curvatures, suggest that, although stresses are transmitted along the solid substance of the bony material, the effective force vectors from one segment to the next follow straight lines passing through joint contacts and joint centers. In the femur or radius, such straight lines connecting joint centers actually fall in part outside the limits of the bony material.

These spanning distances are the functional equivalent of the "links" that are utilized in the kinematics of the engineer.

To the engineer, links are usually regarded as a two-dimensional system, in which the articulating members overlap and are joined by pins, which act as axes of rotation. The link, to him, is a line of constant length, spanning contact centers or elements of adjacent bony members. A bone per se is not a link. Bone is a complex biological material which has many properties. A link is a functional dimension; bone rigidity merely preserves this dimension.

The link is regarded as rigid in the sense that linear compression and tension forces along it do not deform. It is essentially a geometrical entity for the analysis of motion by geometrical or kinematic methods. Forces, such as the transversely acting forces of levers, are ignored as irrelevant to purely kinematic treatments. In engineering mechanisms the links move in relation to a framework, and this framework itself forms a link in the system. Thus, to transmit power, the links of machinery must form a closed system in which the motion of one link has determinate relations to every other link in the system (Reuleaux, 1875). The closed system assures that forces are transmitted in positive predetermined ways, and in no other.

In contrast, body joints rarely overlap, and none has pin-centered axes. The adjacent articulating surfaces of a joint are held together by muscles and ligaments and by atmospheric pressure. In the major limb joints, the articular surfaces of the adjacent members are in contact, and they slide against one another as the bones rotate about a center in one or the other of the bones. The tibia, for instance, has a bending axis which passes through the substance of the adjacent femur proximally and another through the talus bone in the foot distally. The ulna rotates about the humeral condyle proximally and about a center in the wrist distally. In contrast, the femur, or humerus, moves relative to the pelvis and tibia, or scapula and forearm bones, about axes traversing the bone itself.

To apply the concept "link" to such a system of bones would definitely strain the term. The mechanisms are not pin-centered, and movement generally occurs in any of several directions, rather than in a predictable plane. The convenience of the concept of a mechanical axis within a body segment, however, warrants the use of the term "link" as a functional equivalent of the link as used in engineering. Some redefinition, therefore, is required for this special application.

BODY LINKS

The link, in relation to the body system, should be understood as the central straight line or core-line which extends longitudinally through a body segment and terminates at both ends in axes (hinge points), about which the adjacent members rotate. The long bones of the skeleton vary in diameter, curvature, and shape from point to point along their length. Their surface contours represent specializations for muscle attachments and for joint articulation. These specializations are as important to bones as their functions as supporting elements, or their metabolic functions, but for the present they may be ignored. We will be concerned, rather, with the simple fact that a bone as a rigid rod predetermines the span between joint centers at either end.

Figure 32 shows how skeletal elements may be reduced to produce a stick figure composed of links. The scapula, for instance, may be reduced to a link between the functional center of the acromioclavicular joint, near the lateral end of the clavicle, and the center of the humeral head; its anatomical specializations for muscle attachments, and so on, are irrelevant to the link relations of the limb. The forearm link passes from elbow to wrist obliquely through both the ulna and radius; and the femoral link extends directly from the hip center to the knee center, spanning the angle between the femoral neck and shaft.

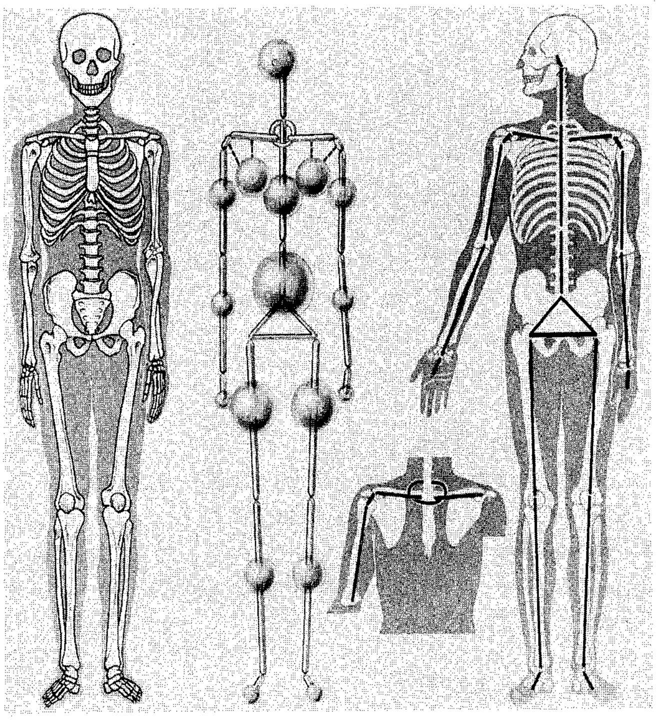


Figure 32. Plan of Body Links. The skeleton is shown at the left. At the right a pattern of body links is represented by heavy black lines. These contact at functional joint centers, represented by the spaces between the links. Note that in the end links of the head, hands, and feet the links end at centers of gravity of the members. The lower insert shows a C-shaped link at the upper thoracic margin, spanning between the right and left sides of the first thoracic vertebrae. It also shows the relations of the clavicle and costosternal link. The second figure shows the loading of the links by segment masses located at appropriate centers of gravity. The relative volumes of these masses correspond with bodies having a density of 8.0—between steel and brass.

The complexity of the pelvis, in spite of its birth canal and its relations to viscera and muscles, may be reduced to a simple plane or fixed triangular linkage, with three connections to adjacent links of the spine and right and left limbs. The right and left upper ribs and the manubrium of the sternum, encircling the upper thorax, may be interpreted as a bucket-handle type of linkage. This would move both in respiratory movements and in upper limb activities. The link-stick figure, if correctly worked out, represents all possible movements of the body members, and allows a correct visualization of the kinematics of the body.

It should be clear that the bones form the more or less rigid support required by the links, but that the bony structure is in itself not the link. The bone may flare out from or bend away from the core-line between adjacent joint centers. These eccentric specializations, resulting from growth processes and formed in harmony with both the genetic constitution of the species and the strains associated with mechanical functioning, have functions irrelevant to, but compatible with, the link mechanism. For instance, the eccentric femoral trochanter, the blade of the scapula, and the projecting heel bone provide extensive areas of muscle or tendon attachment and the necessary leverage for muscle action in the control of link movement.

Just as bones are recognized as calcium and phosphate deposits, as protective mechanisms because of their rigidity, as marrow deposits for blood cell formation, and as surfaces for muscle attachment, it should be recognized that the kinematic function is another facet of the bony structure. The shape and configuration of a bone, its surfaces, curvatures, and thickness are secondary and basically irrelevant. A rigid link dimension spanning rotational centers of adjacent links is the essential feature of the bone for kinematic considerations. It is a simplification or reduction, which may be worked with in analyses of posture and movement.

The link system can be diagrammed on paper as a two-dimensional figure, or it may be considered as a stick figure in the three dimensions of space. In the latter instance, motions of parts are still most easily analyzed as motions in a plane. Links are linear, and their movements sweep over surfaces; if the latter are not in a plane of reference, they may be projected to rectangular coordinates. Rotations about the longitudinal axis of the link itself may be referred to a perpendicular plane.

Such rotations about long axes of links are permitted in the limb systems at the ball-and-socket joints of the hip and shoulder, at the shoulder joints, at the knee, and in the forearm joints. These movements may be very important functionally, but the effects of movement are less gross than motions along other coordinates. That is to say, they involve smaller moments of inertia. For this reason, they may be treated as a special category which, however, does not receive full treatment here. An example of this abridgment appears in the simplification of the forearm to a single link between elbow and wrist; movements of pronation and supination have been largely ignored.

The links are interconnected by joints, and the only movement possible between adjacent links is the particular rotational movement permitted by the joint mechanism. For each joint the type, range, and limits of movement depend on the anatomical structure of the articulation. The movement of one link relative to the next at a specific joint is pure rotation. For example, when one link is immobilized and the next in series is moved, that movement is an angular motion; every point on the moving member describes a circular arc about the joint center.

Translatory movements of parts, although not possible between adjacent links, may be effected by reciprocal rotations of three or more links at two or more intervening joints. For instance, if the end member of a chain of three links interconnected by mobile joints is attached to a stable body of reference, appropriate, relative, and rotatory motions of the mobile links will allow a point on the terminal link to describe a straight-line translatory motion in relation to the stable part; all other points on the terminal link, however, will show angular motion. When an additional link is added, all points in the new link may be made to execute a translatory movement. Thus, the hand or foot may move in translation relative to the trunk by composite, rotatory motions at the different limb links because there are enough links in the limbs. Both translatory and rotatory movements of an end member are possible within such a system. Only rotation, however, is permitted at the intervening joints.

Reuleaux pointed out, in 1875, that in the machinery of engineering and industry the links operate in a supporting framework, which itself is a link, and that the delivery of a specialized type and magnitude of force necessitates a closed chain having determinate motions at each link. Fischer (1907) showed that the body skeleton, in contrast to machinery, consists of open-chain systems. Simple closed-chain systems are, of course, to be found in the body, as in the forearm, where the radius, ulna, and humerus join in linkages at the distal radio-ulnar joint, the proximal radio-ulnar joint, and the humero-radio-ulnar joint. Movements of forearm pronation and supination relative to the humerus are strictly determinate, that is, predictable on the basis of the character of the articulation and the link dimensions. Other determinate closed-chain systems are in the intercarpal and intertarsal joint systems of the wrist and foot, respectively. The sternum, ribs, and thoracic vertebrae have certain resemblances to the closed-chain system, too.

The body mechanism, however, is basically an open-chain system. For instance, the units of the upper limb skeleton provide a chain of links attached to the trunk by shoulder linkages, but free at the hand. It is an open-chain system of five links and five joints (counting the trunk-limb joint); because of this system, the hand may execute a wide range of non-determinate movements. Thus, when the parts of a limb are initially in a given posture, it is impossible to predict link positions in a subsequent posture.

Because of the indeterminate motion of the body link system, many resultant body postures are possible. The motions, however, are limited by the range of movement permitted by the various joints, by the character of joint action, and by intrinsic mechanical factors imposed by the bulkiness of body parts or limitations of muscular control. The body operates not in vacuum, but in a framework of mechanical realities. The parts have mass and inertia, and the earth's surface or other substrate must necessarily provide counter forces.

LINKS AND SEGMENT MASS

Segment mass is distributed about the body links. It may be regarded as concentrated at the center of gravity of each part. Such loadings may be on the links, or they may be eccentrically located according to the part represented. In Figure 32 the masses associated with body links of varying size were shown as spheres. If the figure were to represent a life-sized individual, spheres of steel or brass (density ± 8.0) of the relative size shown would represent the weights of the anatomical parts that load the various links.

INTERPRETATIONS OF LINKS

It is convenient to define links according to context. Thus, instead of 25 separate vertebral links above the sacrum, it is often desirable to ignore minor link movements and to group a chain of links into units, such as the cervical link, the lumbar link, and so on. This grouping of links has consciously been done in the construction of test dummies, such as the Air Force anthropomorphic dummy (unpublished), "Mark II and III" (Alderson, 1954), and "Elmer" (Swearingen, 1951). In Figure 32 both the chain of head and neck links and the lumbar and pelvic links were loaded as if they were single links. Furthermore, one may think of a hand links alone, or, if the purpose demands, he may think of further subdivisions, involving finger-segment links. It is also convenient to consider such end member or cantilever systems as the head and free hand or foot as links, even though the distal end of each is without a second hinge connection. Such free end-links may be defined as lines extending from the terminal hinge to the center of gravity of the end member.

As seen in Figure 32, the body link system for the general mechanical purposes of this study are simplified and treated as follows: the trunk links are grouped as (1) a head-end member from atlanto-occipital joint to head center of gravity, plus a cervical chain of seven links, (2) a thoracic link, consisting of the thoracic column and thorax, and (3) a lumbar chain of five minor links plus a pelvic link—the latter part is complex in that it ties into the last lumbar link and the right and left femoral links. Note that pelvic specializations for muscle attachment, for housing pelvic viscera, and for the birth canal, are irrelevant to the linkage structure, which alone calls for emphasis here. The thoracic mass with the ribs and sternum likewise were played down as secondary to the axial links through the trunk. For special analyses involving respiratory movements, these extra linkages would need to be considered.

The chain of lower limb links consists of (1) a femoral link, (2) a leg link, and (3) a foot (end member) link (from ankle to foot center of gravity). For certain purposes, the foot link may be separated into two links, one above and one below the subtalar joint.

The upper limb chain of links connects to the thoracic column by (1) an upper rib linkage (sternovertebral bridge of ribs); and the remaining links of the limb proper consist of (2) a clavicular link between the sternoclavicular joint medially and the resultant functional center of the acromioclavicular and coracoclavicular joints, (3) a scapular link between the latter joints and the center of the humeroscapular joint, (4) the humeral link, (5) the forearm link, and (6) the hand, or end member, link. The radio-ulnar linkage involved in pronation-supination movements was not included in our simplified system. The lower limb shows a simpler system of links: (1) femur, (2) leg link, and (3) foot link.

JOINTS IN RELATION TO LINKS

It is unnecessary here to speak of the standard anatomy of joints as treated in such texts as Gray (Goss, 1948), Cunningham (Brash, 1951), or Morris (Schaeffer, 1953), other than to call attention to features which are common to joints in general. It should be remembered, however, that each type of joint is a unique mechanical system. Right joints are structurally mirror images of those on the left. The extremities of the bones, which provide distinctive articular surfaces, are generally thickened for broad joint contacts. Each movable joint in the link system of a limb, to some degree, presents male and female surfaces.

Extensive analyses of theoretical joint contours in relation to the type of movement permitted are found in Fischer (1907) and in Fick (1911). Also available in the literature are mechanically-oriented treatments of joint anatomy by Strasser (1917), Braus (1921), Steindler (1935), von Lanz and Wachsmuth (1938), and Mollier (1938). Each extremity joint consists of compression components of bone and articular cartilage and tension components of ligament and muscle. A thickness of articular cartioverlies the faces of the bones, which form joint contacts. It forms a resilient and deformable surface.

The articular surfaces are moulded into distinctive shapes, which both permit and facilitate movement. A male and female contour may be recognized on contiguous bony members, but all joints do not have reciprocal or congruous contacts. The fibrous tissue about the articulation is also specialized. It has regions of tough, more or less parallel, ligamentous tissue that spans the bony members. These ligaments, according to the joint, are arranged in such a way that bony members are free to rotate through a whole range of movement. In the latter instance, the tension forces developed in taut ligaments are reciprocally related to compressive forces at regions of articular contact. Muscle forces on joints, although they may be reflexly protective, are entirely indeterminate in action. That is, they may produce movement, or they may stop movement at any point on a movement range, but they do not form fixed limits to a joint range. They must be considered as a superimposed force system rather than a part of the joint anatomy.

An exhaustive treatment by Reuleaux (1875) of rigid linkages showed that there are only three possible reciprocal contours which permit sliding motion while the surfaces remain in mutual contact. There are: (1) plane surfaces, (2) spherical, conical, or cylindrical surfaces of circular cross-section, and (3) the circular helix; examples are: the plane-sliding contact (viz., tongue and groove), the pin and eye (or shaft and bearing), and the nut and screw. If the nature of the contacting surfaces is to control and guide movement in specific ways, all other types of movement must be prevented. In man-made machines flanges and locking pins prevent axial shift of bearings and wheels relative to shafts and axles, but permit free rotation about the central axis. Other machine joints similarly must eliminate accessory movements, if forces are to be transmitted in a determinate fashion.

Among the major joints of the limbs the ankle and elbow joints provide the closest approximations to machine joints in the sense of eliminating accessory movements. In these joints the contiguous male (humerus:talus) and female (ulna:tibia) surfaces are nearly congruent. The closeness of fit and the collateral ligaments (hinges) virtually eliminate sidewise sliding and rotation while permitting flexion-extension rotation along a predetermined path. Only negligible deviations from a path of motion are allowed by these joints; differences from purely rigid systems, which reduce the positive action of organic joints, are the renitent properties of the cartilage, tensile strains on the ligaments at points of binding, and looseness of ligaments at intermediate regions. Bending (flexion-extension) movements alone are permitted by the guided joints of the ankle and elbow, and the rotations occur about more or less transverse axes.

Although the rotations of the foot and forearm do not fall in a single plane for the whole range of movement, the movements are so guided and controlled that instantaneous or short-span angular movements may be considered as uni-planar. Thus, within the range of motion allowed, the joint permits freedom of motion in one sense, and it restricts motion in two senses. Before ligaments bind or bony stops operate to restrict movement, each joint exhibits a characteristic range of motion. Certain joints as the ankle or elbow restrict motion to a fixed angular path; others permit freedom of motion in other axes as well.

DEGREES OF FREEDOM AT JOINTS

Fischer (1907) dealt adequately with general principles concerning the degrees of freedom permitted by various extremity joints. In the elbow and ankle joints the flexion-extension movement of adjacent links was restrained to fixed angular paths, which, although roughly in a single plane, were characterized by contingent movements in other planes (Figure 5). Free movements in other planes, however, were not permitted. Thus, there were two degrees of restraint and one degree of freedom at these joints.

Ball-and-socket joints at the hip and shoulder permitted three degrees of freedom, and there was no restraint except at the terminal range of movement. The movements permitted were: abduction-adduction (outward-inward), flexion-extension (forward-backward), and medial (inward) and lateral (outward) rotation of the thigh and upper arm. Various possibilities of combination movements were possible, viz., flexion-adduction-medial rotation, abduction-extension-medial rotation, etc., but there were no invariant contingent movements. Both the wrist and knee were found to have one degree of restraint (for longitudinal rotation at the wrist and for abduction-adduction at the knee) and two degrees of freedom of movement (wrist: flexion-extension, abduction-adduction; knee: flexion-extension, medial and lateral rotation). The restraints at the wrist and knee were not absolute; slight amounts of wrist rotation about the longitudinal axis occur; knee abduction in certain positions of flexion has been described (Schwarz, 1950).

The sternoclavicular joint permitted three degrees of freedom (protraction-retraction, i.e., forward-backward; elevation-depression, i.e., up-down; and upward and downward rotation, i.e., of the front edge of the clavicle); and the combined acromioclavicular and coracoclavicular joints likewise permitted three degrees of movement. In each of the limb joints the degrees of freedom or of restraint were dependent on both articular contours and the restraining effects of ligaments.

The foot as the end member of the chain of lower limb links had six degrees of freedom relative to the pelvis (three degrees at the hip, two degrees at the knee, and one degree at the ankle). The foot showed additional degrees of freedom beyond the ankle joint. In contrast, the hand as end member had 13 degrees of freedom relative to the thoracic attachment of the link chain. These were: three degrees of freedom at the sternoclavicular joint, three degrees at the composite system formed by the acromioclavicular and coracoclavicular joints, three degrees at the humeroscapular joint, one degree at the elbow, one degree at the radio-ulnar joints, and two degrees at the wrist. Additional degrees of freedom could be included, as additional trunk joints are considered relative to some more remote region of reference.

RESTRAINTS TO RANGE OF MOVEMENT

Although the joints had the degrees of freedom indicated, the extent of free movement in each sense was limited to a specific range by the binding of check ligaments or by the impingement of bony contacts as at the elbow joint. Fat padding, muscle bulk, or stretched skin could in certain instances form additional impediments to movement, before the above-mentioned restraints operated; bulky or binding clothing are more obviously restrictive. The range of movement for several types of cadaver joints was shown by Fick (1911), Strasser (1917), Mollier (1938), Braus (1921), and Pfuhl (1934). (These and new data have been summarized in the following chapter, using the Albert-Strasser globographic method showing joint range.)

The Albert-Strasser method required that one member of a joint system be rigidly fixed and that the other member be rotated to its limits in all directions. The joint center was regarded as the center of a sphere, which had a radius of curvature equal to the length of the moving members. As the moving member was rotated about, a point on its distal end described a curved outline, which bounded a segment of the sphere. This outline represented the extreme range in every direction. Rotations about the axis of the moving member could be measured and indicated at various stations within the range contour of the sphere.

The globographic method (Figures 37, 39, 42-49) showed two features significant to joint kinematics: (1) it showed the angular location of joint restraints (and provided a method for evaluating ligamentous and other binding influences functionally), and (2) it showed the relative freedom for movement in two, or even in three, planes. The detailed anatomical reasons for one restraint boundary or another (i.e., which specific ligaments restricted movement) are not pertinent here; the position of boundaries and their quantitative locations, however, are essential. Further comment on joint range is reserved for Chapter IV.

RESUMEʹ

In summarizing the background for the foregoing paragraphs, one finds that the bones form a rigid structural organization for the body links and that these in turn become the units necessary for analyses of motion and position. The links rotate about joint centers, and they exhibit a variety of angular positions relative to one another. Anatomical specializations at each joint predetermine the degrees of restraint and the degrees of freedom permitted by a joint. The limits of the angular range of joints are not rigidly determined, because cartilage and ligaments are deformable; within limits a greater force applied will ordinarily widen the range by a few degrees. On the average, however, the range of motion at a joint for any individual is limited to specific angulations. Joints are provided with terminal stops which, as indicated in globographic records, delimit a spherical triangle comparable to the range of free movement.

Movements at a joint must be either to-and-fro, reciprocating rotations or rotations where the end of the free member describes a circular path. Joints of two or three degrees of freedom may permit movements, called circumductions, in which the free member describes a circuit of any size within the boundaries of the spherical triangle. It should be noted, however, that such movements are complex in that they involve some axial rotations of the free member, and a second circuit cannot, without the action of counter forces, duplicate a first circuit (MacConaill, 1946 a, b, and c; 1948).

The limits of joint range have perhaps been discussed above in too rigidly a mechanical way. Joints are not inert, but are biological mechanisms where synovia, blood vessels, and nerves cannot be ignored. Partridge (1924), many years ago, suggested that the body used muscles reflexly to protect joints against injury; more recent work (Gardner, 1950 a and b) has explored reflex mechanisms at joints—the relationships are complex. Joints tend to be protected either by counter muscle forces or by widespread withdrawal movements.

The joint-and-link system of the body, except for certain localized mechanisms, does not form a closed-chain system as in machinery. Instead, it is an open-chain system, where link positions are basically indeterminate. The degrees of freedom of motion at various joints range from one to three, and the resultant degree of freedom of an end member relative to a more proximal part in a chain of limbs may be large.

UTILITY OF BODY LINKS

The very indeterminate nature of the open-chain link system provides certain advantages for the body. An end member may be placed at a variety of point positions in space relative to the trunk; the reciprocal relation is also possible. The open-chain link system permits free movements such as reaching, kicking, throwing, and the use of hand tools. The open-chain mechanism, moreover, permits the development of temporary closed chains for the accomplishment of various body purposes.

The fingers of the two hands, for instance, may be interlocked and a closed chain is formed of the limb segments plus the intervening region of the trunk. Folding of the arms across the chest forms a similar chain of fewer links. Such temporary closed-chain linkages may also involve parts entirely extrinsic to the body, as in the two-handed use of a bicycle pump, pruning shears, or in the two-handed grasping of a steering gear. When a seated subject pushes a foot pedal, a closed-chain linkage may be recognized, involving the foot and the limb segments, the pelvis, the buttock tissues, and the seat, floor, and pedal. Similarly, the hand lever of a machine, the links in the machine, its frame, and the body links from foot to hand form a complex, closed chain.

These temporary, closed chains must involve at least one additional link due to soft tissues, which are far from rigid. For instance, the palm and finger skin and subcutaneous tissues or the buttock tissues at a seating surface may provide a soft tissue linkage. Typically, the contacts between one part of the body surface and another, or between a body end member and an extrinsic linkage, are friction contacts. For example, when the hand grips an extrinsic object, the contact is secured by friction forces. These static-frictional contacts at the skin surface may be increased by stronger muscular force, i.e., a tighter grip, acting normally to the skin surface. In addition, there are various methods of increasing the coefficient of skin friction, such as resin on the hands or the use of cloth, rubber hand pads, or gloves. In contrast, wet or soapy hands provide a low coefficient of friction. Whether the contact at a body surface is relatively firm or not, it will be recognized that soft tissue cannot form rigid links. Action across such links is basically indeterminate.

For power transmission the link systems of machinery must have determinate actions.

In contrast, the chain of body links, whether open or temporarily closed, is indeterminate. This is inherent in the nature of the joints between the linkages. Although the ankle and elbow are determinate joints, the remaining joints have either two or three degrees of freedom and are thus indeterminate; hence the whole chain becomes indeterminate. Muscle action may momentarily anchor a joint so that in effect two adjacent links are made one. A joint may also be immobilized, if it is maintained at the end of its normal range against ligament or other resistances.

In general, however, temporary closed chains involving body segments require momentary stabilization by muscular action, so that power may be transmitted at all. Muscle stabilization permits the transmission of power in a number of selected ways rather than in a strictly determinate manner. Thus the body link mechanism under neuromuscular control presents a mechanism capable to a degree of selective and discriminatory action in the transmission of forces. In dynamic situations as well, the muscles stabilize joints in certain axes and permit free motion in others so that discriminative patterns of movement appear. The skilled baseball pitcher or billiard player attest to the potential accuracy of control of momentarily active, stabilizing mechanisms on linkage chains for the expression of dynamic actions.

If all but one of the joints in a closed chain permit determinate actions, the exception also becomes determinate. Thus, if the upper arm is stabilized and the elbow flexes and extends to move a lever associated with a determinate system, the hand and wrist move in a predictable way. Many aspects of open and closed chains available to the body remain to be explored; there are, for instance, stabilizing systems based on linkage positions such as the cross-legged posture and arms akimbo, and there are a multitude of activity patterns. It is the function of these paragraphs, however, to define the characteristics of the link system rather than to explore kinematic actions in general.

LINKS AND ANTHROPOMETRY

From the foregoing it is apparent that links are functional rather than structural entities. Since they represent deep-lying relationships, measurements from surface landmarks give no direct idea of their dimensions. Conventional anthropometry has completely missed this functional concept. What has been said so far about body links has been primarily qualitative—the broad view. It is of interest to explore further, in a qualitative way, to see how far the idea may be pressed and to find what limits and qualifications are imposed. Quantitative methods for measuring the dimensions of links should have importance. It is of interest, also, to find correlations or correction values relating to the more superficial measurements of standard anthropometry. The following chapter will be directed to this purpose; principal attention will be focused on the joints—the connectives of the linkage systems.

CHAPTER IV

KINEMATIC ASPECTS OF EXTREMITY JOINTS

GENERAL INTRODUCTION

Though the links, just examined, are basic units for a consideration of the movement and positioning of parts, the type and range of link movements depend upon joint structure. The present section will direct the reader to certain geometrical features, which are consequences of the joint anatomy and which have pertinence to the practical objectives of this report. Information on the general anatomy of articular configurations and ligament relations, such as may be found in textbooks of human anatomy, may be presumed;(Goss, 1948; Brash, 1951; Schaeffer, 1953); attention, then, may be directed to features of more specialized interest.

It should be emphasized, however, that each type of joint is distinctive. Articular contours and traversing ligaments at joints strictly determine the type of joint movement. The range and the limits of movement or angular position which are exhibited at each joint depend on these features also and on reflex muscular actions of a protective nature. Though they may differ in the range of movement permitted, right and left side joints are essentially mirror-image structures. Joints, like other biological structures, show variability from individual to individual, but apart from pathological variants, the differences are more quantitative than qualitative in character.

AXES OF ROTATION

Movements in body joints are rotatory movements. The physics of rotation applies. Kinematic treatments of limb positions and movements must be based on a consideration of axes of rotation and the angular movements of links relative to these axes.

The German engineer Reuleaux, in 1875, outlined the method of locating instantaneous axes of rotation for movement in a plane (Chapter II, Item 14). In the Reuleaux method one member of a pair of bodies is regarded as fixed in space, while the other member moves (Figure 7). If there is a rotatory component in the movement, two points on the moving member will change their angular relation from moment to moment, and instantaneous centers of rotation may be found for each phase of the movement. In the single instance where the successive instantaneous centers fall on a point, there is a constant radius of curvature, and the movement is circular. This movement is commonly seen in pin-centered mechanisms.

When the path of rotatory movement is of any other type, however, the radius of curvature changes, the successive instantaneous axes are displaced, and a path of instantaneous centers is produced. The character of this path correlates with the angular pattern of the movement. Each instantaneous center in the path in succession is the zero point about which angular movement occurs. Lever dimension, the radius of gyration and torques, among other mechanical features, depend on this center of reference. The moving and fixed members treated in the analysis may be separate and unattached like a shell and the gun from which it was fired; they may be moving and fixed links in machinery or links in the body system.

When one member at a joint is held fixed and the other member is moved, the path of rotation may be analyzed in terms of instantaneous centers. Since the analysis relates to movement in a plane, it is necessary to orient joints so that movements in specific planes may be tested. In this study the limb joints of cadavers have received principal attention; the wrist joint of a living subject has also been analyzed for joint center location. Earlier work using the method has given information on knee centers (Zuppinger, 1904) and jaw centers (Chissin, 1906; Bennett 1908) of living subjects.

The following joints have been analyzed by the Reuleaux method: ankle, knee (flexion-extension plane), hip (abduction-adduction plane and flexion-extension plane), elbow, and the glenohumeral joint (abduction-adduction plane parallel to the scapular blade and flexion-extension plane at right angles to the scapular blade). For each of the joints mentioned three or four cadaver specimens were analyzed. Joints from one unpreserved body were studied, but the other material was embalmed. Since it was uncertain that the complex carpal movements of the cadaver joints would be comparable to movements during life, a special method was developed (Item 13, Chapter II) for the study of the living wrist for movements of abduction-adduction and flexion-extension. Two sternoclavicular and claviscapular joints from one body were also analyzed for movements in each of three planes. In the other joints with three degrees of freedom only two classes of movement, the major displacements, were studied; accordingly, we have no data on axes for longitudinal rotation along the leg, thigh, and arm.

Since the findings at each joint present certain common characteristics, a detailed joint-by-joint description correlated with anatomical features is unnecessary here. Attention instead may be directed to one type of joint, the ankle, for an understanding of the problems. Then, brief comments on the characteristics of other joints may be made.

Figure 33 shows the lateral aspect of the ankle joint with the fibula (f) and tibia (t) in the standing position relative to the talus (a); leg positions representing dorsiflexion (toward the left) and plantar flexion (right) are also shown (DF and PF). Instantaneous centers of rotation for successive 10° positions of the leg bones are shown as a cluster of interconnected black dots. A sequence from the triangle to the square shown by the zig-zag pattern of interconnecting lines represents successive positions of instantaneous axes for successive 10° positions of the joint from dorsiflexion through plantar flexion. The reverse movement follows the opposite sequence of points. It will be noted that in the sketch to the left the points lie in the upper anterior third of the talus contour and that axes for the extreme leg position, where ligament binding appears are most displaced.

The figure on the right shows a similar cluster of instantaneous centers; in this instance the foot and talus were treated as moving parts, while the leg bones were regarded as fixed. The sequence of points corresponds with successive 10° rotations of

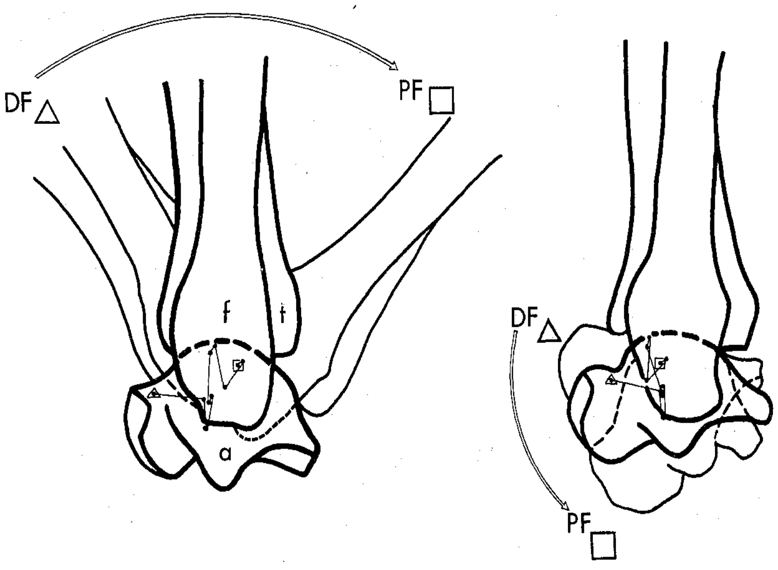


Figure 33. Instantaneous Joint Centers of the Ankle Joint. To the left, the talus bone (a) is stationary, and the tibia (t) and fibula (f) are shown in a midrange (standing) position; dorsiflexed (DF) and plantar-flexed (PF) positions are also shown. The sequence of dots from triangle to square shows a pattern of erratic shifting of joint centers for successive angulations of the joint. At the right, the path of instantaneous centers corresponds with the condition of fixed leg bones and rotating talus.

the talus. The cluster of centers now lay in the anterior part of the fibular malleolus, except for the extreme dorsiflexion center (triangle), which was displaced more forward. It may be seen that the relative position of points in each cluster is different. The second group for the fixed leg and rotating talus was derived mathematically from the first. The difference is simply that a sequence of 10° rotations of the first cluster about successive points of the cluster located a sequence of points for a second cluster.

A 10° rotation about the first point of the original cluster moved the second point to a new locus; a subsequent rotation now about the second point determined a new locus for the third point. Proceeding in this way, we constructed a second cluster of points that is mathematically related to the first. With the two clusters at hand it is possible to reconstruct the complete pattern of joint movement in the plane of relevance.

If one were to draw the path of interconnected points for each cluster on separate pieces of paper, he could superimpose equivalent points, say the triangles, on each path. If a pin were placed through the first points of each cluster, the rotation of the upper curve upon the lower then would allow the second points in each cluster to be superimposed. The pin then could be moved to the locus of the second points and another rotation would bring the third points together. Similar 10° rotations of the upper curve at successive points in sequence causes the superimposed paper to execute all the rotations of one member of the joint relative to the other.

Movement at the ankle involves a rotation in which centers shift and shuttle about as the bones move. Although the centers shift erratically, the articular surfaces of the leg bones and talus are in continuous gliding contact, and the relative movement proceeds smoothly.

The paths of instantaneous centers in different ankle joints were not identical. Point positions formed different patterns; the pattern in each joint, however, was distinctive in that the position and sequence of centers were not duplicated from specimen to specimen. Even so, the clusters of joint centers had a generally similar location, with the centers for extreme movement usually displaced from the remainder of the group. Analyses of repetitive records derived from the same joint, in contrast, produced axis paths which were highly similar; axis paths, moreover, were similar for movement in either direction. Barnett and Napier (1952), after a study of talus shape and the curvatures of the medial and lateral profiles of the bone, concluded that the axis of ankle rotation is a changing one, subject to wide variations from subject to subject in accordance with "wedging" of the trochlear articulation.

It should be remembered that instantaneous axes are points in a plane for movement in that plane. In these experiments, as indicated in Chapter II, Item 12, both the leg bones and the talus were free to rotate about their longitudinal axes as the leg was dorsi- or plantar-flexed. The amount of contingent rotation was measured by protractor (Figure 5). As the ankle dorsiflexed, the foot pronated and abducted at this joint; conversely, in plantar flexion it supinated and adducted. These were concomitant and invariant movements. The movements at the talotibial (true ankle) joint had the same sense as the more pronounced subtalar and intertarsal movements of the foot as a whole in dorsiflexion and plantar flexion (Morton, 1935; Manter 1941). The movements of dorsiflexion, pronation, and abduction cannot be separated; they are coexistent in the sense that each degree of flexion is invariably correlated with the other components.

Figure 5 shows the interrelations of motion components for a typical ankle joint. From instant to instant during movement there is only one degree of freedom of movement; the movement permitted, however, has components in each of the three planes of space. At each instant there is only one path in which forward or backward motion may continue, even though the direction may be different from that of an earlier or later phase. There is but one degree of freedom even though the movement of flexion-extension is not strictly in a plane. Joint center loci like those of Figure 33 represent a planar projection of positions of successive parallel axes. The bones were free to adjust their concomitant movements about axes perpendicular to that for movement in the plane so that contingent movements did not intrude. If an entirely different method (Braune and Fischer, 1887, 1891), involving fixation of one of the joint members and measuring movements of the other in X, Y, and Z coordinates, had been employed, the axes would not have been parallel.

RELATION OF LEG AND FOOT LINKS

If the reader refers back to the figures of the two superimposable paths of instantaneous centers, he will remember that one path related to the talus as the more fixed unit and the other to the leg bones as the more fixed members. As one path rolled upon the other, only one point at a time on each path served as an instantaneous center of rotation. This point represented the momentary junction of adjacent links. As axis positions shuttled about in sequence, one link was momentarily longer and the other shorter, or the dimensions were reversed.

The implication from joint-center data was that link dimensions in the leg and foot elongated and shortened in a reciprocal fashion as the parts rotated. This difference in length amounted to a half-inch or more. For the practical treatment of joints, such as the ankle, one may visualize a mean joint-center position based on a study of various specimens, and he may designate a surrounding area as a zone of probability of position of actual joint centers. Mean link dimensions may be similarly determined.

The use of fixed average or nominal link dimension appears to be the only way of avoiding variable link lengths which would be impractical to use in kinematic analyses. When fixed mean link dimensions are used in analyses of body mechanics, calculations of leverages, torques, etc., must have a limiting accuracy value, which cannot be exceeded. Thus, for a given nominal link dimension, each end of the link has a region of probability of joint-center position. The radius of the area over which the joint centers range, perhaps expressed as percentage of nominal link dimensions, gives a plus or minus range of accuracy in computing torques, etc. Likewise, in the frame-by-frame analysis of motion picture records of movement (as in physiological work or motion and time study) there is an intrinsic limit of accuracy imposed by the body system itself, entirely independent of measurement techniques.

WHY DO AXES SHIFT ABOUT?

It is of interest to inquire why the axes shift position erratically during movement. Figure 34 shows an evolute analysis of the curvatures of sagittal sections at the same plane through the tibia (A) and talus (B). These sections were cut at the mid-trochlear region along planes corresponding with the left hand section line (a) shown in sketches E and F. Each curvature was represented by two evolutes (Cf. Item 5, Chapter II), but the distances from the articular surfaces, and the curvatures and slopes of the evolutes for the tibia and for the talus were entirely different. Accordingly, the articular curvatures were nowhere the same, and articular congruence was not possible along the plane of section for any joint position. Only contacts of limited area were possible between such curvatures.

The same incongruence is shown for more lateral sections C and D, which correspond with the positions of section lines toward the right of the bones shown at E and F, line "b". The tibia had one evolute, and the talus had two; again the curvatures were distinctly different. When sections which are in corresponding planes have different curvatures, it is obvious that complete congruence of the articulation is impossible for any joint angulation. A further analysis is helpful.

Sketches E and F show the articular faces of the tibia and fibula and of the talus, respectively. When moist casein paint was coated on the concave (or convex) member, and the articulation was pressed together while the bones were held at a given angulation, a paint imprint was transferred to the reciprocal surface. In sketches E and F the stippled area on each articular face shows the imprint which appeared repeatedly on the joint surfaces, when the articular faces were approximated for an ankle inclination corresponding to that for the standing position.

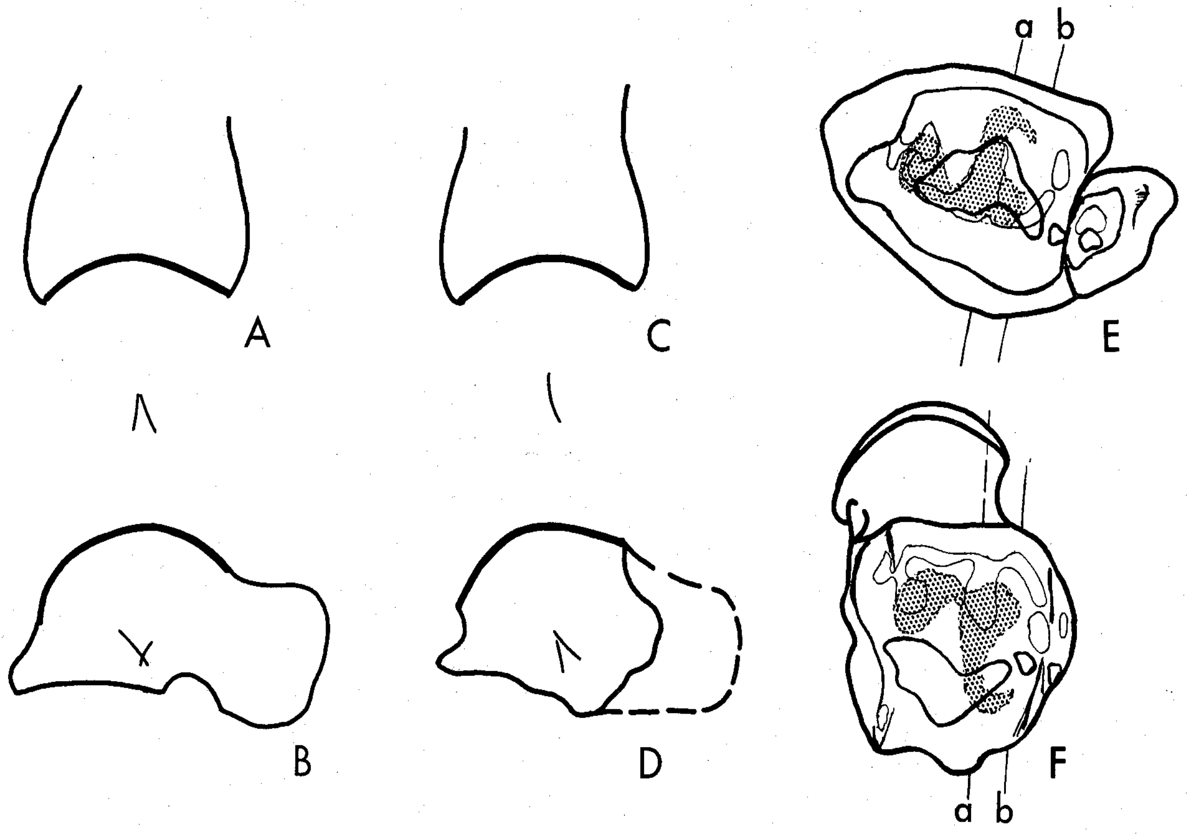


Figure 34. Contours and Contact Areas at the Ankle Joint. The three upper sketches show the tibia, and the three lower show the talus bone. A to D show sagittal sections through the bones and evolutes, which correspond with the articular curvatures. Lines "a" and "b" of sketches E and F show the plane of sections for A-B and C-D. In addition, E and F show average patterns of paint imprints transferred from one articular surface to the other for different joint angulations.

The heavily outlined areas represent the regions of contact occurring when the bones were approximated in the plantar flexion position, after paint had been applied to one articulation. Similarly, the fine-lined outlines represent contact positions for dorsiflexion. According to the angle between the foot and leg bones (i.e., ankle angulation), there were one or several areas of contact on the opposed articular faces. As the ankle moved from dorsiflexion to plantar flexion, one group of contacting areas gave way to another, then to another, and through that to still another, for the whole sequence of angular positions. Contacting areas, however, formed only a small proportion of the opposed articular faces. Most of the opposed faces, between contact points, were bathed in synovial fluid. Instantaneous contact areas during rotation are surfaces for sliding contact. As one contact gives way to the next during movement, each new contact will ordinarily be freshly lubricated. The advantages to the body in having such an automatic system for lubrication are obvious. Well-lubricated surfaces should reduce joint attrition.

Two factors doubtless contributed to the erratic shuttling of instantaneous axes of rotation. First, the incongruence of articular surfaces appeared to provide a certain irregularity in the height of contacting points for the sliding movement of articular surfaces during rotation of the bone. Thus, as the contacts shifted from one bearing pattern to another, the distance from contact to rotational axis shifted materially. Secondly, successive contacts varied in area; stress, thus, should vary from region to region for a given joint pressure. Friction effects at the contact areas should accordingly vary from one contact region to another; different amounts of friction and variable patterns of pressure for different angular positions of a joint would account for erratic patterns of stops and sliding. This in turn would produce an erratic shifting of joint-center position during movement. At a moment of free gliding the center should be farther from the articular contact than at moments of relative sticking at contact points. The movement of the bones, however, would appear smooth, because joint bearings would be continuous.

RELATIONS AT OTHER JOINTS

Since certain features outlined above for the ankle can be found at other limb joints, an exhaustive joint-by-joint treatment of our results is unwarranted here. Like the ankle, the elbow joint permitted one degree of freedom of movement—flexion and extension. Sagittal plane contours through the trochlea and through the capitulum of the humerus, as well as through the equivalent planes in the ulna and radius, showed different patterns of evolutes for each curvature (Figure 35). Evolutes representing contours through the humeral trochlea were small and centrally located. The humeral part of the elbow joint was the closest approximation found among all joints studied to a circular contour. The ulnar part typically showed three regions of relatively flat curvature.

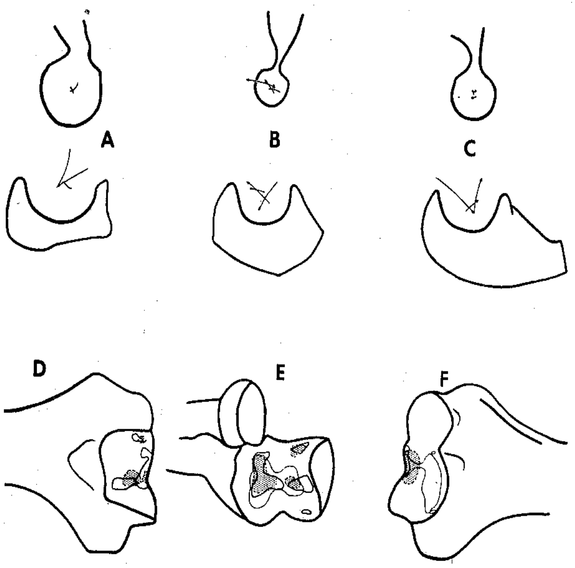


Figure 35. Contours and Contact Areas at the Elbow. Upper figures show sections through equivalent regions of the humeral trochlea and sigmoid fossa of the ulna. A, B, and C cut the medial, intermediate, and lateral regions of the trochlea, respectively. Evolutes representing the joint contours are shown. D and F show posterior and anterior views, respectively, of the humeral articulation. E shows the reciprocal ulnar articulation. Contact areas at a mid-flexion position are stippled. Contacts during extension are heavily outlined; fine outlines represent contacts at the extreme flexion position.

As in the ankle, the contours were different in adjacent sections, and evolutes representing the curvatures of the male (humeral) and female (ulnar) elements were totally different. Contact points shown by the paint imprint method again showed that only a small part of the articular faces made contact at one time. The contact areas also were different for each position of the bones. Instantaneous centers of rotation derived by the Reuleaux method formed a familiar, erratic cluster of points in the condylar (trochlear) regions of the humerus (not illustrated here). The cluster spread over an area of about one-half-inch diameter. As for the ankle, points corresponding with extreme joint positions were often eccentric in position.

The hip and shoulder (glenohumeral) joints permitted three degrees of freedom, but in each joint, and for both the flexion-extension movement and abduction-adduction movement, the instantaneous axes again formed an erratic cluster of points in the central regions of the heads of the bones. Contact points shown by the paint impression method were different for different joint angulations. Contact areas occupied a small percentage of the joint surface. Recent data by Knese (1950 a and b) showed similar data by another method. The curvature of the convex member was represented by a criss-cross pattern of several evolutes. The male member, according to the evolute analysis, had an entirely different curvature from that of the female member.

The kinematics of the knee joint are uniquely different from the other joints studied (Meyer, 1853; Braune and Fischer, 1891; Zuppinger, 1904; Fischer, 1907; Haines, 1941; Knese, 1950 c) in that forces applied to the joint by muscles and by the cruciate ligaments are different for each angulation of the flexion-extension movement. The patella, under tension produced by the quadriceps muscle, presses the condyles backward on the tibia; the popliteus muscle exerts a force tending to twist the joint members. The changing force pattern during different joint angulation should affect the equilibrium positions of the joint members. A posterior displacement of the femur on the tibial condyle occurs early during the flexion movement (Knese, 1950; Barnett, 1953).

Sections through femoral condyles have been analyzed (Langer, 1858; Bugnion, 1892) by the evolute method; evolutes for each condyle correspond with a spiral sagittal articular contour. In addition, for certain specimens the most posterior part of the condyles (involved in flexion beyond 90°) sometimes had another curvature (Dempster, 1953). Other unique features of the joint were the menisci and the locking movement of the knee in the last 15°, or more, of extension (Barnett, 1953).

Zuppinger indicated that instantaneous joint centers in a living subject were initially in the mid-condylar region for the more extreme flexion positions and that the axes moved toward the anterior tibial region with extension. Present work on cadaver knee joints, although limited somewhat in scope, showed a cluster of points suggesting zig-zag changes in axis position. The clusters were chiefly in the posterior condylar region for the flexed angulations of the joint (cf. Zuppinger), but there were erratic shifts forward and backward for more extended positions of the joint.

As indicated in Chapter II, Item 12, tensions produced by elastic bands were substituted on the specimens for whatever muscle tensions were operative during life. There was less assurance for the knee than for other joints that the conditions of joint testing were strictly comparable to those during life. Additional work like that of Zuppinger, possibly using refined x-ray techniques comparable to that of Chapter II, Item 13, is desirable. Nothing seen in the records, however, was qualitatively different from data from other joints. There were the same erratic shifts in position of instantaneous axes, and the size of the cluster of centers relative to the size of the joint was similar.

The analysis of wrist flexion and extension and of abduction and adduction on the living subject, using angiocardiographic equipment and the Reuleaux analysis, showed a cluster of points of instantaneous axes of rotation, chiefly in the region of the head of the capitate bone and adjacent region of the lunate. An analysis of a cinefluoroscopic film of wrist movement by the same method showed a similar cluster of centers about the same region, but points were less concentrated. (The film had been loaned by Dr. Arthur Carpenter of Fort Knox.) For more extreme joint positions instantaneous axes according to both analyses tended to be eccentric in position relative to the remainder of the cluster.

THE SHOULDER MECHANISM

The sternoclavicular and claviscapular joints (i.e., acromioclavicular plus coracoclavicular joints) warrant a brief comment on their anatomical peculiarities before the results are stated. The two joints are structurally quite unlike the arthrodial joints just treated. Between the ends of the articulating bones (i.e., between sternum and clavicle and between clavicle and acromion process of the scapula) are articular discs; the acromioclavicular disc, however, may be absent. Gliding movements of the bony members are ordinarily different on each side of the disc. Both joints are conventionally treated as diarthrodial joints; the standard descriptions treat adequately of the disc, capsule, accessory ligaments, etc., (Goss, 1948; Schaeffer, 1953; Brash, 1951; Fick, 1911; Strasser, 1917; von Lanz and Wachsmuth, 1938).

In the present functional approach, however, it is especially important to note that each joint has ligaments at some distance from the contact region and that these affect movement. The bones thus, in addition to having a contact within joint capsules, are bound together at a distance by a syndesmosis. In reality these joints are "desmo-arthroses" (see glossary).

At the sternoclavicular joint the sternoclavicular and interclavicular ligaments are close against the joint capsule, but the costoclavicular, or rhomboid, ligament is placed so that its lateral fibers are an inch or so from the joint contact. When the clavicle is elevated, the ligament binds, and the sternal end of the clavicle moves downward; in depression, however, the ligament offers no restraint. In the same way, the ligament influences the direction and extent of joint sliding in protrusion and retraction and in upward and downward rotation of the clavicle.

Similarly, the coracoclavicular (trapezoid and conoid) ligaments lie medial to the acromioclavicular articulation. These ligaments act as a syndesmosis between the coracoid process of the scapula and the clavicle. Part of the movement is acromioclavicular, and part is coracoclavicular; the whole system provides three degrees of freedom. The composite system of coracoclavicular and acromioclavicular joints, viewed functionally, will be called the claviscapular joint.

Too frequently the importance of this joint is neglected; it is usually considered merely as a device for allowing the blade of the scapula to accommodate its movements to the form of the thoracic wall. It is much more than that. A more important function is that it notably extends the range of the humerus. The claviscapular joint moves the glenoid fossa, the base of humeral movements, so that it faces in different directions. Humeral flexion, abduction, and rotation are greater than they would be otherwise because of this joint.

Desmo-arthrodial joints, such as the sternoclavicular and claviscapular, because of their composite nature and the binding effects of the ligaments at a distance, should be expected to show highly mobile joint centers. This should be even more true for the effective center of the composite system operative between the trunk and the humerus, where three joints (sternoclavicular, claviscapular, and glenohumeral), each with three degrees of freedom, are concerned. Figure 36 presents an analysis by the Reuleaux method for a cinefluorographic film strip*, showing humeral abduction relative to the trunk in a living subject. The figure shows a very large and erratic pathway for effective centers. Work mentioned earlier on the glenohumeral joint by the Reuleaux method shows a relatively circumscribed pattern for this component of the shoulder system. The cumulative effects of other joints upon the effective center should be large.

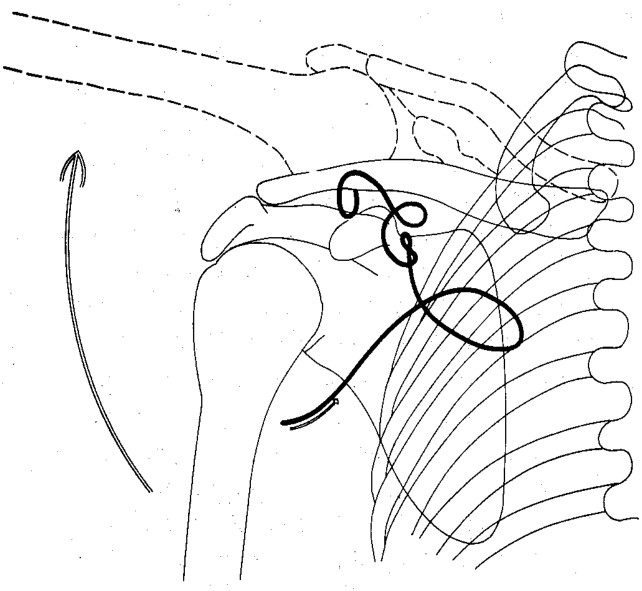


Figure 36. Path of instantaneous center of rotation during shoulder abduction (from Reuleaux analysis of a cinefluorographic film).

The sternoclavicular and the claviscapular joints on the two sides of one cadaver were analyzed by the Reuleaux method, and movements in the three cardinal planes were studied for each joint. Joint centers for both joints tended, in general, to lie in the span between the syndesmosis and the arthrosis. For certain movements joint-center position ranged over 3-5 cm, or more. Joint centers at the claviscapular joint actually covered a span as long as or longer, than the scapular link itself, i.e., the distance from a mean claviscapular joint center to the mid-region of the joint center cluster at the head of the humerus. Such a system at the sternoclavicular and at the

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*Loaned by Dr. Arthur Carpenter of the Fort Knox Radiographic Laboratory.

claviscapular joints can readily account for the movement of a common or effective rotational center such as that shown in Figure 36 for the composite shoulder mechanism.

CHARACTER OF JOINT MOVEMENTS

In the anatomical literature the types of movements permitted at joints are stereotyped in a qualitative and conventionalized terminology—flexion, extension, supination, abduction, etc. Such terms relate to directions of movement over axes that are visualized as vertical, transverse, or anteroposterior relative to a standard textbook "anatomical position" of the body. The terminology, although helpful, is self-limited. It ignores such local peculiarities of joint movement as concomitantly guided movements not in a plane; it is cumbersome in the way it handles movements in space and circuits (circumductions) at the marginal limits of a joint range.

An older generation of German and Swiss investigators, however, studied the range of excursion permitted at individual joints, but their work has not received the general recognition it deserves. According to the method developed, one member of a cadaver joint was rigidly fixed, and the other was moved to the limits of its excursion in every direction. Angular measurements were made with a protractor of different end-range positions. The free end of the moving member, when moved to its limits in all directions, described what Langer (1865) first called an "excursion cone." These limiting angular positions of the femur were measured by protractor and were plotted on a sphere provided with meridians and parallels. Albert (1876) first used an excursion sphere in his study of the hip joint to define the extent of femur movement. Strasser and Gassmann (1893) improved on the method and referred to it as a globographic presentation. Several joint systems have been subsequently studied, and graphic treatments are to be found in Fick, 1911; Shino, 1913; Braus, 1921; Pfuhl, 1934; Mollier, 1938; von Lanz and Wachsmuth, 1938, on the shoulder; Roschdeswenski and Fick, 1913, on the hip; Braune and Fischer, 1887 a, and Fick, 1911, on the the wrist; and Mollier, 1938, on the knee. Steindler (1935) appears to be the only American author who has publicized parts of the European literature. Careful data on the elbow, knee, shoulder, and on various other joints were gathered by Braune and Fischer (1885, 1887 a, b, 1888, and 1891) and by O. Fischer (1907), but these often involved another method involving X, Y, and Z coordinates.

This work, except for Pfuhl, who used 10 glenohumeral joints, including arthritic joints as well as normal, was ordinarily done on only one or two joints. Accordingly, the data did not present a notion of the range of variability which might be expected. The method, however, did show the qualitative character of joint movements.

GLOBOGRAPHIC DATA ON CADAVER JOINTS

Work on actual specimens was done on every major limb joint for this report. Where the published records provide a reasonably accurate account of joint range as seen by the author, these are presented, although usually recast in modified figures; where the older data or the manner of presentation are inadequate for present purposes, information from new specimens is supplied.

The Shoulder

The shoulder mechanism, as a composite of three joints—glenohumeral, claviscapular, and sternoclavicular—is functionally much more complex than the other major joint systems of the limbs. Accordingly, it is convenient to consider link movements at the joints both separately and collectively.

Shino (1913) and Pfuhl (1934) presented data on the angular range of the humerus relative to the scapula, i.e., glenohumeral joint. Additional data were derived by Braune and Fischer (1888), who presented measurements of humeral movement related to X, Y, and Z coordinates. However, these could not be grouped with the angular data of the other authors; their data on movement of the whole shoulder mechanism are presented later as Figure 41. In the work of Shino and Pfuhl the blade of the scapula of a bone-ligament preparation was clamped rigidly with the vertebral margin of scapula vertical; the plane of the scapular blade was taken as coinciding with the 0° meridian. Data by the two authors were presented graphically in different ways; Figure 37, however, shows a reconversion of their data to the same standard globographic grid. Shino's two curves relate to the right and left sides. Both are converted in Figure 37 as left side curves. Pfuhl's data were originally presented for 10 cadavers, including arthritic joints. Because of the elimination of arthritic individuals from the present globographic presentation, only seven of Pfuhl's curves are shown.

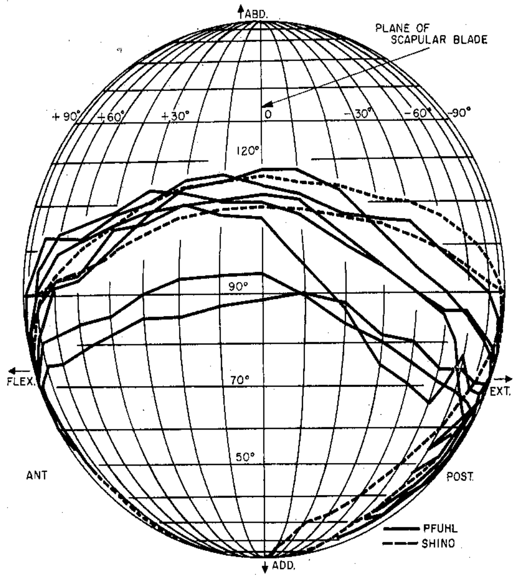


Figure 37. Globographic presentation of the range of movement of the humerus at the glenohumeral joint—cadaver material. Data from graphs by Shino (1913) and by Pfuhl (1934) grouped as for the left side.

The principal significance of the data on the nine shoulders shown is that some idea of the variability in range for a joint may be visualized. The curves, however, do show a general similarity in pattern. A maximum abduction in the plane of the scapula is shown to vary from 90 to 120°. Since the blade of the scapula for the ordinary standing position is tilted so that the glenoid fossa lies 30-45° forward to the coronal plane (i.e., 60-45° from the sagittal plane), the globographic curves presented should be visualized as a view of individuals seen obliquely from the side and front. Furthermore, since the scapula tilts some 10° (upper border forward) to fit the thoracic curvature, the 0° vertical of the reference sphere and curves should be tipped forward by this amount to represent the orientation in standing individuals.

In general, it should be noted that the humerus may be raised over 90° in the plane of the scapula and that roughly half, or more, of the lateral surface of the sphere below the equator is within humeral range. Curves in the forward sector between the 0 and 90 or 100° meridians, more nearly parallel one another than they do in the posterior sector (0° to -30° and beyond). The humerus reaches forward for a farther distance above the level of the 90° parallel than it does behind the plane of the scapula.

In Sketch C of Figure 38 a comparable range of humeral movement is shown from data on our ligament-skeleton preparation (Chapter II, Item 17). The skeleton was oriented so that a view perpendicular to the scapular blade (as for the Shino and Pfuhl data) would be shown; the specimen, however, shows the 10° forward tilt of the scapula to fit the thorax. The sketch shows how the humerus rotates about its excursion cone representing maximum range. (Fischer (1907) used the excellent term "joint sinus" in place of "excursion cone."

Sketch C also shows that the humerus rotates upon its longitudinal axis as it moves through its maximum range in the sinus; in the abducted and adducted positions of the humerus the anterior face of the humerus was directed forward. In the upper anterior quadrant it faced inward and upward; in the upper posterior quadrant it turned downward and forward; in the lower posterior quadrant it was directed laterally; and in the anterior lower quadrant it looked forward and inward. Joint center determinations (Chapter II, Item 13) show that the flexion-extension and abduction-adduction movements at the glenohumeral joint involve instantaneous joint centers, which are typically distributed over a diameter of 20 mm within the central part of the humeral head; some such range may be visualized for Sketch C.

Sketch A of Figure 38 shows that in a full range of humeral movement involving all three shoulder joints the front surface of the humerus was directed forward in the vertical downward position. It faced inward (and slightly up and back) in the forward horizontal position; it faced forward and inward at the vertical up position; and it looked outward at the posterior horizontal position. The humeral head moved on the clavicle and scapula and described a circular path with a diameter that is roughly two-fifth of the humeral length. This shift in position of the humeral head was due to sternoclavicular and claviscapular joint movements.

Sketch B shows the range of glenohumeral movement in dashed lines (cf. Sketch C) and the range of composite shoulder movement (Sketch A) in solid line. The positions of the humerus that are shown were restricted by the elimination of sternoclavicular joint functioning through anchoring the clavicle firmly to the trunk skeleton. Movements thus involved the glenohumeral and claviscapular joints only. The humeral head showed an appreciable, though smaller, range of movement than it did when the effect of the sternoclavicular joint was added. Posteriorly, the range of movement was similar to that for the glenohumeral joint alone (Sketch C); anteriorly, the range was increased, especially in the upper forward quadrant, the elbow, in addition, approached the mid-sagittal plane.

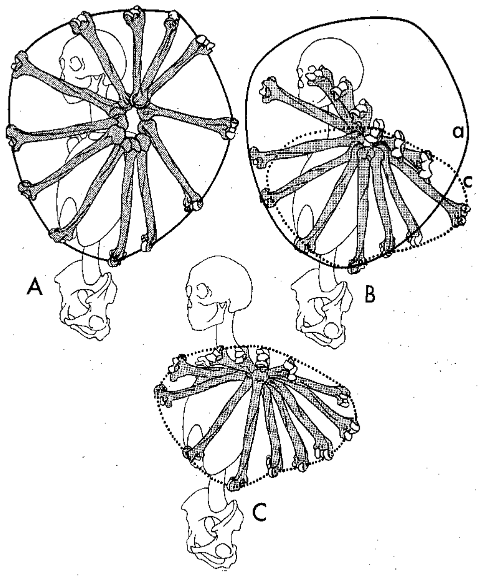


Figure 38. Humeral Movement from a Skeleton-Ligament Preparation. Composite photographic tracings of different humerus positions shown in a skeleton-ligament preparation. A—Maximum movement in different directions with unrestricted movements of both clavicle and humerus. B—Reduced pattern of movement when clavicle was anchored; movement of the scapula, however, was unrestricted. The solid line shows the same range of unrestricted movement shown at A. C—Humeral movement seen when both clavicle and scapula were anchored and the glenohumeral joint alone was free. The view is perpendicular to the plane of the scapular blade. The dashed outline showing range of humeral movement is shown also in Sketch B.

As in the other sketches, the front face of the humerus (Sketch B) turned forward in the vertical downward position; it faced medially in the horizontal forward position; upward and inward in the anterior superior quadrant; upward, forward, and inward in the abducted position; and outward and upward in the horizontal posterior position. It will be noted in Sketch C that the humeral head was more or less central in the glenoid fossa, as the bone moved about its instantaneous joint centers; in Sketch B the head had a marked amplitude of movement; this range of head movement was still greater in Sketch A.

Figure 39 (A and B) shows the joint sinus for the sternoclavicular joint. The distal end of the link axis of the clavicle to and just below the distal tip of the bone (i.e., to the mean center of the claviscapular joint) is shown as sweeping over an excursion cone of 35° from protraction to retraction and 44° from the elevated to the depressed position. These values are a composite based on four living subjects and our ligament-skeleton preparation. The rest position of the distal relative to the proximal end of the clavicular link for seated individuals averaged 8° upward from the most depressed position and 15° behind the most protruded position.

Generally similar curves were shown by Fick (1911), Strasser (1917), Mollier (1938), Braus (1921), and von Lanz and Wachsmuth (1938). Our curves are most like those of Fick. The obliquely-oriented surface swept by the distal end of the clavicle is seen as concave from the front and convex as seen from the side.

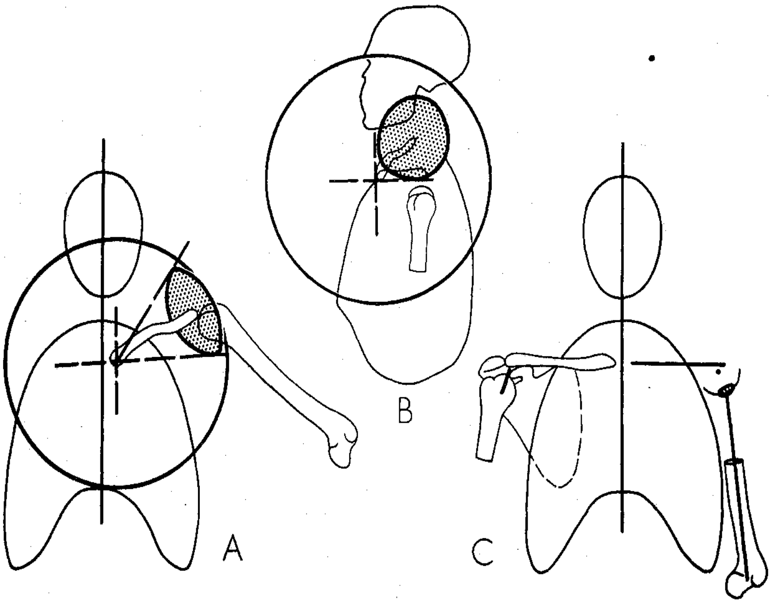


Figure 39. Range of Sternoclavicular and Claviscapular Joint Movement. A and B are front and side views, respectively, of the sternoclavicular joint sinus. The clavicular link is the radius of the circular outline; vertical and transverse lines intersect at an average joint center. At C the scapular link length is shown to the left; on the right the stippled area shows the range of movement of the distal end of the scapular link.

In Sketch C the scapular link (mean claviscapular joint center to mean glenohumeral center) is shown to the left; the distal end of this link sweeps over a small concavo-convex surface, such as that shown on the right. This surface, however, was notably flatter than a spherical surface with a radius equal to the link length. Our joint center data actually show that the instantaneous centers ranged over a span which was as long as the link itself.

The dashed lines in the sketches of Figure 40 which extend along the coracoid tuberosity of the clavicle (posteriorly) to the anterior part of the acromioclavicular articulation represent an axis on the lower face of the clavicle. It corresponds in large part with the roughed surface of the clavicle for attachment of the coracoclavicular ligaments (conoid and trapezoid ligaments); this roughened surface (coracoid tuberosity) is shown in Sketch D between the arrows. Instantaneous centers for various scapular movements range about this line over a distance of some four centimeters, about the same length as the scapular link.

The scapula swings fore and aft on the coracoclavicular ligaments to produce the major movement at the claviscapular joint. Observe that the clavicle itself lies oblique to the frontal-transverse body plane and that the axis line of the claviscapular joint is in turn oblique to the clavicle; consequently, the plane of scapular swing is somewhat oblique to the frontal plane of the body, but less so than the clavicle. The scapula may tilt endwise along the coracoclavicular ligament axis, or it may twist on the ligaments. Three degrees of freedom were permitted by the system.

The short scapular link and the extensive movement at its proximal end during scapular rotation creates a special situation at this joint. Rotation of the link about a mean center below the clavicle does not correctly describe movements of the glenoid joint center. The surface over which the distal end of the link moves is more complex than a simple spherical surface. Sketches A, B, and C of Figure 40 show the orientation of the actual surface.

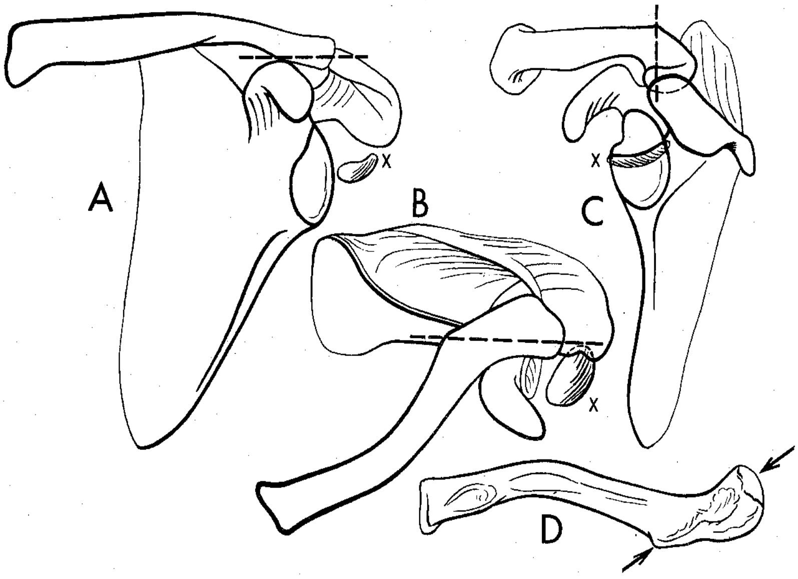


Figure 40. Structural Relations at the Claviscapular Joint. In sketches A, B, and C note the heavy dashed line; this corresponds with a line between the arrows at D—the attachment to the lower surface of the clavicle of the coracoclavicular ligaments. A, B, and C, respectively, are oriented normal to and end-on relative to the line; anterior, superior, and lateral views of the articulated clavicle and scapula are shown.

These figures were derived from data on bone-ligament preparations of the claviscapular joint. A stylus point was driven into the center of the glenoid surface of the scapula, until the projecting length was equal to the mean radius of curvature of humeral head; the clavicle was clamped in a vise, and the scapula was moved to its limits in all directions. In these movements the stylus point had a range that corresponded with movements of the scapular link. A block of modeling clay was set in contact with the point of the stylus. As claviscapular movements were made in all directions, clay was moved bit by bit from the path of the stylus. Eventually a concave area was produced over which the stylus point could range freely. The surface shown in the sketches appears convex as seen from below, in front, and laterally. Sketch B from above shows its concave surface.

Where the functional range that is characteristic of the scapular link is to be duplicated accurately in the design of a manikin or dummy, the large range in joint center position for the proximal end of the link and the shortness of the link pose a special problem. This may be met in three ways: (1) by using a short, pin-centered link with a suitable template to limit the range of movement, (2) by ignoring the link per se and providing a suitable surface, properly oriented relative to the clavicle link, on which the upper humeral link center may range, or (3) by ignoring both the clavicle and scapular links per se and providing a suitable template relative to the trunk for humeral movement.

Braune and Fischer (1888) measured X, Y, and Z coordinates of three needle points attached to the humerus of right and left shoulder joint preparations. The humerus was moved to the limits of movement permitted by the three joints of the shoulder sys-

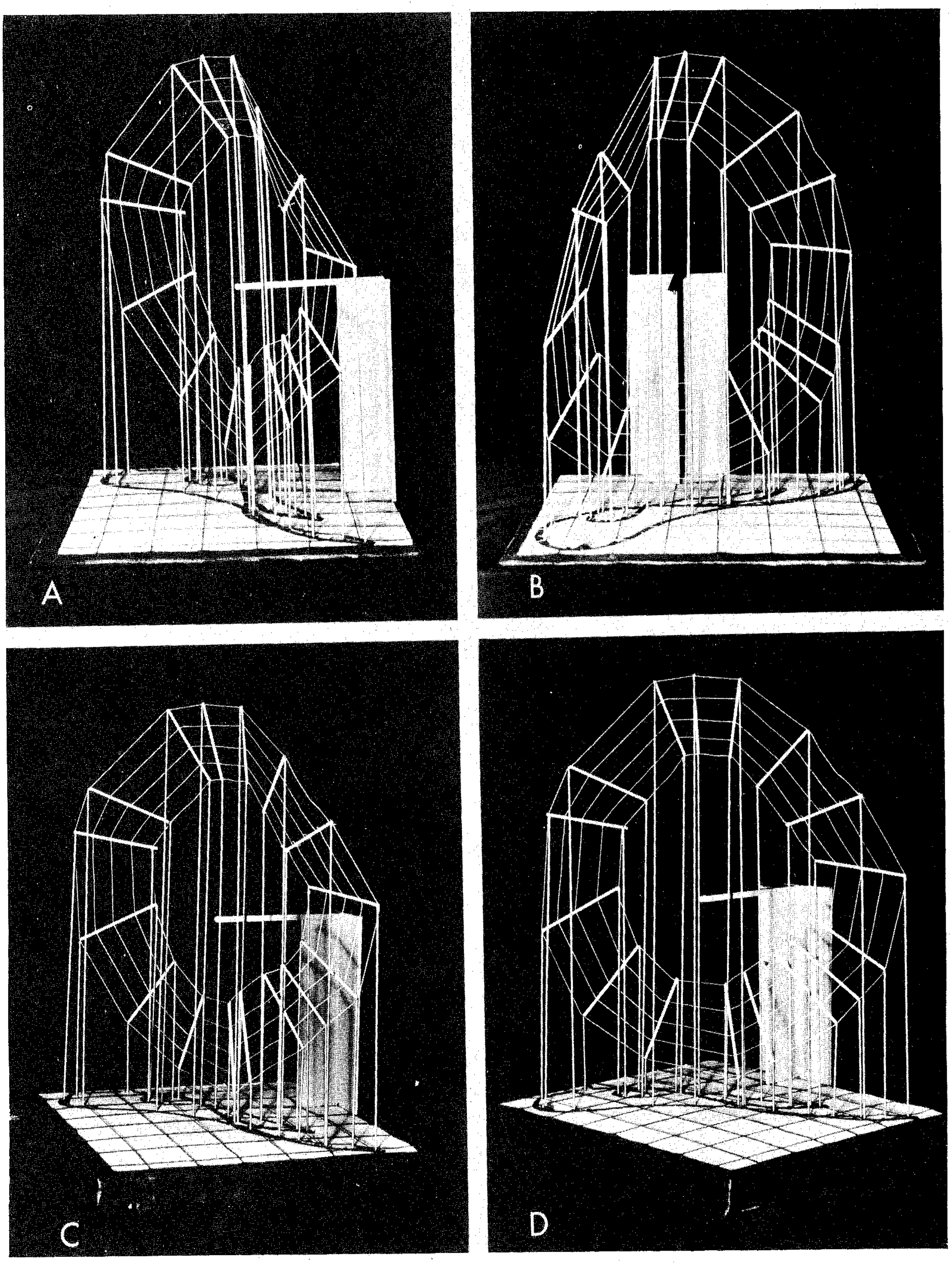
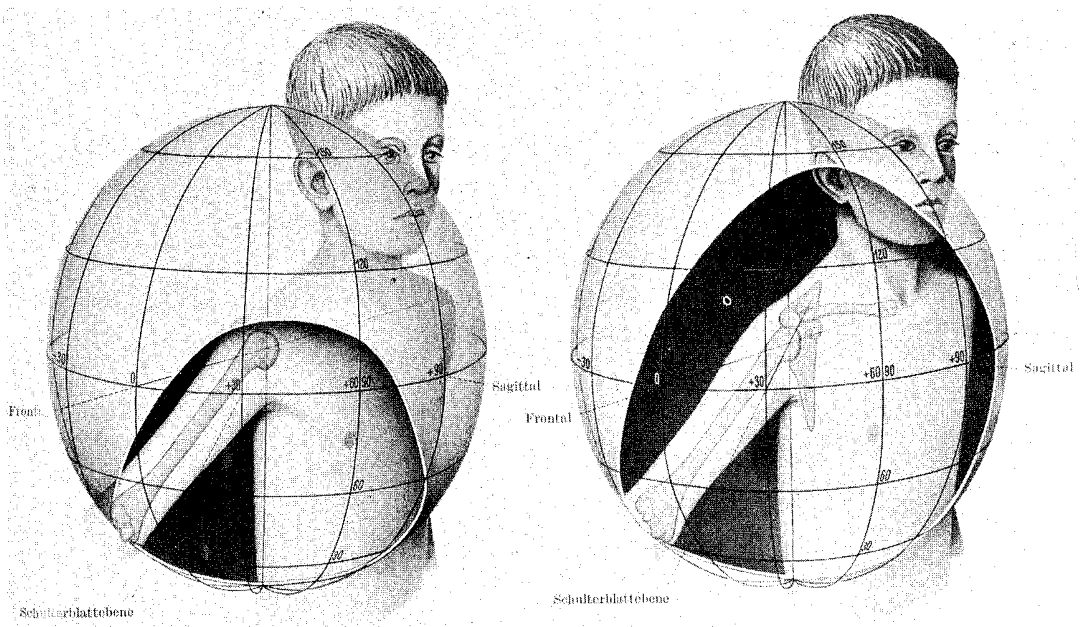


Figure 41. Three-Dimensional Model of Humerus Movement. Fischer's data on overall movement of the humerus involving all three shoulder joints are shown. A—front view. B—side view. C and D—oblique anterolateral views. The sticks interconnected by threads represent a fixed span along the length of the humerus.

tem (sternoclavicular, claviscapular, and glenohumeral), and the Xy and YZ coordinates of the two needle points were plotted for a number of positions. Their data were presented graphically. The string and stick model, supported on metal rods, that is shown as Figure 41 was prepared by us from the Braune and Fischer data. The three-dimensional model is shown from the front, side, and oblique positions. Sticks interconnected by threads represent a fixed length (originally marked by needle points) of the humerus. The irregular path described by the threads outlines an undulating surface like the brim of a much-worn, old, felt hat. A fixed span of the humerus slides about on such a surface and describes the maximum range of the bone. This model, like Figure 38, shows the complexity of humeral movement relative to the trunk.

From the foregoing (Figures 36, 38, and 41) it will be apparent that the total shoulder mechanism does not lend itself well to globographic illustrations of humeral range because the locus of the center of rotation is not constant enough for accurate data. Nevertheless, illustrations such as that (Figure 42-B) of von Lanz and Wachsmuth (1938) do suggest the overall range of the composite girdle-joint systems in comparison with simple movement of the humerus on the scapula (Figure 42-A).



a) Im Schultergelenk allein.

b) Bei freibeweglichem Schultergürtel.

Figure 42. Globographic illustrations of shoulder movement (from von Lanz and Wachsmuth). A—Movement of humerus at glenohumeral joint for a fixed scapular position. B—Movement permitted by glenohumeral, claviscapular, and sternoclavicular joints.

Fick's plots of data (Figure 43) are subject to the same criticism, but as a general gross representation of humeral range, they do have value. These views assume a point center location for the instantaneous centers of rotation and ignore the marked shifts found by analysis (Figure 36).

Figure 44 illustrates the range of possible locations of the elbow for one seated subject as seen in tracings of multiple photographic exposures; the surface described by elbow movement is only approximately spherical.

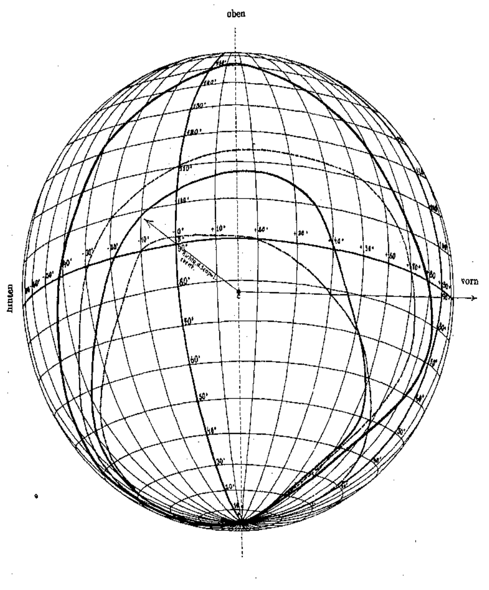


Figure 43. Excursion cones (from Fick) showing right shoulder joint and shoulder girdle joints as seen in an anterolateral view, somewhat from below. The inner dash-dot curve is the sinus of the shoulder joint alone from Strasser's preparation. The inner solid line represents data of Fischer. The dashed curve shows the sinus of the humerus with freedom at shoulder and claviscapular joint. The outer solid line shows the excursion cone, which includes sternosclavicular action as well.

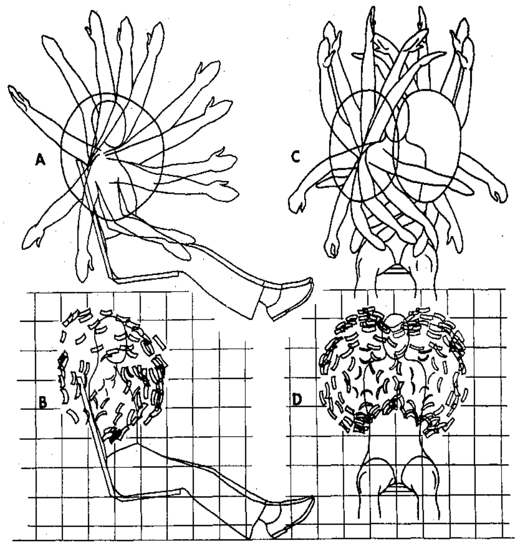


Figure 44. Views Showing the Amplitude of Arm and Elbow Motions. A and B—tracings of front and side-view multiple exposures of a seated subject moving the upper arm to its limits in all directions. C and D—same views, but showing the positions of an arm band of light-reflecting tape at elbow level. The spacing of the grid lines is 6 inches.

The Elbow

The elbow is a much simpler mechanism than the shoulder. Accounts of its movements and mechanics have been written by Braune and Fischer (1885, 1887 a), by Hultkrantz (1897), and by Fischer (1909). Standard globographic plots do not seem to have been made. Figure 45 shows a globographic presentation of the range of movement permitted by the elbow joint. Data were obtained from bone-ligament preparations of the humerus and forearm bones; a needle point was placed at the styloid process of the ulna as a measuring point. The humeral shaft was clamped horizontally in vise jaws, and the forearm was aligned in extension; the humerus was adjusted to the vise until a line from the center of the humeral head to the needle point at the styloid process was horizontal. This line was planned as the pole of the reference sphere. By trial and error the humerus was rotated and reclamped until, when the elbow was flexed to 90°, the needle was vertically above the pole line. Then, for various positions of elbow flexion, points were projected vertically downward and plotted on a paper surface. A line drawn through the points represented the curve of flexion illustrated.

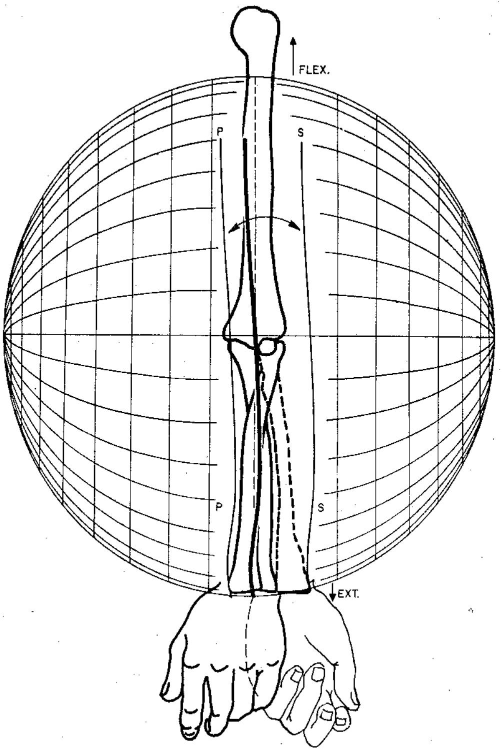


Figure 45. Globographic Plot of Elbow Flexion. Lines P and S indicate parallel curves showing position of the radial styloid process in extreme pronation and in extreme supination.

In Figure 45 the 0° meridian is the finely-dashed line of the figure; the sinuously heavy line shows the path of styloid movement as the elbow flexed or extended through some 140°. From extension to 90° flexion the styloid process may be visualized as scratching a 90° arc upon the surface of a reference sphere. During the first 45° of flexion the styloid process swung medially and then back to the zero meridian; in the next 45° it swung laterally and back. For the 90 to 140° range it swung medially. Since all the deviations, however, were less than 3°, a description of the movement as planar was a reasonable approximation.

Additional points at the radial styloid process were also plotted throughout the flexion-extension movement. In this instance points were plotted for the extreme pronation and extreme supination positions. These paths "P" and "S" closely paralleled the ulnar styloid curve, suggesting that the radio-ulnar joint range of pronation-supination was fairly constant for the whole flexion-extension range. Darcus and Salter (1935) and Salter and Darcus (1953) showed that in the living subject the amount of forearm rotation varied in use according to the amount of axial humeral rotation.

The Wrist

Figure 46 shows a modification of one of Braune and Fischer's (1887 a) plots of wrist joint range. The outer dashed line of the plot delineates the movement of a point on the third metacarpophalangeal knuckle, as it follows in sequence the range of wrist flexion, abduction-extension-adduction. A flexion-extension range of nearly 180° is shown; abduction and adduction are each nearly 30°. The inner curves are analytical relative to the radiocarpal and intercarpal joint systems and these are of secondary importance here. Braune and Fischer's data on the amount of wrist joint movement due to the radiocarpal joint alone are shown in dots; the range of intercarpal joint movement is shown in crosses.

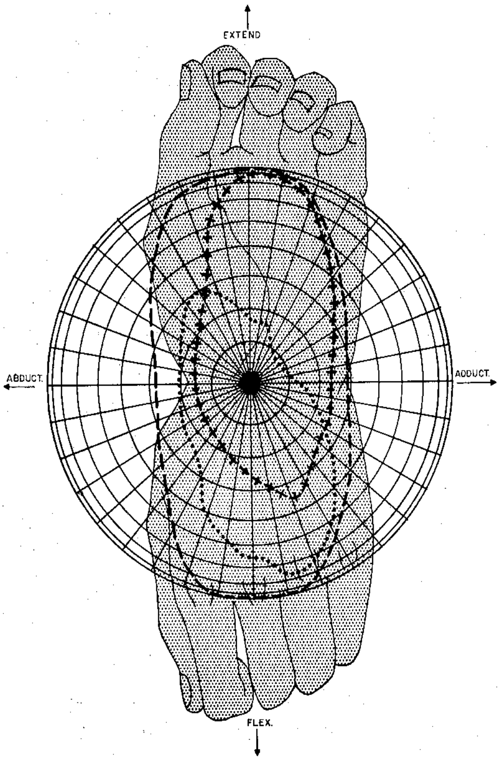


Figure 46. Modified presentation of Braune and Fischer's data on the maximum range of wrist movement (outer dashed line). The dotted line shows the range represented by the proximal wrist joints; the crosses show the range of the distal joints.

The Hip Joint

Strasser and Gassman's (1893) and Strasser's (1917) data on the range of hip joint movement appear to be entirely suitable for present purposes. Figure 47 shows a globographic representation of the hip sinus. The pelvis may be visualized as in the standing position with the anterior superior iliac spines and pubic symphysis in a vertical plane. According to the figure, the hip flexes some 115°, abducts 50 to 55°, and adducts 30 to 35°. The highest point is above and lateral to the hip joint;

the greatest sidewise range is some 30° below hip level. The degree of hip rotation along the axis of the femur is omitted from this figure, although the sense of rotation is shown by arrows. It may be stated, however, that the range is widened a few degrees laterally by lateral rotation and is narrowed by medial rotation; adduction at the medial border of the sinus is increased by medial rotation and is decreased by lateral rotation.

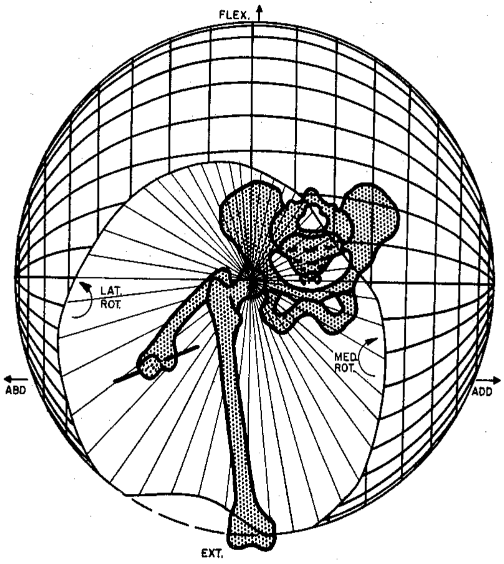


Figure 47. Strasser's globographic presentation of hip joint movement (redrawn and modified).

Movement is more restrained in the upper medial quadrant than in the upper lateral. It will be noted that in the extension and extension-abduction positions the femur is actually hyperextended beyond the plane of the paper. Fick (1911) and Roschdestwenski and Fick (1913) had additional globographic data; these authors showed that movement in the cadaver preparation was much decreased when muscles remained or when skin and muscles remained intact. The restraining effects of a loading by dead skin and muscle in the cadaver, however, have limited significance relative to physiological joint range. Other illustrations of the hip joint movement are to be found in Braus (1921), Mollier (1938), and von Lanz and Wachsmuth (1938).

The Knee Joint

The data on the knee joint are entirely ours; Figure 48 shows a globographic presentation, where the leg bones remain fixed and vertical on the pole of the sphere, while the femur bends downward at the knee. The up position of the femur is the extended position as in standing, while the bent position, as in squatting, depresses the femoral head and trochanters. Some 160° of flexion are shown in the 0° meridian. Flexion-extension movements of the femur, however, were not limited to the plane of the meridian as elbow movements were; it rotated medially on the polar axis in medial rotation or laterally in lateral rotation. Lateral rotation amounted from 20 to 25° for over a 90° span of the midflexion range; medial rotation was less than 20°, except for a 30° span between 115° and 145°. The 30° range and particularly the last 10° nearest full extension showed markedly reduced medial and lateral rotation; at 0° there was none. This reduced range was associated with the knee-locking mechanism at the end of the extension position of the joint.

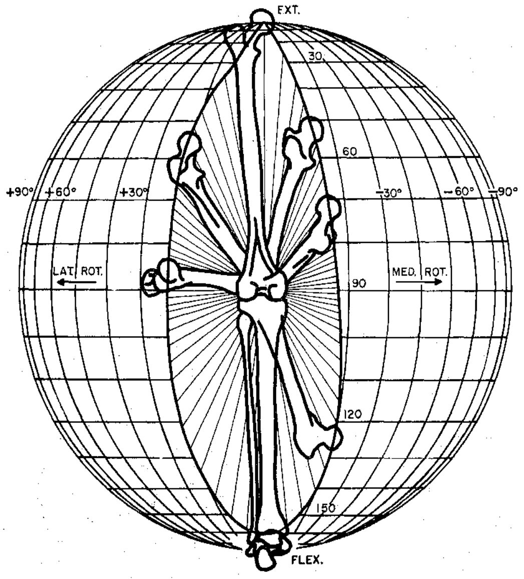


Figure 48. Globographic Plot of Knee Joint Range. The leg bones are regarded as stationary (the foot axis is perpendicular to the page), and the femur is flexed and rotated to its limits.

The Ankle and Foot Joints

The range of ankle and root movements is shown on the sphere of Figure 49. The foot is visualized as standing on a horizontal plane with the mean ankle center at the center of the sphere. Joint movements in the standard terminology are named by the foot position relative to the fixed ankle—a reciprocal relation to that illustrated here. Dorsiflexion here means that the leg bones move forward on the ankle; the leg moves backward in plantar flexion. Movement of the leg laterally is equivalent to foot pronation; movement medially is supination.

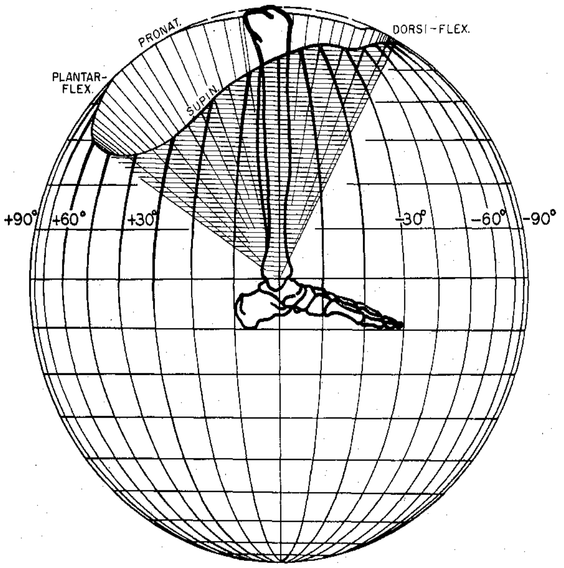


Figure 49. Globographic data on ankle and foot joints of the left foot.

The movement shown in the figure is a composite movement due to both the supratalar (true ankle) and subtalar (intertarsal) joints. The joint sinus illustrated shows that the greatest range of the leg axis from the pole position is 60° to 70° backward and 65° medially (plantar flexion-supination). Movements are somewhat more restrained in other directions, notably for pronation.

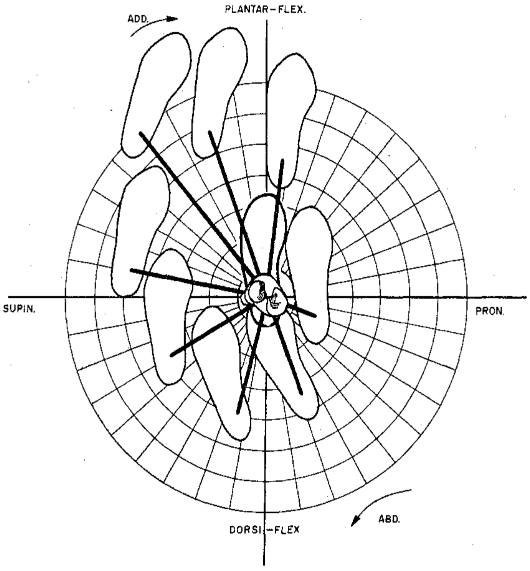


Figure 50. Possible foot positions compatible with horizontal localization of the knee. The knee lies on the zero of the polar graph but at various levels from the flat surface over which the foot moves.

Since the joint sinus shown ignores the fact that there are rotations (abduc- ion-adduction) about the pole axis of the foot, a different type of graphical pre- entation was used to supplement and extend the globographic figures. In Figure 50 he mean standing position of the foot is shown with the leg vertical (i.e., normal o the paper plane); the upper surface of the leg axis, including the tibial tuber- les, is shown at the zero position of the polar graph. The tibial tubercles re- ained on the 0° normal throughout all movements of the foot on the paper plane. Obviously, the height above the plane varied. The farther the foot position was from the 0° normal, the closer the tibial tubercles were to the paper surface.

Our figure shows eight representative positions of the foot sole at maximum distance away from the polar normal. The maximum distance from the 0° pole was toward plantar flexion and supination; the minimum distance involved pronation with some dorsiflexion. It will be noted also from the figure that the obliquity of the foot relative to the fore-to-back axis is different for each of its positions. It adducted to varying degrees in plantar flexion and supination; it abducted in the dorsiflexed positions.

These relations in which the positions of flexion-extension, abduction-adduction, and pronation-supination are inflexibly interrelated have considerable significance in problems involving foot orientation. The illustration suggests the amount of associated abduction of adduction, when the two feet are to be a given distance apart, i.e., medial or lateral to the knee centers, and a given degree of dorsiflexion or plantar flexion is associated. Practical problems of foot angulation in different two-footed stance positions may be planned for by the help of our figures.

CRITICISM OF CADAVER VERSUS LIVING JOINT RANGE

The various globographic curves of joint range may be used as an indication of the degree of free range allowed a joint, as has been done here; in addition, the curves may be analyzed further to determine the reasons for a limit being where it is. A critical treatment of the anatomical arrangement of ligaments (and muscles) about a joint and the shape of articular curvatures as well can explain much. Further treatment along this line, however, would become a bypath relative to the primary interest of this write-up. It should be emphasized, however, that the binding of ligaments and other stops built into a joint system do determine quite positively both the type and range of movement.

Even without further analysis, one may recognize that the general shape of the joint sinuses are important qualitatively. Much of the difficulty in joint work with living subjects has arisen because such qualitative features have been ignored. Satisfactory globographic data have previously been gathered on but few specimens—a single specimen by a given author is not uncommon. In certain instances, however, similar specimens have been studied by more than one investigator. Only Pfuhl (1934) presented as many as ten specimens of a joint. So far, the globographic method has not given an understanding of the range of variability among groups of people because too few records are available. In short, cadaver data permit one to say why a joint produces a type and range of movement, but data are not at hand to show the variability of joint movement for any population—even the dissecting room population.

Ligaments, as mentioned earlier, may not be the sole reason for the limitation of a joint range. Tension on ligaments during life may give rise to protective reflexes involving muscular actions at the joints. Muscle tensions in many instances may determine the actual sinus border. Even passive or stiff muscles may have an effect quite apart from ligament restraint. Everyone is familiar with the limits to hip flexion because of stiff thigh muscles—touching the finger tips to the floor with knees straight—in comparison to the same action with flexible, active muscles.

The limits of a joint sinus are regions of force equilibrium. Displacing forces tending toward movement away from the mean center position are balanced by counterforces at the margins of a joint sinus; these latter forces may be either active or passive. Boundaries of this sort may be due to ligament binding, as in the cadaver bone-joint systems; they may be due to bony stops (elbow), to muscular action, or to fat padding. Clothing might very well restrain joint movement much further.

Data previously gathered on living subjects have been perhaps as unsatisfactory as certain of the data on cadavers. Living subjects may be assembled and tested in groups, or serial records in a physical education department or hospital situation may be gathered over long periods. Data on age, sex, and population type may be gained for large numbers of persons. Such data, however, have not been systematically presented in the literature.

Techniques of joint measurement have become routinized and data have been presented in the literature as tolerance values to the nearest 5°, or so. In general, means, standard deviations, and other statistical data relating to specific population groups are not available. Many of the standard techniques of measurement have become prematurely standardized, and the anatomical background treated above has been ignored. Much of the attention in the literature of joint goniometry has been directed to devices, to techniques, and to ways of uniformly recording angle positions. Such systematizing is important practically since it allows clinicians and physiotherapists to understand the meaning of hospital records prepared by different persons or at different institutions. Even with such an understanding, the basic methods of study are still only partially satisfactory. Among the least satisfactory features are: the shoulder-joint mechanism, foot and ankle movements, the longitudinal rotations of limb segments, and transverse rotations of the hip and shoulder.

RANGE OF LIVING JOINTS

The globographic method used on cadaver joints involves the fixation of one member of a joint in a vise and the rotation of the other to the limits of the joint sinus in all directions possible. All potential positions of the movable member relative to the fixed member may be determined by this method. In contrast, it is difficult to immobilize most living joint.

Certain joints, like those of the shoulder system, present very difficult technical problems. With special restraining gear, adjustable for size, and plenty of time for the measuring of study subjects—probably nude for best results—it should be possible to obtain good data comparable to those on cadavers.

So far, however, work on living subjects has been directed to joint ranges "in a plane", such as flexion to extension for the knee or elbow, or supination to pronation for the forearm joint. The wrist joint, for instance, has been measured as "pure" flexion-extension and "pure" abduction-adduction without concern to oblique axes. Such planar measurements have not been necessarily in planes normal to one another. Moreover, it has been shown earlier that for joints of one degree of freedom (ankle, elbow), because of contingent movements, truly planar movements do not occur. The wrist also shows contingent motions.

In joint goniometry, the concept of links and joint centers has been utilized practically, though not consciously. The links have been tacitly regarded as rigid members, rotating at fixed joint centers. It has been assumed that one properly skilled in measurement should be able to align a protractor relative to segments and a joint center, so that measurements of 2 to 5° accuracy could be obtained.

An extensive literature on joint goniometry has included: Clark (1920), Rosen (1922), Wiechec and Krusen (1939), Moore (1949 a, 1949 b), Hellebrandt, Duvall, and Moore (1949), and many others. Most authors have been concerned with terminology problems and most of the range data are reported only to the nearest 5°. Notable exceptions are the three papers commented on below; their joint amplitude data are presented as Table 6.

Glanville and Kreezer (1937) studied 10 male subjects, ranging in age from 20 to 30 years. Of special interest was the fact that the coauthors reported both voluntary and forced ranges for the different joints. Right and left side joints were measured with a pendulum goniometer and were averaged separately by the side. Only the right side values are shown in Table 6, but the left are comparable.

Sinelnikoff and Grigorowitsch (1931) measured 100 males and 100 females in the 20- to 50-year range with a protractor-type goniometer; only the male data are recorded in Table 6. The authors attempted to correlate constitutional body types with joint range. Joint measurements were greater in females than in males, greater for asthenic male builds than for muscular, and least for pyknic builds. Female asthenics had generally greater ranges than pyknic females. Females in addition had notably greater movement than males for the smaller joints of the hand and foot. Gilliland's brief table averaged right and left sides.

Joint range data on our study sample of 39 subjects are presented as Table 5. Details of the method of measurement, subject posture, and other procedural factors were listed in Chapter II, Item 24, and Table 3. Our techniques involved certain departures from more standard goniometric techniques. For instance, the hand and foot were held fast, and the more proximal forearm and leg segments were moved. For the knee measurements, both voluntary and forced measurements were made; certain hip and knee measurements were made with different body postures. The most notable feature was the carrying through of measurements on subjects of four described body physiques on young men of approximately the same age range.

Our procedures were photographic—an advantage insofar as permanent records and easy measurement are concerned. The procedures, however, did involve the voluntary cooperation of subjects and this factqr was undoubtedly a variable. Double exposures were made at the instant the subject said that his joint was at maximum range. The photograph, measured long after the procedure, had to be taken, perhaps arbitrarily, as a measure of maximum range. In certain instances, however, additional photographs were available for measurement and these additional measurements were rarely much different from the original measurements.

Table 5 shows the average values and standard deviations of our measurements for the conditions indicated in Chapter II, Item 24. The table shows the joint range data for the four types of subject physique studied. Even a cursory check of the table shows, like the data of Sinelnikoff and Grigorowitsch (1931), that thin men have larger ranges than rotund subjects. A check of both the lowest and highest values for each type of movement in the table reveals that the thin men showed the highest range for 28 movements; the rotund showed high for one value only (shoulder rotation), and presented the lowest values for 28 types of movement. The median sample was highest for nine values and lowest for four, while the muscular men were highest for four values and lowest for six.

Standard deviations were relatively low for the large flexion-extension arcs of movement; the variability was relatively large, however, for rotations about longitudinal axes. Mean values as presented in the table often showed large differences, but the standard deviations showed that the various body types overlapped considerably. In general, for a given type of joint movement, any mean for one body type fell within one standard deviation of the mean for one of the other body types; the notable exceptions were the occasional low values for the rotund subjects.

It should be recalled that the 39 subjects of this study were highly selected for body build and that collectively they do not correspond with any ordinary population. The joint amplitude data, however, should have some significance as an in-

TABLE 5

JOINT RANGE OF STUDY SUBJECTS

Joint and Type of Movement	Median (n=11)		Muscular (n=11)		Thin (n=10)		Rotund (n=7)	
WRIST:								
Flexion	94.6°	± 5.2	91.9°	± 9.4	95.6°	± 9.0	79.7°	±14.8
Extension	102.0°	± 8.9	97.0°	± 9.0	100.0°	± 8.3	86.8°	±17.8
	196.6°	±12.2	188.9°	±14.5	195.6°	±14.1	166.5°	±26.7
Abduction	25.1°	±10.2	27.1°	± 7.6	28.8°	± 7.9	27.5°	± 8.0
Adduction	46.3°	± 5.1	47.4°	± 6.4	47.1°	± 6.7	46.1°	± 6.4
	71.4°	±13.6	74.5°	±12.4	75.9°	± 9.8	73.6°	±12.9
FOREARM:								
Supination	100.6°	±22.1	113.3°	+15.8	123.8°	±20.0	114.8°	±19.2
Pronation	74.0°	±17.0	69.1°	±14.8	75.0°	±18.0	89.0°	±37.9
	174.6°	±26.0	182.4°	±18.6	198.8°	±22.9	203.8°	±42.3
ELBOW:								
Flexion	141.0°	± 9.8	140.3°	± 7.6	144.6°	±10.2	143.2°	± 8.6
SHOULDER:								
Flexion	193.2°	± 9.6	190.2°	± 9.9	186.0°	±11.7	184.0°	±12.2
Extension	63.0°	±14.3	58.1°	± 9.1	67.0°	±11.1	54.5°	±14.8
	256.2°	±17.7	248.3°	±10.3	253.0°	±17.3	238.5°	±23.9
Abduction	132.1°	±16.5	135.0°	±10.4	142.5°	±19.0	127.5°	±12.3
Adduction	50.8°	± 6.4	44.3°	± 6.7	53.5°	± 8.9	43.6°	± 5.2
	182.9°	±17.1	179.3°	±12.8	196.0°	±23.3	171.1°	±16.2
Medial Rotation	95.7°	±25.4	95.2°	±20.9	97.0°	±13.8	100.1°	±24.6
Lateral Rotation	30.7°	±13.1	33.0°	±13.7	39.5°	±10.1	32.5°	± 8.5
	126.4°	±24.4	128.2°	±28.5	136.5°	±16.7	132.6°	±15.6
HIP:								
Flexion	117.1°	±12.7	118.2°	±12.2	116.5°	± 8.3	99.9°	± 7.7
Abduction	58.0°	±10.1	54.4°	±10.3	53.0°	±10.2	47.5°	±11.9
Adduction	27.7°	± 8.4	30.2°	±11.6	32.0°	± 9.4	34.2°	±15.7
	85.7°	± 9.5	84.6°	±10.9	85.0°	±16.3	81.7°	±14.9
PRONE								
Medial Rotation	38.7°	± 5.6	39.0°	±11.0	41.0°	±10.0	39.0°	±11.6
Lateral Rotation	34.7°	± 8.6	33.1°	± 7.3	40.5°	± 9.3	28.2°	± 9.1
	73.4°	± 8.5	72.1°	±16.0	81.5°	±14.6	67.2°	±19.7
SITTING								
Medial Rotation	31.4°	± 7.6	29.3°	± 5.8	34.5°	± 8.4	28.2°	±11.2
Lateral Rotation	31.9°	± 6.2	31.0°	± 7.9	33.0°	± 6.5	22.5°	± 8.5
	63.3°	± 5.9	60.3°	±13.0	67.5°	±11.2	50.7°	±17.4

TABLE 5 (continued)

Joint and Type of Movement	Median (n=11)		Muscular (n=11)		Thin (n=10)		Rotund (n=7)	
KNEE:								
PRONE								
Flexion (voluntary)	123.8°	± 7.8	127.0°	± 6.7	135.5°	± 6.4	114.0°	± 6.4
Flexion (forced)	142.1°	± 5.8	147.8°	± 4.9	152.0°	± 7.3	136.1°	± 8.8
STANDING								
Flexion (voluntary)	112.2°	±13.3	119.6°	±10.8	117.5°	±10.7	102.5°	± 9.3
Flexion (forced)	162.4°	± 5.0	160.3°	± 5.6	165.0°	± 6.0	146.8°	± 6.1
KNEELING								
Medial Rotation	40.9°	± 8.7	38.9°	±12.4	32.0°	±10.1	29.0°	± 6.7
Lateral Rotation	43.3°	± 8.5	39.3°	± 9.1	46.4°	±10.5	41.7°	±15.1
	84.2°	±11.5	78.2°	±19.8	78.4°	±13.6	70.7°	±11.8
ANKLE:								
Flexion	39.0°	± 7.8	34.2°	± 4.7	39.3°	± 4.7	29.0°	± 4.0
Extension	41.6°	±10.6	44.9°	± 9.5	35.5°	± 8.4	28.9°	±10.0
	80.6°	± 9.4	79.1°	±10.6	74.8°	±11.1	57.9°	±11.0
FOOT:								
Inversion	23.4°	± 6.7	20.9°	± 7.5	29.5°	±10.8	22.1°	± 6.2
Eversion	23.2°	± 5.2	23.5°	± 4.9	26.5°	± 8.3	20.7°	± 4.8
	46.6°	±10.8	44.4°	±10.8	56.0°	±16.0	42.8°	± 4.3
GRIP ANGLE:	100.7°	± 5.4	99.7°	± 4.9	102.6°	± 7.0	104.1°	± 6.9

dication of the inside and outside range which might be found in a much larger population of normal young men as in a military group. Average values from a sample of highly selected and diverse types must be regarded as only nominal approximations to the mean joint amplitude which might be found in a military population. Our median group averages (alone) should be close; the sample, however, was small. Probably the median group averages and the whole group averages are about equally representative. Table 5 shows the former; the averages for the whole group of subjects are presented in Table 6.

Table 6 in addition records joint range data presented by Glanville and Kreezer (1937), Sinelnikoff and Grigorowitsch (1931), and Gilliland (1921). These authors have been notable exceptions to others contributing to the literature on joint goniometry in that their publications have presented means and such pertinent factors as range and standard deviation.

A check through Table 6 shows similarities and differences in joint range for the four sources of data that require comment. Among the values that are very close throughout the table one may note: forearm rotation, elbow flexion, shoulder flexion and shoulder extension, lateral rotation of the hip (prone), knee flexion (prone), and ankle dorsi- and plantar flexion. In most instances, procedures were very similar for these measurements.

The amount of joint forcing certainly accounted for much of the wrist flexion-extension differences. Entirely different body and joint postures accounted for such differences as shoulder abduction and rotation and hip abduction. According to the position of the moving member, the force of gravity either increased or decreased the joint angle.

In reality, all the measurements recorded in the table have been arbitrarily dependent on body and joint position. The measurements on joints of two or three degrees of freedom were in planes that traversed joint sinuses in arbitrary directions; composite joints—especially the shoulder—were handled in a very arbitrary style. How should the data be used? Obviously, clinical comparisons of the range of movement of normal versus diseased joints, the progressive deterioration of joint movement with disease, or the progress of recovery may be followed by any standard type of measurement.

For functional problems of the normal worker, however, ranges of voluntary movement comparable with those available to the standard seated or standing postures are desirable. It should be of interest to know inside and outside ranges of joint movement for the middle 90 percent of the population. Possibly the effect of fatigue and the effect of practice on joint range should have meaning. Such values, however, are not now available.

A practical objective of this research relates to manikin design. The best joint data now available must involve a compromise of data on cadaver sinuses and data on living joints moving "in a plane." The tabulated values, despite their limitations, can quantitatively supplement the ranges of cadaver data. Further work upon joint range for representative populations of young men should be a desirable objective in regard to military or industrial applications of body data.

TABLE 6

JOINT RANGE DATA: COMPARISON WITH PUBLISHED VALUES

Joint and Type of Movement	Present Data (n=39)	Glanville and Kreezer (n=10)				Sinelnikoff and Grigorowitsch (n=100)		Gilliland (n=100)	
		Voluntary		Forced					
	M	M	σ	M	σ	M	σ	M	σ
WRIST:									
Flexion	90°	95.0°	±10.6	105.6°	±13.0	78.2°	± 9.2		
Extension	99°	54.1°	±15.2	91.8°	±13.0	63.2°	± 8.4		
Sum	189°	149.1°		197.4°		141.4°	±11.5	166.0°	± 9.0
Abduction	27°	27.1°	± 7.1	39.7°	± 6.1	23.9°	± 5.3		
Adduction	47°	66.1°	± 8.1	74.1°	± 7.4	38.3°	± 7.6		
Sum	74°	93.2°		113.8°		62.2°		96.5°	±16.7
FOREARM:									
Supination	113°	99.4°	±11.0	114.3°	±15.2				
Pronation	77°	91.1°	±25.8	104.9°	±22.1				
Sum	190°	190.5°		219.2°					
ELBOW:									
Flexion	142°	138.3°	± 8.5	143.2°	± 7.6	142.1°		152.3°	± 9.5
Extension						180.5°			
SHOULDER:									
Flexion	188°	179.0°	± 7.2	184.6°	± 6.4	180.0°			
Extension	61°	55.2°	±10.1	67.7°	±11.9	59.8°	± 8.0		
Sum	249°	234.2°		252.3°		239.8°		261.8°	±13.5
Abduction in coronal plane		129.3°	±11.7 (no humerus rotation)	136.7°	±12.4			207.5° (with hum. rotation ?)	±10.5
Abduction in transverse plane	134°								

TABLE 6 (continued)

Joint and Type of Movement	Present Data (n=39)	Glanville and Kreezer (n=10) Voluntary		Glanville and Kreezer (n=10) Forced		Sinelnikoff and Grigorowitsch (n=100)		Gilliland (n=100)	
	M	M	σ	M	σ	M	σ	M	σ
Adduction in transverse plane	48°								
Sum	182°								
Medial Rotation	97°	94.1°	±22.1	101.1°	±22.5				
Lateral Rotation	34°	82.7°	±10.0	92.0°	± 7.2				
Sum	131°	176.8°		193.1°					
HIP:									
Flexion	113°	146.2°		167.9°		117.9°	± 8.6	129.0°	±19.3
Abduction in coronal plane		70.1°	±17.0	79.3°	±10.4	70.2°	±12.2	54.5°	±11.3
Abduction in transverse plane	53°								
Adduction in transverse plane	31°								
Sum	84°								
Medial Rotation (prone)	39°	60.6°	±15.2	73.0°	±16.6				
Lateral Rotation	34°	37.0°	± 6.6	45.6°	± 6.7				
Sum	73°	97.6°		118.6°					
Medial Rotation (sitting)	31°								
Lateral Rotation	30°								
Sum	61°								

TABLE 6 (concluded)

Joint and Type of Movement	Present Data (n=39)	Glanville and Kreezer (n=10)				Sinelnikoff and Grigorowitsch (n=100)		Gilliland (n=100)	
		Voluntary		Forced					
	M	M	σ	M	σ	M	σ	M	σ
KNEE:									
Voluntary Flexion (prone)	125°	126.6°	± 6.7			140.5°	± 5.3	133.0°	±11.3
Forced Flexion	144°			139.9°	± 6.8				
Voluntary Flexion (standing)	113°								
Forced Flexion (kneeling)	159°								
Medial Rotation	35°								
Lateral Rotation	43°								
Sum	78°								
ANKLE:									
Dorsiflexion	35°	36.8°	± 6.6	43.9°	± 4.7				
Plantar Flexion	38°	28.2°	± 7.4	36.1°	± 9.9				
Sum	73°	65.0°		80.0°		62.6°	± 8.5	63.0°	± 6.3
Inversion	24°								
Eversion	23°								
Sum	47°								

ORIENTATION OF THE PELVIS AND THORAX IN A SEATED INDIVIDUAL

When a standing person sits, it is obvious that the anterior vertical distance between thorax and pelvis shortens. Sitting involves an entirely new adjustment of the trunk to gravitational forces. Centers of gravity of the trunk segments are realigned, and the vertebral curvatures adapt to the altered pattern. To locate the hip and shoulder joints for the seated individual, in accord with present practical objectives, a determination of the degree of mean pelvic and thoracic tilt is a first essential.

Chapter II, Item 25, outlined procedures involved in the measurement of pelvic and thoracic tilt. A study sample of 41 subjects was used. The pelvic and manubrial guides (Figures 14 and 15) were affixed and side-view photographs were made of the subjects as they stood, lay supine, and sat; the height of seat varied from 0 inches (floor height) to 30 inches or more.

When the four body types were compared, the same general pattern of pelvic and thoracic tilting was repeated for all types; thin men had a slightly greater (3 to 5°) mean pelvic and thoracic tilt than median and muscular types; rotund individuals were usually a degree or two lower. Perusal of the data, however, showed no remarkable qualitative differences owing to body type; accordingly, the data were averaged and are presented as Figure 51. Standard deviations for the pelvic angulations should run ± 6-7°, based on one-fourth of the range of the angles measured. For the manubrial angle, the standard deviation, when estimated in the same manner, was roughly ± 5°.

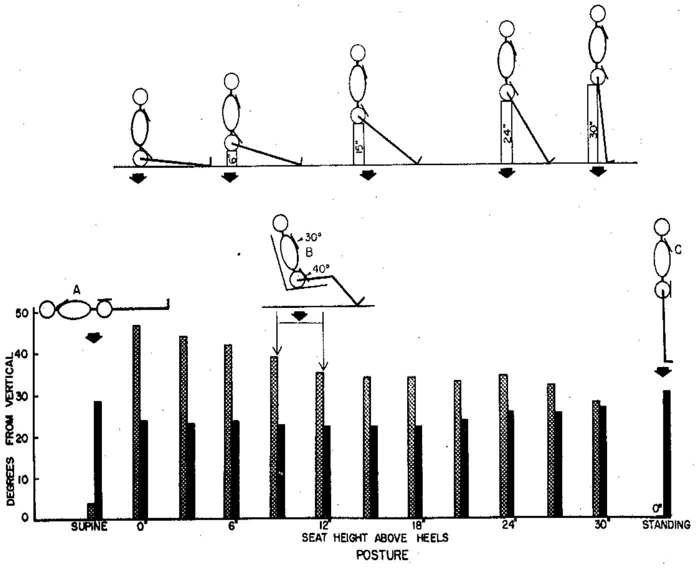


Figure 51. Histogram showing angulation of sternal manubrium (black) and of a plane touching the pubic symphysis and the two anterior-superior iliac spines of the pelvis (shaded) for different seat heights without back rest. These relations are diagrammed also on stick figures above certain of the histograms.

For the standing individual the manubrial plane averaged 30° to the vertical and the plane making three-point contant with the anterior superior iliac spines and the pubic symphysis was 0° (vertical). For the supine subject, when the 90° postural difference was allowed for, the thoracic angulation was unchanged; the pelvic tilt was only 3.5° greater. (Measurements on 10 supine cadavers gave a mean manubrial angle of 22.50; the subjects, however, were entirely different—variable in type, often emaciated, and notably older—and a fairly extreme expiration posture was assumed.)

Pelvic tilt was greatest when the subject sat on the floor (Figure 51) and it decreased gradually (46 to 35°) to a seat height of about 12 to 15 inches. The tilt varied but little, until the seat height reached 24 inches. Above 27 inches seat height, the pelvic tilt decreased to 30° or less. When a subject sat without a back rest he slumped forward, especially for seat heights below 24 inches. The slump also tilted the thorax 6 to 8°, i.e., 20 to 24° manubrial angle.

When a seat back was provided and seat heights were between 9 and 12 inches, according to subject (standard pilot seat), the mean pelvic tilt was about the same (40°) as when no seat back was provided. More significantly, the thorax did not slump forward; its tilt was the same as that for the standing individual.

These tilt angles of the pelvis (40°) and thorax (30°) were of special interest in regard to the orientation of the reference globes for joint sinuses of the shoulder and hip mechanisms. When the pelvic and thoracic orientation is known, joint sinuses for the shoulder and hip systems derived for the standing posture may be used for kinematic treatments of limb movements of the seated subject. For the hip joint, the pole of the reference globe should be tilted upward by 40° so that the joint sinus may be directed correctly. Since the manubrial tilt was the same for both standing subjects and sitting subjects (seat with a back) globographic data are directly applicable.

It should be noted that the foregoing account dealt only with symmetrical relations of the lower limbs. Asymmetrical movements of the thighs and legs are probably no less important for the seated operator. Accordingly, a brief test was made on two individuals to see how the pelvis of the seated subject tilted when one thigh was raised higher than the other. The subjects sat side view to the camera in the standard seat with eye height at 39-1/2 inches above the floor level. Both feet were initially placed flat and symmetrical; then the far foot was raised on a series of 3-inch blocks, so that increments from 0 to 15 inches above the level of the foot on the floor were obtained. The guide which indicated pelvic tilt changed only a little for the first 6 inches that the foot was raised, but it showed an increased pelvic tilt through 9 to 15 inches, until it showed an eventual increment in tilt of 10.7° in one instance and 5.5° in the other beyond the angulation found for symmetrical sitting. For the planning of seated manikins one may conclude, from the data on the lifting of one thigh, that globographic joint range data based upon the standing posture of the pelvis should be adjusted 5° or more beyond the 40° shown in Figure 51.

LOCATION OF SHOULDER AND HIP CENTERS OF THE SEATED SUBJECT

Side-view photographs of all our subjects seated in the standard "pilot" seat were available for study. A selection of these photographs was made, so that a small group corresponding closely with the fiftieth percentile of the Air Force flying personnel could be obtained. The selection included only those of our subjects whose stature, crotch height, and sitting height fell at the fiftieth percentile. The fiftieth percentile was indicated in Hertzberg, Daniels, and Churchill (1954).

Enlarged, superimposed tracings were made and points representing the best estimates of shoulder and hip joint centers for each subject were marked in. To assure accuracy in this, several nude subjects were palpated and the skin marks were made overlying the joint centers.

Reasonable approximations were possible for the shoulder joint. The center of the hip joint was more of a problem since only the trochanteric region could be palpated. The angle of inclination of the femoral neck (i.e., angle to the femur shaft in the frontal plane) and the declination angle (torsion angle or angle between the neck and the shaft in the bicondylar plane) produced a notable offset of the trochanter relative to the center of the head of the femur (Ingalls, 1927; Elftman, 1945; Kingsley and Olmstead, 1948). For this reason a group of osteological measurements was taken on femora and pelves.

Measurements of 16 femora showed that the direct lateral projection of the center of the head of the femur fell 0.1 ± 0.25 inch proximal to the highest point of the trochanter and 0.41 ± 0.2 inch anterior (i.e., away from the seat surface for the seated subject) to the greatest level of projection of the trochanter. Considering a $\pm 3\sigma$ range of variability in the two directions, we inferred that, without additional errors due to palpation (i.e., because of superficial padding) it could be predicted that the joint center position based on the trochanter would fall within a 1.2- x 1.5-inch ellipse (i.e., an ellipse with semiaxes of 0.6 and 0.75 inches).

An additional osteometric check on the relative location of the midacetabular point, or hip-joint center, was made on 9 normal male pelves. Measurements relating to the hip center were geared to what could be applied in the study of side-view photographs of the study subjects, who were seated nude on the standard seat. From these photographs the anterior superior spine could be reasonably well located; the iliac crest was less clear, but no other bony pelvic landmarks could be noticed. The pelvic guide (Figure 14) clearly indicated the tilt of the plane across the symphysis pubis and the two anterior superior iliac spines. No other pelvic dimensions could be checked from side-view photographs, except the height of the anterior superior spine above the seat plane and the perpendicular distance to the seat back.

A simple but accurate pelvimeter was constructed and several dimensions and angles, relating chiefly to the anterior superior spine, were determined on the 9 pelves mentioned above. For measurement, the pelves lay prone on a horizontal surface with contacts at the right and left anterior superior iliac spines and the pubic symphysis. A transverse line from one anterior superior spine to the other formed a zero line for most measurements. The dimensions recorded on both right and left sides were vertical height from anterior superior spine (1) to upper acetabular margin, (2) to the lower acetabular margin, (3) to the mid-acetabular point, and (4) to a tuberosity point of the ischium, defined below. Additional sagittal measurements taken were (5) anterior superior spine to the top of the iliac crest, (6) anterior superior spine to the lowest point of the ischial convexity, and (7) the perpendicular distance from the reference plane to the posterior superior spine. Angles relative to the reference plane with centers at anterior superior spine level were measured (8) to a tuberosity point of the ischium, the only point on the lower convex ischial border from which a normal could be erected to intersect the anterior superior spine, and (9) to the midacetabular point.

In addition, right-side photographs of the pelvis, resting upon the standard seat, were taken at the same camera distance as that for the study subjects, i.e., same parallax factor. Two 1/2-inch thicknesses of board were placed on the seat at the back rest (Figure 52), so that the bone made contact with these; the 1/2-inch thickness arbitrarily represented a padding factor, which in life would be represented by skin and subcutaneous tissue. The pelves were oriented on the seat and photographed with the anterior superior spine to symphysis reference plane at 40° to the vertical. Thus, the photographs represented pelves in approximately the same position that they would occupy in seated study subjects.

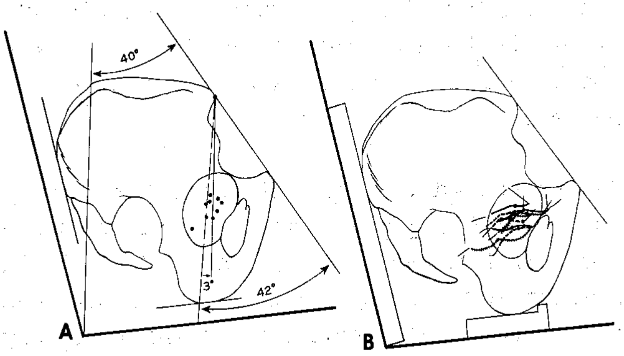


Figure 52. Right lateral view of an average-shaped male pelvis resting on the standard test seat. In sketch "A" the relation of hip-center position relative to the seat is shown by dots for 9 different pelves; the pelves, which were tilted 40° to the vertical, contacted the seat at ischia and at the posterior parts of the iliac crests. At "B", the irregular tracks show the path of hip-center movement as the pelves are tilted from 0° to over 60°.

In addition the pelves were photographed at two or three larger and smaller tilts. The pelvis that had the most nearly average proportions was photographed in ten different angulations.

Figure 52 illustrates the findings derived from these procedures. The acetabular point for all but one of the pelves fell within a circle of 0.75-inch diameter (Figure 52-A). The location of the hip center for a pelvis in the seated posture, accordingly, cannot be predicted more accurately than this. For pelves oriented, as for the seated subject, with a mean tilt angle of the reference plane at 40° to the vertical, a line from the anterior superior spine to the ischial point was, on the average, 2° off (posterior to) the vertical. The cluster of points indicating acetabular center were centered about a line that lay approximately 3° anterior to the line between the anterior superior spine and the ischial point (Figure 52-A). Since the angular difference was negligible, a line dropped vertically from the anterior superior spine for the seated subject cuts as close to the mean joint-center position as can be wished.

Half the distance from the anterior superior spine to the seat surface for the bony pelvis is a reasonable estimate of the midacetabular point.

The variability in height of the anterior superior spine above the acetabulum and in the height of the acetabulum above the seat surface is appreciable. More or less padding could further change the locus.

Sketch B of Figure 52 shows the type of shifting in position of the midacetabular point associated with forward and backward tilting in the nine pelves studied. Cardboard cutouts of a series of photo enlargements of the various pelves were made and a midacetabular point was marked by a pinhole. These cardboard cutouts were then placed individually within an angle of 101°, representing the junction of the seat and seat-back planes for the standard seat. Pelvic contacts were made with both the seat and the seat-back.

Initially, the reference plane of the cutout was oriented to 40° from the vertical. The pinhole position was marked through. Next, the cardboard pelvis was rotated a few degrees and a new pinpoint location was marked. In this way a row of pinpoints represented the movement of the midacetabular point for varying degrees of tilting. Sketch B, Figure 52, shows such curves for the nine pelves. The heavy lines indicate the path of the acetabular point for various positions of simultaneous contact of the ischial tuberosities with the seat and of the ilium with the back rest. The fine lines anterior to the main curve represent the position of the midacetabular point when the sacrum and iliac crests made contact with seat and back, respectively (i.e., no ischial contact); when the sacrum and ischial tuberosities were the parts in contact with the back rest and seat, the midacetabular point shifted more posteriorly (fine posterior lines).

These paths, of course, assume that the pelvis was equally padded below and behind, and that the pelvis was oriented very accurately on a transverse line. Side-view photographs of the pelvis in different orientations showed generally similar displacements of the hip center but the data were less precise than those from cutouts. If an individual pelvis were obliquely placed on a seat, or if the buttocks were somewhat forward from the seat-back rest position, the line representing acetabular position would be displaced forward.

The earlier study of instantaneous axes for joint movement pointed out that centers of rotation shift about over an appreciable range. The cluster of center locations varied somewhat from one cadaver joint specimen to another. A "mean center" position for the hip is surrounded by a circle of probability of joint-center position with a 1-cm radius. This factor, added to the range of variability of the midacetabular position in relation to the seated position of the pelvis, could very well be double the 0.75-inch circle mentioned above; this variability in position would be further augmented for forward movements of a subject in the seat.

Thus, our analysis on pelves has only confirmed that made on femora, suggesting the joint center could at best be predicted only within a 1.2- to 1.5-inch ellipse. For the subject seated with the reference plane at 40° to the vertical, a line dropped vertically from the anterior superior spine becomes the best estimate. This prediction, however, is a nominal location that may be modified by forward displacement of the trunk, forward or backward rotation of the pelvis, oblique orientations of the pelvis, and variable amounts of fat padding or padding caused by clothing.

BONE LENGTH-STATURE DATA

The identification of stature from the length of skeletal bones has received much attention since Rollet (1888, 1889) and Manouvrier (1892). Representative studies on different populations are available by Pearson (1899), Pan (1924), Breitinger (1937), and Telkkä (1950). Only the work of Dupertuis and Hadden (1951) and of Trotter and Gleser (1952), however, deals with American material. Published work by these authors permits the estimation of stature from long bone length with stated limits of accuracy.

Dupertuis and Hadden reported on cadaver measurements made long ago by Professor T. W. Todd on dissecting-room material at Western Reserve University, Cleveland, Ohio. Trotter and Gleser reported similar material from Washington University, St. Louis; the cadaver postures, as measured for stature by the two groups of investigators, however, were entirely different in the two groups of measurements. Fortunately, it is not necessary to make an arbitrary choice between the two groups of data. A most remarkable advance in this field of identification measurement was made by Trotter and Gleser, who were able to correlate measurements of stature made on military personnel during life with measurements on dried skeletal bones of the same individuals, young males of known age, after death.

These papers give formulae from which probable statures can be predicted from measurements of long bone length. The range of bone length for various statures, however, cannot be obtained from the research papers. The author has been especially fortunate to obtain through Professor W. C. Dupertuis a group of plots of bone length of one long bone against another (plots of the length of one long bone against another (i.e., femur-tibia, tibia-radius, etc.). In addition, Professor Mildred Trotter kindly made available a copy of the measurements on the 710 military subjects—including identification number, stature, and the lengths of the right and left femur, tibia, fibula, humerus, radius, and ulna. The author is deeply indebted to these colleagues for their kindness and help. The bone length of four bones, humerus, radius, femur, and tibia were selected as of especial interest to this study.

The measurements on the 710 military personnel were plotted on ten correlation charts, similar to those obtained for the Western Reserve cadavers. Because of the unique character of the measurements on Army personnel, and since the measurements were made on young males, these data were of especial importance here. Figures 53 and 54 show plots of the Trotter-Gleser data for the femur, tibia, humerus, and radius. On the plots of Figure 53, representing army personnel, arrows have been placed at stature levels which, according to measurements of Hertzberg, Daniels, and Churchill (1954), represent 5th, 50th, and 95th stature percentiles for Air Force flying personnel.

The army group from which bone lengths were taken and the Air Force group were of course entirely different samples; the latter averaged four to five years older and an inch taller and probably was more select a physical group (Table 1), but both groups were derived from the same healthy segment of the American population; both were selected within military personnel standards. There should be little expectation that

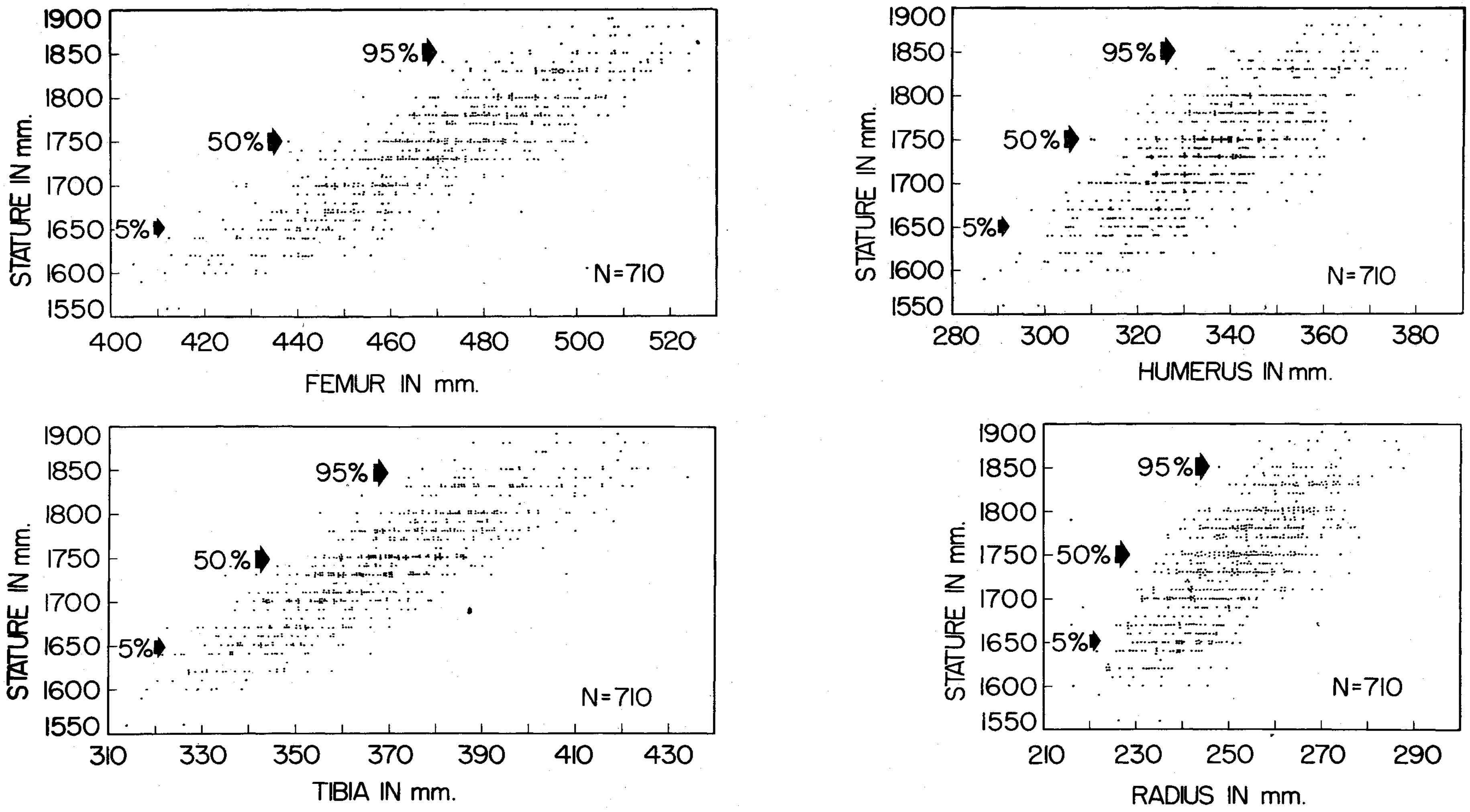


Figure 53. Plot of raw data of Trotter and Gleser on the relationships between the length of 4 skeletal limb bones and living stature; the data apply to 710 white army males. Arrows point to statures corresponding to the 5th, 50th, and 95th percentiles of Air Force flying personnel.

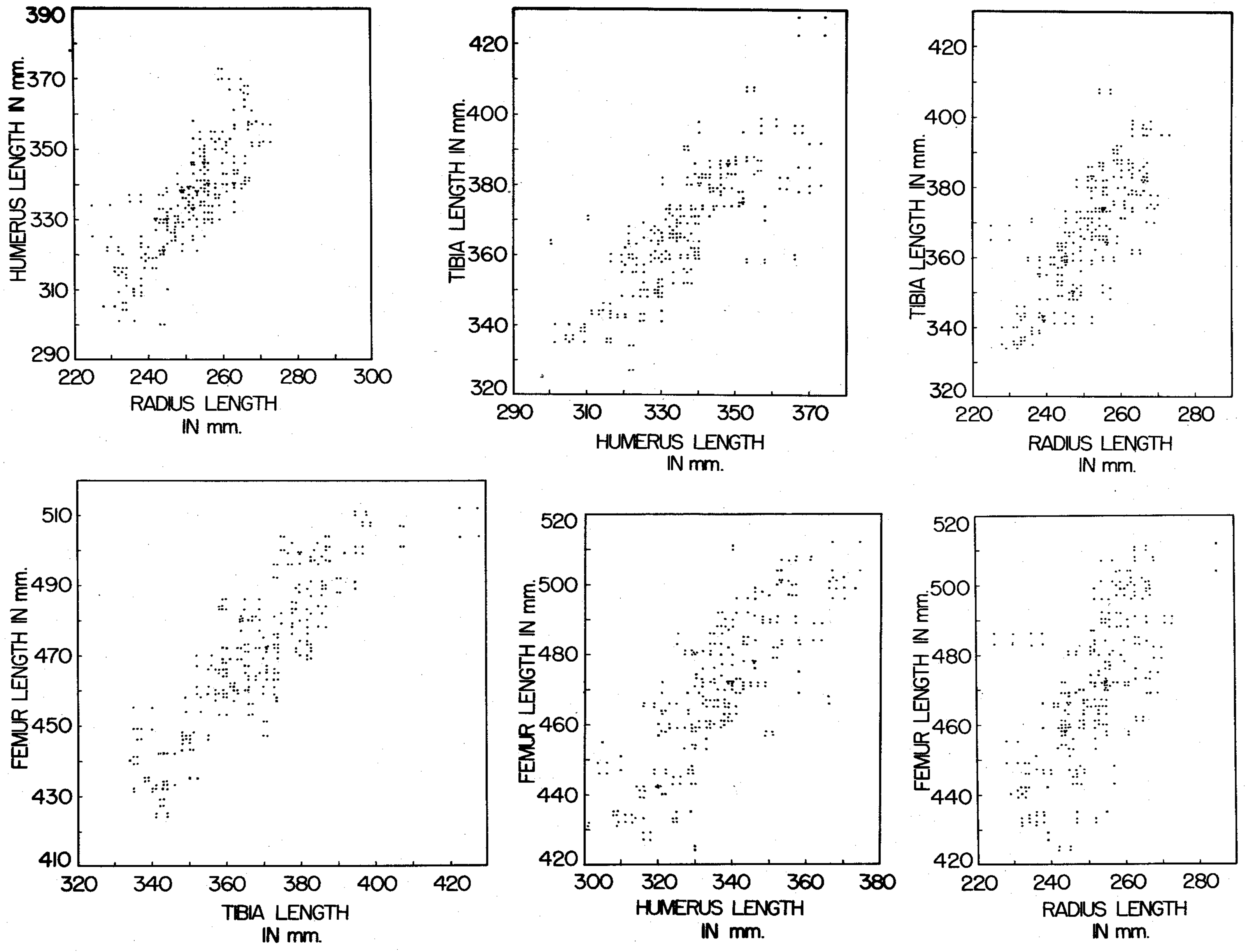


Figure 54. Correlation plots of bone lengths for individuals of selected statures (comparable to 5th, 50th, and 95th percentiles of Air Force flying personnel) from raw data of Trotter and Gleser.

bone lengths for the selected statures should vary materially in the two groups. The dimensions of bone lengths increased for increases in stature in a similar fashion for Western Reserve cadavers but here the stature data were obviously high (too high?).

In Figure 54 bone lengths were plotted relative to one another for those individuals whose statures corresponded with the three selected percentile levels; in each instance the plots showed trends which indicated that longer bones tended to be associated with longer bones and that shorter were associated with shorter. The variability was appreciable and the continuous cluster of points in no way suggested that bones from 3 separate stature levels were involved. The areas occupied by the clusters of points were entirely comparable with those in plots derived from Western Reserve cadavers. A range of variability of 30 to 40 mm according to the bone is evident in all instances. The nominal character of average bone measurements thus is clearly evident; an inherent variability of ± 20 mm for femora and ± 15 mm for radii (with the other two bones between) should be visualized when average values are used, as below.

RELATION BETWEEN LINK AND LONG BONE DIMENSIONS

The preceding paragraphs bring out the dimensions of selected long bones for three stature levels, and show their variability, but these measurements still do not meet functional requirements. The need is to know mean link dimensions rather than bone dimensions. This obviously meant that correction factors had to be found so that humeral and femoral lengths could be suitably shortened and tibial and radial lengths lengthened.

The simplest type of correction would be expressed as a percentage of total bone length but this could not be assumed until it was known that the same ratios of link-to-bone length applied to all sizes of bones. To this end a series of measurements on bones and on their articulations was made.

Our study of instantaneous centers for joint rotation (Chapter IV) showed that centers of rotation shifted about over an appreciable range. For any joint, however, the centers were clustered over a definite area and it was possible to select a central point in this area as a mean center. Although the instantaneous centers in a cluster varied in location from joint to joint, each cluster was sufficiently localized relative to the articular contours that it was possible to superimpose data from different joints and select a representative mean point for each type of joint. Because of the small number of joints analyzed, the selected mean centers for the different types of joints were merely reasonable approximations.

After a "mean center" position had been located in the central region of the clusters for from 3 to 4 specimens of a joint, it was necessary to know what dimension should be added to or subtracted from a measured bone length to find its link dimension; since large and small bones were both involved, a single correction dimension for each joint center seemed inappropriate for this purpose. Consequently, the correction was related to the radius of curvature of the articular surfaces for bones of different sizes. Then with this new information correction factors expressed as percentage of bone length were applied.

To this end, a group of 25 humeri and 30 femora from the available osteological material were measured. These were selected from 150 samples of each bone; we attempted to obtain bones which, insofar as possible, were fairly evenly distributed for each centimeter of the range of bone length corresponding with statures of 1850 mm, 1750 mm, and 1650 mm, e.g., statures at the 95th, 50th, and 5th percentiles of the Air Force flying personnel (Figures 53 and 54). Values for radius of curvature of the humeral head, of the medial edge of the humeral trochlea, and of the femoral head, plus an average for the two femoral condyles, were made with the lensometer technique (Figure 1) for each bone.

Prior to these procedures, the articular curvatures were worked out by the evolute method for the articulations that had been used for joint-center determinations and the "correction distance" was matched with a radius of curvature of the same length. In this way an equivalent region of the curvatures of the different joints could be selected; measurements of radius of curvature made over this region on different bones, then, should give radii or curvature of the same length as the desired correction lengths. If the ratios between these correction lengths and total bone length were the same or nearly so for different bones, a fixed percentage of bone length could be taken as the link dimension.

The radii at each end of a bone were arbitrarily added and the ratio of the sum of the radii of curvature to total bone length was determined. The summated radii of curvatures of the articular faces of the femur, relative to total femur length, formed a straight-line relationship for various bone lengths; here a percentage correction was entirely feasible.

The smaller humeri, however, had slightly larger summated radii than the larger bones. The deviation lay more at the upper end than at the lower end of the humerus. Humeri corresponding to those of the 5th percentile of the Air Force flying personnel had, on the average, 0.6 percent larger radii of curvature than the 50th percentile bones; 95th percentile bones were 0.55 percent smaller. For humeral lengths in the range of interest (from 32 to 36 cm) these percentages implied a variability in link dimension of 2 mm, or less. In view of the range of variability of bone length relative to stature (Figures 53 and 54), this deviation was considered negligible. The assumption, then, that link lengths bear a constant ratio to bone length is a reasonable approximation.

Now that our data showed that femoral and humeral links could be determined by a simple percentage correction of bone length, it was necessary to work out corrections for the tibia and radius. In this instance distal femoral and humeral corrections should be added to bone length; further corrections must be added to allow for the distances to the ankle and wrist centers. Obviously, further procedures on bones from the same individuals were called for. If the principle of deriving link dimensions from bone dimensions by percentage corrections was carried further, approximations, at least, of the transpelvic link, clavicular links, and head and foot links can be developed.

With this end in view, 20 cadaver upper limbs and 15 lowers were dismembered and defleshed so that bone lengths and radii or curvature, using the lensometer technique, could be determined for the humerus, radius, clavicle, femur, and tibia. Hands and feet were also measured; for the former, a direct lunate-surface to midcapitate-head measurement served as a distal radius correction. The distance from the center of the head of the capitate bone to the average anatomical locus of the center of gravity of the hand (Chapter VII) was also measured on sawcut sections through the hands. For the foot a radius of curvature of the midsection of the trochlea of the talus was measured and used as a tibial correction factor; the distance of this point to the mean anatomical locus of the center of gravity (Chapter VII) was measured on sawcut sections.

Only three pelves with limbs attached were available for measurement of the transpelvic link. Percentage ratios of link and bone length were determined from these measurements. The ratios of one link length to another were also worked out. Table 7 presents these data and relates them to the dimensions of bones of the 95th, 50th, and 5th percentiles of the Air Force flying personnel. These link measurements have been used in the manikins of the next chapter.

Although these link dimensions should be reasonable estimates of mean dimensions for the selected groups, it should be recognized that the average individual is a nominal being. Limb bone lengths as indicated above, vary from +15 to +20 mm relative to mean dimensions; in given individuals, bones longer or shorter than average may be found in any of the limb segments. If the ratios to bone length hold, the variation in link length should be of the same general magnitude.

A link dimension, however, is not a static correlate with bone length; this is true only for mean dimensions based upon the mean-center position of joint axes. Actually, joint axes shift over a zone of probable location and a link may momentarily be longer or shorter than dimensions based upon mean centers. An additional range of +2 to 3 cm in link dimensions may be involved. Nevertheless, the nominal link dimensions as tabulated (Table 7) are approximations that should have practical utility in manikins. The approximate character of the dimensions should not be forgotten in the use of manikins. It is always well to keep an eye upon the functional postures and activity patterns of actual living subjects as a corrective to unduly rigid use of manikins. Data like those of Chapter VI on living subjects are apropos.

LINK DIMENSIONS ON LIVING SUBJECTS

As indicated earlier, links are kinematic entities concerned with the rotatory motions at joints; their dimensions cannot be measured directly from surface landmarks Approximate mean joint center positions can be estimated by the bending and testing of joints. Work with cadaver joints (Chapter II, Item 9) has indicated that a pin inserted into a bone may serve as an approximate center for part of the joint range, but it does not hold equally well for another part of the range. Our study of instantaneous joint centers has affirmed this. Nominal joint-center positions, however, may be laid off from these. A suggested pattern for locating such nominal joint centers on the living subject is as follows:

Sternoclavicular joint center.—Midpoint position of the palpable junction between the proximal end of the clavicle and the sternum at the upper border (jugular notch) of the sternum.

Claviscapular joint center.—Midpoint of a line between the coracoid tuberosity of the clavicle (at the posterior border of the bone) and the acromioclavicular articulation (or the tubercle) at the lateral end of the clavicle); the point, however, should be visualized as on the underside of the clavicle.

TABLE 7

ESTIMATION OF LINK DIMENSIONS OF AIR FORCE FLYING PERSONNEL BASED ON RATIOS FROM CADAVER MEASUREMENTS

	95th Percentile cm	50th Percentile cm	5th Percentile cm
Clavicle length (40.7% of biacromial width)	17.6	16.3	15.1
Biacromial width	43.1	40.1	37.0
Clavicle Link (86.4% of clavicle length)	15.2	14.1 (sternal end 26 mm from midline)	13.1
Scapula Link		±3.5	
Humerus length	35.9	33.9	32.1
Humerus Link (89.0% of humerus length)	32.0	30.2	28.6
Radius length	26.6	25.4	24.0
Radius Link (107.0% of radius length)	28.5	27.2	25.7
Hand length	20.4	19.0	17.6
Hand Link (wrist center to center of gravity) (20.6% of humerus length)	7.4	7.0	6.7
Transpelvic Link (37.2% of femur length)		17.1	
Femur length	50.3	47.5	44.3
Femur Link (91.4% of femur length)	46.0	43.4	40.5
Tibial length	39.9	37.2	34.5
Tibial Link (110.0% of tibial length)	43.9	40.9	38.0
Foot length (heel to toe I)	28.6	26.7	24.8
Foot Link (talus center point to center of gravity) (30.6% of foot length)	8.8	8.2	7.6
Vertical distance from midtalus to floor level		8.2	

Clavicular link.—The direct distance between the two joint centers listed above.

Glenohumeral joint center.—Midregion of the palpable bony mass of the head and tuberosities of the humerus; with the arm abducted about 45°, relative to the vertebral margin of the scapula; a line dropped perpendicular to the long axis of the arm from the outermost margin of the acromion will approximately bisect the joint.

Scapular link.—The distance between the centers of the foregoing mean claviscapular and glenohumeral joints—an unsatisfactory measurement—approximately 3.5 cm.

Elbow joint center.—Midpoint of a line between (1) the lowest palpable point of the medial epicondyle of the humerus, and (2) a point 8 mm above the radiale (radiohumeral junction).

Humeral link.—The distance between the glenohumeral and elbow joint centers.

Wrist joint center.—On the palmar side of the hand, the distal wrist crease at the palmaris longus tendon, or the midpoint of a line between the radial styloid and the center of the pisiform bone; on the dorsal side of the hand, the palpable groove between the lunate and capitate bones, on a line with metacarpal bone III.

Radial link.—The spanning distance between the wrist and elbow joint centers.

Center of gravity of the hand (position of rest).—A point on the skin surface midway in the angle between the proximal transverse palmar crease and the radial longitudinal crease in line with the third digit; flattening or cupping the hand changes the relative location of this point very little, except to change the position normal to the skin surface.

Hand link.—The slightly oblique line from the wrist center to the center of gravity of the hand.

Hip joint center.—(Lateral aspect of the hip). A point at the tip of the femoral trochanter 0.4 inch anterior to the most laterally projecting part of the femoral trochanter.

Knee joint center.—Midpoint of a line between the centers of the posterior convexities of the femoral condyles.

Femoral link.—Distance between the foregoing centers.

Ankle joint center.—Level of a line between the tip of the lateral malleolus of the fibula and a point 5 mm distal to the tibial malleolus.

Leg link.—The distance between knee and ankle centers.

Center of gravity of the foot.—Halfway along an oblique line between the ankle joint center and the ball of the foot, at the head of metatarsal II.

Foot link.—The distance between the ankle joint center and the center of gravity of the foot.

The points in the foregoing list, relating to joint centers and centers of gravity are approximations. Link dimensions measured in this way, however, give working data on the link system of the extremities. It should be feasible, also, to develop a series of plus-or-minus correction values involving standard anthropometric measurements. A few additional measurements, however, would be required, beyond those found in current tabulations, to provide a complete series of link dimensions.

Probably the most useful application of the information just presented would be in the analysis of photographic records of posture and movement. If nominal joint-center locations like these are understood clearly one can readily draw in joint-center locations on photographs. The information should also be of use in the study of frame-by-frame motion picture records. Relative link dimensions form a general check on the accuracy of pinpointing centers. The values of Table 8, following, give a breakdown of link ratios relative to length of bones or body parts.

RELATIVE ORIENTATION OF ADJACENT LINKS

The preceding sections of the present chapter have systematically explored a series of body features which are involved in the kinematics of the active individual. Trunk regions have been largely beyond the scope of our study but, for the limbs, the study has gained information on link dimensions of the limb segments, the character of movement at the major joints, and the range of movement allowed at each joint. These features are essentials for the synthesis of a manikin which will duplicate with reasonable accuracy the kinematic behavior of the living body.

One further point remains, however, before the information may be assembled into a workable whole. It will be remembered that the hand has 13 degrees of freedom relative to the trunk, and the foot 9 degrees. Each more distal joint in a limb system adds cumulatively to the range of the more proximal joint. For the hand to have a normal range of movement it is essential not only that the elbow and forearm joints have the correct type and range of motion, but that the orientation of the field of potential motion be correct also. How different the range of hand movement would be if the elbow bent backward or outward instead of inward and forward.

We need to know how each bone and link in a limb system is oriented relative to the adjacent parts proximally and distally before a comparable artificial system may be synthesized. Figure 55 illustrates the problem. Both a series of special dissections of the joints of the limbs and our skeleton-ligament preparation (Chapter II, Item 17) have been carefully studied to get this wanted information. What was needed were data on the relative angular orientation of each bone in a limb at some known position within the range of motion permitted by the adjacent joints. It was necessary to know for each sequence of two links: (1) spatial orientation of the proximal bone, (2) the relative orientation of the distal bone to the proximal for some arbitrary position, and (3) the range of motion permitted in each direction beyond the selected position of reference. In general, these features were studied joint-by-joint in a proximal-distal direction relative to the sagittal plane of the body. Methods relating to the lower limb, and then to the upper limb, are outlined in more detail below.

For the lower limbs the femur was the primary unit of reference; it was oriented simply by laying it on a table with the posterior parts of the condyle touching; in

TABLE 8

RELATIVE DIMENSIONS OF EXTREMITY LINKS

Expressed as Ratios of One Dimension to Another*

	Thigh	Leg	Foot	Arm	Forearm	Hand	Clavicular	Transpelvic
Thigh		(16:15) 107%	(16:3) 533%	(10:7) 144%	(8:5) 161%	(6:1) 625%	(3:1) 310%	(5:2) 255%
Leg	(15:16) 94%		(5:1) 500%	(4.3) 135%	(3:2) 150%	(6:1) 585%	(3:1) 290%	(7:3) 239%
Foot	(3:16) 19%	(1:5) 20%		(3:8) 27%	(3:10) 30%	(7:6) 117%	(4:7) 58%	(1:2) 48%
Arm	(7:10) 69%	(3:4) 74%	(8:3) 369%		(10:9) 111%	(13:3) 432%	(15:7) 214%	(7:4) 176%
Forearm	(5:8) 62%	(2:3) 66%	(10:3) 332%	(9:10) 90%		(4:1) 388%	(2:1) 193%	(8:5) 159%
Hand	(1:6) 16%	(1:6) 17%	(6:7) 85%	(3:13) 23%	(1:4) 26%		(1:2) 50%	(2:5) 41%
Clavicular	(1:3) 32%	(1:3) 34%	(7:4) 172%	(7:15) 47%	(1:2) 52%	(2:1) 201%		(5:6) 82%
Transpelvic	(2:5) 39%	(3:7) 42%	(2:1) 209%	(4:7) 57%	(5:8) 63%	(5:2) 244%	(6:5) 121%	

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*Figures in parentheses represent simple proportions, which figure to the approximate percentage values immediately below. Links listed in the column to the left are numerators; those of the transverse row are denominators. Hand-and-foot links terminate in centers of gravity of the segments.

this way an antero-posterior axis was determined. Next, when a perpendicular plane was placed so that it touched the distal ends of both condyles, an axis normal to the plane could be projected from the center of the head to the condylar region; now superior and inferior as well as medial and lateral axes were determined.

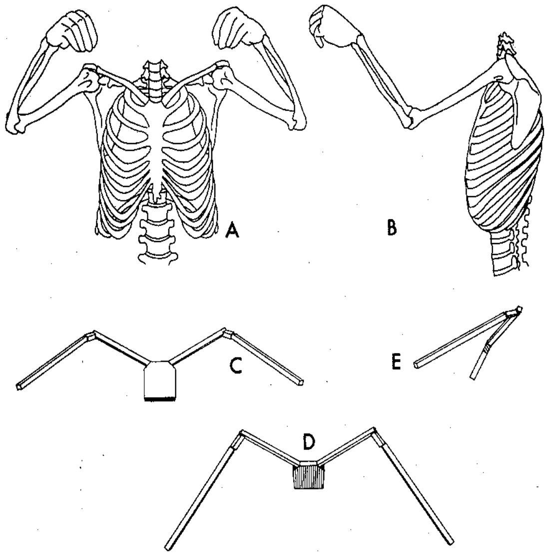

Figure 55. Midrange orientations of the upper limb bones and links. "A" and "B" show midrange positions of the bones for a skeleton-ligament preparation seen from the front and side. "C", "D", and "E" show a stick model of the humerus and girdle links as seen from the front, rear, and side.

The longitudinal axis from the center of the head fell 1.9 mm lateral to the anteriorly-projecting palpable tubercle lateral to the patellar articulation of the femur. A line from the center of the femoral head to the tubercle was 0°11' medial (range 3° medial to 1°35' lateral) to the longitudinal axis of the femur. When the transverse reference line, instead of contacting at the condylar ends of the bone, interconnected points of the two condyles which were in contact with the table surface, the amount of offset of the tubercle averaged 0°41' lateral (range 2°53' medial to 2°54') to the longitudinal femoral axis. From these measurements a line from the femoral head to the tubercle as seen from the front falls very close to the longitudinal femoral link axis.

When the longitudinal axes of the right and left femora were aligned parallel to one another, the transpelvic distance (transpelvic link) between the centers of the femoral head could be laid off between the distal projections of the axes. This distance was approximately 30 mm (the knuckle thickness of an outstretched hand; cf. Hertzberg, Daniels, and Churchill, 1954—thickness at metacarpale) more than the distance between the patellar tubercles. In the living subject the transpelvic link may be estimated by clamping the right and left knees against the knuckles of the outstretched hand and measuring the span between the projecting tubercles lateral to the patella.

With this background which determines the orientation of the femoral link, data from the globographic representation of Figure 47 may be applied; the vertical axis of the femur corresponds with the pole of the globe. Corrections based upon the abduction-adduction and flexion data on the hip joint from Tables 5 and 6 may also be transferred directly.

Next, when a stripped-down bone-ligament preparation of the lower limb was laid posterior surface down on a table top with the longitudinal femoral axis normal to the table edge and with the lower leg overhanging and flexed at the knee to 90°, the leg did not hang straight downward. Instead, it hung with the midankle region an average of 5° medial (10 measurements) to a vertical from the distal projection of the femoral axis. With the femur, leg, and foot so oriented, a horizontal platform was then raised until the foot sole just touched. Seen sidewise, the foot sole was 90° to the leg axis, i.e., parallel to the femur axis on the table top, but when seen from above the foot toed inward. The foot-sole axis from midheel to the head of metatarsal II averaged 8° of adduction relative to the long axis of the femur.

Six living subjects were checked for range of movement of leg rotation. They sat with their two femora horizontal, with the knees separated by a knuckle width, with the leg segments tilted slightly inward from the vertical and with a turntable below the foot centered at the ankle. The amount of medial and lateral knee rotation was measured (1) by the change in position of the foot axis (the initial position of the axis of foot reference was 8° adducted relative to the longitudinal femoral axis), and (2) by a pointer clamped to the leg bones at the ankle. Different amounts of rotation were shown by the two methods.

Leg bone rotation averaged 24° laterally and 20° medially while the leg plus foot abducted 45° and adducted 31°. The former values are comparable to those of the globographic plot of Figure 48 showing knee rotation and the latter were comparable to those of Table 5 derived from living subjects. Movement (1) thus was a composite motion involving both knee rotation and foot adduction or abduction. The latter measurement was recorded as "knee rotation" in Tables 5 and 6. The ankle, in the strict sense, has but one degree of freedom, but the tarsal joints beyond have three (Manter, 1941; Hicks, 1953); the latter were clearly involved in the composite knee-foot movement. If the 8° foot adduction value is added to that for lateral rotation of the knee and subtracted from the medial rotation value, corrections relating to the natural position of the foot would be 51° lateral rotation and 27° medial rotation when the foot and knee are both concerned; the angles are 32° and 12° when knee rotation alone is related to the natural foot position (8° adduction). The flexion-extension range at the ankle was taken directly from Tables 5 and 6.

The above procedures gave values of the sort needed; thigh, leg, and foot orientations were defined for a fixed posture in which the foot and thigh axes were perpendicular to the shank axis. In addition the range of movement at the hip, knee, and ankle were keyed into these reference positions of the bones. An artificially-articulated system of links interconnected by joints having the proper degree of freedom and the proper range of movement should show the same quality and range of kinematic behavior as the body structures. The practical synthesis of the next chapter will show these data applied.

A more complicated system is found in the upper limb where there are more links, more joints, and more degrees of freedom. The system, however, may be treated in two units; since the elbow has but one degree of freedom it may be arbitrarily fixed at some position in its range—say 90°—and the orientation of more proximal and more distal bones may be considered separately.

In the ordinary standing posture the position of rest of the clavicle and scapula may be standardized and their ranges of movement may be considered in relation to these postures; similarly, humeral position may be defined and its range of movement may be considered in relation to this orientation of the shoulder girdle. Then the more distal parts may be treated.

In the rest position of the clavicle, its upper surface from front to back may be taken as horizontal; from subject to subject, the lateral end may be above (rarely below) or horizontal to the sternal articulation in the position of rest. The mean clavicular link, however, ends below the clavicle on the undersurface of the bone between the coracoid process and the acromio-clavicular articulation (Figure 40). Accordingly, a horizontal clavicular link orientation has been considered as standard here. Its backward slant was taken as 30°.

When the scapula lies against the posterior base of the thorax with its vertebral margin vertical, as seen from the rear, the inferior angle is tilted backward about 10°, and the transverse section of the blade is approximately 40° to the coronal plane. The glenoid fossa looks outward and forward relative to the body and it faces upward 67-1/2° to the vertebral border (Harrower, 1924). A normal to the glenoid fossa, however, is not quite in the plane of the scapular blade. Figure 56B shows an angle "Y" which implies that the glenoid fossa faces even more outward (average 5-1/2°) relative to the blade of the scapula.

In its position of rest the central and lower region of the articular face of the humeral head contacts with the glenoid fossa. In this position relative to the scapula the lesser tubercle faces almost directly forward (Figure 56B). Figure 56A looks downward along the longitudinal axis of the humerus; the transverse line represents a normal to the glenoid fossa (or midpoint of the humeral articular contour). The slightly oblique dashed line (16° off the transverse line) represents the mean axis of the humeral condyles. Krahl (1947) has shown this torsion angle of the humerus (expressed as the shaded angle of the figure); it averages 74° in the adult. What is more pertinent functionally, however, is the angle between the plane of elbow bending (i.e., normal to the elbow axis) and the normal to the glenoid fossa—an angle which, according to Krahl's data, averages 106° (Figure 56A). When the elbow is bent 90° to the humeral axis the styloid process of the ulna lies lateral to the normal to the elbow axis as determined by Krahl; that is, the shape of the ulna and the set of the sigmoid fossa relative to the length of the bone is such that the bone points laterally by an angle "X" (±15°).

In the globographic presentation of elbow movement (Figure 45) the zero meridian corresponds with a plane defined by three points: (1) center of the humeral head and the styloid process (2) when the elbow was straight and (3) when it was bent to 90°. If the globe were to be oriented correctly to the selected neutral position of the scapula (above) it should be rotated so that the 0° meridian falls some 15° lateral to the position shown.

The heavy line of Figure 56B representing the normal to the glenoid fossa will serve as a reference for humeral movement. Flexion-extension movements of the humerus relative to the scapula may be treated as though this line formed a hinge axis; in the humeral movements shown by Shino and Pfuhl (Figure 37) pure flexion-extension movement of the humerus about this axis would be in the plane of the paper. Pure abduction-adduction movements are away from the paper surface or toward or beyond it. Medial and lateral rotation, as read from Tables 5 and 6, may be taken directly as a measure of movement about the humeral link relative to a reference meridian which corresponds to the plane of elbow flexion and extension; it should be noted, however, that those values were taken with the humerus horizontal for subjects that were seated.

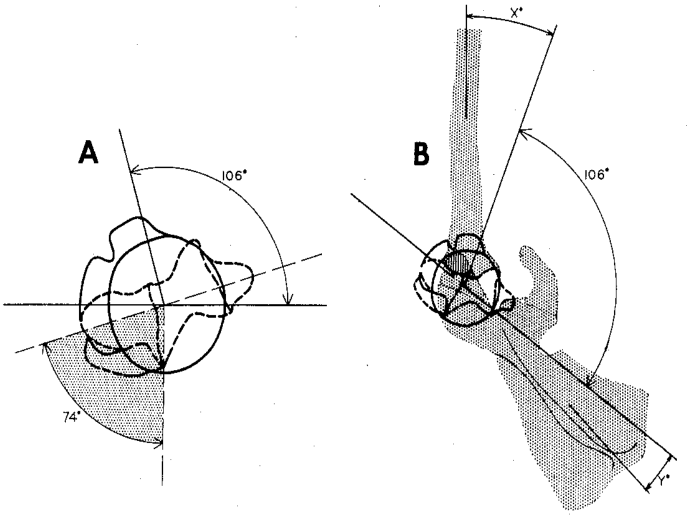

Figure 56. Relative orientations of glenohumeral and elbow axes. "A" shows the vertical view of the head and tuberosities of the humerus (solid outline) and elbow region (dashes) showing 106° angle between normals to joint axes. "B" depicts the same relation but with shaded scapular and ulnar contours added, showing the amount of offset of bone axes (angles X and Y) relative to normals to joint axes.

We come now to scapular movements relative to the clavicle. Five stripped-down, articulated preparations of the shoulder joints provided material; the clavicles were held horizontally in a vise and the zero reference position of the scapula was such that its vertebral border was vertical as seen in a direction normal to the blade; the angle of the blade to the clavicle, as seen from above, was taken as a nominal 70°, an angulation corresponding with the set of the clavicle to the scapular blade in the rest position (cf. above). The line of attachment of the coraco-clavicular ligaments to the clavicle has an average angle of 35° to a line through the length of the bone (Figure 40). Accordingly, the line of ligament attachment is directed 5° anterior to the coronal plane of the body for the rest position of the shoulder girdle. Scapular rotation in a plane normal to this line was measured for displacements forward and backward to the assumed rest position; these movements were termed scapular flexion-extension. Movements of scapular abduction-adduction about a fore-to-back axis were perpendicular to these; the terms scapular medial and lateral rotation were applied to twisting movements about a vertical axis. Abduction-adduction movements were measured in a vertical plane through the line between the coracoid tubercle and the acromio-clavicular joint; inward and outward rotations were measured in relation to a vertical axis through the clavi-scapular joint; these measurements were:

Flexion-extension	40°
Abduction-adduction	30°
Medial-lateral rotation	15°.

The remaining joint of the upper section of the upper limb system to be oriented relative to its range of movement was the sterno-clavicular joint. From the measurements made on several living subjects (Figure 39), the position of rest was located and the amount of elevation, depression, protrusion, retraction, and upward rotation was determined. These points were also checked on girdle-joint preparations including the whole skeleton-ligament preparation. From these data an elevation of 44°, a depression of 8°, protrusion of 15°, retraction of 18°, and upward rotation of 40° was regarded as a fair estimate of normal range relative to the rest position. Inman, Saunders, and Abbott (1944), using pins drilled into clavicles of living subjects, measured and plotted maximum upward rotation of 45°; their illustrations of subjects with the arm vertically overhead show rotations in the 30 to 40° range. Clavicular elevation associated with arm raising was roughly 30°; further forcible elevation of the clavicles and shoulders, however, is possible.

Figures 55A and B show the midrange position of the girdle and upper limb joints as seen on our skeleton-ligament preparation; midrange rotations for each of the axes at each joint were determined and the parts were then wired in place. The sketches were based on both photographs and tracings made on translucent sheets of plastic laid over the ground glass of a camera. Sketches C, D, and E show the midrange positions of a stick model showing the manubrium of the sternum, the clavicular link, the scapular link, and the humeral link; the surfaces of the square sections represent surfaces which in the position of rest faced directly forward, backward, upward, downward, or medially and laterally.

When the humerus is vertical and the ulna is bent to a horizontal position the angular range of movement of the radial styloid in pronation and supination may be measured. Our measurements upon the pronation-supination movements of our various study subjects (Table 5) are apropos; in these the rotation of a hand grip had been measured. A check upon several of these subjects later showed that the line of the hand grip seen end-on to the forearm was supinated 14° more than a line passing between the radial and ulnar styloids. This value subtracted from the supination average and added to the pronation measurement gave a pronation-supination range for the forearm relative to the humerus. These corrected values were: 99° supination and 91° pronation.

Flexion-extension measurements of the wrist taken directly from Table 5 and 6 represent angulation of the palmar plane; abduction-adduction measurements were normal to this plane. This plane of reference is comparable to the grip angle. Longitudinal sawcut sections made through cadaver hands normal to the palmar plane showed that an angle of approximately 23° exists between the palmar plane and a line from the head of the capitate bone to the mean anatomical location of the hand center of gravity for the rest position. The latter line was earlier regarded as the axis of the hand link. When this angle was added to the flexion range and subtracted from the extension range the range of movement of the link could be expressed. The comparable correction for abduction-adduction was negligible since the line of reference for measurements of range of motion was the third digit; this line was very close to the hand center of gravity.

The above data on the orientation of bony members to one another with concern for the range of motion of each should provide the requisite information to allow the assembly of links into an artificial system that will be kinematically similar to the body system.

In the next chapter such an artificial system will be presented. It will be apparent from the data of the present chapter that the background information for the construction of an artificial system is irregular; in some instances average values were based upon many data, in others only a few measurements were available. In no case, however, were data derived from only one or two specimens. Thus, it is highly unlikely that aberrant joint relations were unduly emphasized. The aim in the present study of joint mechanisms, like that in anatomical work generally, has been to derive information that relates to "typical" or "normal" individuals; to the extent that this has been successful, the kinematics of the linkages should approximate reasonably the motions observed in a typical normal subject. The derived link and joint system, since it is based upon averaged data, will itself show an individuality that may not correspond entirely with that of some given individual or selected group. The construction of actual linkages, however, will provide a test system which can be compared kinematically with the range of motion observed in actual subjects to see in what areas, if any, it falls down.

The joint range data utilized in the present study were derived from both cadaver joints (shown in the globographic figures) and living subjects under specifically defined conditions. In general, the ranges of movement were less limited than if the basic data had been obtained under other conditions. For instance, wrist flexion and extension were measured with the hand flat; had the hand been doubled as a fist both values would have been notably smaller. Hip flexion would have been less had the knee been kept straight during the measurement. Shoulder and ankle range data could have been less also under the influence of muscle tensions if the measurements had been planned for different extremes of bending or straightening at the adjacent neighboring elbow and knee. Clothing could have further restricted most of the ranges. Although data on both maximal and restrained ranges should have pertinence for applications to manikins we do not have quantitative data for the restricted ranges.

CHAPTER V

APPLICATIONS TO MANIKIN DESIGN

This chapter is directed primarily to the design engineer. The kinematic information about the body, outlined in the preceding chapter, will here be synthesized into constructions which, insofar as feasible, duplicate the dimensions and movements of the average individual. Since the trunk was not specifically a subject of this investigation, the data presented must emphasize limb mechanisms, our primary subject for study. Furthermore, since the investigations were primarily directed to the kinematics of the seated individual, this factor will dominate our manikin designs. That is to say, the designs as presented cannot be fully realistic for standing, prone, and kneeling postures, or for other positions than the seated. The reason is that we simply do not have the necessary dimensional and kinematic data on the trunk for a correct universal manikin.

Our data on the limb mechanisms, of course, should be capable of transfer to a universal manikin, if equally good data were to become available at a later date. Rough approximations relating to the trunk system, such as the link system of Figure 32 or the linkages of the Alderson (Mark III), Swearingen (Elmer), or the Air Force (Sierra Sam) manikins are all that can be expected for general posture dummies—except, of course, for the seated position—until further functional data are assembled.

The information now at hand will permit the construction of a three-dimensional manikin, which should be kinematically correct, insofar as the limbs are concerned. The type of joint movement and the angular range of movement seen in our data should be appropriate for the white male population in general but, since no data are available, precise quantitative data on joint range cannot be assigned for any selected military group. The link dimensions that have been utilized correspond with a specific population—the Air Force flying personnel. Any other set of link dimensions could be adapted instead, if it were desired to match some other population.

McFarland (1953 a and b) has clearly pointed out that average body dimensions of a population have little or no practical meaning. The practical problem to be faced is the effective fitting of clothing, utensils, or the work space to the largest possible number of individuals in the population. Thus, in an airplane cockpit or in the driver's compartment of a land vehicle, the smaller individuals should be able to reach controls conveniently, and the larger individuals should not be restrained or inconvenienced by insufficient or crowded quarters. Clearly, if manikins are to have significance in design, there must be different sizes to represent the large men and the small. The mean may or may not have comparable significance. It was Darcus and Weddell (1947) who first proposed the defining of large and small men in terms of the percentile distribution of significant body measurements.

Since percentile data are now available on military populations (Hertzberg, Daniels, and Churchill, 1954), the 10th and 90th or the 5th and 95th percentiles of a population represent reasonably significant small- and large-sized-body dimensions. In the first instance, 80% of the population will be included between the extremes; in the second, 90% are included. Individuals with extra-large or extra-small dimensions form a very small segment of the population; they are simply excluded from consideration in this system. Where installations based upon percentile dimensions are utilized, men with extra-large or extra-small body measurements would be assigned to some alternate service where their body sizes would be of no consequence. For the present constructions, dimensions roughly comparable to the 95th, 50th, and 5th percentiles of the Air Force flying personnel are used. These correspond to men having statures of 72.8 inches (185 cm), 69.2 inches (175 cm), and 65.0 inches (165 cm).

Two types of manikins are presented. The first is a three-dimensional construction, emphasizing the limbs. In the second, the manikin is a two-dimensional, sagittal-plane design, which can be placed on a drawing board. This manikin is an articulated system that can be placed on a drawing board and which will permit adjustments of the body segments to correspond with a number of different postures. The latter was actually constructed at one-fourth scale; joint-center positions and stops were provided, so that movements in the sagittal plane could be duplicated. Large-, medium-, and small-sized body dimensions were considered in the design of the sagittal plane models.

The three-dimensional model purports to represent accurately link dimensions and all movements found for the major joints during life. Plans have been drawn up and an actual life-size model of each joint has been machined to serve both as a test of functional accuracy and as an object for illustration. This model was never intended as more than an attempt to present to engineers in their own language a type of construction which will very closely approximate the movements of the body members. In the body, bones, joints, and ligaments do this in unique ways because of their anatomical arrangement. The engineer must work with different materials and with standard methods of shaping and fashioning them.

The body does not have pin-centered joints, universals, gimbals, or templates. Our constructions, using these features, show dimensions and a type of mechanism which duplicate reasonably well the range of movement found in the body members—nothing more. There may never be a call for a duplicate model of such limited function. The engineer may, however, wish to approximate, simplify, compromise, or duplicate various parts, according to his purpose. He may want to redesign with friction joints or with concern for the strength of parts; he may need to load parts in special ways. Our data on the mass of body segments (Chapters VII and VIII) may have pertinence in the latter respect. The illustrations and plans presented here attempt to solve no such special mechanical problems. In the following pages, plans and specifications will be given for both the three-dimensional and two-dimensional designs.

THE THREE-DIMENSIONAL MODEL

Upper and lower limb links were constructed of square section aluminum rod, and interconnecting joints were machined as the movable elements. The flat faces of the square section rod were oriented so that in the rest position they were directed parallel to some cardinal plane of the body. The joints consisted of centered mechanisms such as hinges, rod and sleeve joints, and universals; the range of movement was controlled by end stops or by metal guides or templates which limited movement to specific angular ranges. Figure 57 shows the general plan for assembly. Mean length dimensions shown in the figure relate to average-sized men (i.e., 50th percentile of the Air Force flying personnel), large men (95th percentile), and small men (5th percentile). All dimensions were measured from joint center to joint center. The general character of the several joints is indicated in the figure also.

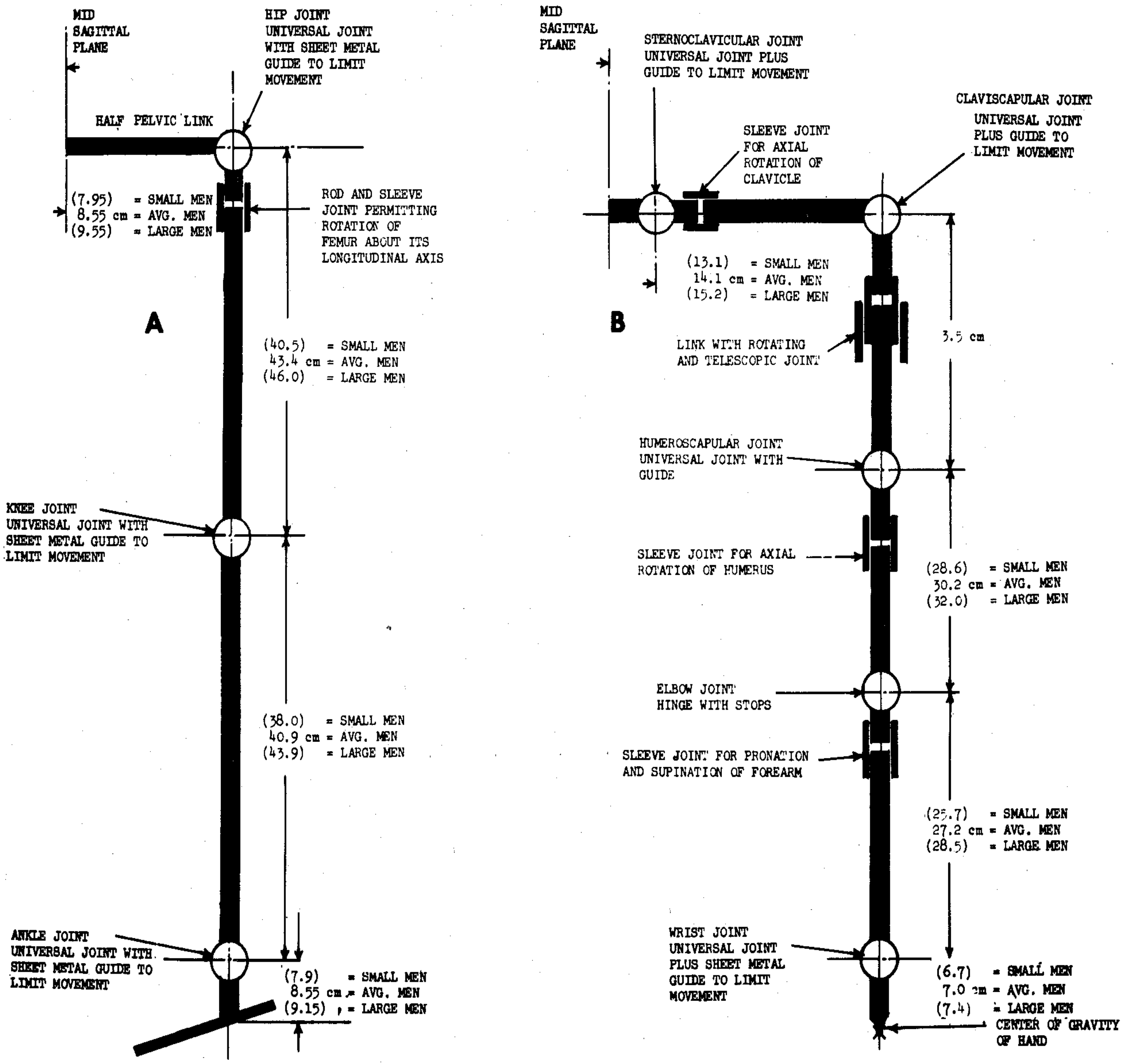

Figure 57. General plan of linkage assembly for the lower (A) and upper (B) limb systems.

For the construction of an actual model of the limb system only the dimensions of the fiftieth-percentile group were utilized. Plans and photographs based on this model are included below. Alternate dimensions for the small or large men or for any other body proportions might readily have been substituted in connection with the joints shown.

The ranges of movement permitted by each joint were carefully geared to the amplitudes shown by globographic data presented earlier; the globographic records, however, were ordinarily taken as qualitatively correct first approximations which were modified by the substitution of quantitative data on range derived on the study subjects (Tables 5 and 6). The orientation data of the final section of Chapter IV were applied to assure that the field of joint range of each joint was directed properly relative to the more proximal and more distal links.

Figure 58 illustrates the general appearance of the various upper and lower limb joints as constructed for the model, and Figures 59 through 69 show detailed plans for their construction. Only joints for the left side of the body are figured. The joints were designed as hinges, rod and sleeve joints, universals, or as joints involving both a universal plus a rod and sleeve joint. Most of the joints were planned to give more than a sufficient range of motion and a guide or template properly oriented, was added to limit motion to fixed amplitudes. Hinges or rod and sleeve joints simply had terminal stops at proper positions relative to joint range; for bi-axial joints sheet metal plates with a central cut-out were set across one end of the universal joint. These templates permitted a range of free motion within the limits of the cutout; the margins of the templates and their relations to the joint center defined a joint sinus. The distance from joint center to sheet metal margin and the shape of the cut-outs were critical in the duplication of a range of motion comparable to that shown in globographic representations of joint range.

NOTES CONCERNING JOINTS AND LINKS

(1) Sternoclavicular joint: A universal joint was set transversely with its inner or sternal end normal to the body mid-plane; its support represented the upper portion of the manubrium of the sternum and the joint center was one inch from the side of the midplane. Between the center of the universal and the sheet metal guide a rod and sleeve joint permitted additional rotation about the axis of the clavicular link. Suitable stops corresponding with the range of upward and downward rotation of the clavicle were built in.

(2) Claviscapular joint, scapular link, and gleno-humeral joint: These three components were planned as an integral unit. The claviscapular joint permits three degrees of freedom of movements of the scapula with respect to clavicle; a universal joint duplicated these movements in two axes normal to the scapular link. The additional rotation about the longitudinal axis of the link was built into a telescoping rod and sleeve joint. The distal end of the telescoping link moved over a flat surface placed obliquely in the joint unit and its range of motion was controlled by a template. The socket in which the humerus sits is a part of the scapula. If one considers the movement of the geometrical center of this socket with respect to the clavicle the point actually moves on a surface which has a very slight curvature (Figure 40). Since the error introduced is small, the slight curvature was replaced with a plane and the center of the gleno-humeral (humerus-scapula) joint traveled over this. The construction of a telescoping scapular link was a necessary compensation because of this plane. Since, as intimated, the link also rotated about its axis, this feature was also included.

At the end of the scapular link was the center of the gleno-humeral joint which represented the movement of the humerus with respect to its socket on the scapula. This movement was provided for by a universal joint and its angular limits were assured by an attached sheet metal guide with a central cut-out. In this instance, the universal joint was a gimbal to permit an adequate range of motion. Beyond the gimbal was a rod and sleeve joint to permit an axial rotation of the humeral link. Each joint (claviscapular and gleno-humeral) thus had three degrees of freedom.

(3) Elbow joint: This joint was a hinge with terminal stops to limit motion at each end of the range of movement.

(4) Forearm joints: Beyond the elbow joint proper, a rod and sleeve joint with suitable stops provided for pronation-supination movement of the forearm link and regions beyond.

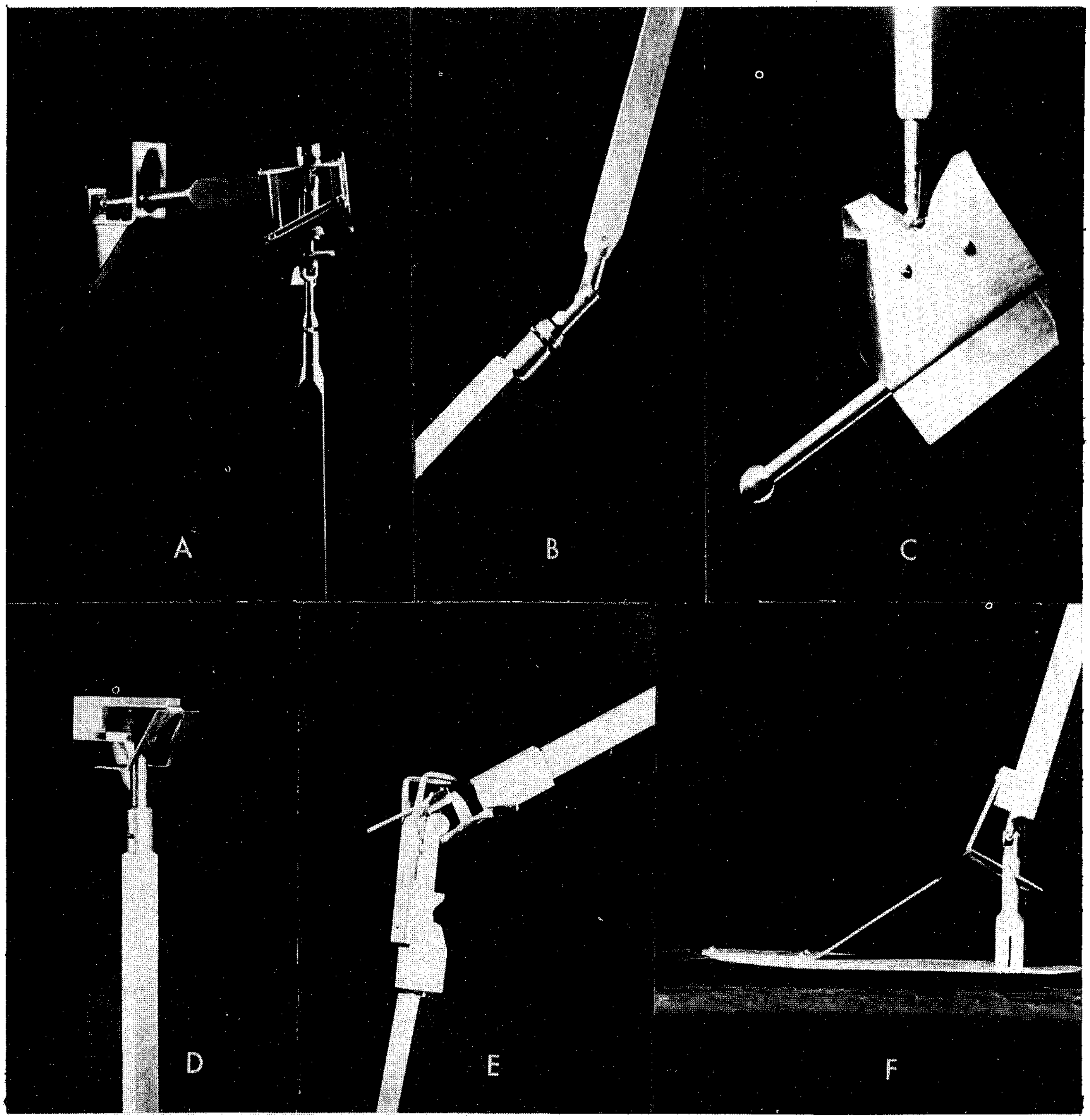

Figure 58. Photographs of machined joints of the upper and lower limbs. A-sternoclavicular, claviscapular, and glenohumeral joints. B-elbow hinge and forearm sleeve joints. C-wrist universal joint with hand shape and grip axis. D-universal and sleeve joint of hip assembly. E-knee joint. F-ankle universal and foot assembly.

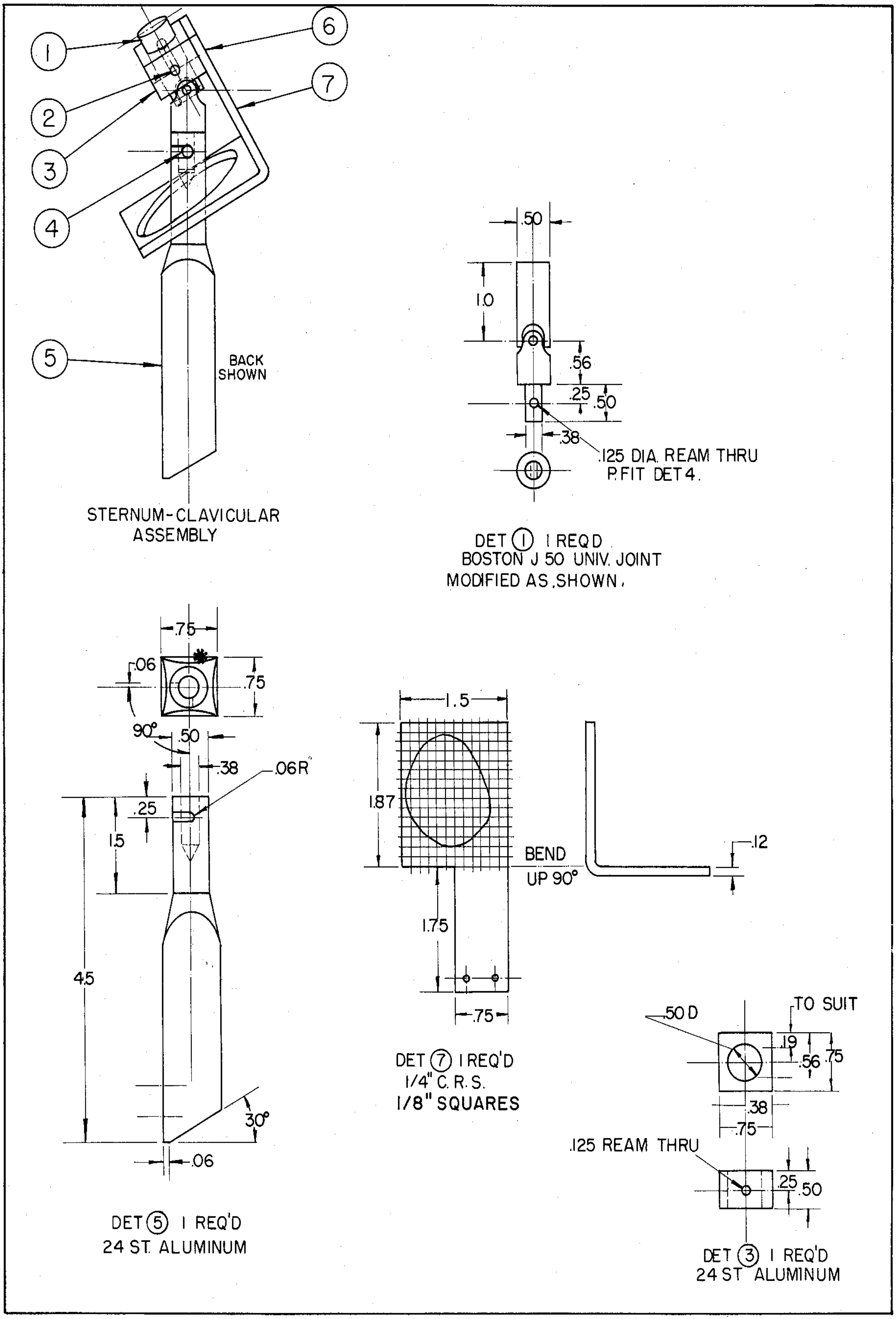

Figure 59. Plan for model of sternoclavicular joint.

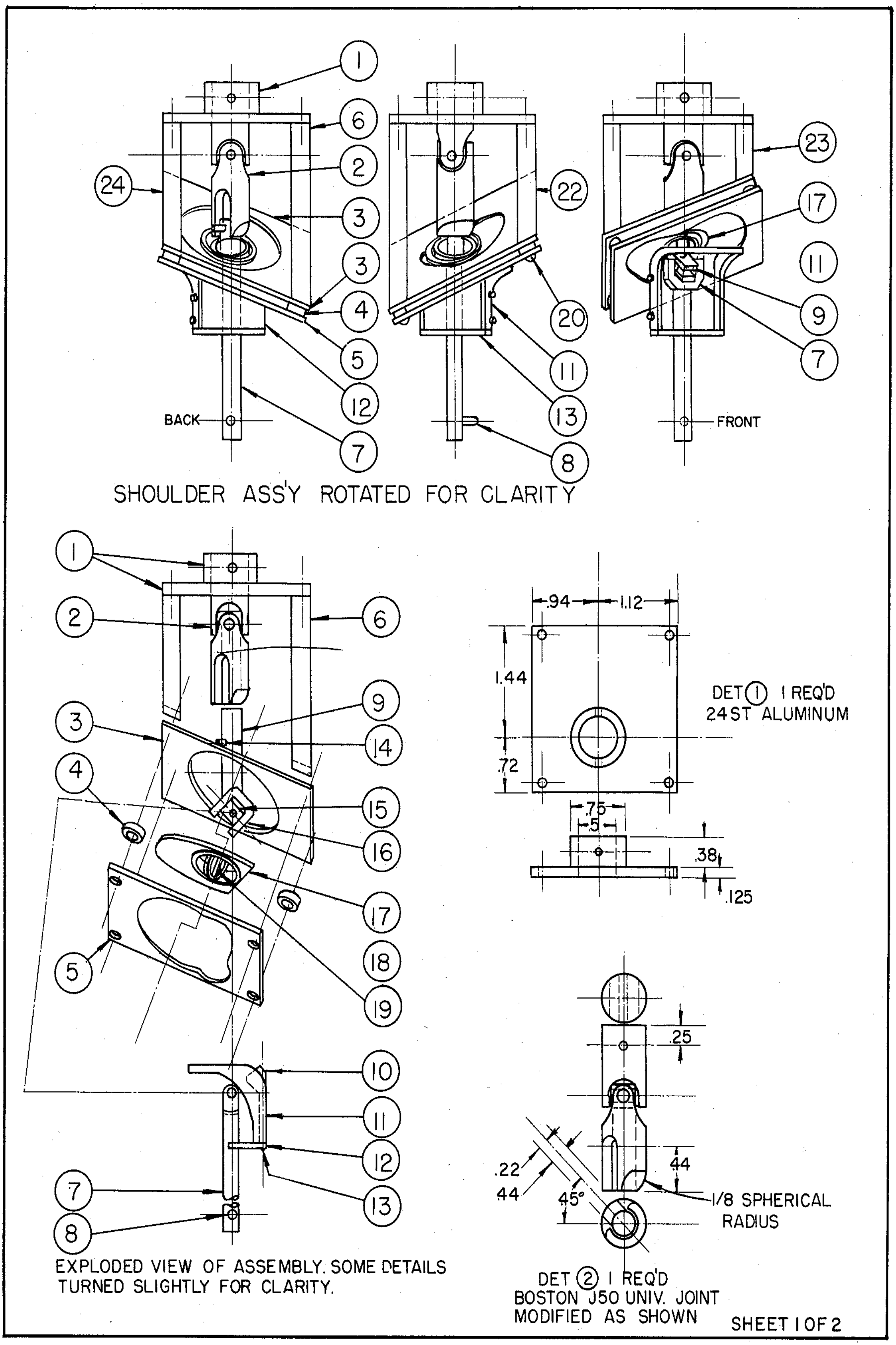

Figure 60. Plan for model of combined shoulder joints.

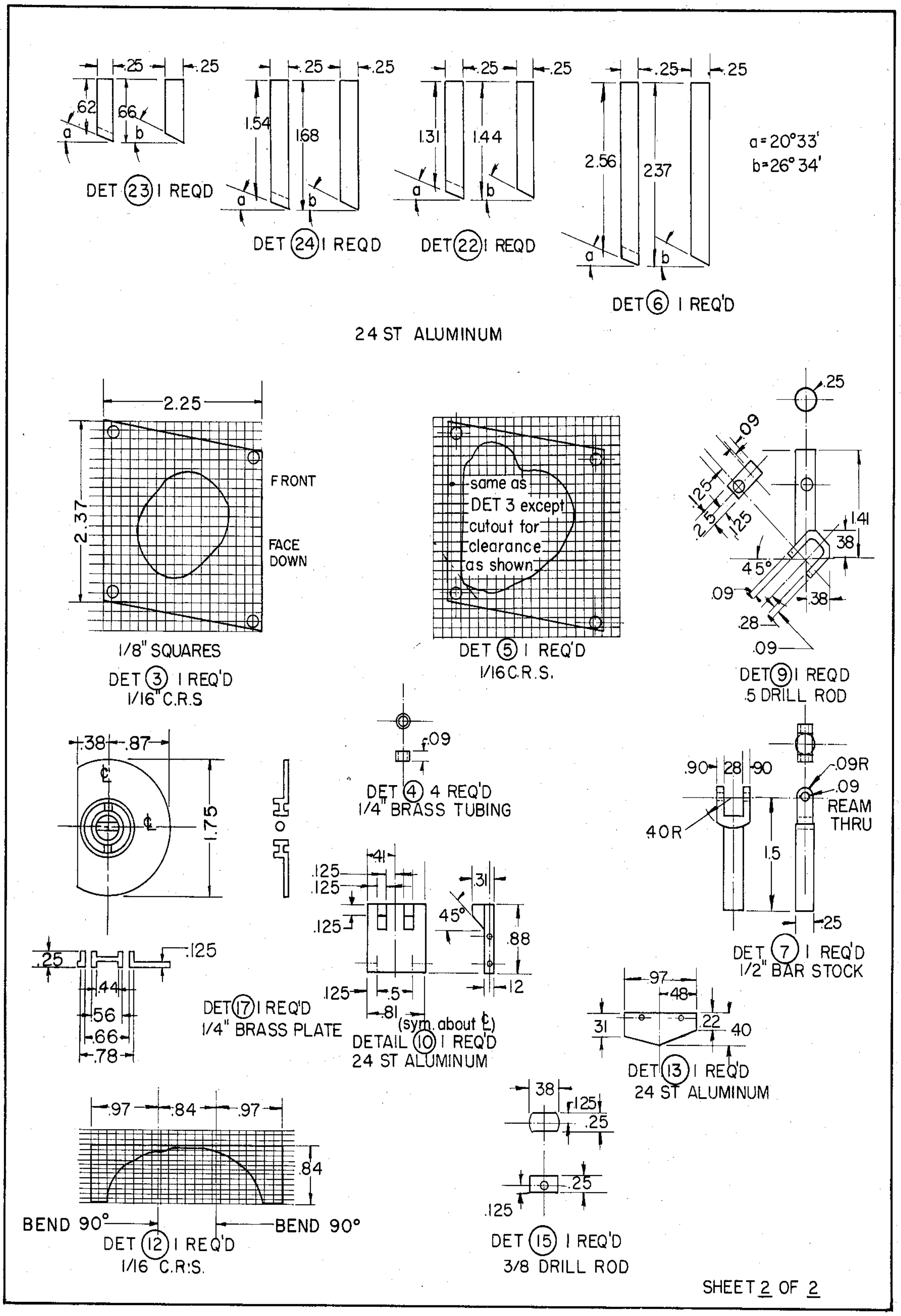

Figure 61. Details of plan for shoulder joint.

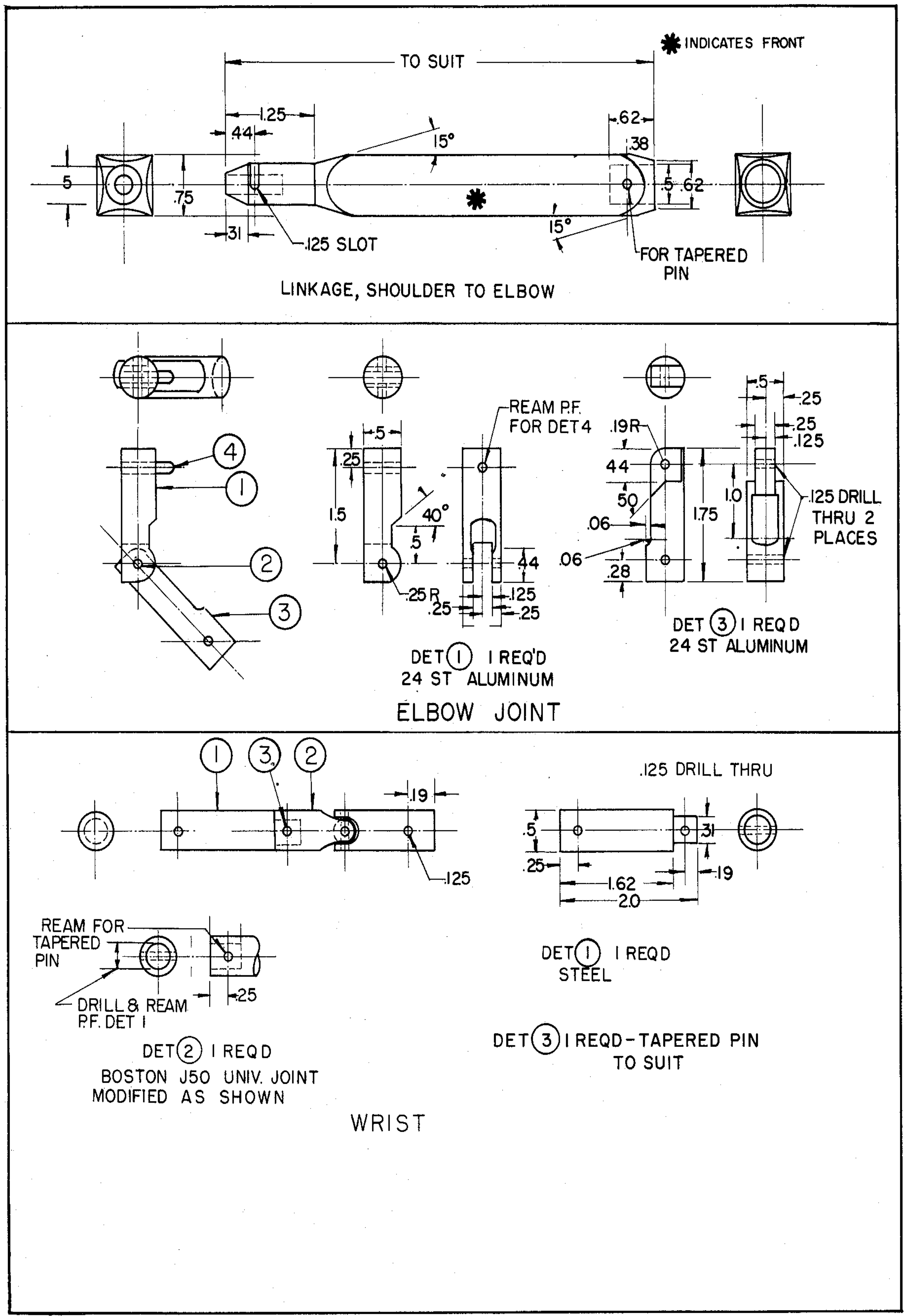

Figure 62. Plans for arm link and for elbow, forearm, and wrist joints.

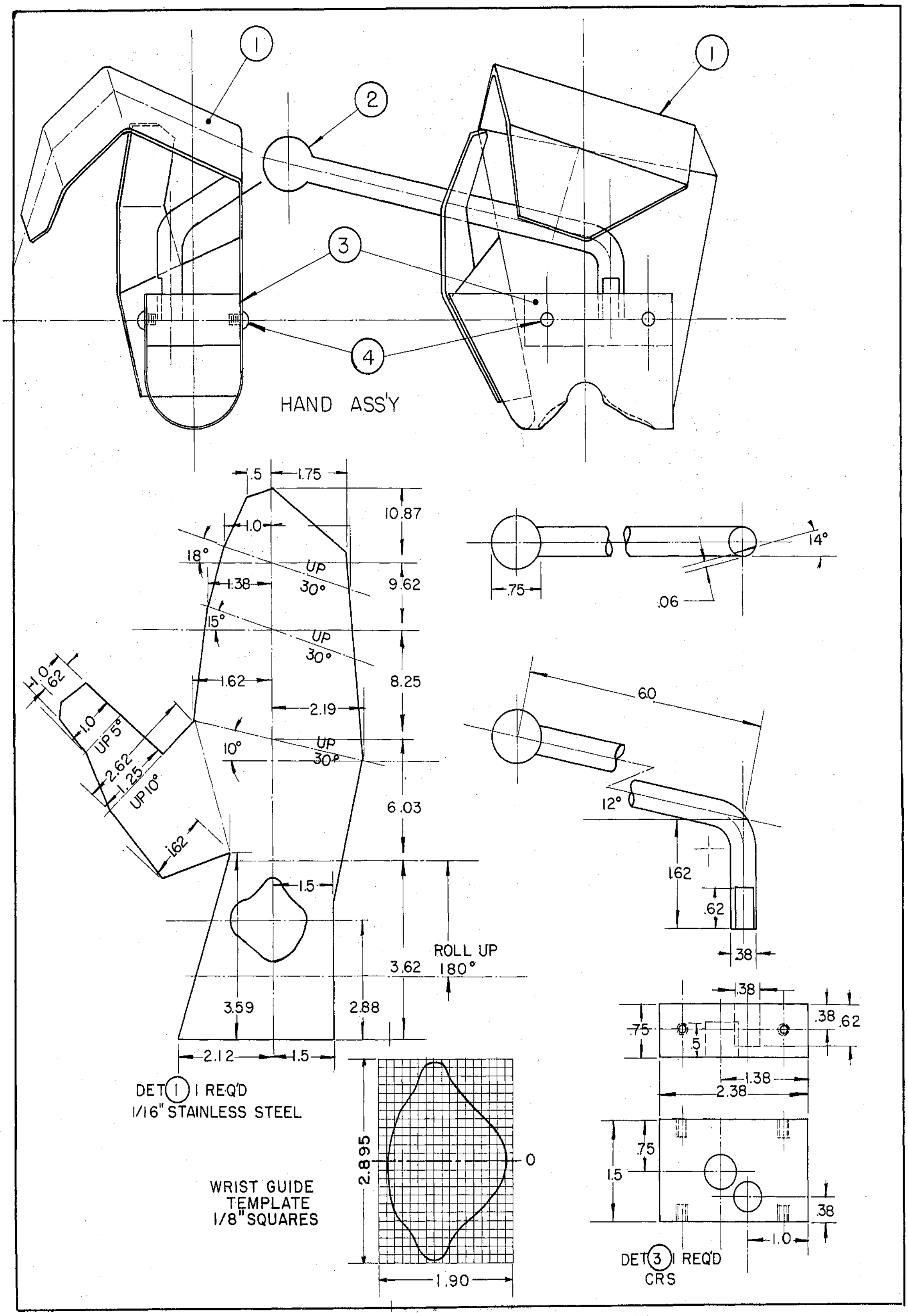

Figure 63. Details of plans for hand and wrist joint assemblies.

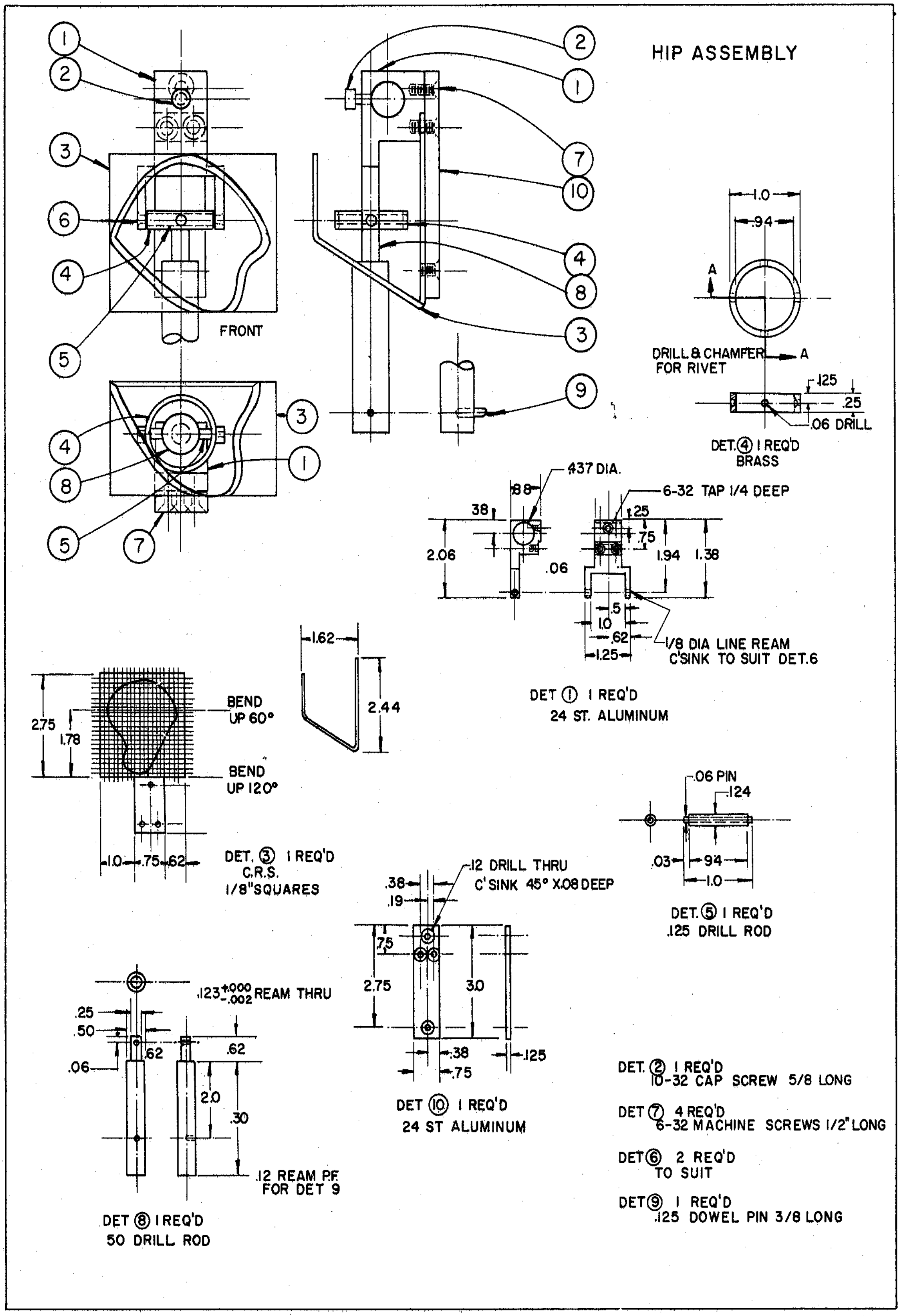

Figure 64. Plan for hip joint model.

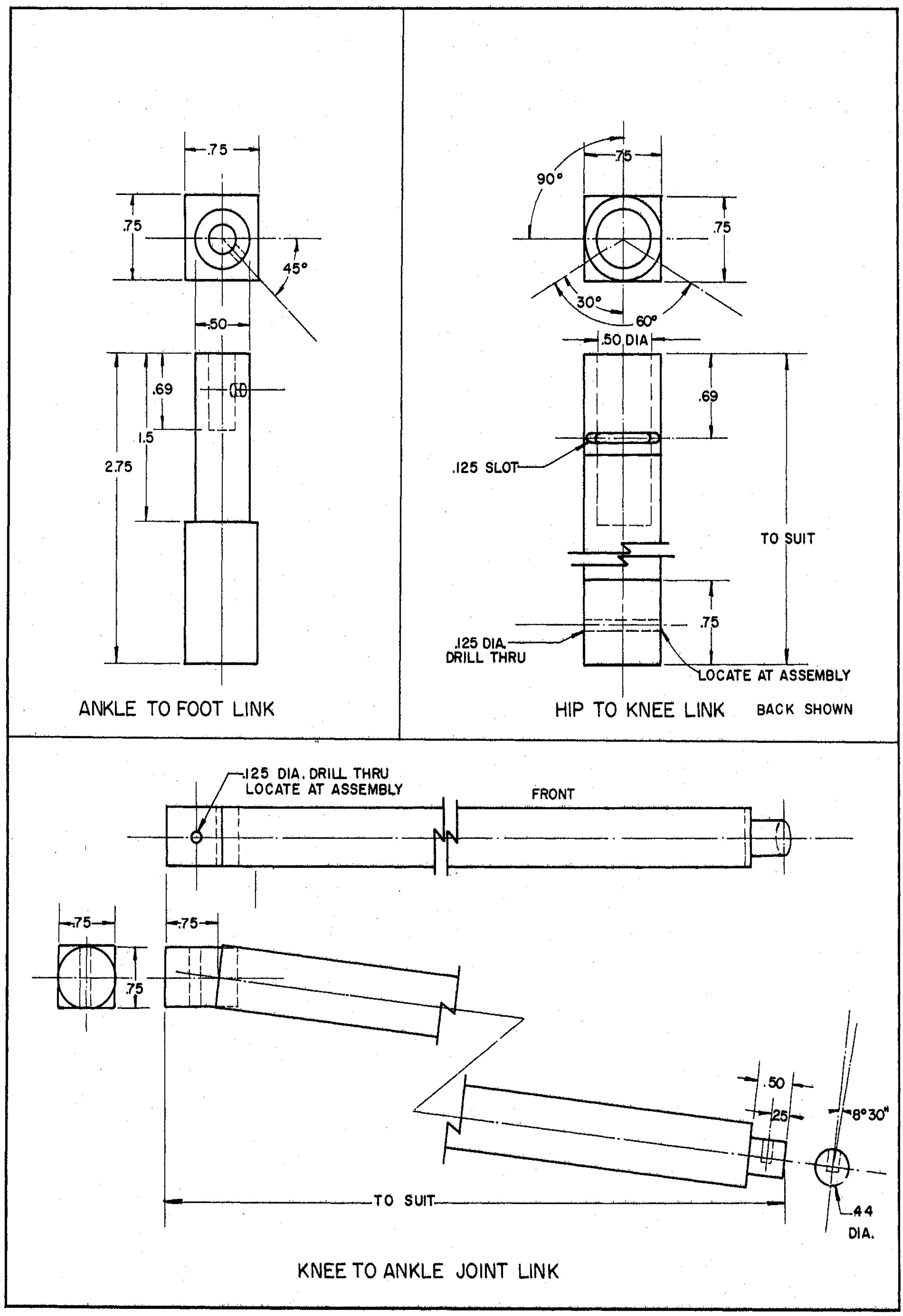

Figure 65. Plan of lower limb links for models.

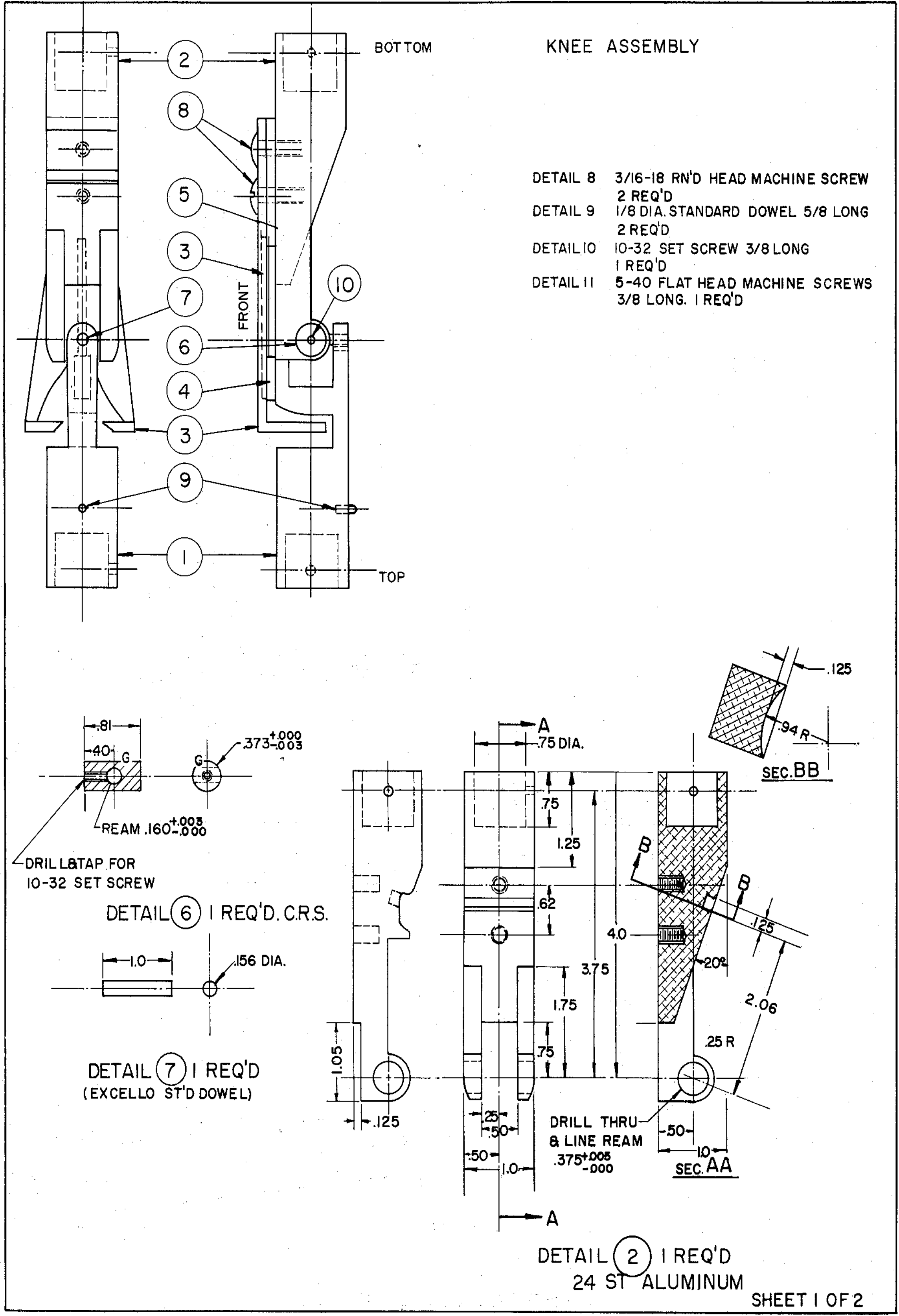

Figure 66. Plan for knee joint model.

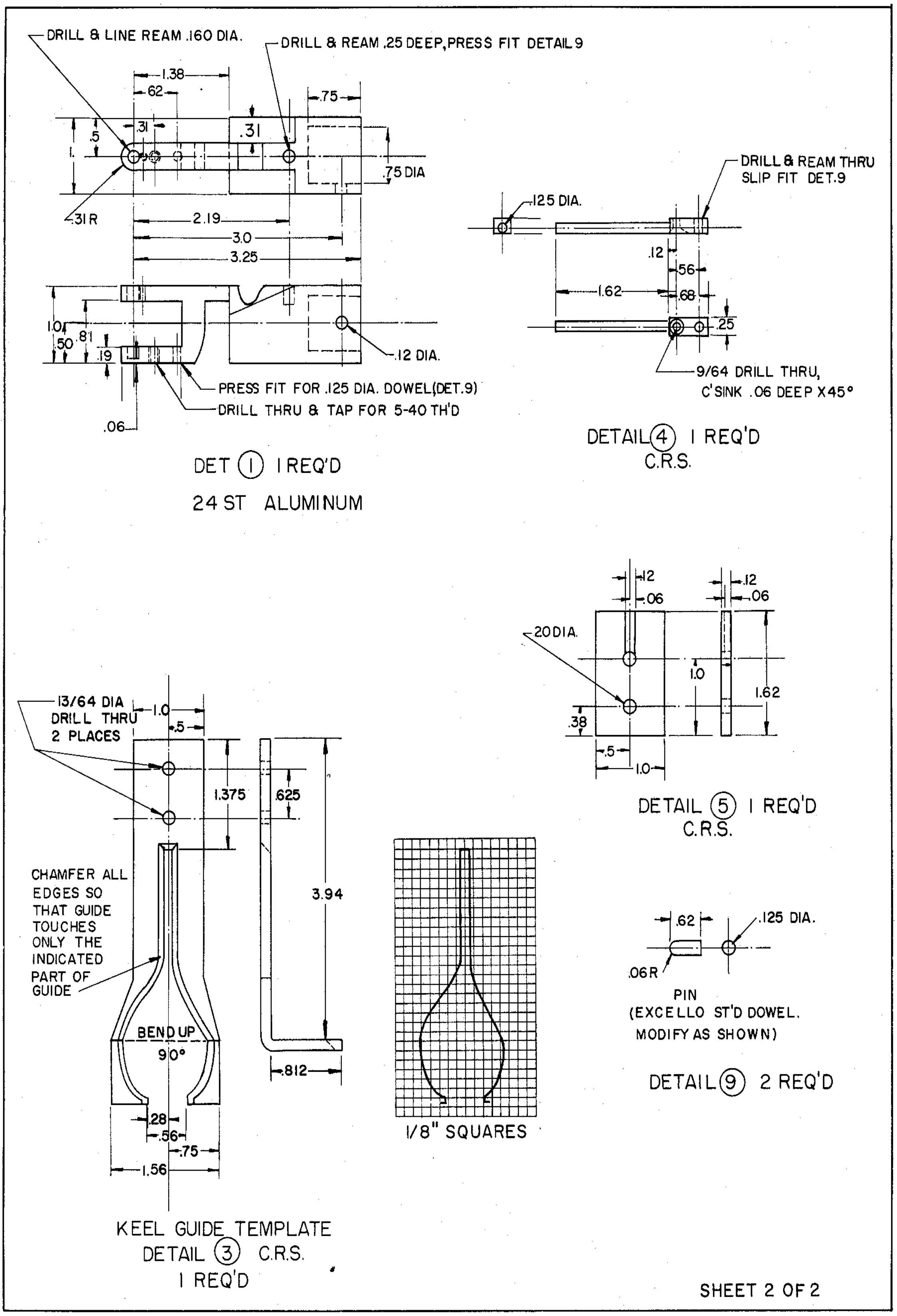

Figure 67. Details of plan for knee joint model.

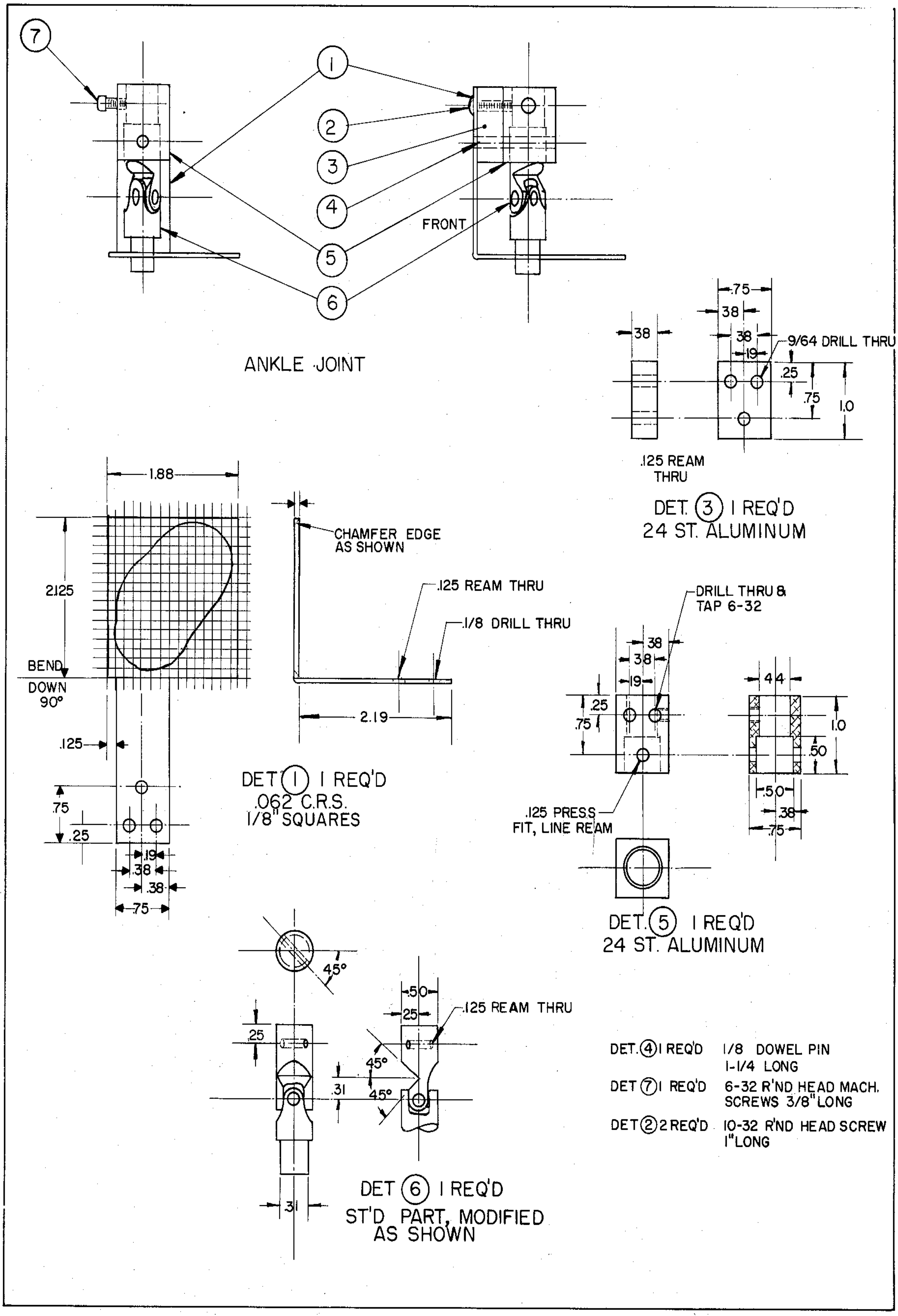

Figure 68. Plan for ankle joint model.

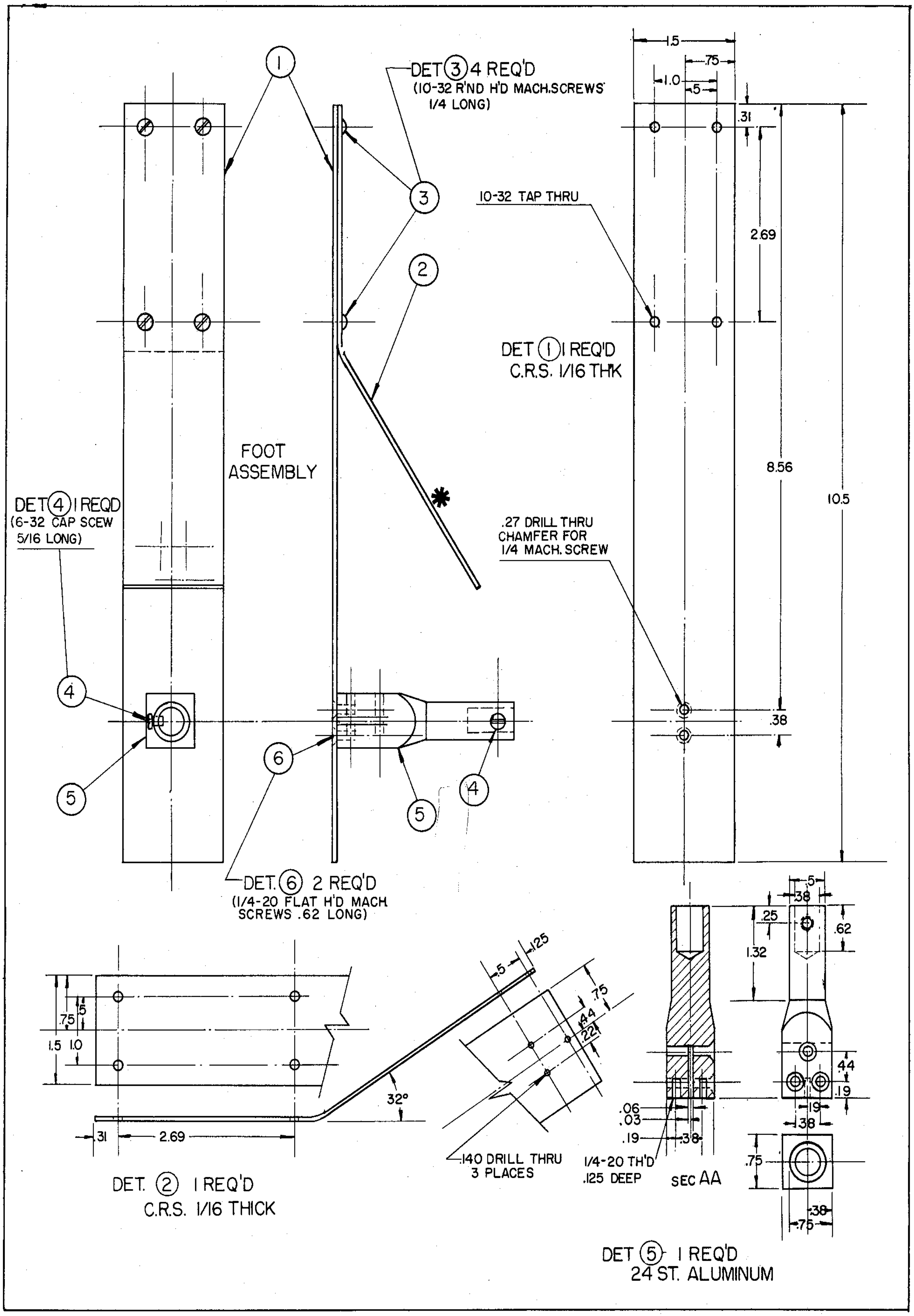

Figure 69. Plan for foot assembly and ankle joint.

(5) Wrist joint and hand assembly: This joint was a universal joint; it was provided with a sheet metal guide which was bent into a half cylinder; on its longitudinal axis was the center of the universal joint. In this instance the guide was a part of a larger sheet metal piece which was shaped and bent as indicated in Figure 63 to give a general form that suggested hand, thumb, and finger shape. Into this hand shape was built a projecting knobbed rod that represented the grip angle relative to the axis of wrist motion; the knob end corresponded with a rod gripped in the hand and projecting from the thumb side of the hand.

(6) Hip joint: The center of the hip joint was mounted on a link rod, representing half of the transpelvic link, which projected 86 mm as a normal to the midsagittal plane; its surfaces represented fore-and-aft and upper-and-lower directions relative to the standing position of a man. The joint itself consisted of a universal joint with a rod and sleeve joint just beyond; the universal joint was specially constructed to permit an adequate range of movement and the sheet metal guide which limited the range of movement was bent to an angle to provide sufficient clearance for the femoral link in its movement.

(7) Knee joint: The knee joint in the constructed model permitted axial rotation of the shank link as well as flexion-extension movements; its movements corresponded with the globographic data (Figure 48) as corrected for data on living subjects. The range of shank rotation was actually increased to correspond with knee rotation plus foot abduction or adduction. Accordingly, values of Tables 5 and 6 on knee rotation were utilized. In the detail drawings the joint is shown to be a combined hinge and axial joint; it was provided with a guide and template system to limit motion to a normal range. The joint was locked in the extended position with no rotation possible except straight flexion; with further flexion, however, increasing amounts of axial shank rotation were permitted.

(8) Ankle joint and foot assembly: The shape of the foot was represented simply as a flat plate of sheet metal, suggesting the foot sole from heel to toe, and an oblique piece from the ball of the foot upward toward the ankle. (The foot form might have been more elaborately worked out like the hand section.) From the foot sole piece a vertical pillar, at a suitable distance between the heel and toe, extended upward to the ankle joint level. This joint was represented by a universal joint and the movement of the lower section of it was guided by a sheet metal guide plate attached to the lower end of the shank section.

The femoral link in the standing position was vertical but the shank section was bent inward so that a line between the knee center and the ankle center made an angle of 5° to the vertical. Adjustments on the pillar below the ankle center permitted the long axis of the foot to be turned inward (adducted) and set 8-1/2° relative to the front-to-back axis of the shank.

It should be noted that in the earlier paragraph on the knee, the foot abduction-adduction range was simply added to the range of axial rotation of the shank; more correctly, a rod and sleeve joint below the ankle would provide for the separate foot movements and the knee movement would be represented by a more restricted range.

The drawings were made after the model had been constructed from preliminary sketches and they include certain refinements not shown in the actual models. Our twofold aim was (1) the construction of a model with constant lengths of links and constant centered joints that could be machined readily, and (2) the development of designs which represented clearly the range of angular motions shown in the body. Much of the joint construction, for instance that of the knee and shoulder system, was much too delicate for any practical use other than the demonstration of a range of motion; the model was built solely as a device which would allow comparisons with body range. If movements of the overall model were correct the adequacies of our plans was demonstrated.

As indicated above, our globographic treatment of the joints was designed to define the range of joint sinuses; the only attention directed to axial rotations of the hip and shoulder were measurements on living subjects which involved but one position of measurement within the whole flexion range. Interestingly enough, it is in just these respects that our model shows inadequacies; otherwise, the model proved adequate to within (ordinarily, well within) a 5° range of the movement planned.

The failures may be shown as follows: When an individual sits cross-legged or with one ankle resting upon the opposite knee, the angle of the shank to the vertical is about 75°; the opposed lateral movement of the shank, with the knee at the same location relative to the trunk, brings the shank some 15° beyond the vertical, i.e., foot outward. The model does this. Now, if the hip joint is half or fully extended, the inward rotation is about 45° and the outward rotation of a similar order. The 75-15° angulations in the model, however, are constant throughout the whole range. The twisting and tightening of capsular ligaments in the organic system produces different amounts of rotation for different degrees of flexion; there was no equivalent provision built into the model.

Again for the upper limb, when the humerus hangs vertically downward and the elbow is bent to a right angle, the humerus can rotate nearly 180° (i.e., forearm outward and forward, or backward and inward behind the back). When the humerus is directed vertically upward, the range of axial-humeral rotation is reduced by nearly half. In the model these axial movements of the humeral link are the same for every part of the range of humeral movement. Both the hip and shoulder movements referred to are very specialized and, for most movements of the end members, the influence is negligible. With this exception and the point noted above on combining foot abduction-adduction movements with knee rotation, our plans should be adequate as a basis for model construction. For the construction of rugged models, possibly with friction fittings, our designs can be only first approximations which solve only the problem of range of motion. Where other features are essential in the construction of manikins, compromises relative to the range of motion may be necessary.

Plans for the limb joints shown as Figures 59-69 have ranges of movement built into the templates. Equivalent data on specimens and subjects are shown in the globographic figures and in Tables 5 and 6. A statement on the placement of stops to limit axial rotation of the several links is, however, necessary.

When the clavicle was aligned so that a line cross-ways to its front surface was vertical, stops on the model were built in at one rod and sleeve joint to permit 40° upward rotation on the longitudinal axis of the clavicle and 12° downward rotation. Axial rotations equivalent to the total range of rotation permitted were built into the telescoping scapular link; consequently, adjustments for this link and for the humerus as well may be grouped together. A cumulative axial rotation of the humerus about both the scapular link and its own longitudinal axis represented 105° inward rotation and 60° outward rotation relative to the front surface of the humeral link, when the reference alignment of the latter was in a vertical transverse plane. When the elbow was bent 90° the front face of the forearm rotated 101° outward and 90° inward relative to a reference position where the radial side was uppermost. The only other axial rotation in the models not built into the templates was axial rotation of the femur; when the reference surface of the femur was taken as a vertical-transverse plane, movements at the rod and sleeve joint in the hip region should permit 57° inward and 40° outward rotation about the long axis of the link.

DRAFTING BOARD MANIKINS

Woodson (1954) shows a current design for a drafting board manikin. From our data on joint range and link dimensions a different design will provide a notably more accurate manikin for applications to the seated posture. Our manikin, however, was not intended for standing or other postures than the seated. Although a manikin representing a mean build may be useful alone, it should be more appropriate for designing purposes to utilize two manikins scaled to the 5th and 95th percentiles of the population of interest. The following manikin designs have been developed in relation to the dimensions of the 5th, 50th, and 95th percentiles of the Air Force flying personnel.

After the small manikin has been adjusted to a particular working posture and the effect of hand and foot positions (or knee, elbow, etc.) is marked on a drawing, the large manikin may be substituted and equivalent positions may be marked. The designers' problem is to determine the best functional balance between the two locations. Sufficient clearance space should be allowed for the large man, but assemblies should be within the convenient reach of the small man.

The three sizes of design were developed as follows: Our median and muscular subjects were screened to find those men who most nearly duplicated the dimensions found in the 5th, 50th, or the 95th percentiles of the Air Force personnel. Stature, crotch height, acromial sitting height, and upper limb length were the dimensions selected for the screening. For each percentile level only three to five men of the sample fell within the one-standard-deviation range for all four characteristics; the three groups of men so selected were studied for general profile contour. Nude side-view photographic negatives of the selected men seated in the standard cockpit seat (heel-to-eye height = 39.4 inches) were projected at a standard magnification of exactly one-fourth actual size. Tracings of the small men were superimposed. The same was separately done for the average size and for the large men. Then joint center positions for the shoulder, hip, knee, and ankle of each subject were marked in.

Next, to correct for incidental angulations of the segments, lower limb segments were aligned so that thigh, shank, and foot contours coincided as closely as possible. Average joint center and link lines were now drawn in as was a mean contour of the body and limb outline. A further correction involved the substitution of link dimensions of the three Air Force sizes from data in Table 7. The profile contours of the limb were modified to fit. A similar procedure was adopted for the side-view contours of the upper limb segments for the three sizes.

The mean trunk contour was worked out separately from photographs of the three sizes of men and the best estimate position of the hip and resting shoulder (glenohumeral) joint centers were made; from these the mean position of the joint centers relative to the trunk contour were drawn in. The mean position of the hip was then enlarged to dimensions corresponding with the uncertainty factor for hip center location (Figure 52). The shoulder position was similarly widened to correspond with the range of shoulder joint position found in globographic work with the sternoclavicular joint (Figure 39).

Side view motion pictures of the subjects had been taken showing a variety of arm movements relative to the seated posture. These pictures included manipulation of the cockpit "stick", throwing a paper dart (up, forward, and down), a punch, a bowling ball delivery, as well as reverse movements corresponding to each of these. These movements were considered as representative of a much larger series of possible movements. A frame-by-frame analysis of these movements for the selected subjects showed that when one-sided upper arm movements are made rapidly, counter thrusts and follow-through movements often bring the shoulder point beyond the confines of the simple globographic representations of static movement. Occasionally, the humeral center moves entirely beyond the contour of the man as he sits in the rest position. The joint-center positions of the shoulder as derived from the dynamic data of the frame-by-frame analysis were then superimposed on the globographic range shown in the one-fourth size composite drawing. The globographic range was then enlarged in appropriate directions to include the more common positions of the humeral head in dynamic behavior of the limb.

Now we had composite drawings of the trunk and limb regions scaled to mean contours for the three builds; link dimensions and joint-center positions were correct, the range of hip- and shoulder-center positions was marked in and the body postures corresponded to the mean sitting postures for the standard seat. Next, cardboard cut-outs were made of the tracings and these were cut apart; adjacent parts were united by a pin at the joint centers and the segments were rotated about these centers. Segment ends were trimmed and rounded until end contours were obtained that did not intrude upon the body profile. Realistic knee, elbow, ankle, and wrist contours were sought for all normal positions of bending.

Since the quarter-sized manikins were to be assembled with bolts of 5/32-inch shaft diameter, allowances for the corresponding radius were built into the areas representing possible hip- and shoulder-center positions. In the assembly of segments it was planned that the trunk, forearm, and shank sections rest directly upon the substrate and that the arm, hand, thigh, and foot overlap these. The range of movement for each joint was marked in the region of mutual overlap. In the overlapping segment sector corresponding with the range of sagittal plane movement was marked out and an arc of corresponding length was cut; a reference hole was placed in the segment which rested below. Additional allowances were made in the arc at the end of the range of normal movement for the size of this reference hole. With this system, permissible ranges of movement could be defined as any movement at a joint where the reference hole showed within the cut out arc; conversely, if a joint was moved so that the reference hole did not show, such a movement was beyond the normal range.

Plans for the contours of segments of the three sizes of manikins are shown separately as Figures 70, 71, and 72; cut-outs for the average manikin were marked "A" on each piece, for the large manikin they were marked "L", for the small manikin they were marked "S". On the thigh section of each manikin, a line representing the full-scale dimension of the pieces on each plate is shown; when a specific scale of manikin (1/3-, 1/4-, 1/5-scale, etc.) is desired, a photographic scaling to size for the whole

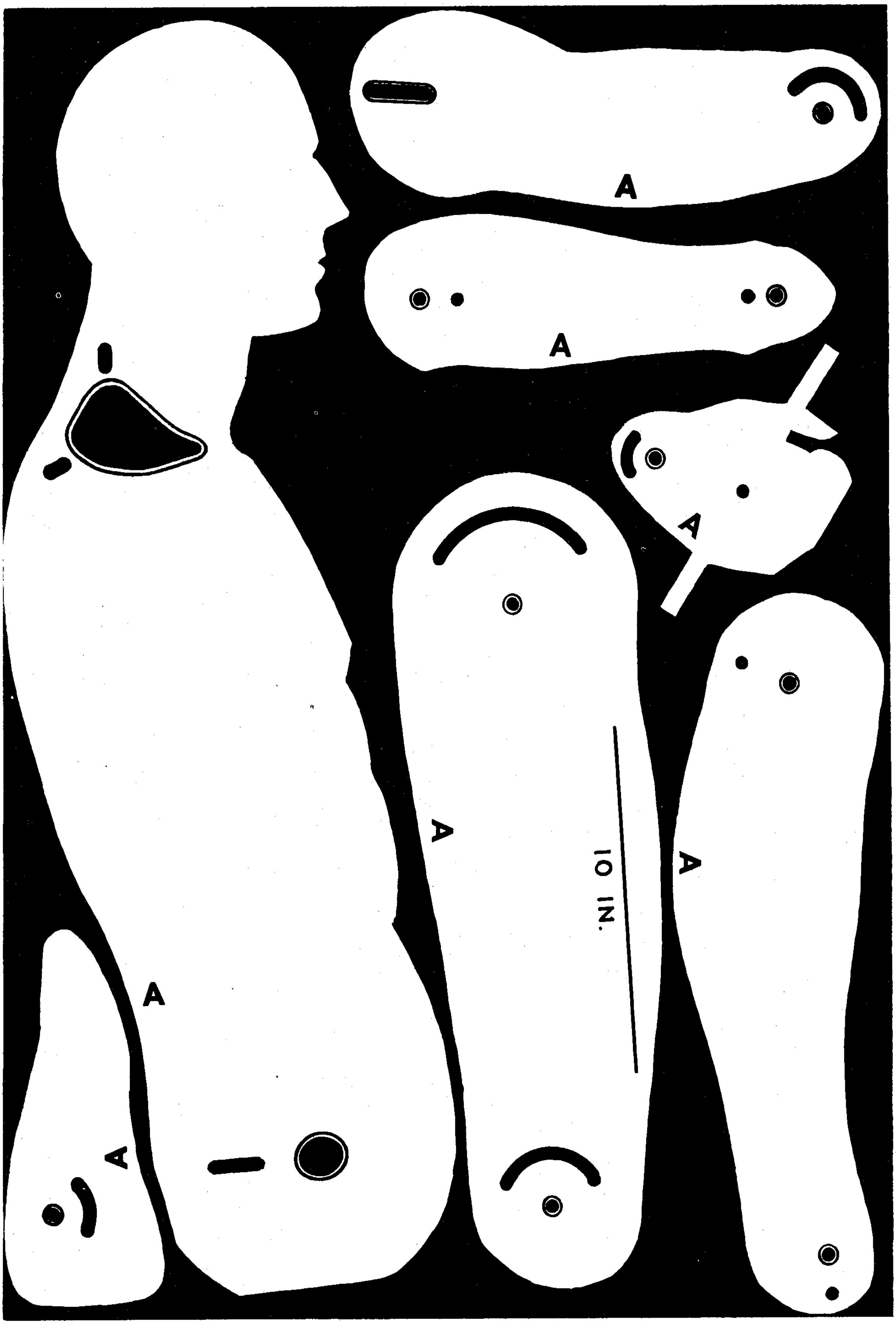

Figure 70. Pattern of body segments for drafting board manikin of average build. Note line on thigh segment which indicates scale.

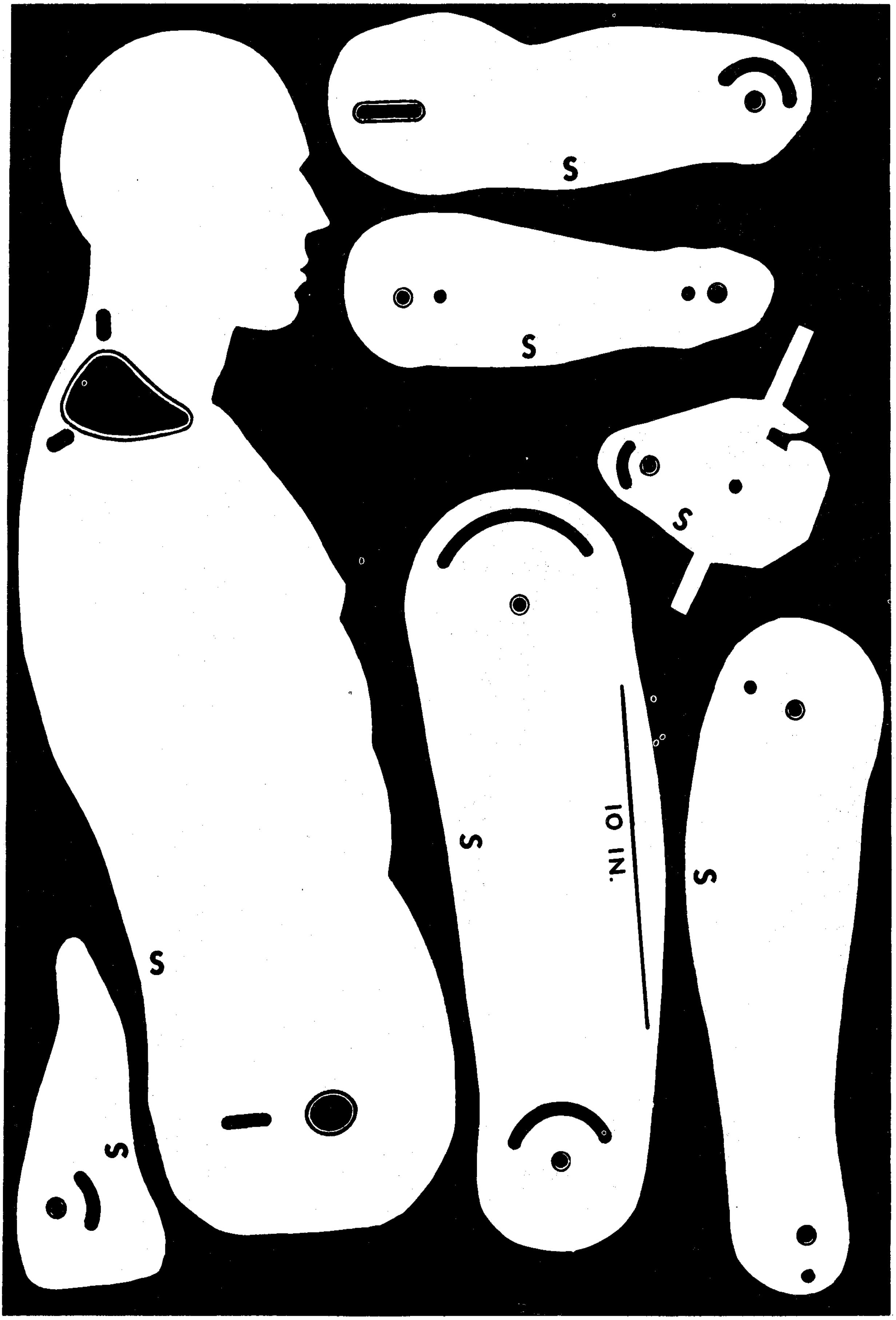

Figure 71. Segments for small-sized manikin.

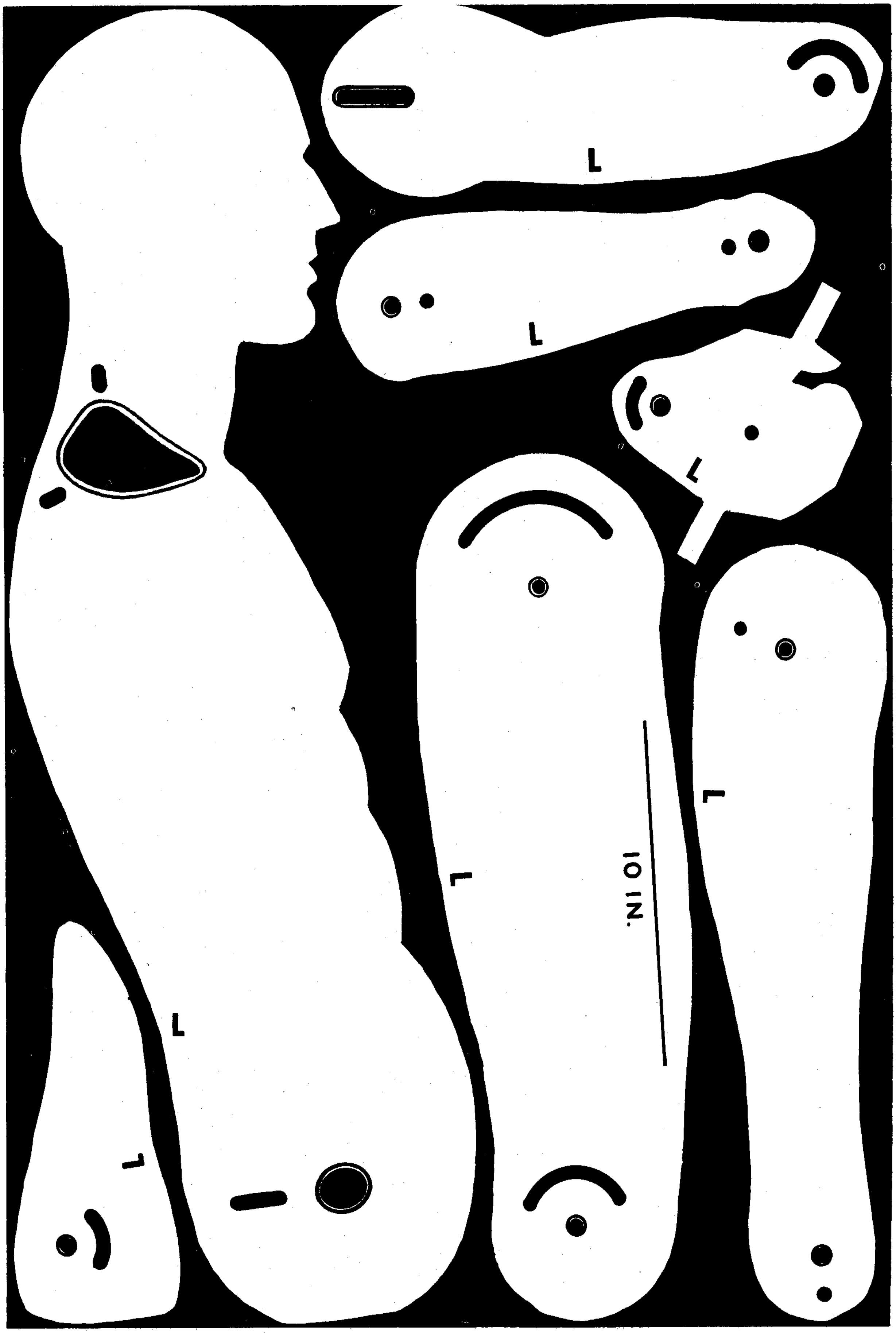

Figure 72. Segments for large-sized manikin.

plate may be made with the aid of this reference line. Cut-outs may be made from cardboard, metal, or plastic. Due allowance for the scale of reduction of assembly pins should be provided for, especially in the shoulder and hip assembly; the correct diameter of bolt for a one-fourth-scale manikin was 5/32 inch. Figure 73 shows a one-fourth-scale manikin of the average man (manikin A) made from sheet aluminum. It may be seen that the trunk, shank, and forearm sections rested on the substrate, as indicated above, and the other segments overlapped. The hand and foot segments beyond the joint region were of triple thickness in the model shown so that the part could also rest on the substrate. A hole through the hand for a pencil point represented the midpoint (metacarpal III) region of the hand grip. The pieces may be separated and reassembled with the arrangement of segments mentioned so that the units face right or face left. To aid in reassembly of the metal model a surface texture of whorls as shown was machined into the right side of the segments while the reverse side was made plain.

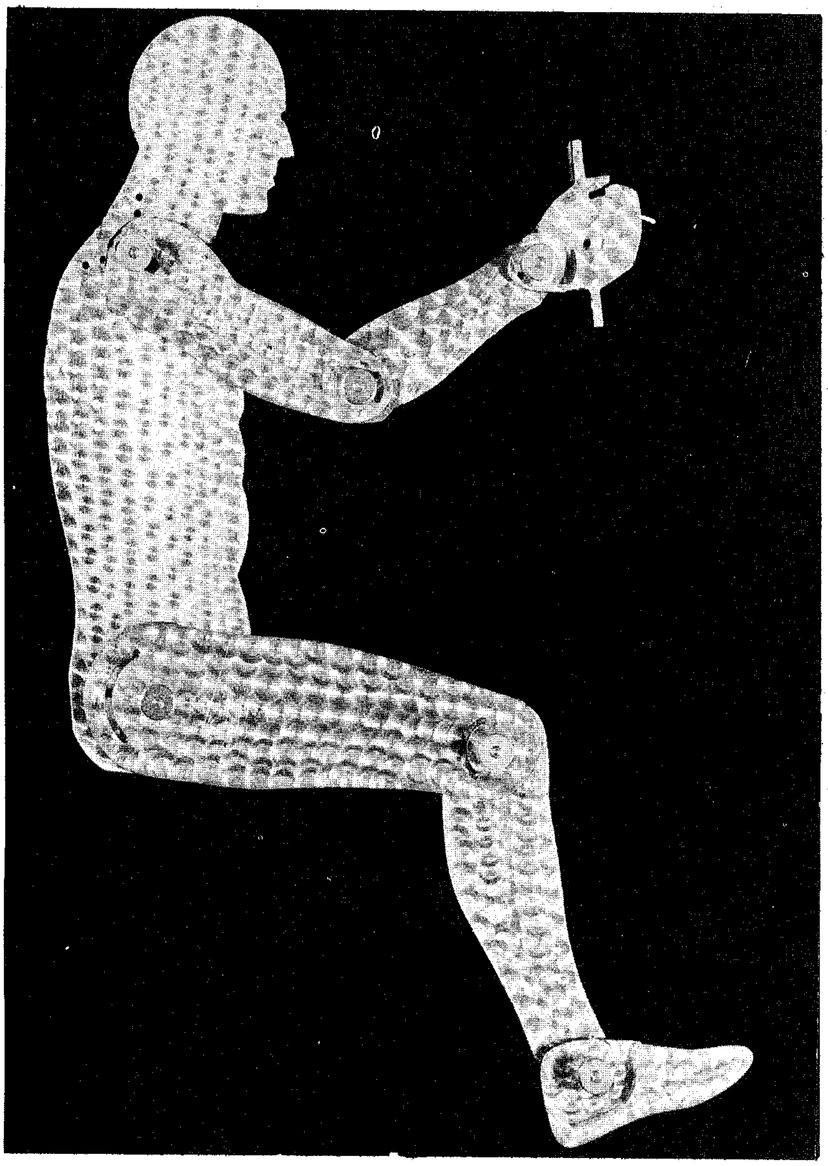

Figure 73. Metal model of drawing board manikin for the average build of the Air Force flying personnel.

All work on joints, as had been noted earlier, has been limited to the limb system, and virtually nothing has related to the trunk. The procedures indicated above, however, have dealt with trunk dimensions insofar as body profile is concerned. Figures 70, 71, and 72 for the three mean sizes of subjects show the distances between the actual positions of hip and shoulder for the seated subjects. Moreover, these positions are indicated in relation to the "R" point of the standard pilot seat. Distances may be scaled off from the seat, from the seat-back, or from coordinates through the "R" point. These positions would be pertinent also for three-dimensional models, if the lower and upper limb systems were to be assembled in a single installation representing the seating posture.

It should be noted that a sagittal-plane manikin does not allow for inward or outward angulations of the limb segments. If an operator, in life, were to project his elbow laterally, the hand position would be closer to the trunk for a given elbow angulation than the manikin would show. Caution should be used to assure that manikin postures truly reflect the positions of choice which a subject would actually assume. The manipulation of the manikin into a certain posture by the fingers is in no way comparable to the act that the living individual performs, when he must provide for stability, balance, and comfort. The wholly artificial character of manipulation of a manikin should constantly be kept in mind. Is the manikin posture the same as that which a man would actually take to do a purposeful act?

CHAPTER VI

WORK SPACE REQUIREMENTS OF THE SEATED INDIVIDUAL

THE WORK SPACE

In this chapter the space requirements of the seated operator will be explored with special concern to the range of active movement permitted the hand and foot. We will be concerned with actual living subjects rather than with anatomical material.

It has been assumed here as a working premise that the seated worker most frequently uses his hands within the field of his vision and that his feet are more or less toe-forward or toe-upward, with the foot sole not slanted to the side. There is no question that other hand and arm postures are used often, viz. hair combing, back scratching, valise carrying, the subway handstrap, etc. These and other postures, such as body positions in which the hand and forearm reach transversely across the body or are directed to the side, are considered as miscellaneous. Similarly, when the foot of the seated operator toes in or out or the foot sole slants in or out, the functional postures are less common than the more direct foot orientations.

In line with these assumptions, the present study deals exclusively with the hand and foot in the more forwardly-directed positions. Movements of the end members have been studied for postures involving standard angular positions of the part concerned; even though the hand and foot are held in a certain way there is still a wide range of movement possible. To be consistent with the hand orientations used, the forearm always has a forward component though for certain hand positions it may be directed 45° or more away from the sagittal direction. For the foot postures the shank will always have a downward or forward component.

In the research approaches primary attention has been directed to possible end-member positions in space rather than to the ranges of motion of the more proximal facilitating joints of the limb chain. In fact, a joint-by-joint synthesis of the angular ranges of motion would undoubtedly fail totally in getting at functional patterns of end-member range. Globographic data on joint range as presented in Chapter IV represent two degrees of rotational freedom of the joint; additional separate axes at the surface of the globe have been used (Strasser and Gassmann, 1893, et al.) to show the extent of axial rotation of the moving member, but this has not been done in our work. Studies reported above on the shoulder illustrate the difficulties and eventual breakdown in dealing with a chain of joints. The method fails completely when translatory motions are introduced. Chapter III pointed out that the end member of an open chain of three or more links could have both translatory and rotatory movements. In a chain of links with three degrees of rotational freedom at the intervening joints to allow reciprocal movements, the end member has six possibilities of motion in space: three degrees of translatory and three degrees of rotatory freedom.

Our methods (Items 28 and 29, Chapter II) have been devised to study first the possible ranges of translatory movement of the hand (and of the foot), and then to consider the additional effect of one degree of rotation; the analysis has been planned also to carry to at least one further degree of rotational freedom. The method of study for the hand and for the foot, too, has been simply the holding of the end member in some arbitrary, fixed position free of rotatory motion, but permitting the fullest possible range of translatory motion allowed by the various facilitating joints. Thus, a space was described in which the hand could range up, down, forward, sidewise, etc., in straight, oblique, or curved paths; but the palm and grip angle were constantly the same relative to the space of the observer.

The space envelopes that enclosed such patterns of translatory motion have been called kinetospheres. For purposes of defining the space shapes, a point on the moving member was defined—the central axis of the grip at the third knuckle and the midposterior point of the heel at the foot sole level—and the envelope for this point in all possible translatory motions for a given orientation, were defined in relation to a fixed reference at the seat. Figure 74 shows the shape of a kinetosphere as reconstructed from data on one subject for the prone hand with a grip angle constantly horizontal and transverse. A different arbitrary hand orientation would show differences in kinetosphere shape, as one joint or another would limit motion.

Numerous similar, three-dimensional reconstructions were made of different subjects and different hand orientations. Figure 84 shows the different kinetosphere shapes for the flat (90°) foot and for the more tilted (15°) position. These two shapes were markedly different; the flat foot had a wide range of translatory motion near floor level and less and less at higher levels. When held at 15°, the foot ranged farther from the seat, it did not touch the floor at all, and its largest horizontal range of motion was above seat level.

The special point for present emphasis is that each kinetosphere, involving translatory motion by an end member and no rotatory movement, had a distinctive shape and volume and a distinctive position relative to the seat. A change to a new end-member orientation permitted a new kinetosphere analysis in which positions and shapes were in some way different.

The kinetosphere is an analytical tool for the study of motion range; each different end-member orientation permitted a new analysis of the range of translatory motion. When a series of kinetospheres representing different degrees of hand orientation in some plane of reference are systematically grouped, it becomes possible to study the patterns of end-member movement involving one degree of rotatory motion in addition to the three classes of translatory movement. This grouping of systematically changing orientations may be done for orientations in any three perpendicular planes in space, as for the sagittal, frontal, or transverse planes of the body.

The new patterns of movement have been termed strophspheres; a strophosphere involves one degree of rotational freedom in addition to three degrees of translatory freedom for the end member. A given strophosphere may be still further widened by grouping with strophospheres involving different planes of rotation. Thus a strophosphere involving changes in orientation in the sagittal plane may be combined with another involving changes in transverse orientation. The widest possible grouping of kinetospheres and strophospheres is equivalent to the total work space. The strophospheres and kinetospheres are essentially ways of dissecting the work space in terms of motion patterns.

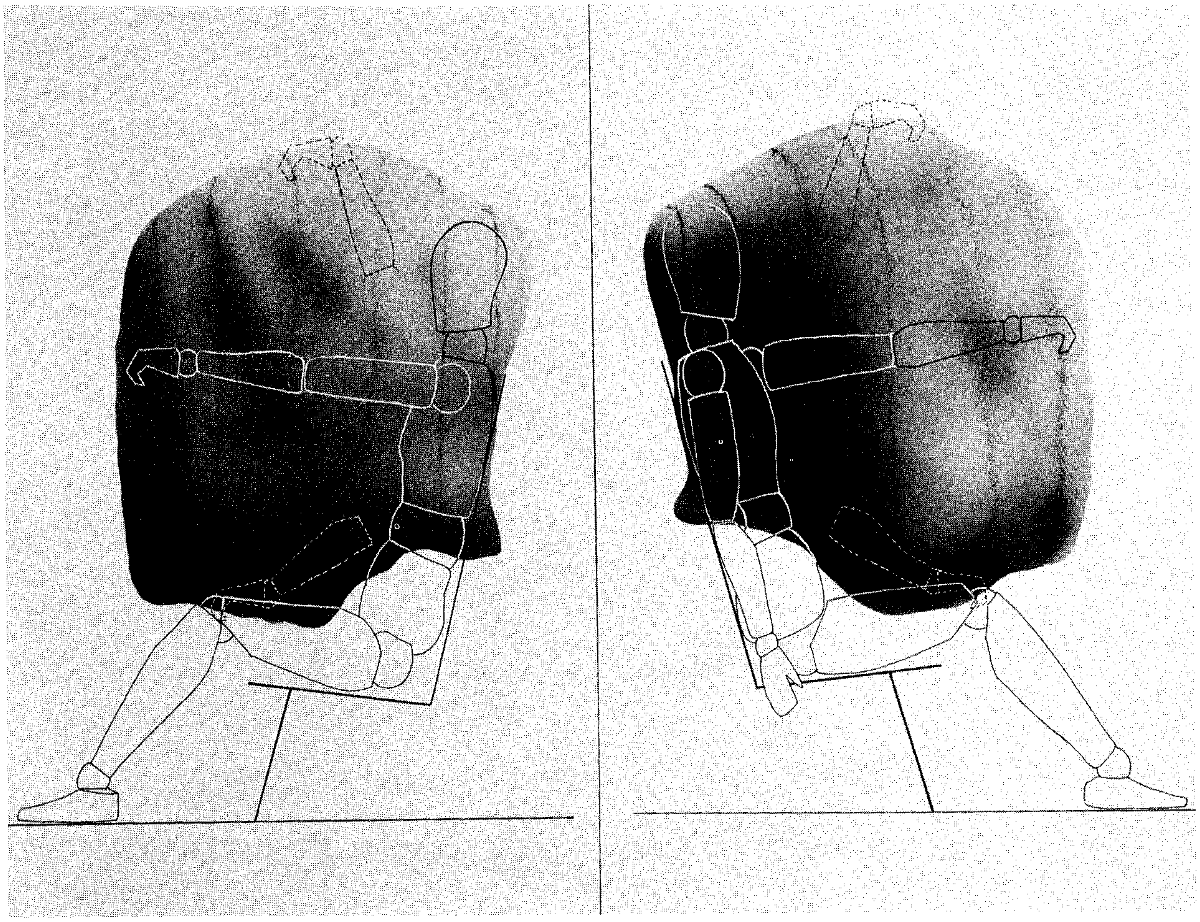

Figure 74. Lateral and medial views of a reconstruction of a hand kinetosphere, representing the range of movement for the prone left hand for one subject.

Although various three-dimensional reconstructions or models have been made, most value has derived from (1) a study of the original records which represented frontal plane serial sections through the kinetosphere for the hand and horizontal sections for the foot, and (2) replots of data to represent contours in planes which pass through the centroids, or center of gravity, of the shapes.

The location of kinetosphere centroids from individual records, as described in Items 28 and 29, Chapter II, was calculated from moments of section-area-to-distance data relative to the "R" point of the seat and from the suspension of cardboard cut-outs of critical sections. Plots of the vertical distance from centroid up and from centroid down to the contours of the individual sections gave sagittal projections of the kinetosphere. Similar transverse plots gave horizontal projections; the frontal contour was reconstructed by weighting sections ahead of and behind the centroid level.

These three derived contours representing mutually perpendicular sections through kinetospheres allowed comparison of equivalent kinetosphere shapes for different individuals and different hand or foot orientations for the same subject. The sections through centroids could be superimposed, measured, averaged, treated for variation, etc., as the occasion demanded.

It will be convenient to focus attention first upon the characteristics of the hand space; the foot space will be considered subsequently. Figure 75, on the hand space, shows a plot of the average frontal-plane cross-sectional area relative to distance from the "R" point for 22 men of median and muscular builds. The area increased rapidly from zero to from 400 to 600 square inches at arm's length, and then from 10 to 12 inches farther back, hand range increased to from 500 to 1100 square inches, varying according to hand orientations; then gradually the area decreased to values of from 100 to 300 square inches at the seat "R" point, and there was still less cross-sectional area farther back.

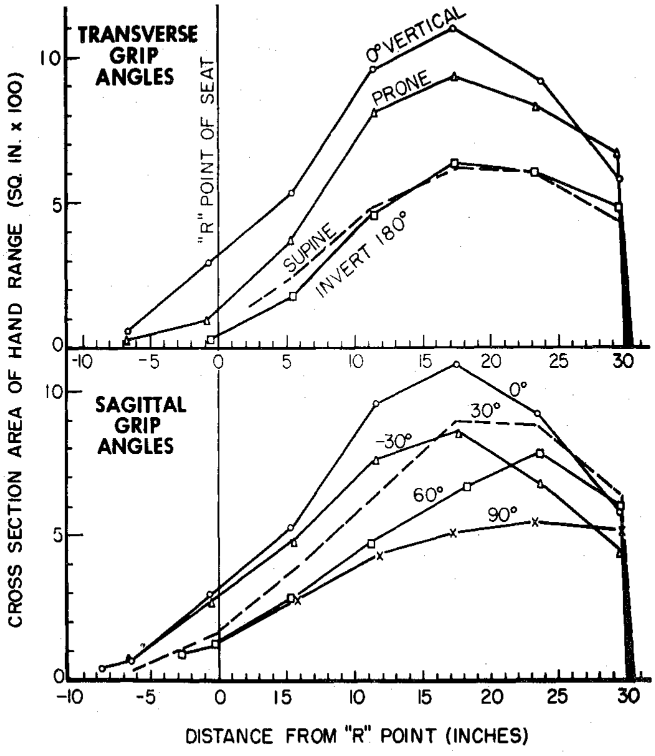

Figure 75. Plots showing frontal plane areas available to different orientations of the hand at various distances from the "R" point of the seat.

The areas were appreciably large over a span from 12 to 24 inches ahead of the "R" point, and they ordinarily decreased farther forward or backward. It should be noted that the 0° vertical and ±30° hand orientations in the sagittal plane and the prone hand had large cross-sectional areas at from 15 to 18 inches forward from the "R" point.

Thus, the area-distance plots point to a region from 15 to 18 inches more or less ahead of the "R" point as especially important for the placement of controls, which will be operated by the prone, or the more or less vertical hand; at the distance mentioned the reach upward, to the side, and downward for the forward distance mentioned is maximal for the hand when it is directed forward.

As the hand tilted toward 60° and 90° (grip horizontal, thumb forward) the area of reach was wider at 2 feet or more from the "R" point than farther back. The supine, 90°, and invert positions of the hand utilize little more than half of the frontal cross section that was available for the 0° grip orientation.

The area under each curve represents kinetosphere volume. Table 9 shows mean kinetosphere volumes for different hand orientations. The larger volumes (0°, prone, -30°, and +30°) clearly point to the wide-ranging character of the hand when held in certain orientations. Controls planned for these hand orientations should be of generally greater value than 60°, 90°, supine or invert—unless controls are designed specifically for these hand orientations and are put in more or less restricted locations, as will be indicated below.

TABLE 9

AVERAGE KINETOSPHERE VOLUMES FOR 22 MEDIAN AND MUSCULAR SUBJECTS

Hand Orientation	Volumes, cu. in.	Hand Orientation	Volumes, cu. in.
-30	19,990	90	13,040
0	24,630	Supine	13,180
30	19,940	Prone	20,670
60	15,850	Invert	12,920
90	13,030		

The histograms of Figure 76 show kinetosphere volumes for the different hand orientations as separately summarized for the four types of subject studied. Quite uniformly, the thin men had large hand ranges and rotund men had small; the muscular and median builds were intermediate with the muscular ahead. The three vertical scales in the figure show the volumes expressed as cubic inches, as cubic feet, and as a linear measure (to the right) where the volume is arbitrarily considered as a cube; the latter measure is more readily comprehended in relation to practical experience. An average of volumes for the muscular and median subjects could be considered reasonably equivalent to those obtaining in a military population.

Figures 77, 78, and 79 show the differing shapes of the hand kinetospheres averaged for the 22 muscular and median subjects. One sees a general transition in shape and in the relationship to the seat for the hand orientations: -30, 0, 30, 60, to 90°; there is also a graded change from supine through 0°, prone, and invert.

Some decrease in kinetosphere size is seen from 0° to -30°, and the decrease is marked toward 90°. The amount of right-left side overlap was large for 0° and notably smaller toward 90°. The 0° kinetosphere was higher; the 90° was lower relative to the seat; the centroid (small cross) shifted slightly farther forward from the "R" point, slightly lower, and farther to the side. Differences in the shape and position of the posterolateral wing may be noted also.

In the transverse series, size increased from supine to 0°, decreased slightly to prone, and then decreased notably more to invert. Supine was notably lower than 0° orientations of the hand and, it will be noted, were characterized by relatively low ranges of hand motion.

The small insert sketches (Figures 77, 78, and 79) which show shaded halos indicate for our sample of 22 men the variability (mean deviation) of extreme hand positions in the 0° and 90° orientations. To obtain this measure of variability, section

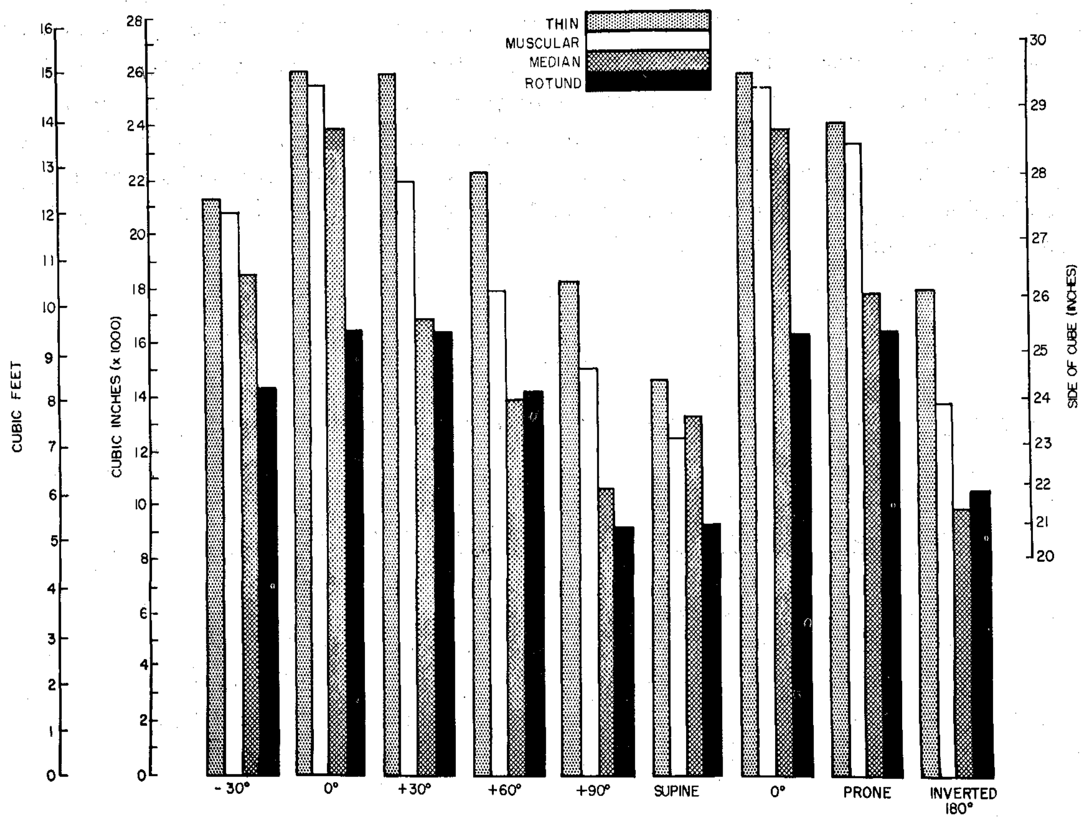

Figure 76. Histograms for different physiques showing mean volumes of kinetospheres for varying hand orientations.

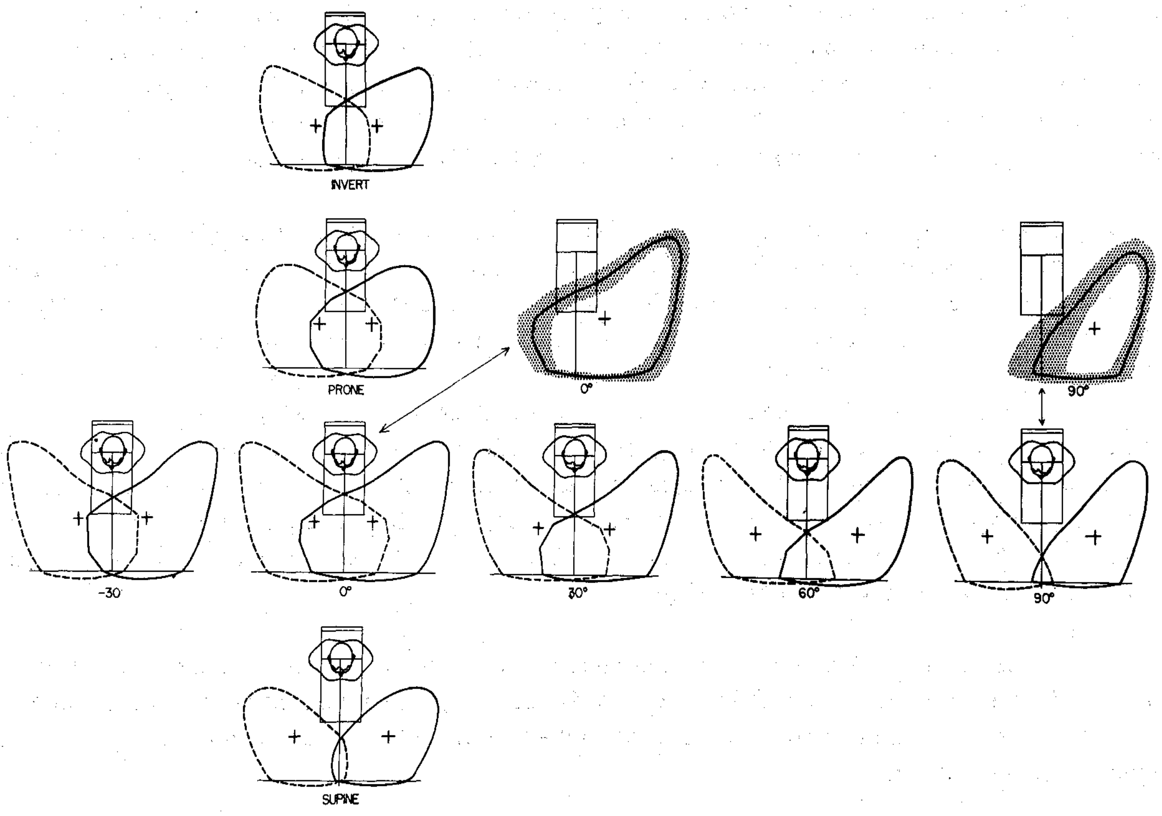

Figure 77. Mean shapes of 8 hand kinetospheres for muscular and median subjects as seen in horizontal sections through centroids. Shaded figures show mean deviations of the contours for two representative hand postures.

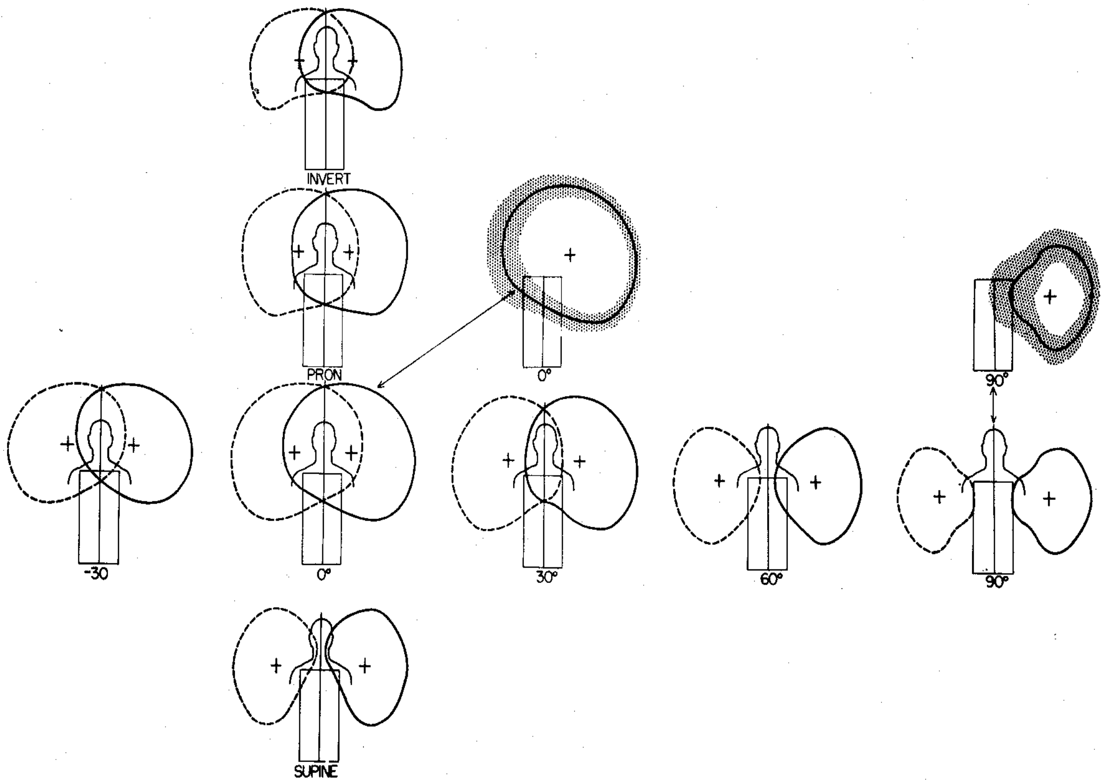

Figure 78. Frontal sections through the centroids of 8 hand kinetospheres. Shaded sketches show the mean deviation of contours for two different hand orientations.

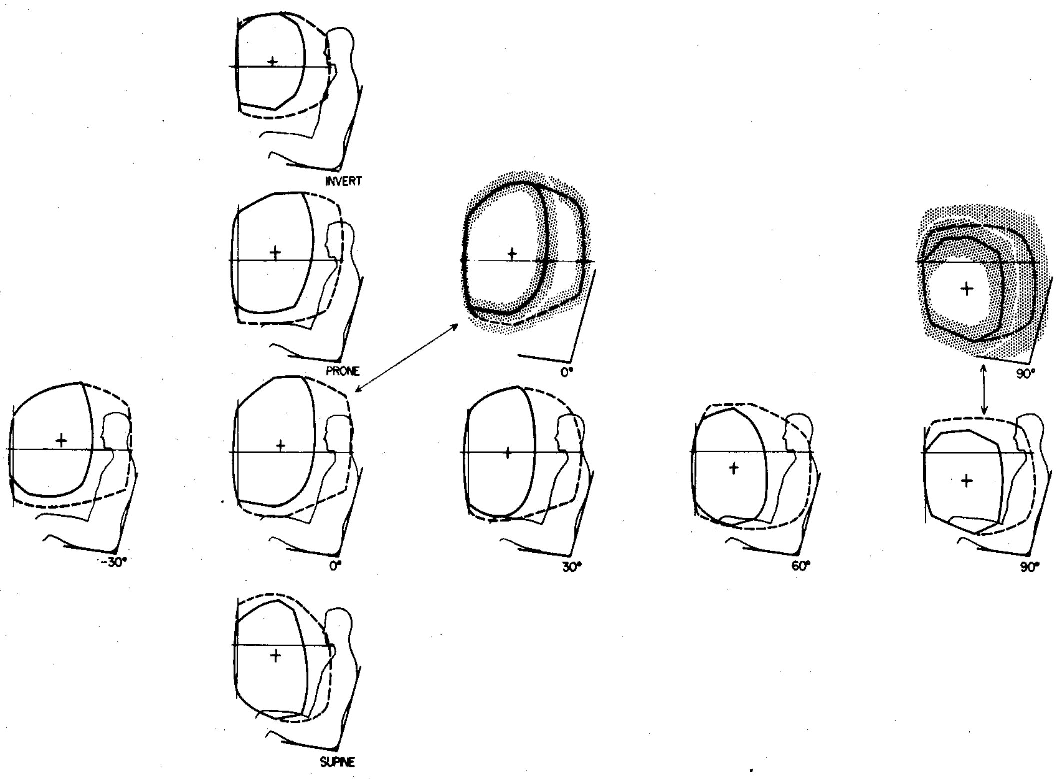

Figure 79. Sagittal sections through the centroids of the different hand kinetospheres. Shaded outlines show mean deviations of two contours.

contours for different individuals were superimposed at the mean centroid locus (this was comparable to superimposing seat "R" points for the records), and a number of radiating lines from the centroid were drawn in. On these, distances between the average contour and the individual contour lines were measured; then the mean deviation was computed and plotted.

Such mean deviations show differences in certain regions of the contour. The forward reach was markedly less variable than the upward and downward; the posterior range and the region toward the body were most variable. These relations were found also for the contours not supplied with halos.

Standard deviations were also figured relative to the average contour positions of the different kinetospheres. These values ranged between ±2.8 inches for the 0° contours to ±4.7 inches for the 90° kinetospheres. Supine and 60° kinetospheres were above ±4.0 inches, while prone, invert, and the ±30° positions were below. The variability of the most forward reach was about half the mean values.

The reader may wonder why only the median and muscular subjects have been described, when the standard procedures were followed on a larger test sample, including extremely thin and extremely rotund subjects. A careful comparison of the four groups of subjects for average kinetosphere contours in the three cardinal planes was made for each of the eight kinetospheres. Certain similar trends in contour shape and position relative to the seat appeared in each group of subjects.

General differences based on physique, however, showed three trends: (1) the thin subjects had large kinetosphere sections, the contours reached high, low, and back, the contours reached at a greater distance in front of the subject, and there was a notable area of right-left crossing; (2) the rotund subject had kinetospheres of smaller size, the height and antero-posterior depth were somewhat reduced, the rear contours in front of the seat were farther from the rear of the seat, and the amount of right-left overlap was markedly smaller than was found for any of the other groups of subjects; (3) the median and muscular men showed intermediate kinetosphere characteristics, now one or the other physique would show slight increases over the other, but no consistent differences showed up that would separate the body types.

Because of the low frequency of extremely rotund and extremely thin subjects in the working population, these comments on the general trends should suffice. Since the distinguishing kinetosphere characteristics for the muscular and median subjects were so slight, data on the 11 median and 11 muscular subjects were arbitrarily pooled.

It should be appreciated that hand kinetosphere shapes are rigorously controlled by limitations of joint movement at the wrist, elbow, or shoulder. The principle is illustrated in Figure 80, which represents a link analysis of one subject from side-view motion pictures. At A, B, and C the subject grasped the standard hand grip in the 0°, 90°, and supine positions respectively and swept the hand to its maximum range in the plane of the shoulder; at D and E, movements for the 0° and 90° hand orientations were limited to the midsagittal plane.

Limiting factors in each instance were occasioned by the limit of range at one or more joints. Where the positions are marked 1, 2, 3, or 4 the wrist could not be moved to increase the range; at positions marked "X" maximum elbow flexion provided a limit; and at 5, 6, 7, and 8 shoulder protrusion, elevation, depression or retraction, respectively, were limiting factors. In the same way medial or lateral boundaries were determined by the limitations of one or more of the joints of the limb. The lengths of the arm and forearm and the width of the shoulder to a lesser extent were reflected in kinetosphere shape.

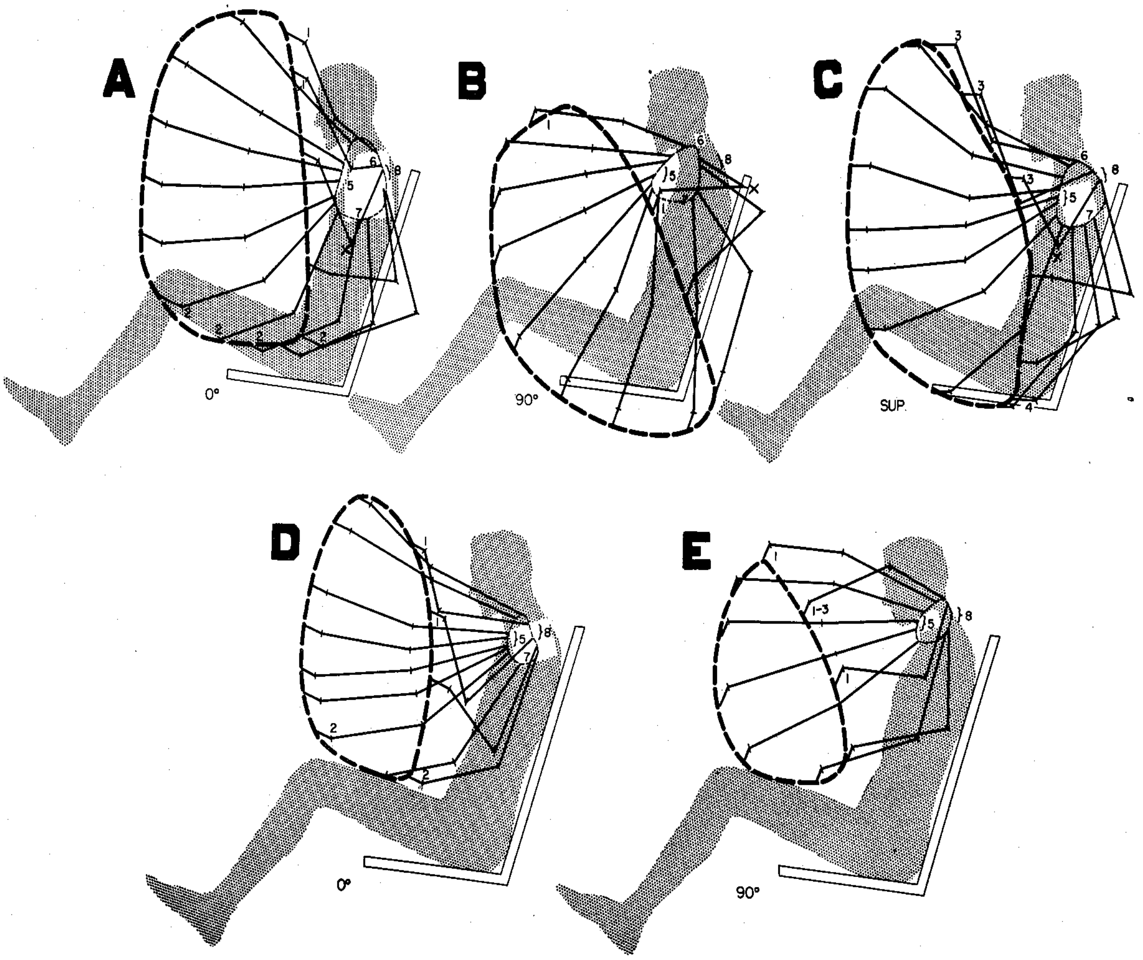

Figure 80. A link analysis of sagittal sections through kinetospheres based on motion picture records. At A, B, and C sections are at left shoulder level; at D and E midsagittal sections are represented.

In certain instances, subjects may not have exerted themselves fully to their limits. The variability expressed above as mean deviation and as standard deviation reflect three factors: variations in exertion, link proportions in individuals, and differences in joint range at one or another of the joints. An additional factor affected kinetosphere shape; in Figure 78 showing frontal views, the lower ranges of the shapes are above the knees and thighs of the seated subjects. In many instances, from the individual records it was obvious that the subjects cleared the thighs with the hand in the clockwise and counterclockwise sweeps at a higher level than was necessary. The lower borders of the kinetospheres as illustrated thus may be 2 or 3 inches high for those hand orientations where this factor was most pertinent.

STROPHOSPHERES

When the sagittal series of kinetosphere tracings were superimposed relative to the seat, the contours overlaid one another as in Figure 81. A similar superimposition of the transverse series of kinetospheres (supine, 0°, prone, and invert) shows at Figure 82. The enveloping outline in each of the figures represents the total space required for one degree of rotational freedom within the range of hand angulations studied, plus three degrees of freedom for translational movement. The space within the common outline thus meets the earlier definition of strophosphere.

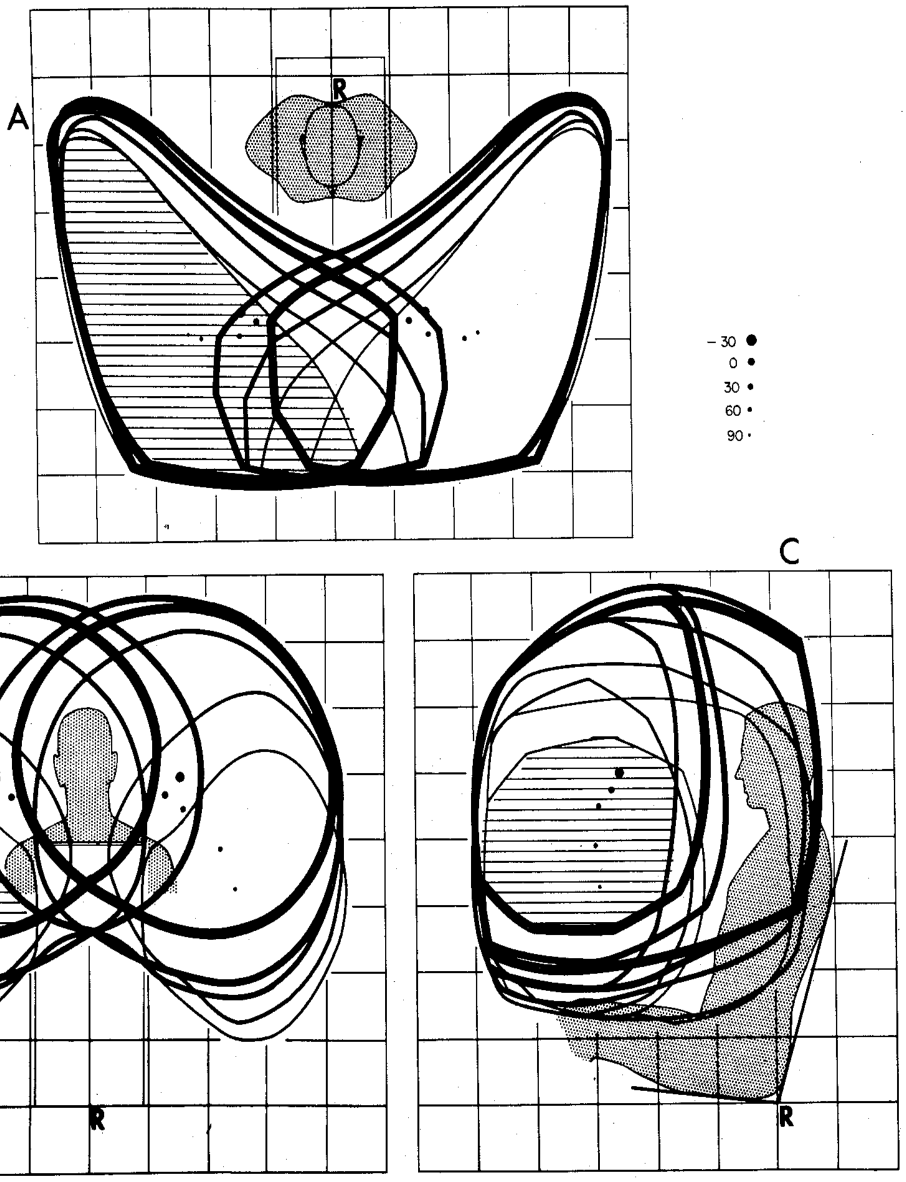

Figure 81. Hand strophospheres showing 5 superimposed kinetospheres representing different sagittal orientations of the hand grip. The shaded area calls attention to the common region where all sagittal orientations of the hand are possible. The dots indicate centroid locations. The grid represents 6-inch intervals.

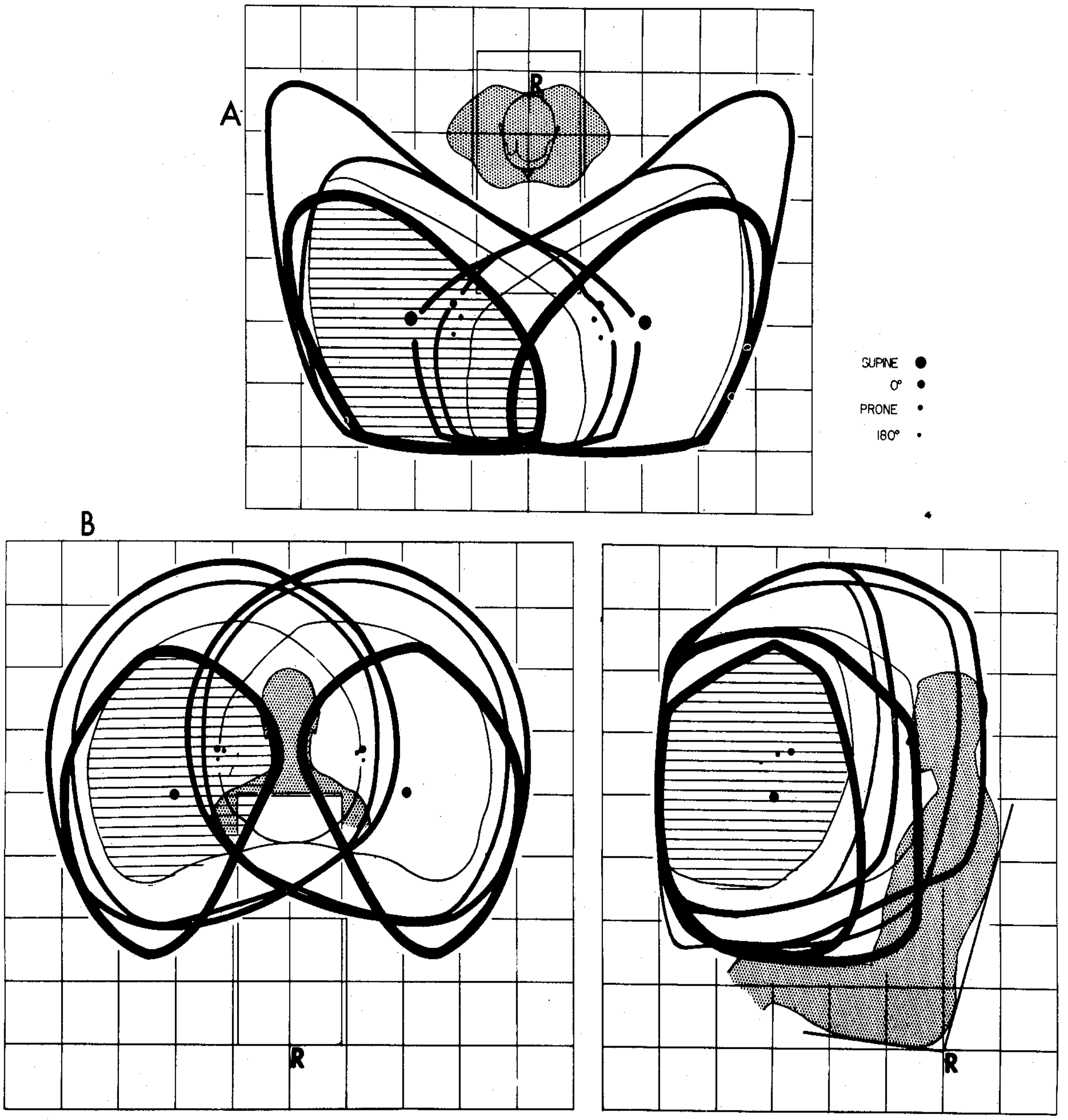

Figure 82. Hand strophosphere showing superimposed kinetospheres representing transverse orientations of the hand grip. Shaded areas show the common region of the strophosphere.

Each strophosphere shows within it a pattern and sequence of kinetosphere contour lines that requires comment; note that the 0° kinetosphere is present in each strophosphere. The forward and lateral contours are generally similar for the different components; most of the kinetosphere differences are in the postero-medial regions of the strophosphere. For the sagittal strophosphere the region of right-left overlap decreased notably through the kinetosphere sequence 0, -30, 30, 60, to 90°. The rear of the overlap area lay farther and farther forward through the series, and the wing region also decreased in size. In the same sequence, contours of the upper and lower borders, including those of the wing, came to lie lower and lower.

The transverse series of kinetospheres showed that the supine hand orientation occupied a relatively small share of the strophosphere; its shape was rounded; the wing was reduced; and the height was low. The height, the medial contour, and especially the right-left overlap increased markedly at the 0° grip orientation. When the hand became prone, both the wing and the region of right-left overlap were reduced. This trend continued to the invert position. These features are seen also in the tracings of separate kinetosphere sections (Figures 77, 78, and 79.

The transverse shading of Figure 81 shows the space which is common to the different kinetospheres of the sagittal series of hand orientations. The common area extended from the forward reach of the strophosphere to the "R" point, but the region was compressed both vertically and mediolaterally. In the transverse series (Figure 82) the common region was less deep from front to back but it was higher vertically. When the sagittal and transverse strophospheres were superimposed the mean common region in which all hand positions are possible (not figured) was even smaller.

As gauged by the 6-inch reference grid in the figure, the common region for all different hand orientations had a height of from 16 to 18 inches, a width of from 15 to 20 inches, and a depth of from 18 to 24 inches. The space lay obliquely to the seat and subject with an extreme reach of about 30 inches. Most of the space was lateral to the shoulder region, and the amount of right-left overlap was small. The common space for all hand orientations extended from the nose to the waist level, from the chest to the limit of forward hand reach, and it lay generally in front and to the side of the shoulder.

This region and particularly its outward limits should be the preferred region for the placement of controls calling for miscellaneous orientations of the hand grip axis. For more specific orientations of the grip axis, as in prone, supine, 90°, etc., regions beyond the common overlap should be equally good. Close study of the figures should pay dividends in the planning of control orientations. It should be appreciated, however, that our whole analysis to this point has been exclusively kinematic and geometrical.

There are doubtless regions of preference within the space outlined which should warrant further consideration. For instance, the strength and direction of a hand pull or push, the speed of movement from one control to another, or the precision of one operation as contrasted with another may very well differ, and maximum efficiency may call for very accurate placement. The posterior part of the strophosphere wing, at the side of the body, is outside of the visual field of the subject; unless the head is turned, precise movements here are not easily performed. The location of the common region of the strophosphere relative to the "R" point of the slot should have even more importance in the defining of regions in which certain hand positions are either impossible for most subjects or difficult for others.

The earlier comments on area/"R" point distance (Figure 75) are pertinent also; at from 15 to 18 inches ahead of the "R" point, the maximum reach upward, downward, and to either side was greater for the more important hand orientations than for distances closer to or farther from the "R" point.

A look at the cluster of kinetosphere centroids (dots of different sizes) in the strophosphere figures, however, goes a step farther. The 60° and 90° centroids actually fell within the common region of the strophosphere, while the 0°, -30°, +30°, prone, and invert centroids fell above or medial to the common area. A region of 15 to 19 inches forward to the "R" point of the seat, from 7 to 15 inches lateral to the midline, and from 19 to 30 inches above the "R" point encloses all the kinetosphere centroids.

The centroids extended in an oblique band, which began 30 inches above the "R" point and 7 inches from the midline, and extended to a position 19 inches above the "R" point and 15 inches lateral to the midline. As mentioned above, the lower lateral extremity of this band fell within the common region of the strophosphere and related to the 60° and 90° hand orientations. Figure 83 shows a heavy outline for the combined sagittal and transverse strophospheres; the centroids of the sagittal and of the transverse series of kinetospheres are separately interconnected. The transverse series shows a curved pattern and the sagittal, a sigmoid pattern when the centroids are taken in sequence. Collectively, they fell about the shoulder distance width lateral to the midline, between ear and pectoral height, and roughly at elbow distance forward. The mean kinetosphere centroid location may be taken as equivalent to the strophosphere centroid.

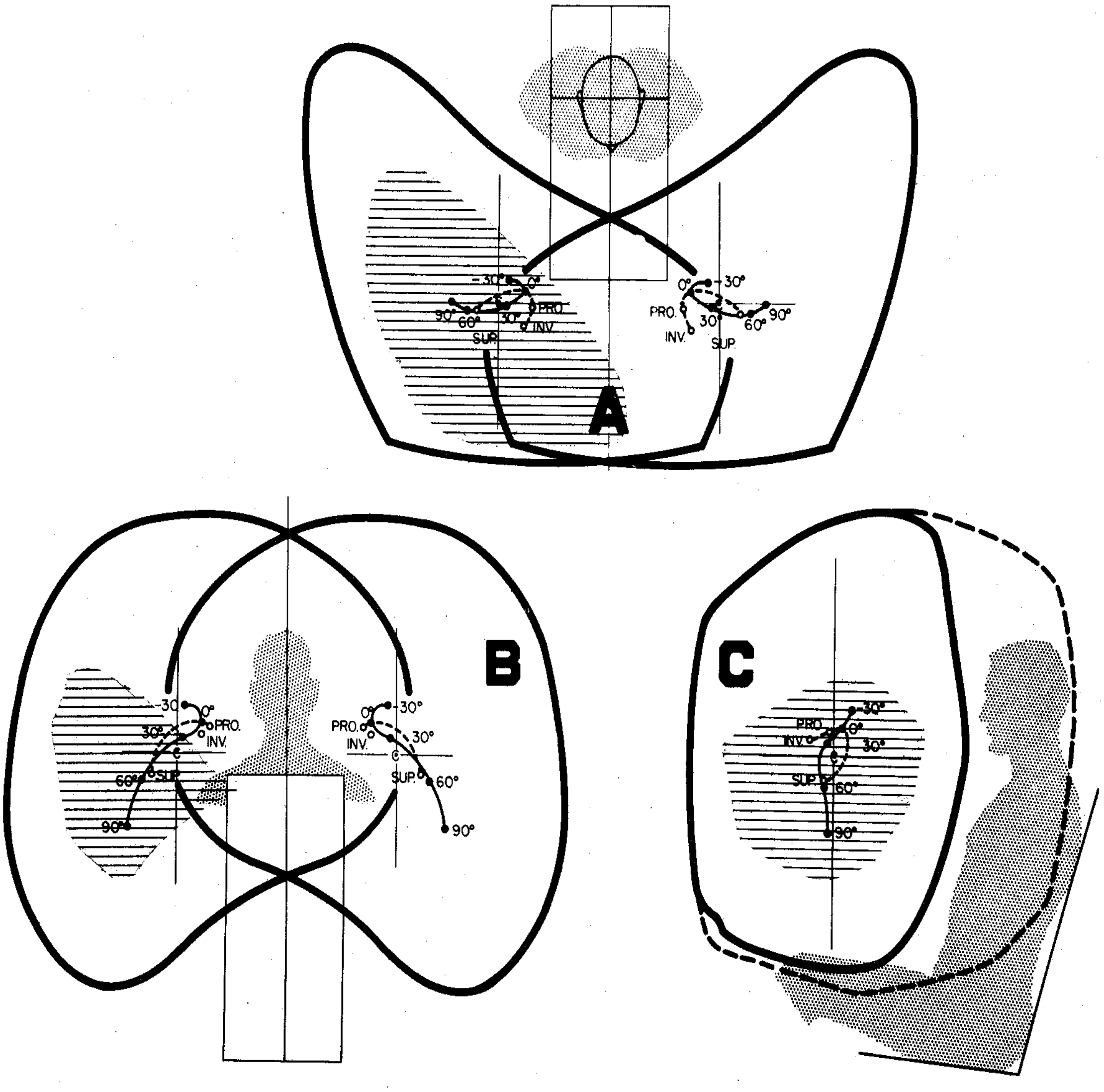

Figure 83. Combined sagittal and transverse strophosphere for the hand with centroids of kinetospheres connected in sequence. Horizontal shading shows the common region of the work space.

The centroid position for a given kinetosphere was in effect the farthest possible mean distance from the limits of the kinetosphere in all directions. Conversely, if the prone hand of a seated subject were to be held at its centroid position, it could move in an infinite number of straight lines in any direction, and the distance to the kinetosphere limit will on the average be longer than for any other initial position for the hand. This hand position implies a mean joint position for the whole chain of limb joints. The mean joint position in turn correlates with muscle functioning.

Upper limb muscles will tend to have roughly average lengths when the hand is at the centroid position. This will not be strictly true, however, since a variety of relatively small correlated wrist, elbow, and shoulder movements are possible, when the hand is in a fixed position. For instance, even though the hand may grip rigidly at a fixed location in space—automobile steering wheel, table edge, etc.—the elbow and shoulder still have an appreciable range of movement. Of course, variations in joint locations may result when the hand is at other positions than the centroid, but the centroidal position is postulated as the point where the largest potential range should be possible.

When the joints are held at average positions, consistent with the hand at the centroid locus, one may assume that muscles over the whole joint system are at or near average length. Now, when the hand moves forward from the centroid locus, wrist and elbow extensor muscles shorten and flexors elongate over the two joints; the reverse moment will involve flexor shortening and extensor elongation. Movement laterally from the centroid involve shortening of shoulder retractions and abductor muscles, and correlated movements at other joints; the opposite movement will involve shortening of the opposing muscles. These relationships, of course, are nothing but dimensional relations associated with limb geometry, but functional correlations are involved also, as will be shown.

For instance, if the hand were at a distance well forward to the centroid, the flexor muscles would be initially elongated to more than their midrange length; a passive movement that would move the hand through the centroid toward the near limits of the kinetosphere would involve a progressive shortening of these muscles. The antagonistic muscles would progressively elongate.

Now if instead of a passive movement, the movement were actuated by muscular contraction, the shortening of flexor muscles would actually carry the hand through the centroid; active contraction of the extensors would effect the opposite movement. According to a commonly recognized principle of muscular physiology, the long state of the muscle can exert a greater force than the short state.(Ramsey, 1944; Wiggers, 1944). Muscular forces for efforts involving maximal effort thus would progressively decrease as the hand moves through or beyond the centroid. Muscle force vectors should exhibit progressively decreasing gradients from moment to moment, as the hand moves toward, through, and away from the centroid.

There is no question that this picture oversimplifies limb functioning; it ignores changing, and to some extent partially compensating, leverages of muscles at joints, it ignores the fact that torques are greater at one joint than at another, and it ignores accelerations, momentum, and the effect of body dead weight (Chapter IX) in affecting forces. In general, insofar as the limb is concerned and ignoring the effect of body dead weight and counter supports, hand forces should be more powerful as the hand moves toward rather than away from the centroidal position of the hand for a given grip orientation. Although the centroid is only a position of reference for a variety of hand movements, it should correlate with the midrange of force gradients more than other points within reach.

Over and above our data on upper limb kinematics, additional information on force, speed, precision, and psychological factors should point the way to further refinements in work space organization. These pages still leave much room for the designer's art; they should, however, direct his attention toward the proposition that certain regions of the work space are of greater importance to an operator than others.

FOOT KINETOSPHERES

We will have occasion to return to the hand strophospheres in a later consideration of the overall work space. Prior attention to the kinetospheres and strophospheres involved in foot movement should, however, first merit attention. Figure 84 shows the general shape of reconstructions of the flat foot (90°) kinetosphere and the kinetosphere which represents a very steep foot sole angulation, 15° from the vertical. The former appears generally dome-shaped; it was compressed from before backward; and horizontal sections through it appeared oval or ovoid. It lay across the midline with most of the region to the left (test limb) side of the subject's midsagittal plane.

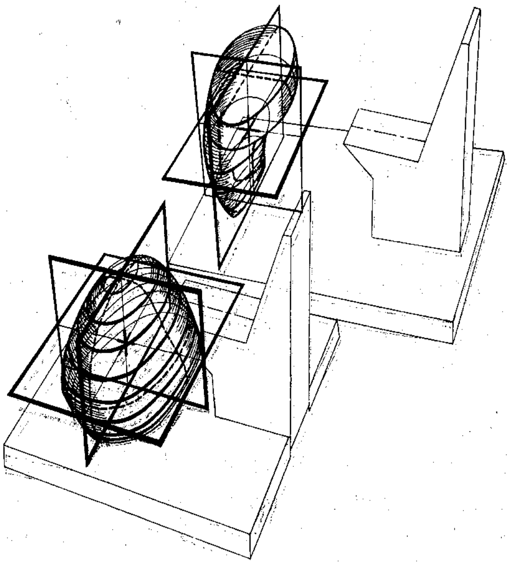

Figure 84. Foot kinetospheres. Reconstructions of mean kinetospheres for the flat foot (lower sketch) and for the 15° angulation (upper sketch).

The 15° kinetosphere did not touch the floor level; its bulk increased notably at higher levels and its principal mass lay above seat level. It was much farther forward from the seat than the 0° shape; in fact, it was almost wholly beyond the kinetosphere for the flat foot. Centroid positions are shown by crosses within the figures; the 15° centroid was much higher from the floor than the 90° centroid.

As for the hand, sagittal, transverse, and horizontal sections through the centroids permit a more ready analysis of similarities and differences in kinetosphere shape. For the hand kinetospheres, the primary records were photographic negatives from which enlarged tracings were made; the tracings of the extreme limit of hand movement were frontal plane serial sections. For the foot, the primary records were direct 1/5-size tracings representing horizontal sections through kinetospheres at 3-inch levels.

Details of the technique were outlined in Chapter II, Item 28. As for the hand, data locating the seat "R" point were indicated with each record. The derived sagittal, transverse, and horizontal sections through kinetosphere centroids were prepared by comparable methods for both the hand and foot.

Figure 85 shows plots of average horizontal areas relative to the distance from the floor for the subjects of muscular and median build; areas of actual records at each of the 3-inch levels were measured by planimeter and these were averaged in the figure. The halos of shaded lines on three of the curves representing mean deviation show the relative variability at different levels. The variability of the other two curves was comparable.

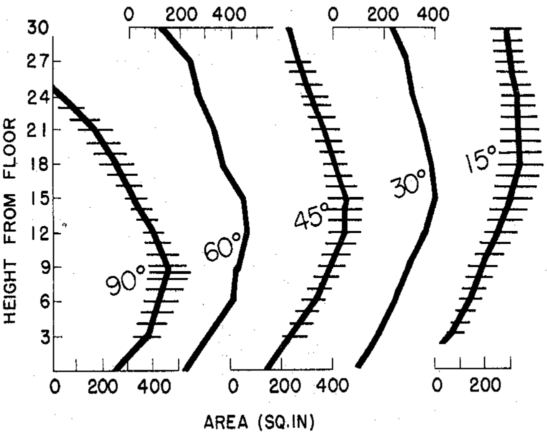

Figure 85. Area-to-heights plots for mean foot kinetospheres of muscular and median men. Horizontal shading shows the mean deviation of individual contours.

It may be noted that for the 90° foot-sole position the greatest area circumscribed by a reference point at the heel occurred at 9 inches above the floor. The area available to the foot decreased as shown below this level. Since the mean "R" point height from the floor averaged 15.5 inches when the seat was adjusted so that popliteal heights fell at the level of the front edge of the seat, 9 inches above the floor level was 6.5 inches below the "R" point.

Maximum areas were at higher and higher levels from the floor for increased foot inclinations; the maximum area for the 15° foot inclination fell at approximately 20 inches above the floor (4.5 inches above the "R" point). For a foot inclination of 45° to 30° the maximum area fell at approximately the height of the "R" point. The more vertical foot inclinations had less and less range of movement at heights below the maximum range; the 15° foot, in no instance, could even touch the floor.

The technique which was employed related the range of foot movement to a point on the foot sole at the midposterior border of the heel (heel point). If the whole foot were to be provided for, an additional forward dimension equivalent to the foot length would have to be added. Figure 86 shows the mean proportions of foot outlines for those of our subjects who were most like the average dimensions of the Air Force flying personnel (stature of 69.1 inches, 175.5 cm). Thin men had long foot lengths, then came muscular, median, and rotund builds. An adequate allowance for the longer foot would be reasonable.

The lower tier of figures shows that with increasing inclinations of the foot, the floor projection of the distance from heel to toe, or from heel to ball of the foot, decreases from 100 percent to 26 percent of the length. These lengths for different inclinations of the foot have been provided for in our figures of the work space envelope. Since, however, our data were obtained for the bare foot, an additional inch or inch-and-a-half of forward extension should be appropriate in planning the work space for shoe-wearing subjects; the same or a greater compensation for a half shoe width is equally advisable for the frontal projections.

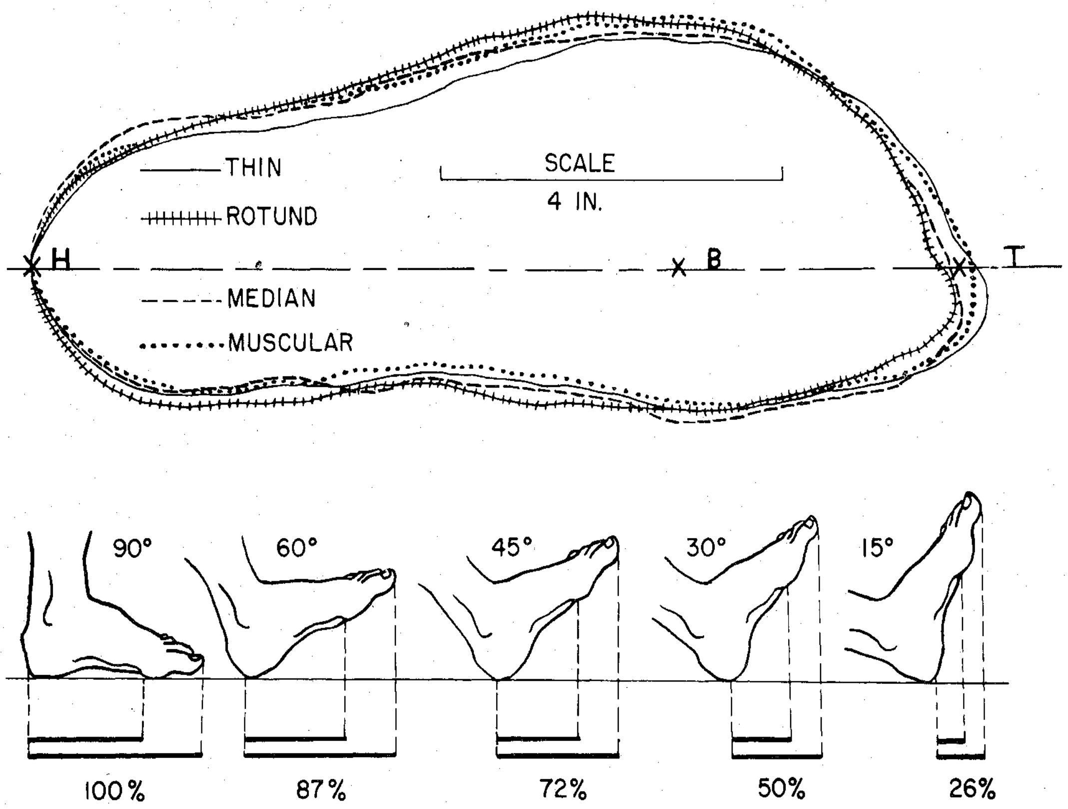

Figure 86. Mean contour of the left foot for average-sized men of different builds and average horizontal lengths from heel to ball of the foot, and from heel to toe for different foot angulations.

Figure 87 shows a superimposition of mean outlines of kinetosphere shapes for our muscular and median subjects; both sagittal sections through acentroid positions and transverse sections are shown. The 90° kintosphere was near the seat; it was low and its upper dimensions were small; the floor area was less than levels half way or higher toward the "R" point of the seat. Its centroid position was indicated in the figure by the largest dot shown.

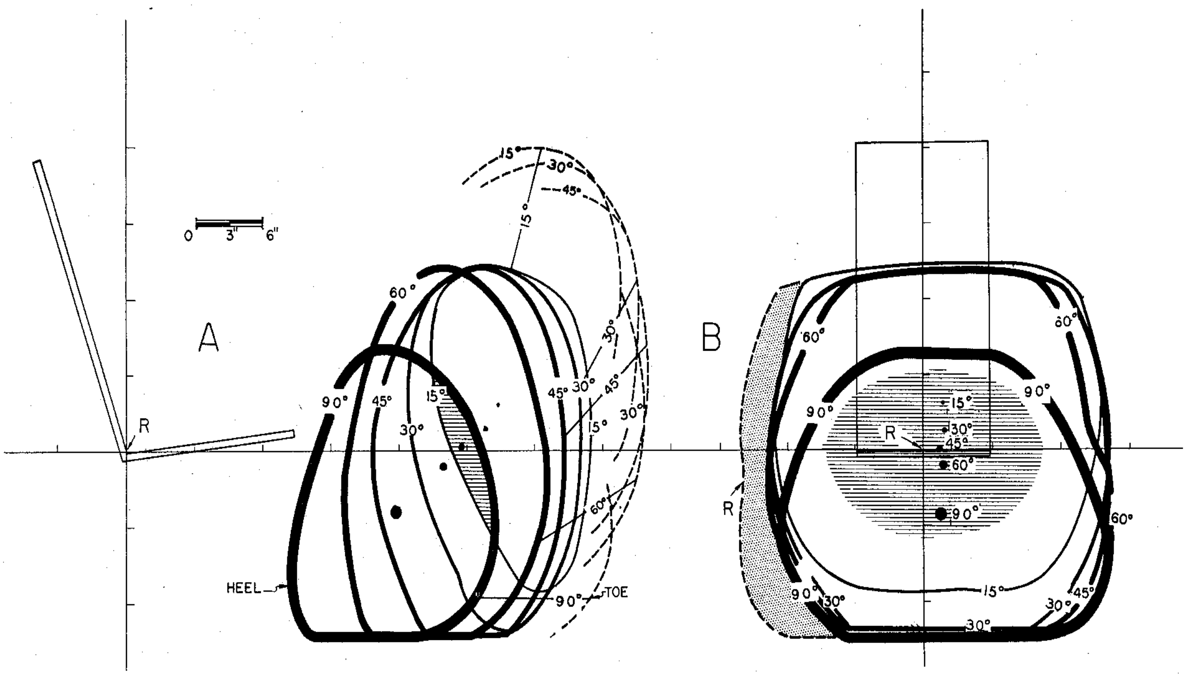

Figure 87. Sagittal (A) and frontal (B) sections at centroidal levels through the mean foot strophosphere of median and muscular subjects. The several kinetospheres are shown in different thickness of outline. Dots represent kinetosphere centroids. Horizontal shading shows the common region. Dashed lines show amount of additional span required for foot tilts of different angulations. The gray stippled shading at B shows on one side the region of no right-left overlap.

In contrast, the 15° kinetosphere (thinnest solid line) did not reach the floor; it was notably farther from the seat "R" point and its greatest dimensions were above seat level. In Sketch A the horizontal shading shows a region of overlap between the 15° and 90° kinetospheres; this region was also a region of common overlap for intermediate foot inclinations. The common region in which the foot may assume any inclination between 90° and 15° was a thin lentiform region tilted backwards 20° to 25° from the vertical; the forward projection of this obliquely placed zone is shown in Sketch B, its location with respect to the "R" point may be scaled off from the dimensions shown in the figure.

Five thicknesses of outline show sections through kinetospheres for the five-foot angulations used in our work. Kinetospheres for foot angulations below 45° were smaller in the upper halves of their height than below; the reverse was true for the more vertical foot inclinations.

The locations of centroids for each foot-range envelope are shown as dots of different size; the largest dot indicated the location of the centroid for the 90° kinetosphere. The dots in Sketch A are aligned 45° to 50° to the vertical with the 90° centroid below and close to the seat, and the 15° centroid above and farther away. These centroid positions, as noted earlier for the hand, represent positions in which straight line motions are on the average longer than for other points in the space. Movements in forward and downward directions relative to the centroids should result in stronger foot thrusts when the foot is proximal to rather than farther from these points. The heel position for the 45° foot, when placed at the 45° centroid position, is quite central relative to the whole foot range; it will be noted also that this position is at the level of the seat "R" point. It will be seen also that the other centroids lie farther from the common region.

In Sketch A, average foot length dimensions have been added to the forward and upper range of the strophosphere so that the lines of dashes representing toe positions make an effective addition to the strophosphere contour. Further provision for shoes was not made. In Sketch B, a stippled area is seen to the left of the strophosphere contour; this represents a region beyond the strophosphere outline for the left foot that would be utilized by the right foot if right and left strophospheres were to be superimposed.

Now, if the shaded area were to be removed and a similar mirror image section were to be removed from the other side, the remaining area, symmetrical on either side of the midline, would represent the common area of right-left overlap. Comparison with strophospheres of the hand (Figures 81 and 82) show that the region of right-left overlap was notably larger for the several inclinations of the foot. The lower limb segments are, of course, larger than those of the upper limb; there are fewer joints and fewer degrees of freedom for the foot than for the hand; and the motor control for precise movements is much less.

Even though the right-left overlap space is larger, it should be noted that very often the whole strophosphere is not available to the foot because objects before the worker interfere with movements of the thigh, knee, and shank. Figure 88 shows how interference with knee movement may limit the foot space. In the lower sketch relating to one of the test subjects a restraint was placed above the knee at point "A", in contact with the femur when the shank was vertical and the foot was flat. The shaded area below "a-a" shows the region available to the foot for the 90° and 15° inclinations of the foot sole; the related dashed arc shows the upper range for a 45° inclination. In the same way arcs limiting foot range below levels "b-b", "c-c", etc. are associated with knee heights B, C, etc. In the figure to the right the large shaded area below "e-e" shows the region available to the foot when the knee can move no higher than "E".

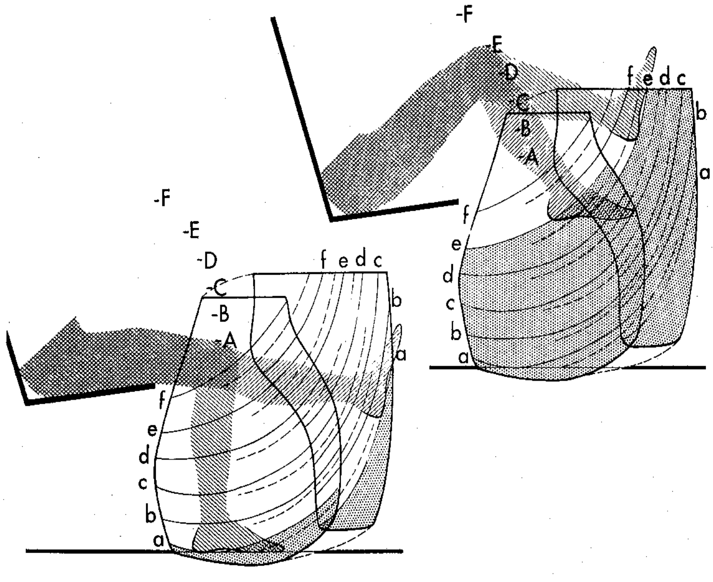

Figure 88. Areas of stippled shading and arc-like bands show (for one subject) regions of the foot strophosphere available to the foot for different knee heights.

This class of information should have significance to the designer since the amount of knee lift may be hampered by a table, desk, steering wheel, or other gear. The figure points up the compromise character of decisions involving the height and placement of hand installations relative to the space allotted to the foot. Unrestrained foot action demands that the space between the knee and trunk (within the A-B-F of the figure) be kept clear of restraints; when restraints are placed at different positions within the arc shown, the strophosphere space is decreased in a predictable way.

THE OVERALL WORK SPACE

It is of interest now to combine our data on the work space for the hand and that for the foot. Figure 89 shows an orthographic projection of a model which represents the mean shape of the combined hand strophospheres (sagittal and transverse series) and the foot strophosphere for our whole group of 22 muscular and median subjects. The figure shows top (A), front (B), rear (C), and side (D) views of the work space; dimensions may be scaled off from the 6-inch tick lines on the coordinates through the "R" point.

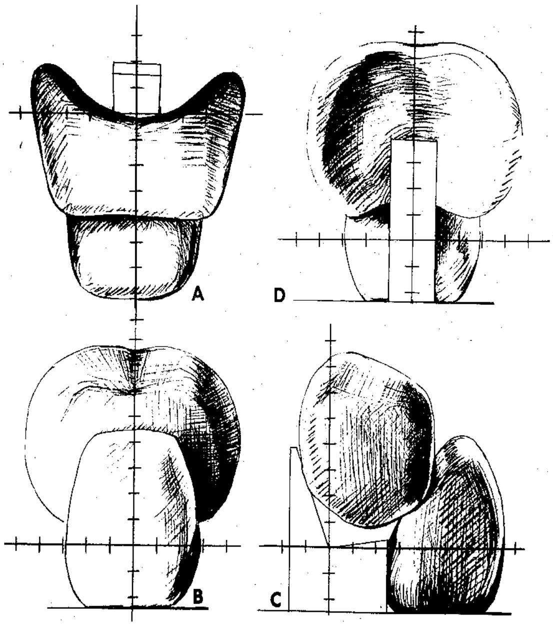

Figure 89. Top (A), front (B), side (C), and rear (D) views of the hand plus foot work space relative to the standard seat. Coordinates through the "R" point of the seat are sealed off in 6-inch intervals.

Obviously, in the design of the whole functional work place (or ergosphere) provision for the seat itself, for the operator's trunk, head, elbows, etc., and for the entrance and egress of the person must be allowed for also. The sketches show the shape and dimensions of the space required on the average for male subjects such as ours when hand and foot orientations are directed forward and end-member orientations are similar to those used in acquiring the basic information. Allowance for the aver-

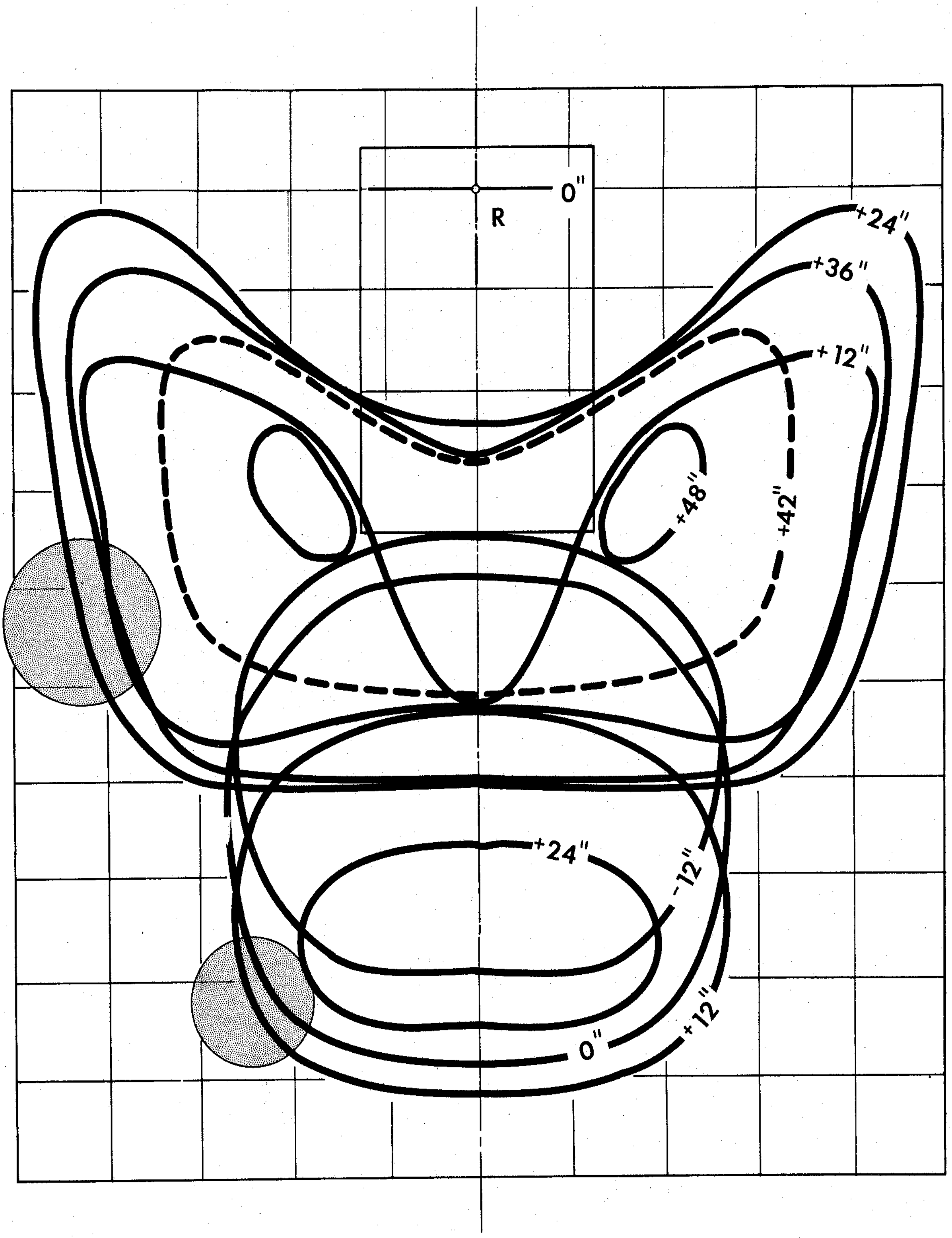

Figure 90. Floor plan of work space relative to the standard seat shown by 12-inch contours. The grid squares are 6 inches. The 0-inch contour is at "R" point level; -12 inches is below and +12 inches, +24 inches, +36 inches, etc., are above "R" point level. The radius of the shaded circles represents a width to be added or subtracted from the different curves to include the 5th and 95th percentiles of movement.

age bare foot length beyond the heel point has been included but no other compensations have been made. It should be remembered that the center of the hand grip and not the exterior of the fist or finger tips was the point of reference which described the hand envelope; additional allowance may be required here for the augmented dimensions of knuckles, fingers, and gloves.

Figure 90 presents the same dimensions in terms of a floor plan, in this instance the grid lines are again 6 inches and the contours represent levels through the "R" point of the seat (0 in.), a level below (-12 in.) and several levels above (+12 in., +24 in., etc.).

Mean work space dimensions as shown, however, are probably misleading; our data on different subjects showed a fluctuation about the average for both hand and foot ranges. The narrow contour lines of Figure 90 are nominal; wide bands suggesting variability would have been more correct for our data. The diameters of the two shaded circles show the width of a band of variability which includes 90 percent of the different hand and foot movements (5th to 95th percentiles) for the different kinetospheres.

If the dimensions of each of the contours were enlarged by the radial dimension of the circles, the contours would include a larger percentage of possible hand or foot movements than the average contours would. This increment would include, generally, movements of men with naturally greater reach and movements also of those men who, although shorter, tend to exert themselves to their limit. Subtraction of the radius dimension from each contour produces a smaller work space but, as will be shown, this has a more or less nominal value. Figure 91 (a and b) shows the side view of a model which involves these augmented and decreased dimensions. The larger space included 95 percent of all hand and foot movements; the smaller model represented a

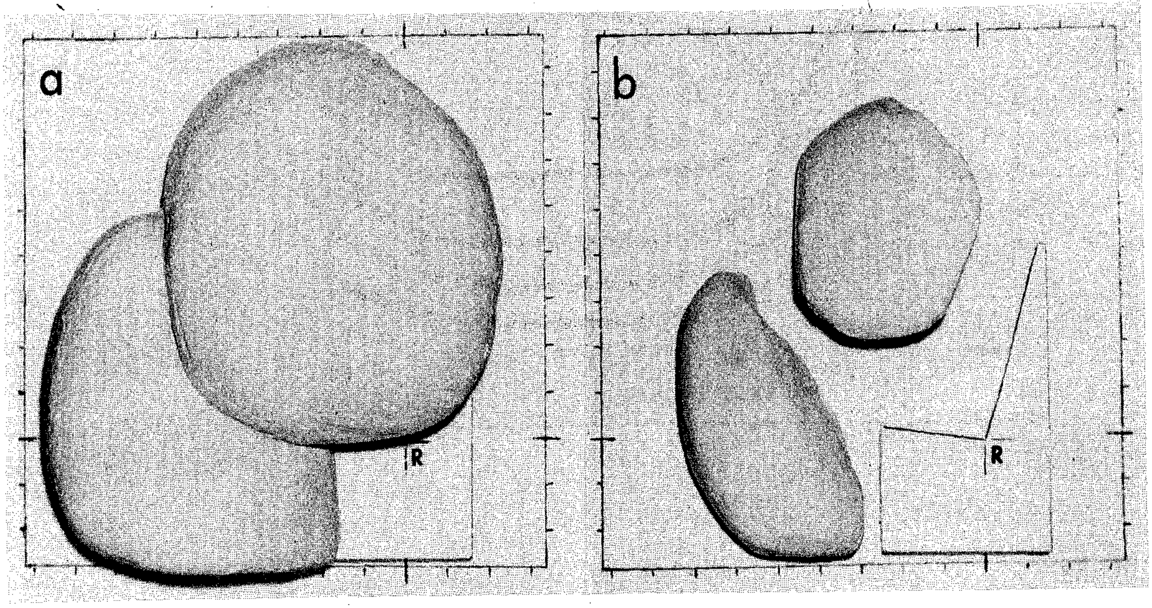

Figure 91. Models of side view of work space. A-Dimensions scaled to 95th percentile of hand and foot movements of muscular and medium subjects. B-Dimensions scaled to the 5th percentile. Tick marks are at 6-inch intervals relative to the seat "R" point.

boundary which would restrict all but 5 percent of the "maximum" reaches. The latter envelope is nominal, however, in that it relates only to overall maximal reaches for the whole gamut of end-member orientations. Earlier it was shown that the reach for specific end-member orientations was more limited, in that common regions for all hand and foot orientations were relatively restricted; combinations of kinetospheres involving a fewer number of hand orientations would permit a larger common space. For practical applications the small contour of Figure 91b should be critically balanced against our more pertinent data on common regions, regions of right-left overlap, centroid locations, etc.

There are always going to be problems calling for judgment when the work space is to be reduced below maximum limits; the only work region that can be planned in advance with no data on the nature of the operation itself is an overall space. A work space, like our Figure 91a, can be planned not only for specific body dimensions, but for operations which include 95 percent, or some other proportion, of the possible movements of the limbs for the seated subject, for given body types in a population. Presumably women, with ordinarily smaller builds but with greater joint range, would utilize smaller work spaces than men, but how much smaller we cannot say.

It should be apparent from our work that forward, and presumably useful, orientations of the hand and foot have received emphasis. King (1948, 1952) measured the sweep of the finger tips in different directions from forward to the side and at different heights; the elbow was generally straight in this measure. With due corrections for the fact that our measurements referred to the center of the hand grip and for orientations of the hand relative to a frontal reference plane it should be apparent that King's lateral reaches should be farther to the side than ours where inherent limitations to wrist joint motion acted as restraints.

Another condition is pertinent for the work space. In all of our work the subjects sat squarely on a standard seat provided with a back of specified inclination. Movements were conditioned by the necessity of the back being against the seat back, the buttocks being well back, and the head resting on a dental-chair headrest. Normally, a seated individual may bend the trunk forward an appreciable amount without threatening his stability; he can, however, move only a little bit to the side and still have stability relative to the support provided by his ischial tuberosities, buttocks, and feet.

Figure 92 shows one of our more mobile subjects describing a hand movement (hand prone) in the sagittal plane of the shoulder. Curve A shows his hand range—a tall, bean-shaped contour—reaching from the seat to the uppermost reach possible. When the trunk was bent forward and stabilized by the opposite elbow on the knees, curve B resulted. The major axis of this contour, relative to the first, tilts about 35° forward; it became notably deeper from fore to aft; it fell below the seat level; and it was less tall. Next, when the subject leaned farther forward with his trunk next his thighs, these changes (height, forward dimension, etc.) were further accentuated; the major axis of the contour was now tilted about 15° farther.

The same general changes were found with repetitions for the same hand orientation and for several other hand-grip positions utilized. These contours suggest that if the side-view work-space profiles (Figures 89 and 91a) were designed so that there was no upper forward notch between the foot and hand space, i.e., so that the anterior contour of the foot space continued up until it was continuous with that of the hand space, adequate provision for hand range with forward bending would be allowed.

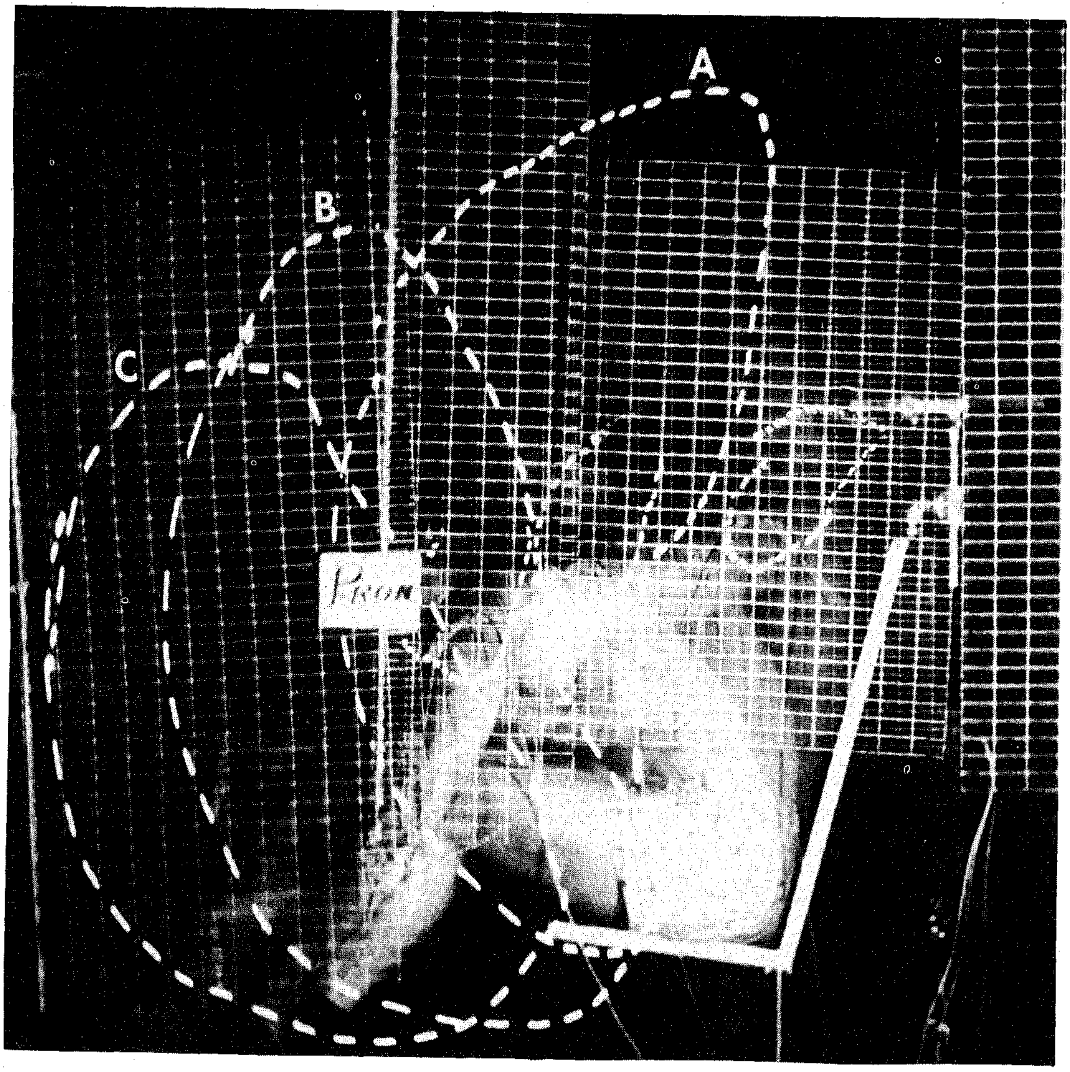

Figure 92. Superimposed traces of the movement of the prone hand in a sagittal plane at shoulder level for 3 trunk positions. A-trunk against seat back; B-trunk set forward so that opposite elbow rests on knees; C-trunk maximally flexed against thighs.

Our figures with coordinates through the "R" point of the seat, and with tick lines showing the dimensions, should permit the scaling off of the work space proportions for practical purposes. The problem, however, is not a simple one of merely transferring a set of cut-and-dried dimensions. Controls and manipulated objects should be within a convenient reach of all operators; use should not be encumbered by crowded space; large-sized operators should not be handicapped by control locations, convenient enough for small men, that interfere with knee and elbow movements.

Clues to effective placement, from the area of body kinematics, however, should not be ignored. We have outlined the significance of common regions for all end member orientations, regions of right-left overlap, centroid positions, regions good only for specific hand orientations, distances from the "R" point of areas of wide range, and other factors presented earlier. Psychological factors, the need for displays of gauges and dials or for window space, and preferences based on habits should also be important in design problems. Preferred hand orientations and regions of maximum force applications (Chapter IX) also deserve consideration.

CHAPTER VII

MASS RELATIONS OF CADAVER SEGMENTS

Relatively few bodies have been dismembered and measured to obtain data relevant to analyses of body mechanics. Harless (1860) dismembered two young adult cadavers (one listed as age 29) and weighed the following segments: whole upper limb, arm, forearm, hand, whole lower limb, thigh, leg, foot, head, and the trunk without head or limbs. He measured segment lengths, and the relative distances from the center of gravity to the extremities of the segment were determined. The mass and centers of gravity of upper and lower trunk sections were estimated rather crudely from calculations based on truncated cones of unit density. He presented an illustration of a loaded stick figure somewhat like that of our Figure 32. Harless' work was a pioneer effort, crude in various respects. The specimens were beheaded criminals with an unknown loss of mass due to the blood drained away. Certain segments were exarticulated and others were cut through joint centers or at neighboring landmarks.

Braune and Fischer (1890) refined the earlier procedures and presented the classical data on body mass that have been used to this day. These "well built" male bodies (two of which were listed as age 45 and age 50) were frozen solid in the supine position, and the limb joints were sawed across at planes which were presumed to transect joint centers. Weights were determined for the following segments: head, trunk without extremities, entire upper limb, arm, forearm plus hand, forearm, hand, entire lower limb, thigh, leg plus foot, leg, and foot.

Saw cuts severing the head and limbs from the trunk were best-estimate oblique cuts; the head was severed on a plane from the hyoid region to the skull base at the occiput. The upper limb was separated by a roughly vertical cut through the axilla planned to transect the center of the humeral head, and the lower limb was separated by an oblique cut, which paralleled the side of the bony pelvis and transected the femoral head. (Because of the curvatures of the lateral side of the os coxae, a "parallel" cut has a distinctly arbitrary character.) It should be noted also that the mass and center of gravity of the trunk section minus extremities were treated as a solid block, and no further dismemberment of the torso was attempted.

Braune and Fischer then went a step farther; they found that with only slight adjustments in the position of the limb segments the various joint centers and the various centers of gravity (except for that of the foot) could be aligned in a horizontal plane relative to the supine body. This posture, with centers of gravity and principal joint centers in a plane, could be approximated reasonably, they claimed, by a living subject in a normal standing posture.

Accordingly, joint centers and centers of gravity of one of their specimens were laid out to the nearest millimeter in a coordinate system in the YZ (vertical frontal) plane. By considering the moments of the various mass centers in the plane of reference, the location of the whole body center of gravity could be calculated; the calculated whole body center of gravity and those for various groupings of extremity parts were well within the limits of measurement error on the actual specimen from which mass and dimensions were obtained.

Only one additional reference requires mention: Meeh (1895) made various measurements of body volume on several living subjects and upon four infant cadavers, varying from premature to 1 year, 10 months in age. The cadavers were, in addition, dismembered, and body sections corresponding to those concerned in the volume measurements were weighed as a check. Meeh's trunk sections have little meaning now, but data on the limb segments and head sections are to some degree comparable with data obtained by procedures used by the two earlier authors discussed.

From the literature above it becomes evident that Harless' two adult specimens and Braune and Fischer's three form a very small sample, even when supplemented by data on Meeh's four infants. It will be inferred correctly that we are without any information on female builds or on children of different ages. Nevertheless, the data of Braune and Fischer and the methods of orienting segment masses relative to X, Y, and Z coordinates have had considerable influence, especially in the hand of Fischer in his studies on locomotion (1904) and by later students in this field, such as the Russian Bernstein (1935) and the Americans Elftman (1939) and Eberhardt (Nat. Res. Council, etc., 1947).

Additional information on more subjects, however, should show better the range of variability of the type of data available on body segments; additional confirmatory data on certain topics, furthermore, should bring added confidence in the use of averages where body constants are concerned. Present data on eight adult males increase the available records from five to thirteen cases. In addition, when data have not been amplified in 60 years or more, only the outlook and experience of an investigator concerned with actual procedures can present a contemporary evaluation of the errors and difficulties involved.

DISTRIBUTION OF BODY MASS

In our approach it has been assumed that the primary current use of body constants would be in the analysis of a variety of problems in body mechanics involving specific test subjects. It was also assumed that if satisfactory data on body constants were available, static postures or instantaneous phases of body movement could be analyzed mechanically from photographic records, including possibly simultaneous records in different planes of space. Probably in many instances static or dynamic data on whole body reaction forces would also be available for analyses of posture and movement. To this end, the Braune and Fischer coordinate system seemed less important than basic data on segment masses, on centers of gravity of parts relative to joint centers, and on moments of inertia of the body members. The data derived from our procedures, accordingly, were concerned with segments per se, rather than with whole body systems.

With this in mind, an attempt has been made here to procure data not on limb segments of straightened and outstretched limbs, but on segments in midrange joint positions. Each limb joint was separated in a plane that sought to divide segment masses into units of mean size, which would more correctly represent values for a variety of possible limb postures. This procedure probably results in very minor differences in comparison to the constants from the older literature, but there is at least theoretical justification for the method.

Furthermore, the current approach sought to divide the trunk mass—previously considered as a single block, except for Harless' crude calculations—into shoulder, neck, thorax, and abdomino-pelvic units. One should realize that the abdomen and pelvis are anatomically confluent regions and no realistic and practical separation of the common mass into two units can be made. The detailed procedures employed and recorded in Chapter II, Items 30-37, and Figures 21 and 22 should be consulted at this point for details of methodology involved in the obtaining of data on body segments.

Our subjects were white adult males who ranged from middle to old age; they were free of obvious physical defects; the general characteristics of the sample were recorded in Table 4. Most of the data derived from the procedures may be presented here in tabular form.

Tables 10, 11, and 12 show the mass of the different body segments for the various subjects. Even though the somatotype records of Table 4 showed that the subjects were of generally average physique, the older subjects were commonly of light build; only two subjects of the sample were more than 70 kg (154 lb). The proportion between the mass of a part and the total body weight forms a convenient gauge of variability.

Certain unavoidable errors resulted from dismemberment and the necessary handling in the different procedures used—especially the moment of inertia procedures with suspensions and some dripping of blood, and volume measurements, which involved thawing with further loss of blood, and water immersion with some ensuing changes in mass. In later procedures with trunk segments the hollow viscera, such as trachea, urinary bladder, pleural space, etc., gained or lost unknown quantities of water following immersion and drainage. General comparison of percentage values, however, showed no marked discrepancies that could be attributed to this cause.

If one adds or subtracts mass values from the tables, discrepancies, which for the larger masses may amount to several hundred grams, are often found. The aforementioned factors are responsible. In addition, masses of 10 kg or more were weighed in pounds on scales of low sensitivity, i.e., approximately 1/4-lb, and then converted to the metric scale. Total body mass prior to dismemberment procedures (Table 4) were also measured in pounds and converted to metric units. In general, the errors appeared to be proportional to the size of the mass treated. These percentage ratios are of most interest in applications to living test subjects.

In several instances, analyses of the records long after the procedures had been completed showed inconsistencies (especially percentages) far out of line with other data on the subject; these were obviously errors in recording. When such discrepancies appeared, as occurred in the 15062 record of trunk-minus-shoulders weight, an alternate value involving subtraction of shoulder mass from the trunk-minus-limbs value was available; here addition or subtraction of values are mathematically correct. Except for several egregious discrepancies, which were corrected in this way (and shown by values in parentheses), recorded measurements have been listed directly in the tables and calculated values have not been used.

It should be apparent from the above comments that inherent procedural errors are

TABLE 10

MASS OF BODY PARTS

Weights in grams; percentages are ratios to total body weight.

Cadaver Number	Body Weight	Trunk Minus Limbs	%	Trunk Minus Shoulders	%	Both Shoulders	%
14815	51364	31363	61.1	26818	52.2	4310	8.4
15059	58409	32955	56.4	26705	45.7	6535	11.2
15062	58409	(34558)	59.1	(27670)	47.3	6888	11.8
15095	49886	29300	58.7	24431	49.0	5743	11.5
15097	72500	40568	56.0	33409	46.1	8039	11.1
15168	71364	38369	53.8	33377	46.8	7229	10.1
15250	60455	31558	52.2	25909	42.9	5708	9.4
15251	55909	30341	54.3	25341	45.3	4942	8.8
Mean %			56.5		46.9		10.3

Cadaver Number	Head and Neck	%	Thorax	%	Abdomen Plus Pelvis	%
14815	----	---	----	----	-----	----
15059	3797	6.5	4803	8.2	18182	31.1
15062	5227	8.9	6136	10.5	16364	28.0
15095	4348	8.7	5341	10.7	14515	29.1
15097	5337	7.4	8754	12.1	19187	22.0
15168	4850	6.8	9053	12.7	17237	24.1
15250	4371	7.2	6620	10.9	(14918)	24.7
15251	4340	7.8	6637	11.9	(14364)	25.7
Mean %		7.9		11.0		26.4

TABLE 11

MASS, UPPER EXTREMITY

Weights are in grams; percentages represent ratios to total body weight.

Cadaver Number	Entire Upper Extremity	%	Arm	%	Forearm and Hand	%	Forearm	%	Hand	%
					Left Side					
14815	2720	5.3	1157	2.3	1290	2.5	850	1.7	445	0.9
15059	2770	4.7	1541	2.6	1256	2.2	934	1.6	325	0.6
15062	2485	4.3	1373	2.4	1080	1.8	747	1.3	332	0.6
15095	2132	4.3	1133	2.3	1003	2.0	703	1.4	317	0.6
15097	3899	5.4	2199	3.0	1691	2.3	1191	1.6	500	0.7
15168	3453	4.8	1909	2.7	1515	2.1	1104	1.5	417	0.6
15250	3080	5.1	1663	2.8	1400	2.3	1002	1.7	390	0.6
15251	2459	4.4	1315	2.4	1140	2.0	780	1.4	339	0.6
Mean %		4.8		2.6		2.1		1.5		0.6
					Right Side					
14815	2641	5.1	1212	2.4	1342	2.6	865	1.7	457	0.9
15059	3277	5.6	1920	3.3	1340	2.3	995	1.7	352	0.6
15062	2695	4.6	1528	2.6	1134	1.9	815	1.4	311	0.5
15095	2125	4.3	1123	2.3	1024	2.1	710	1.4	317	0.6
15097	3947	5.4	2171	3.0	1777	2.5	1250	1.7	517	0.7
15168	3673	5.1	1970	2.8	1699	2.4	1265	1.8	452	0.6
15250	3035	5.0	1614	2.7	1414	2.3	1021	1.7	400	0.7
15251	2394	4.3	1372	2.5	1017	1.8	713	1.3	295	0.5
Mean %		4.9		2.7		2.2		1.6		0.6

TABLE 12

MASS, LOWER EXTREMITY

Weights are in grams; percentages represent ratios to total body weight.

Cadaver Number	Entire Lower Extremity	%	Thigh	%	Leg and Foot	%	Leg	%	Foot	%
					Left Side					
14815	6255	12.1	3495	6.8	2602	5.1	1961	3.8	725	1.4
15059	9855	16.9	6482	11.1	3384	5.8	2629	4.5	760	1.3
15062	8390	14.4	5520	9.5	2835	4.9	2080	3.6	754	1.3
15095	8313	16.7	5285	10.5	3041	6.1	2218	4.4	814	1.6
15097	11907	16.4	7093	9.8	4846	6.7	3860	5.3	967	1.3
15168	11111	15.6	6258	8.8	4812	6.7	3552	5.0	1209	1.7
15250	11337	18.8	7700	12.7	4045	6.7	2991	4.9	949	1.6
15251	(8092)	15.0	4660	8.3	3432	6.1	2564	4.6	796	1.4
Mean %		15.7		9.7		6.0		4.5		1.4
					Right Side					
14815	6176	12.0	3385	6.6	2613	5.1	1963	3.8	655	1.3
15059	9580	16.4	6115	10.5	3472	5.9	2674	4.6	800	1.4
15062	8303	14.2	5370	9.2	2907	5.0	2165	3.7	746	1.3
15095	7715	15.5	4770	9.6	2878	5.8	2205	4.4	767	1.5
15097	11920	16.4	7155	9.9	4825	6.7	3899	5.4	924	1.3
15168	11904	16.7	6902	9.7	4765	6.7	3606	5.1	1095	1.5
15250	11791	19.5	7215	11.9	3955	6.5	2954	4.9	865	1.4
15251	(8457)	15.1	5135	9.2	3322	5.9	2459	4.4	808	1.4
Mean %		15.7		9.6		5.9		4.5		1.4

to be expected in measurements of dismembered cadaver parts, especially where methods involve repeated handling and the determining of a variety of measurements. These points are ordinarily missed when the older data are read. Values on parts, like those of Harless, which add up correctly are most unusual in our experience.

ANATOMICAL LOCATION OF SEGMENT CENTERS OF GRAVITY

After various procedures, including measurements made on segment mass, segment volume, position of center of gravity relative to length, and moment of inertia, the anatomical location of the center of gravity of each segment was determined. Limb segments were balanced along their length with three or four different surfaces in sequence uppermost; vertical drill holes at each position were made into the frozen tissues along the gravity lines, and short, quarter-inch, pointed, dowel sticks were driven home. A transverse saw cut through the plane of the various dowel sticks produced a surface across the segment with the sticks pointing toward the three-dimensional center of gravity. The anatomical locus of this point on the cross section was recorded, and after the tissues thawed, each part was dissected so that the distance up or down from nearby landmark structures could be measured.

Details of alternate procedures for locating the center of gravity of head and trunk segments in three dimensions were outlined in Chapter II, Items 35 and 36. Separate records on the several cadavers were tallied, and the most common or most nearly average site of the center of gravity of each part was determined. Figure 93 illustrates these locations for the free limb segments; the positions are also shown in Tables 13 and 14, as are locations of shoulder, head, and trunk segments. For one trained in gross and surface anatomy these locations have value as aids in estimating the positions of centers of gravity in photographs of nude subjects in different body postures.

The three-dimensional data showed that the centers of gravity of the limb segments, except for the shoulders, were characteristically aligned between the joint-center regions. Braune and Fischer also pointed out that centers of gravity of the limb segments lie on or close to a line between adjacent joint centers. In the foot, the center of gravity lay approximately on a line between the ankle center and the ball of the foot in the plane of the II metatarsal bone; for the hand in the rest position, the center of gravity fell at a point near the skin surface on a line between the center of the head of the capitate bone and the radial side of metacarpal bone III. Since centers of gravity tend to be aligned between adjacent joint centers, data for more or less general use on the location of many centers of gravity of the limb segments may be based simply on the relative distance of the center to adjacent proximal and distal joint centers.

Table 15 lists for the various segments the relative linear distance of a center of gravity from the extremities of the segment links. Measurements had been made between certain terminal landmarks or points of convenient reference; distances from the same landmarks to the center of gravity had been measured also. The data are presented as averaged percentage ratios. For the simple or unit sections little comment is necessary. Ratios on different subjects showed that the percentage distances for the hand were more variable than for other parts since total hand length, involved in the calculations, reflected different degrees of finger bending. The so-called "rest position"

TABLE 13

ANATOMICAL LOCATION OF SEGMENT CENTERS OF GRAVITY

Segment	Proximo-Distal Location	Position in Cross Section
Arm	5 mm proximal to distal end of deltoid M insertion and 24 mm distal to most proximal fibers of medial head of triceps.	In medial head of triceps adjacent to radial nerve and radial groove of humerus.
Forearm	11 mm proximal to most distal part of insertion of pronator teres M.	9 mm anterior to interosseous membrane, usually between flexor digitorum profundus and flexor pollicis longus MM or more toward flexor pollicis longus M or toward flexor digitorum sublimus M.
Hand	(In position of rest) 2 mm proximal to proximal transverse palmar crease in angle between the proximal transverse and the radial longitudinal creases.	On axis of III metacarpal, usually 2 mm deep to skin surface.
Thigh	29 mm below apex of femoral triangle and 18 mm proximal to the most distal fibers of adductor brevis M.	Deep to adductor canal and 13 mm medial to the linea aspera in the adductor brevis M (or in adductor magnus M or vastus medialis M).
Leg	35 mm below popliteus M and 16 mm above the proximal extremity of Achilles tendon.	At posterior part of tibialis posterior M (between flexor digitorum longus and flexor hallucis longus MM); 8 mm posterior to interosseous membrane.
Foot	66 mm from the center of the body of the talus; below the proximal halves of the second and third cuneiform bones.	In plantar ligaments or just superficial in the adjacent layer of deep foot muscles.

TABLE 14

ANATOMICAL LOCATION OF SEGMENT CENTERS OF GRAVITY

Body Part	Location
Shoulder mass	On a line perpendicular to the anterior face of the outer quarter of the blade of the scapula or near its axillary border 20.5 ± 9.0 mm from the bone and 78.0 ± 5.0 mm above the inferior angle; it falls within the axilla or in the adjacent thoracic wall.
Head and neck	8 mm anterior to basion on the inferior surface of the basioccipital bone or within the bone 24.0 ± 5.0 mm from the crest of the dorsum sellae; on the surface of the head a point 10 mm anterior to the supratragic notch above the head of the mandible is directly lateral.
Head alone	A point in the sphenoid sinus averaging 4 mm beyond the antero-inferior margin of the sella; on the surface, its projections lay over the temporal fossa on or near the nasion-inion line at a point about 32 percent back from the nasion; it was equally distant above the zygomatic arch and behind the malar frontosphenoid process.
Thorax	At the level of the disc between the ninth and tenth thoracic vertebrae or of either of the adjacent vertebral bodies at the anterior border of the column (anterior longitudinal ligament) or in the adjacent posterior mediastinum; on the surface, level below the nipples and above the transverse line between pectoral and abdominal muscles, spine of the eighth thoracic vertebra.
Abdomino-pelvic mass	Level of or below disc between L4 and L5 in the posterior region of vertebral body; between umbilicus and crest of ilium.

TABLE 15

RELATIVE DISTANCES BETWEEN CENTER OF GRAVITY AND JOINT AXES OR OTHER LANDMARKS

Segment or Part and Reference Landmarks	No. Observed	Distance from Center of Gravity to Reference Dimension Stated as %
1. Hand (position of rest) wrist axis to knuckle III	16	50.6% to wrist axis 49.4% to knuckle III
2. Forearm, elbow axis to wrist axis	16	43.0% to elbow axis 57.0% to wrist axis
3. Upper arm, gleno-humeral axis to elbow axis	16	43.6% to gleno-humeral axis 56.4% to elbow axis
4. Forearm plus hand, elbow axis to ulnar styloid	16	67.7% to elbow axis 32.3% to ulnar styloid
5. Whole upper limb, gleno-humeral axis to ulnar styloid	16	51.2% to gleno-humeral axis 48.8% to ulnar styloid
6. Shoulder mass, sternal end of clavicle to gleno-humeral axis	14	84.0% of clavicular link dimension to sternal end of clavicle (oblique) 71.2% of clavicular link dimension to gleno-humeral axis (oblique)
7. Foot, heel to toe II	16	*24.9% of foot link dimension to ankle axis (oblique) *43.8% of foot link dimension to heel (oblique) *59.4% of foot link dimension to toe II (oblique)
8. Lower leg, knee axis to ankle axis	16	43.3% to knee axis 56.7% to ankle axis
9. Thigh, hip axis to knee axis	16	43.3% to hip axis 56.7% to knee axis
10. Leg plus foot, knee axis to medial malleolus	16	43.4% to knee axis 56.6% to medial malleolus
11. Whole lower limb, hip axis to medial malleolus	16	43.4% to hip axis 56.6% to medial malleolus

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*Alternately, a ratio of 42.9 to 57.1 along the heel to toe distance establishes a point above which the center of gravity lies; the latter lies on a line between ankle axis and ball of foot.

TABLE 15 (continued)

Segment or Part and Reference Landmarks	No. Observed	Distance from Center of Gravity to Reference Dimension Stated as %
12. Head and trunk minus limbs, vertex to transverse line through hip axes	7	60.4% to vertex 39.6% to hip axes
13. Head and trunk minus limb and shoulders, vertex to line through hip axes	7	64.3% to vertex 35.7% to hip axes
14. Head alone	2	See Table 14
15. Head and neck, vertex to seventh cervical centrum	6	43.3% to vertex 56.7% to centrum
16. Thorax, first thoracic to twelfth thoracic centrum	6	62.7% to first thoracic centrum 37.3% to twelfth thoracic centrum
17. Abdomino-pelvic mass, centrum first lumbar to hip axes	5	59.9% to centrum first lumbar 40.1% to hip axes

into which the fingers were flexed and some varied somewhat on account of finger stiffness.

For the foot the center of gravity was on a line between the ankle and the ball of the foot; the ankle-to-center-of-gravity measurement was along this line, but the heel-to-center-of-gravity and toe-to-center-of-gravity were not; the ratio to foot length is merely an arbitrary comparison of dimensions. For the shoulder mass also, no two of the measurements were in the same line; the two oblique measurements to center of gravity were recorded as ratios to a third measurement at a still different angulation.

The limb and more central trunk segments involved both overall measurements and measurements from each extremity of the mass to the center of gravity as marked on the skin surface. The measurements thus, instead of being aligned, were three sides of a scalene triangle; the sum of the two sides was uniformly greater than the hypotenuse. Accordingly, the ratio of measurement from center of gravity to the extremities (Table 15) involved corrections for the hypotenuse dimension; the ratios recorded applied to the location of the center of gravity as aligned between terminal measuring points. Since compound parts, such as the whole upper and lower limbs, could not be straightened to exactly the same degree, even with cuts through the skin and tendons over the elbow or knee joints, the major dimension was taken as the sum of the two segments.

Data from the table on the relative distances between centers of gravity and terminal landmarks should, in certain instances at least, as noted in the footnote, be related to the data of Tables 13 and 14 and of Figure 94 on the anatomical locations of

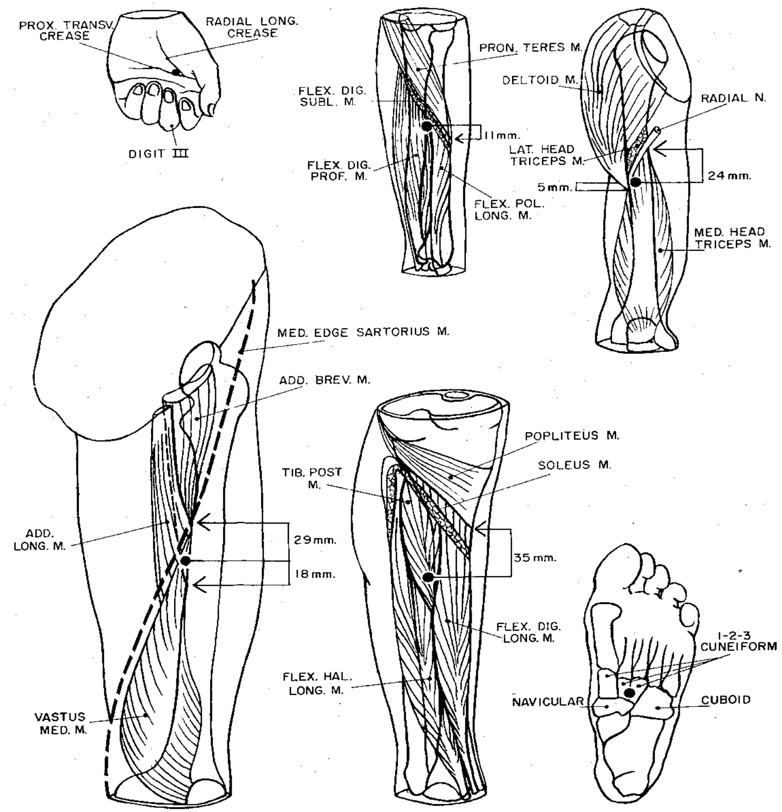

Figure 93. The anatomical location of centers of gravity of limb segments. The large black dot in each segment represents the location of the center of gravity; adjacent muscles and bones and distances from landmarks structures are shown.

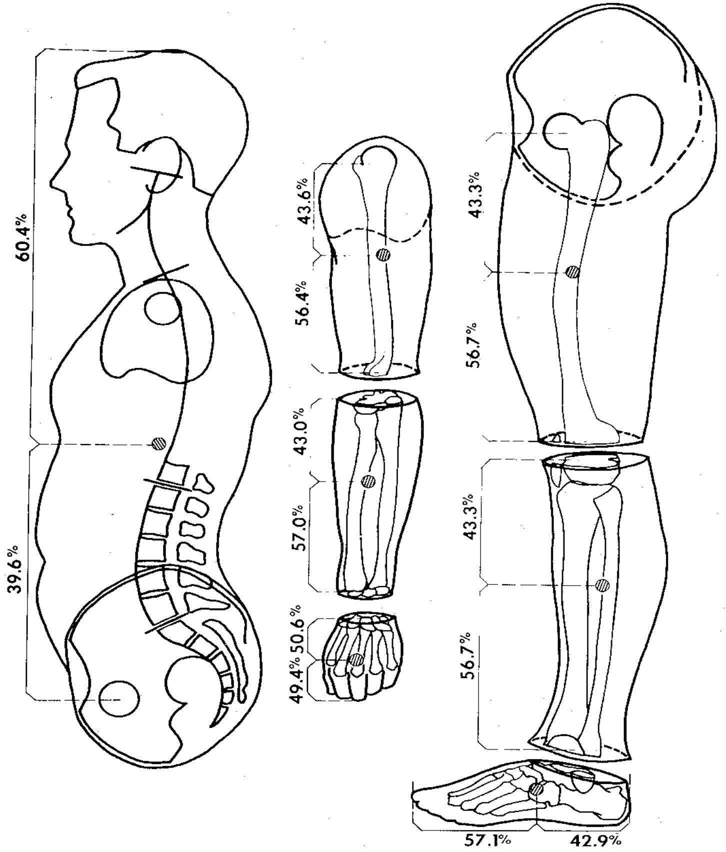

Figure 94. Locations of segment centers of gravity relative to segment length.

centers of gravity.

VOLUME AND DENSITY RELATIONS

Volumes measured by the determinations of the mass of water displaced when parts were submerged, were recorded in the metric system; values were numerically so close to the metric mass figures tabulated above that a separate listing is unnecessary. When the mass figures were divided by volumes, specific gravity or density values were obtained. These have been recorded as Tables 16 and 17.

Data from an extensive literature on overall body density have been summarized by Boyd (1933). A specific gravity of approximately 1.038 may be accepted as a representative average; inhalation and exhalation change lung volume notably, and the specific gravity for respiratory states may range from less than 1.0 to several hundredths more than the figure quoted. Dupertuis, Pitts, Osserman, Welham, and Behnke (1951), and Brozek and Keys (1952) have shown that for subjects with different amounts of body fat the specific gravity ranges from roughly 1.03 to 1.11, when the effect of air in the lungs is excluded. Density values, when the effect of air is excluded, correlate well with the 1st and 3rd component somatotype ratings of the experimental subjects.

TABLE 16

SPECIFIC GRAVITY OF BODY SEGMENTS*

Cadaver Number	Trunk Minus Limbs	Trunk Minus Shoulders	Shoulders	Head and Neck	Thorax	Abdomino-Pelvic
14815	1.04	1.05	1.00	--	--	--
15059	1.05	1.06	1.04	1.12	0.81	1.00
15062	1.05	1.00	1.02	1.13	0.94	1.00
15095	1.04	1.05	1.05	1.12	0.92	1.00
15097	1.03	1.06	1.03	1.10	1.01	1.02
15168	1.02	1.03	1.04	1.10	0.91	1.03
15250	1.02	1.00	1.05	1.10	0.95	1.03
15251	1.00	1.00	1.05	1.11	0.90	1.00
Mean	1.03	1.03	1.04	1.11	0.92	1.01

*Calculated from mass data on cadaver parts and volume data derived by immersion in water.

Tables 16 and 17 shows high density values for the head and neck, hand, forearm, and foot, all regions of high bone and relatively low fat content. The thigh and upper arm had lower densities than the other limb segments; bone content was low and fat high. The whole upper limb was more dense than the lower. Shoulders were less dense than the free upper limb; this reflected the effect of the large subcutaneous fatty blanket covering the pectoralis, trapezius, and latissimus dorsi muscles, which

TABLE 17

SPECIFIC GRAVITY OF THE LIMBS

Cadaver Number	Entire Lower Extremity	Thigh	Leg and Foot	Leg	Foot	Entire Upper Extremity	Arm	Forearm and Hand	Forearm	Hand
					Right Side					
14815	1.06	1.04	1.08	1.10	1.02	1.10	1.09	1.11	1.14	1.14
15059	1.07	1.06	1.11	1.12	1.17	1.25	1.07	1.18	1.12	1.41
15062	1.07	1.04	1.08	1.08	1.08	1.07	1.06	1.10	1.11	1.05
15095	1.07	1.05	1.11	1.11	1.17	1.10	1.01	1.01	1.20	1.33
15097	1.04	1.05	1.07	1.08	1.12	1.07	1.07	1.12	1.08	1.09
15168	1.06	1.05	1.09	1.09	1.11	1.10	1.09	1.13	1.12	1.15
15250	1.04	1.04	1.06	1.07	1.01	1.10	1.10	1.11	1.14	1.13
15251	1.06	1.05	1.07	1.09	1.07	1.09	1.09	1.13	1.10	1.08
Mean	1.06	1.05	1.08	1.09	1.09	1.11	1.07	1.11	1.13	1.17
					Left Side					
14815	1.06	1.04	1.09	1.11	1.02	1.11	1.09	1.09	1.14	1.14
15059	1.07	1.06	1.11	1.12	1.17	1.09	1.07	1.14	1.15	1.27
15062	1.05	1.03	1.08	1.08	1.07	1.08	1.06	1.10	1.11	1.05
15095	1.07	1.05	1.12	1.11	1.15	1.11	1.01	1.16	1.18	1.28
15097	1.05	1.04	1.07	1.08	1.14	1.08	1.07	1.11	1.09	1.12
15168	1.06	1.05	1.10	1.10	1.13	1.10	1.08	1.12	1.14	1.09
15250	1.05	1.05	1.08	1.09	1.05	1.10	1.10	1.12	1.14	1.10
15251	1.06	1.05	1.08	1.09	1.09	1.09	1.08	1.13	1.05	1.09
Mean	1.06	1.05	1.09	1.09	1.10	1.10	1.07	1.12	1.12	1.14

was included in the shoulder mass. The high air content of the thorax makes the density notably less than 1.0. The hollow abdominal organs likewise had some air content. Average density figures for composite trunk and limb parts were ordinarily what might be expected from the density values of component segments.

It will be noted that the larger parts generally showed a greater consistency in density from individual to individual than smaller parts did. The variability of the smallest parts, such as hand, foot, and forearm, reflects no doubt the limits of balance sensitivity for the low magnitude of weight, when parts were immersed and suspended in water.

If measurements of body bulk based on volume, such as those dealt with in the following chapter, are utilized directly as masses of density 1.0 without correction for mechanical analyses and treatments of moments, the density values of the table suggest the magnitude of error to be expected. A consideration of the density of segments, of composite regions, should increase considerably the accuracy of torque analyses based on volume data.

MOMENTS OF INERTIA OF PARTS

A tabulation of the moments of inertia of the various body segments and of composite regions is presented as Tables 18, 19, 20, and 21. Such values are essentials, when treatments of dynamic behavior, involving measurements of the acceleration of parts, are analyzed mechanically. Our tabulated data are comparable to, but relate to more body segments than those of Braune and Fischer (1892). Apart from several studies on locomotion by Fischer (1904) and later authors, dynamic problems involving the motion of body parts have not yet been attempted. The data of the table have been gained on the several parts by the pendulum techniques outlined in Chapter II, Items 33-35.

DISTRIBUTION OF MASS RELATIVE TO HEIGHT

One additional cadaver, an embalmed male body—a small, well-proportioned individual, not emaciated but of light weight, and aged 90—was sawed into transverse sections of 1-inch thickness. When the metric weights of sections were plotted relative to the height of the section above the foot soles for the supine body, Figure 95 resulted. The contour shows slight fluctuations in mass from section to section; this may be accounted for by minor differences in section thickness where one slice weighs more or less than it would if the section thickness were more exact.

The overall contour shows greatest mass for the shoulder regions; the hip mass is relatively large also, and the waist and thoracic section are less. The middle head sections were of greater mass than those above or below. The limbs showed a generally decreasing section from above to the wrists or ankles with slight regional differences at places of larger or smaller circumference. Foot and hand masses were larger than the ankles and wrists. Four additional measurements are shown in the plot; each section was dissected apart, and constituent tissues were weighed as follows:

TABLE 18

MOMENTS OF INERTIA ABOUT THE CENTER OF GRAVITY (I_{cg}) OF BODY SEGMENTS

Cadaver Number	Entire Upper Extremity	Arm	Forearm and Hand	Forearm	Hand	Entire Lower Extremity	Thigh	Leg and Foot	Leg	Foot
					Left Side					
14815	1.10x10^6	.122x10^6	.187x10^6	.059x10^6	.005x10^6	4.90x10^6	0.26x10^6	0.82x10^6	.321x10^6	.021x10^6
15059	0.78x10^6	.118x10^6	----	.051x10^6	.004x10^6	5.70x10^6	0.64x10^6	0.73x10^6	.330x10^6	.025x10^6
15062	0.96x10^6	.115x10^6	.155x10^6	.043x10^6	.005x10^6	6.05x10^6	0.82x10^6	0.55x10^6	.308x10^6	.029x10^6
15095	0.79x10^6	.079x10^6	.128x10^6	.035x10^6	.005x10^6	4.60x10^6	0.65x10^6	0.73x10^6	.260x10^6	.026x10^6
15097	0.98x10^6	.222x10^6	.287x10^6	.055x10^6	.009x10^6	9.10x10^6	1.14x10^6	1.58x10^6	.650x10^6	.037x10^6
15168	1.42x10^6	.191x10^6	.188x10^6	.072x10^6	.002x10^6	10.00x10^6	3.29x10^6	1.66x10^6	.560x10^6	.043x10^6
15250	1.35x10^6	.155x10^6	.218x10^6	.074x10^6	.003x10^6	9.80x10^6	1.22x10^6	1.29x10^6	.560x10^6	.035x10^6
15251	1.02x10^6	.112x10^6	.146x10^6	.050x10^6	.003x10^6	5.60x10^6	0.61x10^6	0.94x10^6	.340x10^6	.033x10^6
					Right Side					
14815	0.90x10^6	.190x10^6	.220x10^6	.058x10^6	.007x10^6	4.60x10^6	0.21x10^6	0.81x10^6	.307x10^6	.018x10^6
15059	0.78x10^6	.130x10^6	.137x10^6	.041x10^6	.005x10^6	6.70x10^6	0.70x10^6	0.85x10^6	.340x10^6	.025x10^6
15062	0.99x10^6	.102x10^6	.180x10^6	.055x10^6	.004x10^6	5.67x10^6	0.76x10^6	0.86x10^6	.298x10^6	.028x10^6
15095	0.58x10^6	.062x10^6	.128x10^6	.039x10^6	.003x10^6	5.20x10^6	0.69x10^6	0.75x10^6	.275x10^6	.013x10^6
15097	1.10x10^6	.220x10^6	.298x10^6	.072x10^6	.011x10^6	9.20x10^6	1.27x10^6	1.65x10^6	.620x10^6	.040x10^6
15168	1.40x10^6	.145x10^6	.197x10^6	.061x10^6	.003x10^6	8.60x10^6	3.12x10^6	1.64x10^6	.620x10^6	.038x10^6
15250	1.57x10^6	.166x10^6	.232x10^6	.068x10^6	.004x10^6	9.50x10^6	1.44x10^6	1.40x10^6	.620x10^6	.035x10^6
15251	0.91x10^6	.120x10^6	.152x10^6	.054x10^6	.003x10^6	5.20x10^6	0.61x10^6	0.96x10^6	.360x10^6	.032x10^6

TABLE 19

MOMENTS OF INERTIA ABOUT THE PROXIMAL JOINT CENTER (I_o) OF BODY SEGMENTS

Cadaver Number	Entire Upper Extremity	Arm	Forearm and Hand	Forearm	Hand	Entire Lower Extremity	Thigh	Leg and Foot	Leg	Foot
					Left Side					
14815	3.82x10^{6}	.334x10^{6}	.675x10^{6}	.188x10^{6}	.028x10^{6}	13.3x10^{6}	2.16x10^{6}	2.46x10^{6}	0.928x10^{6}	.057x10^{6}
15059	2.60x10^{6}	.372x10^{6}	----	.165x10^{6}	.011x10^{6}	13.7x10^{6}	2.33x10^{6}	2.67x10^{6}	1.140x10^{6}	.047x10^{6}
15062	2.66x10^{6}	.252x10^{6}	.456x10^{6}	.121x10^{6}	.015x10^{6}	14.0x10^{6}	2.25x10^{6}	2.00x10^{6}	0.770x10^{6}	.053x10^{6}
15095	2.14x10^{6}	.239x10^{6}	.406x10^{6}	.123x10^{6}	.014x10^{6}	12.3x10^{6}	1.78x10^{6}	2.12x10^{6}	0.805x10^{6}	.046x10^{6}
15097	4.91x10^{6}	.629x10^{6}	.845x10^{6}	.279x10^{6}	.032x10^{6}	24.6x10^{6}	3.44x10^{6}	5.23x10^{6}	2.530x10^{6}	.063x10^{6}
15168	4.36x10^{6}	.566x10^{6}	.715x10^{6}	.236x10^{6}	.025x10^{6}	26.8x10^{6}	5.53x10^{6}	4.89x10^{6}	1.770x10^{6}	.115x10^{6}
15250	4.52x10^{6}	.593x10^{6}	.655x10^{6}	.221x10^{6}	.015x10^{6}	26.7x10^{6}	4.35x10^{6}	3.95x10^{6}	1.950x10^{6}	.064x10^{6}
15251	2.53x10^{6}	.323x10^{6}	.466x10^{6}	.153x10^{6}	.009x10^{6}	15.5x10^{6}	2.27x10^{6}	2.84x10^{6}	1.150x10^{6}	.057x10^{6}
					Right Side					
14815	3.50x10^{6}	.375x10^{6}	.670x10^{6}	.183x10^{6}	.027x10^{6}	12.6x10^{6}	2.08x10^{6}	2.29x10^{6}	0.895x10^{6}	.076x10^{6}
15059	2.23x10^{6}	.278x10^{6}	.443x10^{6}	.155x10^{6}	.016x10^{6}	13.4x10^{6}	2.30x10^{6}	2.64x10^{6}	1.130x10^{6}	.047x10^{6}
15062	2.59x10^{6}	.319x10^{6}	.449x10^{6}	.136x10^{6}	.013x10^{6}	13.6x10^{6}	2.30x10^{6}	2.48x10^{6}	0.882x10^{6}	.051x10^{6}
15095	2.04x10^{6}	.212x10^{6}	.397x10^{6}	.124x10^{6}	.013x10^{6}	13.2x10^{6}	2.08x10^{6}	2.58x10^{6}	0.902x10^{6}	.013x10^{6}
15097	5.07x10^{6}	.657x10^{6}	.852x10^{6}	.249x10^{6}	.031x10^{6}	26.0x10^{6}	3.54x10^{6}	5.09x10^{6}	2.660x10^{6}	.086x10^{6}
15168	4.14x10^{6}	.541x10^{6}	.652x10^{6}	.212x10^{6}	.027x10^{6}	25.5x10^{6}	5.26x10^{6}	5.02x10^{6}	1.810x10^{6}	.136x10^{6}
15250	4.51x10^{6}	.506x10^{6}	.697x10^{6}	.224x10^{6}	.016x10^{6}	24.5x10^{6}	4.28x10^{6}	4.20x10^{6}	1.970x10^{6}	.057x10^{6}
15251	2.71x10^{6}	.320x10^{6}	.455x10^{6}	.145x10^{6}	.011x10^{6}	15.0x10^{6}	1.99x10^{6}	2.84x10^{6}	1.180x10^{6}	.065x10^{6}

TABLE 20

MOMENTS OF INERTIA OF TRUNK SEGMENTS ABOUT THEIR CENTERS OF GRAVITY (I_{cg})

Cadaver Number	Trunk Minus Limbs	Trunk Minus Shoulders	Shoulders Left	Shoulders Right	Head and Neck	Thorax	Abdomino-Pelvic Region
15059	15.5×10^{6}	14.0×10^{6}	0.355×10^{6}	0.378×10^{6}	0.22×10^{6}	0.45×10^{6}	------
15062	23.7×10^{6}	15.9×10^{6}	0.500×10^{6}	0.324×10^{6}	------	------	------
15095	13.4×10^{6}	13.0×10^{6}	0.417×10^{6}	0.421×10^{6}	------	------	------
15097	22.1×10^{6}	21.0×10^{6}	0.800×10^{6}	0.700×10^{6}	0.31×10^{6}	1.19×10^{6}	3.24×10^{6}
15168	24.3×10^{6}	23.1×10^{6}	0.520×10^{6}	0.800×10^{6}	0.23×10^{6}	2.18×10^{6}	9.70×10^{6}
15250	14.9×10^{6}	16.4×10^{6}	0.425×10^{6}	0.425×10^{6}	0.32×10^{6}	0.96×10^{6}	2.44×10^{6}
15251	14.9×10^{6}	14.0×10^{6}	0.480×10^{6}	0.420×10^{6}	0.39×10^{6}	0.99×10^{6}	1.96×10^{6}

TABLE 21

MOMENTS OF INERTIA OF TRUNK SEGMENTS ABOUT SUSPENSION POINTS (I_o)

Cadaver Number	Trunk Minus Limbs[1]	Trunk Minus Shoulders[1]	Shoulders[2] Left	Shoulders[2] Right	Head and Neck[3]	Thorax[4]	Abdomino-Pelvic Region[1]
15059	42.7×10^{6}	30.4×10^{6}	0.539×10^{6}	0.607×10^{6}	1.31×10^{6}	1.51×10^{6}	------
15062	60.5×10^{6}	50.4×10^{6}	0.886×10^{6}	0.735×10^{6}	------	------	------
15095	39.6×10^{6}	32.8×10^{6}	0.937×10^{6}	0.886×10^{6}	------	------	------
15097	64.5×10^{6}	50.4×10^{6}	1.800×10^{6}	1.530×10^{6}	1.87×10^{6}	4.73×10^{6}	8.72×10^{6}
15168	78.0×10^{6}	62.8×10^{6}	1.090×10^{6}	1.300×10^{6}	1.43×10^{6}	6.56×10^{6}	12.60×10^{6}
15250	60.3×10^{6}	37.7×10^{6}	0.799×10^{6}	0.827×10^{6}	1.44×10^{6}	3.48×10^{6}	3.96×10^{6}
15251	50.9×10^{6}	34.6×10^{6}	1.080×10^{6}	0.961×10^{6}	1.04×10^{6}	3.12×10^{6}	3.77×10^{6}

1. Suspension from hip joints.
2. Suspension from sternoclavicular joint.
3. Suspension from 7C vertebral body.
4. Suspension from 12th vertebral body.

(1) skeletal tissue, including bone, cartilage, and ligament, (2) muscle, tendon, and intermuscular fat and associated nerves and blood vessels, (3) visceral organs, including brain and spinal cord, meninges, tongue, throat structures, and the viscera and blood vessels of the neck, thorax, abdomen, and pelvis, and (4) skin and subcutaneous fatty tissues. These have been referred to simply as bone, muscle, organ, and skin.

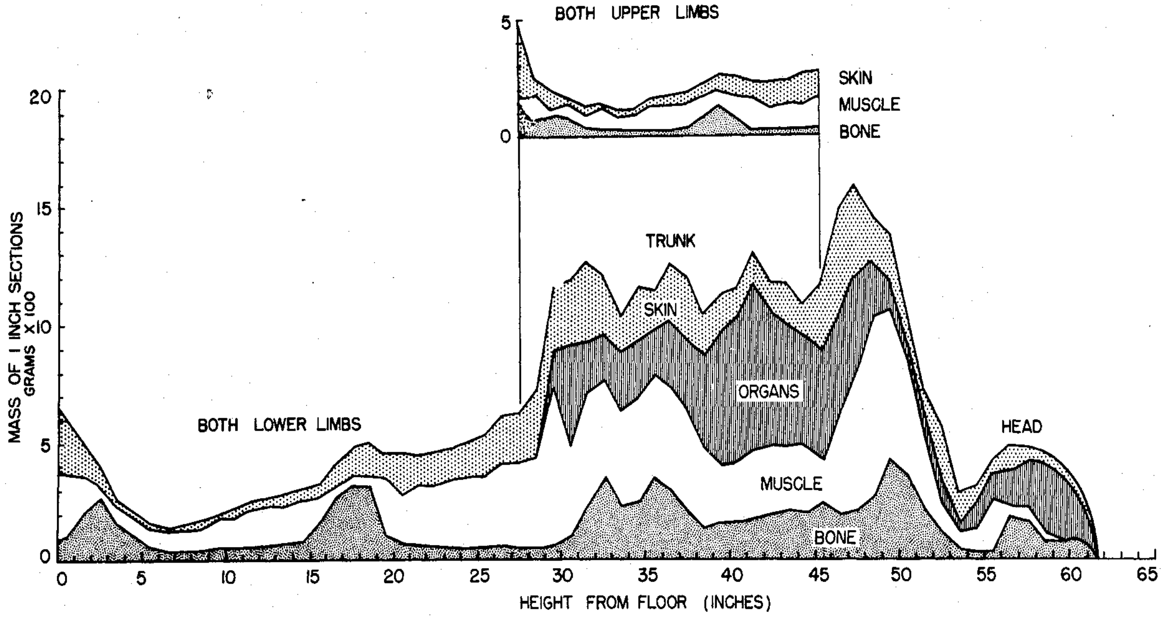

Figure 95. Distribution of the body mass of a cadaver relative to its height. The weights of transverse saw-cut sections of one-inch thickness were plotted relative to height; the weights of bone, muscle, integument and organs in successive sections are shown also.

Although the data relate to only one individual, the plot can at least have illustrative value. Regions of relatively high bone content are shown for the feet, knees, pelvis, thorax, shoulders, and head. Muscle mass concentrated in the calves, thighs, hips, and shoulders; regions of appreciable skin and subcutaneous fat padding as in the thighs and trunk are shown also. Organ mass from the head to the crotch region is shown; the mass was lowest in the neck, head, and thorax and greatest in abdomino-pelvic region. In this individual the overall ratios of the four body constituents may be indicated by the following values: bone, 24.5%; muscle, 39.9%; organ, 22.6%; and skin and fascia, 13.2%. Equivalent values listed by Vierordt (1893) for a roughly comparable dismemberment are: bone, 17.5%; muscle, 43.4%; organ, 21.4%; and skin and subcutaneous tissue, 17.8%.

Tables 16 and 17 and the account presented earlier on the regional differences in the density of parts may be reviewed to advantage in relation to Figure 95.

Data on the distribution of mass relative to height for this one cadaver (Figure 95) should be compared with the more extensive volume/height information of Chapter VIII, based upon our studies of living subjects.

CHAPTER VIII

BODY BULK DISTRIBUTION IN LIVING SUBJECTS

Values of body constants like those of the preceding chapter certainly show the order of magnitude of factors dependent on mass which are operative in the body system. The values, however, can be utilized accurately in analyses of body mechanics, only when extrapolations to given living test subjects may be made. Braune and Fischer (1890), for instance, selected a soldier who matched reasonably well the proportions and weight of the cadaver specimen on which their coordinate system was based; this man was then utilized for analyses of stance and the distribution of the mass of a field pack, rifle, and other military accouterments.

Segment mass values based on German builds of 65 years ago or on older age subjects of today in this country cannot be transferred indiscriminately to present day physiques of younger individuals. Heights and weights on the average have generally increased (Bowles, 1932; Meredith, 1941; Hooton, 1947), and certain body proportions have tended to change.

Masses, centers of gravity, and moments of inertia of separate segments cannot be derived directly from living subjects. The volumes of many parts of the body, though, may be obtained. If the volumes of the segments of a given test subject, or of a sample representing a given physique, are known, data from cadavers on the density of parts should permit more accurate conversions to mass than the assumption of density 1.0 for the various parts. Link dimensions, as indicated elsewhere, may likewise be determined with a reasonable accuracy after suitable measurement of test subjects.

The location of segmental centers of gravity, however, is a different problem. These points, whether in cadavers or in the living subject, are resultants of the disposition of bones, muscles, and other tissues in the segments. Anatomical relations of these structures are, to a high degree, predictable. The same structures with minor exceptions exist in all human material, and variations in proportions can be assumed to harmonize at least to a degree of functional adequacy; thus, if the center of gravity of a segment falls at a point in the anatomy for one individual, it may be expected to fall at or near the same anatomical locus in another subject. Centers of gravity are points about which moments balance; linear shifts in the position of center of gravity thus will not be proportional to simple changes in either mass or linear dimension. There must be in a given individual a systematically different gradient in mass distribution from one end of a segment to the other, to alter materially the expected location of the center.

Shifts in location of segmental centers of gravity, because of this factor, certainly must exist, but the magnitude of these differences will be so small relative to spatial changes in position of the body parts in different postures where mechanical analyses are pertinent, that the mean locations demonstrated in cadavers should have usable transfer value to the living situation. A proper test of adequacy of transfer to the living subject comes in situations where an actual mechanical problem involving the data arises; Chapter IX, following, records the solution of such problems and, in these instances at least, the data on centers of gravity were entirely adequate.

TYPES OF VOLUME MEASUREMENT

Whole body volumes have routinely been measured in relation to specific gravity determinations (Boyd, 1933); little, however, seems to be available on segmental or regional volumes. As mentioned earlier, Meeh (1895) measured the volume of limb segments and head and trunk regions also for 10 individuals. The computations of the volumes of regular conical, spherical, or cylindrical figures from exterior body dimensions, like the computed trunk volumes of Harless (1860), must be little more than rough approximations.

On a different level, however, are computations of volumes based on a series of horizontal measurements at different heights by Weinbach (1938). Transverse and sagittal measurements were made from front and side view, scaled photographs of nude subjects, and elliptical section areas were computed for the different levels above the ground; when these areas were plotted relative to the height of section, plots of volume resulted. These plots looked somewhat like the outer contour of Figure 95.

A check on the accuracy of area computations made in this way versus measured areas (by the pantograph-planimeter technique described in Chapter II, Item 40) showed that the method was very good for certain levels (head, neck, waist, ankles, etc.), but was less good for others (viz., shoulders). The Weinbach technique gives generally satisfactory information on the regional distribution of volumes. Estimated masses based on density 1.0 should be less good. With this technique, however, it is difficult to utilize landmarks for the subdivision of volumes into segments comparable to those obtainable from cadavers.

SEGMENT IMMERSION

By the segment immersion technique outlined in Chapter II, Item 39, volumes of the upper limb, hand, forearm and hand, forearm, and arm, and the lower limb, foot, foot and leg, leg, and thigh were obtained. Figure 96 shows histograms representing the mean volumes of the several parts based on the mass of water displaced. In each group of four histograms the first bar refers to rotund subjects. In each instance the volume of the part was greater than for other physiques shown by adjacent bars. To the right of the bars for rotund subjects were the muscular build, the thin men, and finally the Air Force medians.

For all limb segments the thin subjects (third bars) had the lowest volumes. The muscular and median types had generally comparable average volumes. For each build the proportionate size of hand, forearm, arm and foot, leg, and thigh are as would be expected from general observation. Foot volumes were nearly as large as forearm volumes; leg segments were roughly comparable with whole upper limb volumes.

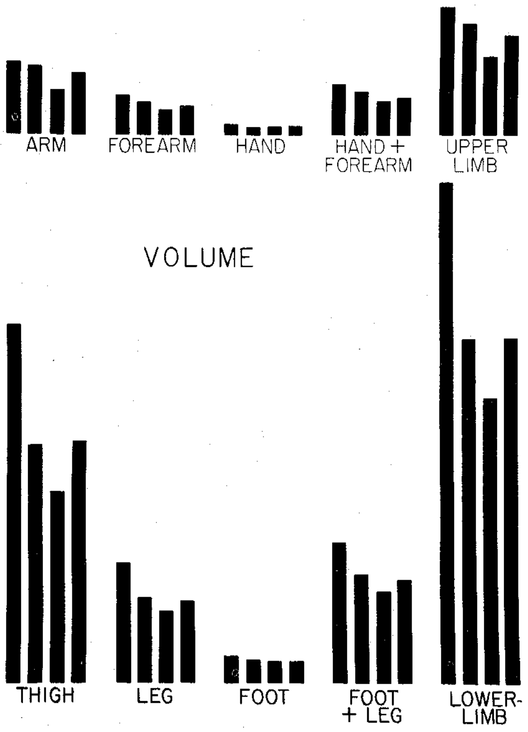

Figure 96. Histograms showing relative volumes of upper and lower limbs and component segments. The first column in each group of four represents rotund builds; the second column refers to muscular builds, the third to thin builds, and the last columns refer to median builds.

When the same data were plotted as percentages of body weight, Figure 97 resulted. Density differences were ignored in these plots. Each group of four bars representing the four physiques showed a more constant height. For the upper limbs the muscular men (second bars) and the median group (fourth bars) showed averages that were quite similar; on the other hand, the median group had a larger proportionate volume for the thigh, leg, and whole lower limb. Thin men, except for foot, leg, and foot plus leg, showed either low values or values comparable with those of the muscular individuals. Despite gross differences in body appearance, rotund and thin men showed generally comparable mean percentage volumes for the various upper limb values. Thin subjects had relatively smaller upper arm segments, while rotund men had relatively smaller hands and forearms. The rotund group had larger relative volumes for the whole lower limb and especially the thighs.

When the different physical types were compared as to relative upper limb volume, rotund men had small hands, thin men had the largest hands; muscular men had large forearms, while rotund men had proportionally small forearms; upper arm volumes were relatively small for rotund subjects, larger for thin men, and largest for muscular and median types. Thin men had relatively large feet; in rotund men the feet were small. Thin men had relatively the largest leg segments; both thin and muscular men had the smallest thigh segments. Rotund and median builds had notably large thigh-and-buttock segments.

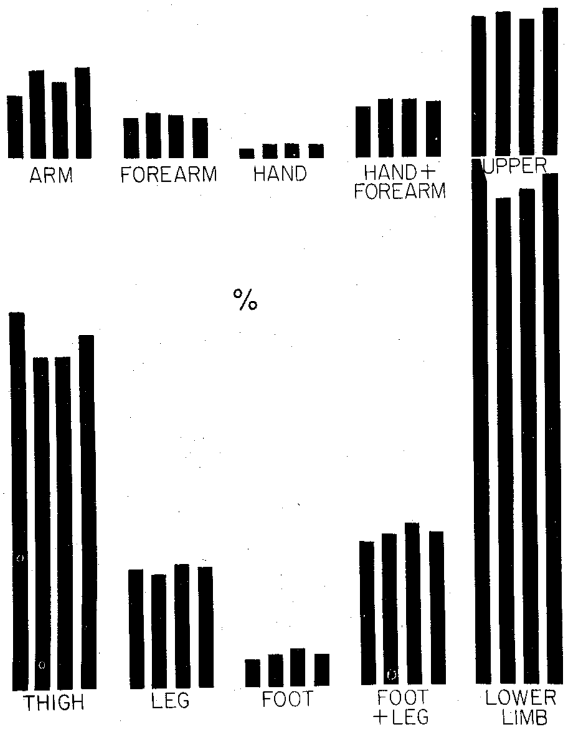

Figure 97. Histograms showing volumes of limb segments expressed as percentage of body volume (i.e., body weight taken as having unit density). For each group of four columns: column 1—rotund build; column 2—muscular build; column 3—thin build; column 4—median build.

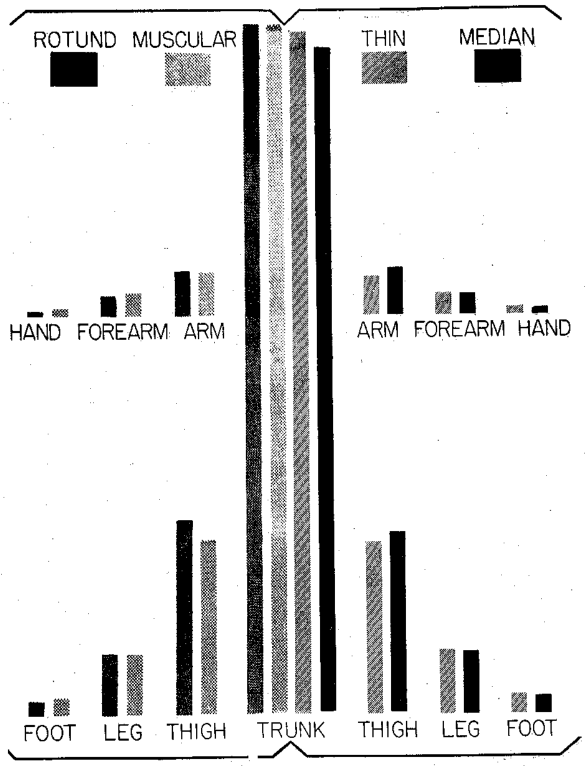

Figure 98. Volume of body segments expressed as percentage of body volume (i.e., mass considered as having unit density).

In Figure 98 the same percentage data have been presented for the simple limb segments. All the values are expressed as a percentage of body weight. If a density of 1.0 is assumed, the histograms will refer to either percentage mass or percentage volume. The tall middle columns show mean percentage values for the body minus the limb segments. The trunk minus limbs for all four body builds averaged between 49 and 52% of total body weight. The rotund and muscular physiques (columns 1 and 2) were most alike. Our median subjects (fourth column) had the smallest relative trunk volumes, and thin subjects were next.

For the limb segments the relative size in relation to body weight was approximately 1/2% for the hand, 1-1/2 to 1-2/3% for the forearm, 3-1/3% for the arm, 1-1/4% for the foot, from 4-1/2 to 4-2/3% for the leg, and 13-1/2% for the thigh. These are approximate average values, which ignore the differences associated with body build that were mentioned earlier.

Values for individual subjects, both absolute measurements and percentages, varied from the means illustrated in the histograms. Tables 22, 23, 24, and 25 show the data on which the histograms were based. In general, the variations of individual values about segment averages were proportional to the bulk of the segment; upper arm and thigh segments, however, had a greater proportional range than other segments.

A comparison of the ratio of segment bulk to body bulk for the living subjects with comparable data for cadavers is of interest. Tables 11 and 12 on cadaver data show as percentages the ratio of segment weight to body weight; Table 26 shows comparable ratios involving segment volumes for the living subjects. Although a conversion of figures to the same scale by a consideration of density would permit an accurate comparison, it will suffice here to note that living subjects showed markedly higher percentage ratios than cadavers for total lower limb volume; the total upper limb ratio was also higher.

Differences in the ratios, however, were minor for the leg, foot, forearm, and hand segments; upper arm and especially thigh and buttock segments were proportionately larger than in the older-aged cadaver. The segment-mass data of Harless (1860) and of Braune and Fischer (1890), when converted to percentage body weight, likewise showed lower thigh and total limb ratios than our living subjects; upper limb values, however, were not notably different. Low limb ratios, or even low lower-limb ratios alone, imply a conversely high trunk ratio for the cadavers than for the living subjects.

The difference in ratios found may be attributed to differences between young adult and older age subjects. Thigh and buttock mass and possibly upper arm mass would appear to decrease with age for a given trunk mass; conversely, trunk mass would increase, relative to the limb parts. Regional differences in fat accumulation may underlie this change, but the whole story probably involves changing ratios of other tissues as well. The number of older subjects is of course small and the interpretation of the ratio differences as an age change is merely suggestive.

In the foregoing presentation segmental body bulks were treated simply as masses without concern for the shape distribution of the material. Trunk bulk, for instance, was regarded simply as the bulk remaining after limb volumes had been subtracted. The pantograph-planimeter technique described in Chapter II, Item 40, and Figure 24, gives information on volume distribution comparable to the data on mass distribution relative to height obtained from cadaver sections (Figure 95). When transverse areas through the body at various heights from the floor are plotted, the resultant contour

TABLE 22

VOLUME OF LIMB SEGMENTS IN CUBIC CENTIMETERS AND PERCENTAGES OF BODY VOLUME*

Rotund Physique (Male)

Subject No.	Body Weight,		Whole Upper Limbs	%	Arm	%	Forearm Plus Hand	%	Forearm	%	Hand	%
	lb	kg										
1	145	65.9	3496	5.3	2217	3.4	1279	1.9	931	1.4	348	0.53
2	185	84.1	4287	5.1	2551	3.0	1736	2.2	1386	1.6	350	0.42
3	224	101.5	5062	5.0	3180	3.1	1882	1.9	1446	1.4	436	0.43
4	224	110.9	5162	4.7	3122	2.8	2040	1.8	1650	1.5	390	0.35
5	261	118.6	7113	6.0	4697	3.9	2418	2.0	1982	1.7	436	0.37
6	272	123.6	6964	5.6	4590	3.7	2374	1.9	1844	1.5	530	0.43

Subject No.	Body Weight,		Whole Lower Limbs	%	Thigh	%	Leg Plus Foot	%	Leg	%	Foot	%
	lb	kg										
1	-	-	15422	23.4	11645	17.7	3777	5.7	2947	4.5	830	1.30
2	-	-	16103	19.2	11655	13.9	4448	5.3	4010	4.8	914	1.20
3	-	-	20236	19.8	14798	14.6	5438	5.4	4605	4.5	833	0.80
4	-	-	20916	18.9	15434	13.9	5482	5.0	4303	3.9	1179	1.10
5	-	-	24368	20.6	17288	14.6	7080	6.0	5724	4.8	1356	1.10
6	-	-	24242	19.7	17248	14.0	6994	5.7	5602	4.5	1392	1.10

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*Body volume equals body weight for an assumed density of 1.0.

TABLE 23

VOLUME OF LIMB SEGMENTS IN CUBIC CENTIMETERS AND PERCENTAGES OF BODY VOLUME*

Muscular Physique (Male)

Subject No.	Body Weight, lb	kg	Whole Upper Limbs	%	Arm	%	Forearm Plus Hand	%	Forearm	%	Hand	%
1a	150	68.4	4094	6.0	2427	3.5	1667	2.4	1253	1.8	414	0.60
2a	151	68.7	3757	5.5	2129	3.1	1628	2.4	1306	1.9	322	0.47
3a	153	69.6	4202	6.0	2630	3.8	1572	2.3	1200	1.7	372	0.54
4a	160	72.7	4342	6.0	2537	3.5	1507	2.1	1100	1.5	407	0.56
5a	167	76.0	4254	5.6	2505	3.3	1749	2.3	1282	1.7	467	0.61
6a	168	76.4	4249	5.5	2501	3.3	1748	2.3	1361	1.8	387	0.51
7a	171	77.8	3821	4.9	2239	2.9	1582	2.0	1184	1.5	398	0.51
8a	172	78.2	3802	4.9	2211	2.8	1591	2.0	1247	1.6	344	0.44
9a	186	84.6	4935	5.8	3000	3.6	1926	2.3	1535	1.8	391	0.46
10a	186	84.6	4952	5.9	3100	3.7	1852	2.2	1400	1.7	452	0.53
11a	211	95.9	5301	5.5	3106	3.3	2195	2.3	1610	1.7	585	0.61

Subject No.	Body Weight, lb	kg	Whole Lower Limbs	%	Thigh	%	Leg Plus Foot	%	Leg	%	Foot	%
1a	-	-	13900	20.4	9788	14.3	4112	6.0	3248	4.8	864	1.30
2a	-	-	11571	16.9	8224	12.0	3347	4.9	2515	3.7	832	1.20
3a	-	-	13026	18.8	9412	13.6	3614	5.2	2805	4.0	809	1.20
4a	-	-	13188	18.1	8994	12.4	4194	5.8	3286	4.5	908	1.20
5a	-	-	13901	18.3	9249	12.2	4652	6.1	3533	4.7	1119	1.50
6a	-	-	13399	17.6	9253	12.1	4146	5.4	3133	4.1	1013	1.30
7a	-	-	14798	18.9	9892	12.7	4906	6.3	3929	5.0	977	1.30
8a	-	-	12286	15.8	8128	10.4	4158	5.3	3258	4.2	900	1.20
9a	-	-	16814	19.9	11972	14.2	4842	5.7	3606	4.3	1236	1.50
10a	-	-	16202	19.2	11788	13.9	4414	5.2	3430	4.1	984	1.20
11a	-	-	18640	19.5	13116	13.5	5524	5.8	4183	4.4	1341	1.40

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*Body volume equals body weight for an assumed density of 1.0.

TABLE 24

VOLUME OF LIMB SEGMENTS IN CUBIC CENTIMETERS AND PERCENTAGES OF BODY VOLUME*

Thin Physique. (Male)

Subject No.	Body Weight,		Whole Upper Limbs	%	Arm	%	Forearm Plus Hand	%	Forearm	%	Hand	%
	lb	kg										
1b	114	51.7	2652	4.9	1487	2.9	1165	2.3	874	1.7	291	0.56
2b	125	56.9	2494	4.4	1392	2.5	1102	1.9	850	1.5	252	0.44
3b	128	58.2	2884	5.0	1642	2.8	1242	2.1	881	1.5	361	0.62
4b	132	60.0	3803	6.4	2359	3.9	1444	2.4	1153	1.9	291	0.48
5b	133	60.4	2904	4.8	1600	2.7	1304	2.2	932	1.5	372	0.62
6b	134	60.9	3415	5.6	2053	3.4	1362	2.2	1004	1.6	358	0.60
7b	134	60.9	3080	5.1	1682	2.8	1398	2.3	1047	1.7	351	0.58
8b	140	63.6	3712	5.8	2225	3.5	1487	2.3	1103	1.7	384	0.61
9b	154	70.0	3872	5.5	2101	3.0	1771	2.5	1271	1.8	500	0.71
10b	172	78.2	3497	4.5	1887	2.4	1610	2.1	1184	1.5	426	0.54

Subject No.	Body Weight,		Whole Lower Limbs	%	Thigh	%	Leg Plus Foot	%	Leg	%	Foot	%
	lb	kg										
1b	-	-	10274	19.9	7167	13.9	3107	6.0	2341	4.6	766	1.50
2b	-	-	11076	19.5	7333	12.9	3743	6.6	2903	5.1	840	1.50
3b	-	-	10578	18.2	7336	12.6	3242	5.6	2465	4.2	777	1.30
4b	-	-	12214	20.4	8422	14.1	3792	6.3	3001	5.0	791	1.30
5b	-	-	11660	19.3	7346	12.2	4314	7.2	3428	5.7	886	1.50
6b	-	-	11334	18.7	7824	12.9	3510	5.8	2593	4.3	917	1.50
7b	-	-	11453	18.9	7680	12.6	3773	6.2	2839	4.7	934	1.50
8b	-	-	13803	21.7	9171	14.4	4632	7.3	3608	5.7	1024	1.60
9b	-	-	13332	19.0	8860	12.7	4472	6.4	3378	4.8	1094	1.60
10b	-	-	12156	15.2	8006	10.2	4150	5.3	3140	4.0	1010	1.30

*Body volume equals body weight for an assumed density of 1.0.

TABLE 26

RATIO OF MEAN VOLUME OF THE LIMB SEGMENTS TO BODY VOLUME*

Segment	Rotund, %	Muscular, %	Thin, %	Median, %
Whole upper limb	5.28	5.60	5.20	5.65
Arm	3.32	3.35	2.99	3.46
Forearm plus hand	1.95	2.24	2.23	2.15
Forearm	1.52	1.70	1.63	1.61
Hand	0.42	0.53	0.58	0.54
Whole lower limb	20.27	18.49	19.08	19.55
Thigh	14.78	12.85	12.90	13.65
Leg plus foot	5.52	5.61	6.27	5.97
Leg	4.50	4.35	4.81	4.65
Foot	1.10	1.30	1.46	1.25

*Body volume considered as body weight for an assumed density of 1.0.

bounds the body volume; the area of this plot, measured by planimeter and expressed in suitable units, is a measure of body volume.

Before routine area-to-height plots could be made, it was necessary to determine how many sections were essential for an accurate plot and at what levels the sections should be made. To this end, two tests were applied. First, the Weinbach type of analysis (Weinbach, 1938) was applied to front and side view photographs of several subjects; the areas of calculated ellipses were determined for some 50 equal-sized levels, and area-to-height plots were made. Secondly, many transverse areas were measured by the pantograph-planimeter technique on two test subjects.

After the data were plotted, one and then another of the areas was eliminated in the different regions, until no more could be sacrificed without the resultant plot showing an unrealistic volume contour. Certain areas at the foot, knee, hip, waist, shoulder, and head, where successive areas changed sharply, were obviously more critical than others in the mid-thigh, lower leg, and mid-thorax. Finally, 21 landmarks at different heights from the floor were selected as levels at which section areas should be taken. In each instance, levels were pegged to specific landmarks. These levels for the standing subject are as follows:

1. Vertex of skull
2. Euryon (widest part of head above the ears)
3. Gonion (angle of the jaw)
4. Thyroid notch (Adam's apple) of thyroid cartilage of larynx
5. Acromion
6. Shoulder at level of sternal angle (joint between manubrium and body of sternum)
7. Shoulder at anterior axillary fold (with arm at side)
8. Trunk alone at the same level (a thin, wooden slat was clamped between the arms and thorax, and the pantograph tracer arms were

moved over the back and anterior thoracic skin between the slats; two straight lines corresponding with the location of the slats completed the contour)

9. Xiphisternum (junction of xiphoid process and body of sternum)
10. Minimum waist level
11. Uppermost palpable part of the iliac crest
12. Top of the pubic symphysis
13. Trunk at the level of the subgluteal crease
14. Left thigh at crotch height (a wooden slat clamped high between the thighs—cf. measure no. 8—provided a medial contour)
15. Left thigh at uppermost margin of patella
16. Left knee at midpatella level
17. Left upper leg at level of tibial tuberosity
18. Left calf at level of maximum circumference
19. Left ankle at level of minimum circumference
20. Tip of left medial malleolus
21. Contour of the left foot standing (1/2 inch above floor level)

The height of each level to the nearest 0.1 inch was measured when the area was traced. Each level with the exception of Nos. 7, 8, 10, 13, 14, 18, and 19, involved hard landmarks; the others were almost equally positive landmarks. According to the technique, small-sized contour tracings (1:2.54 natural size) of each level were measured by the planimeter. Height and areas were then plotted on coordinate paper of convenient scale. These tracings could be superimposed, and composites could be made, representing the body contours of several subjects.

It will be noted that the upper limb below the axillary level was not included in the volume contour data. Equivalent data based on water immersion of the limb were available. Only the left limb was measured in routine body measurements; the values for each level of the limb were simply doubled and plotted as nominal representations of the two limbs. That is, no attention was directed here to possible asymmetries of the lower limbs.

When regularly shaped, rigid, glass or metal objects of the same size range as body parts were measured repeatedly, an inherent 2% error was found between experimental measurements and calculated areas. Tracings of the soft body surface were more variable than rigid surfaces on which the pantograph tracer arm could rest continuously; the skin surface yielded to the slightest pressure, and overshooting of the exact surface by the pantograph tracer was equally common. Cumulatively the inherent error and the measurement error were within 5% of these values.

Figure 99 shows area-height (i.e., volume) contours for our group of rotund, muscular, thin, or median subjects, 39 men in all. Each group was divided into a first and a second choice group. The five men of each build who had the strongest somatotype values and who were not dysplastic were grouped as the solid line of the figures.

The present approach has been concerned with differences associated with body build; the small insert figures show representative, first choice subjects. The horizontal shading in the plots represents a halo equal to one standard deviation of the area measurements for the different levels. The heavy dashed lines refer to the averaged plots of the second choice groups; lighter dashed lines on either side represent the one standard deviation halo.

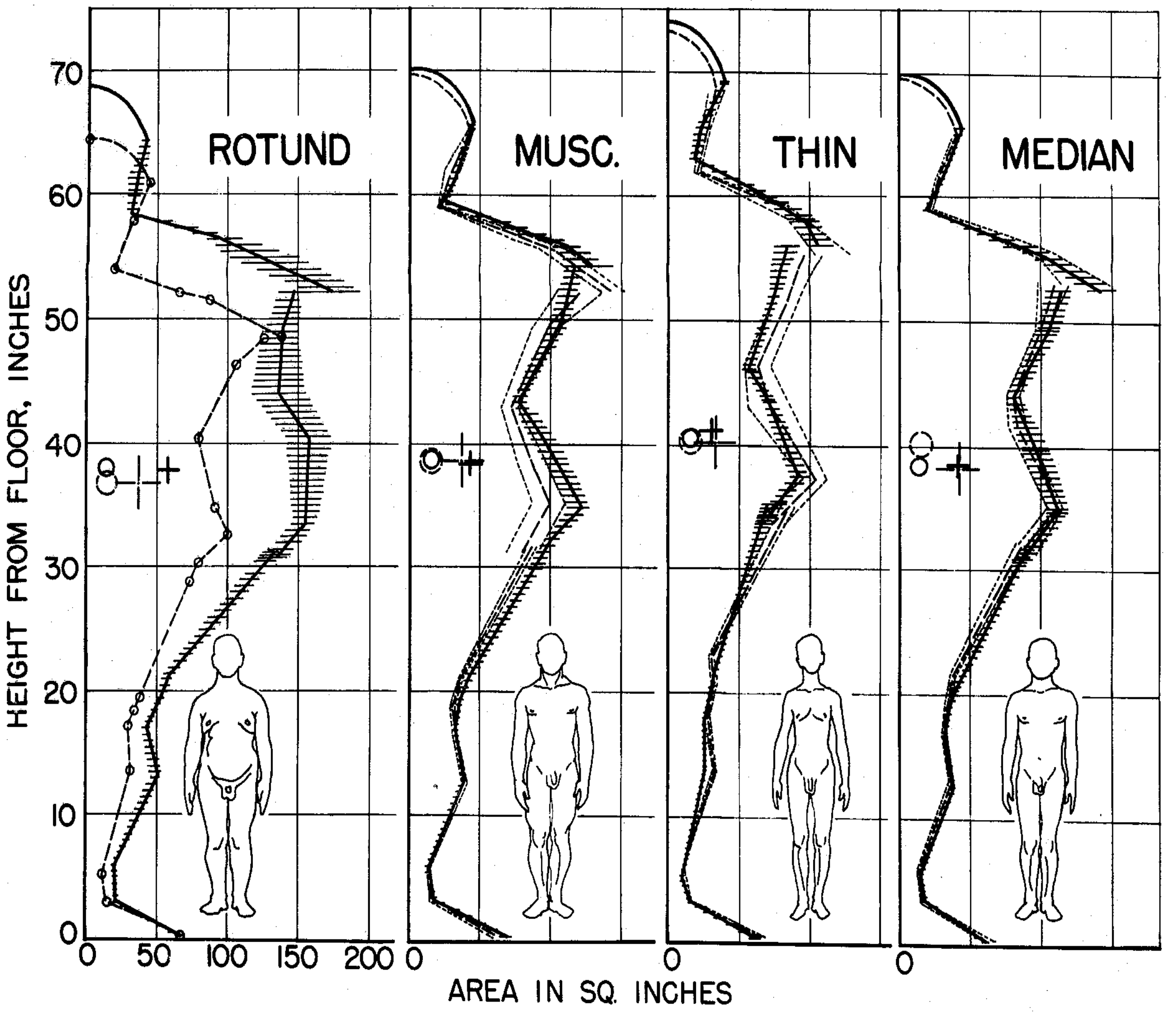

Figure 99. Area-to-height (or volume) contours of the body apart from the upper limbs for different body types. Heavy outlines show mean cross-sectional areas for the more extreme builds in the sample; the shaded halo represents a 1-sigma variation in contour. The heavy dashed outlines refer to the mean of the second choice subjects and the 1-sigma halo is indicated by light dashed lines. Crosses show the height of the volume centroid (without arms) and the circles show the height of the whole body center of gravity (measured on supine subjects).

The small six-man sample of rotund subjects was grouped into a five-man primary sample; only one man was regarded as a second choice subject. He was of special interest, however, since he had recently, before coming to us, reduced his weight from 195 to 145 pounds; yet he was still classed by the somatotyper as a 6-1/2 - 1-1/2 - 2. Presumably the history of weight loss and the trunk and vertebral-column posture weighted the estimate toward the first component. The distribution of body bulk, it may be seen, is much more like that of median subjects than rotund.

In all the groups the shoulder areas were larger than other levels. The hip and pelvic levels were nearly as large in the rotund group. The four builds, in general, showed comparable contours: the rotund men showed largest section areas at each level, the thin men had small areas, and the other two types were intermediate. Finer distinctions are noticeable between the different types when one compares shoulder slope, thoracic wall angulation, pelvic contour, the thigh, calf region, etc.

It is of interest to note the positions of the plus signs for the different groups. These represent balance points (centroids) for cardboard cut-outs of the different plots. In contrast the circles represent the location of mean centers of gravity measured on the different subjects in the supine position. The cut-outs did not include the upper limbs, the centers of gravity related to individuals with the arms to the sides; the slight differences in locations are possibly due in large part to this difference.

Body bulk in the trunk and lower limbs clearly follows a basic plan in which the segments show gradients in size from level to level. If a uniform density were to be assumed, the plots of Figure 99 could be taken as representative of the distribution of body mass. Figure 100 shows the first choice, average, median build with lines drawn in at appropriate landmarks, to divide the limb segments into units of comparable value to those found in the limb immersion technique. When allowances for mean densities of the several segments (data from Tables 16 and 17) are made, the plot may be interpreted as a distribution of mass relative to height comparable to the cadaver plot of Figure 95.

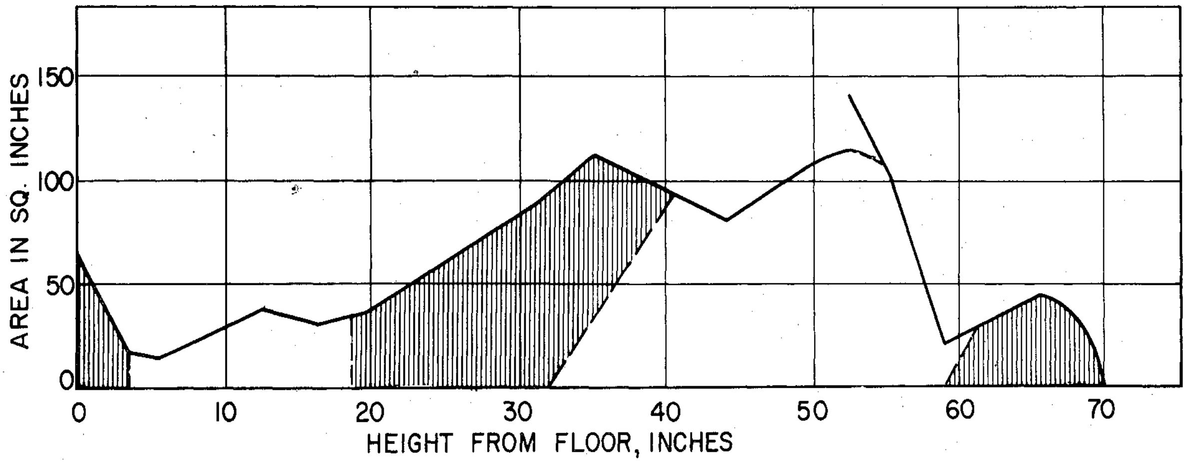

Figure 100. Plot of body volume (without upper limbs) of first choice median subjects expressed as area to height. Lines separating adjacent regions are located according to external body landmarks.

Returning to volume plots, Figure 101 shows a variety of measurements made on one test subject. At the left, Sketch A shows three contours above symphysis level which represent extreme inspiration, extreme expiration, and a mean position. The whole upper trunk is involved in forceful breathing (Dally, 1908). The greater trunk volume of the inspiratory movement (dashed line) with raised head and shoulders, increased thoracic bulk, and raised pelvis may be contrasted to the mean respiratory position (dotted lines) and the expiratory phase (solid lines).

Differences in trunk volume measured by the planimeter corresponded well with differences measured by a spirometer. Plus signs refer to balance points for cardboard cut-outs of the three body contours. The inspiratory centroid of the cardboard cut-out (roughly comparable with the body center of gravity) is higher than the expiratory centroid.

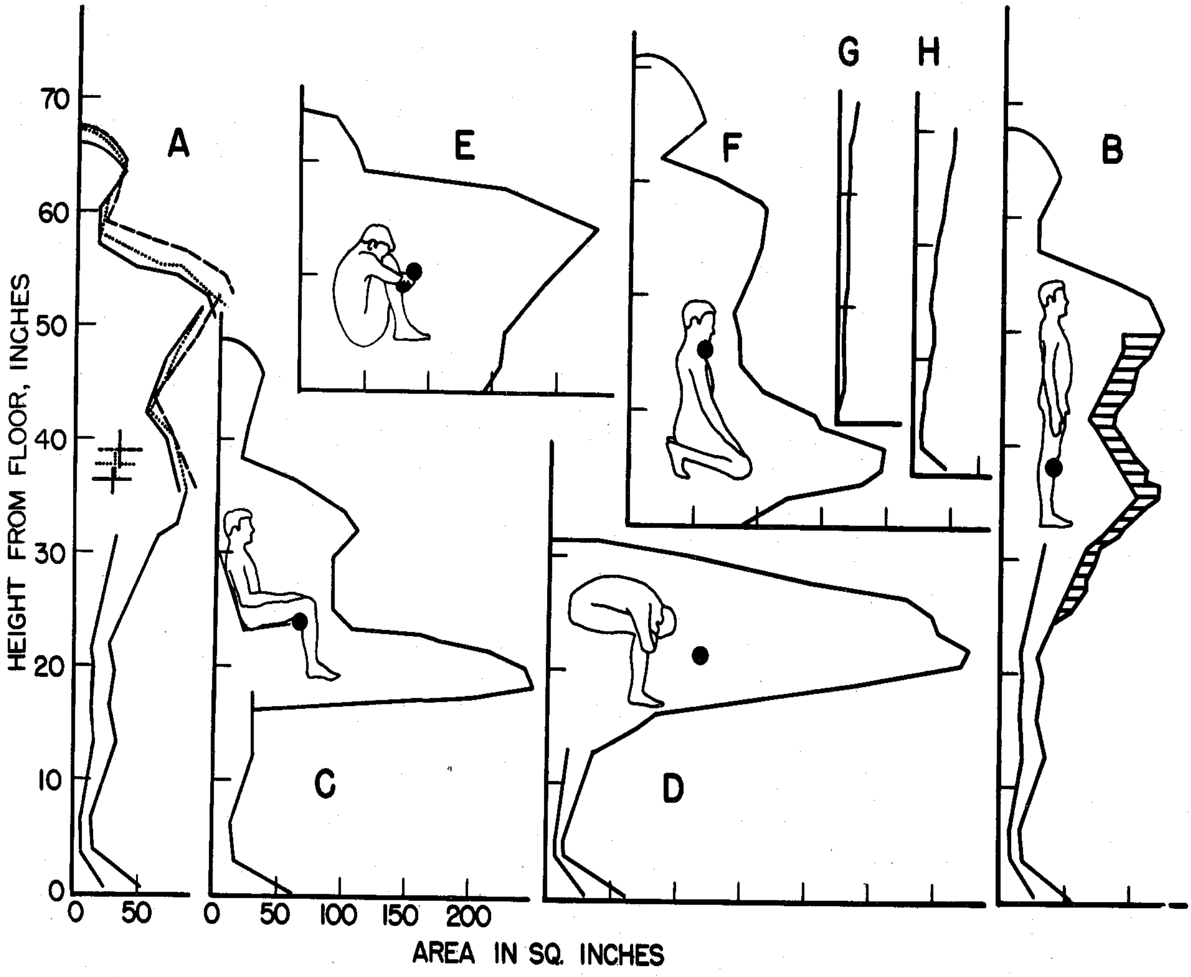

Figure 101. Area-to-height plots of one subject showing different postures. A-phases of respiration; B-standing posture including upper limbs; C, D, E, and F-plots for postures shown; G and H-plots of upper and lower limb values based on water immersion. Crosses on plot A show centroid positions for inspiration, for quiet respiration and for expiratory phases of breathing. Black dots on other figures show centroid locations in relation to the plots.

Sketch B at the right of the figure shows the total body area of the same study subject, when the areas of the upper limbs are included in the plot. With a few exceptions, illustrated in the present figure, upper limb volumes were not included in body volume plots. The alternate procedure (Chapter II, Item 41) involving water immersion and the determination of upper limb volume per inch of limb length proved simpler. Sketch G illustrates a representative record; one can readily recognize the convex curve of the hand volume to the wrist, a low wrist volume, an increasing volume through the forearm to a level above the elbow, a lower upper arm region, and a higher upper arm region. Heavier men had larger areas for each level, and lighter ones had smaller areas, but no marked contour trends related to physique were found.

The water displacement technique outlined earlier (Figure 96) should give more pertinent data. Data on displacements relative to height for the lower limb (Chapter II, Item 41) gave plots like those of Sketch H, Figure 101. A comparison of lower limb volume contours in Sketches B and H show very similar data for the same test subject. Ordinarily, nothing was done with data on lower limb volumes to crotch level (derived by the immersion technique) other than to check data by the pantograph-planimeter technique. Figure 99 already has presented these data.

Sketches C, D, E, and F (Figure 101) are areas-to-height plots (including upper limb volumes) made while the subject maintained the posture shown in the insert figures. The bulk distribution varied considerably. The shaded dots show the height of centroids (balance points) of cardboard cut-outs for the four plots; mass distribution and center of gravity heights should not be markedly different from the volume and centroid data shown. Consequently, the plots may be taken as a graphical illustration of the effects of body inertia under various accelerations in some horizontal direction.

Plot C, for instance, shows that a seat and back rest should provide an effective stop for backward accelerations as far as most of the body is concerned. Forward accelerations would obviously require special support (harness) to counteract inertia forces such as those of airplane or automobile crashes. The different postures of the figure clearly show different distributions of body bulk and different inertia effects should be expected in each instance.

One may think of inertia forces involving high acceleration in terms of translatory vectors, where the same posture remains unchanged and the body tends to move en masse. Alternately and probably more importantly, the segmental parts will change relations in line with bone and joint kinematics. The plots of Figure 101 are probably of more illustrative than analytical value. Certain of the plots presented here (Figure 99) might be related to the recumbent individual as plots of pressure distribution on a horizontal substrate.

Data of this chapter cannot be well segregated from those of Chapter VII on cadaver masses. Graphical and algebraic analyses of moments based upon photographic records of specific postures, where masses, centers of gravity, and joint centers may be assigned, should be possible with the data presented. In certain instances (centers of gravity, moments of inertia) cadaver data will have primary importance; in others, data on living subjects may be more applicable. In still other instances, direct measurements of the distribution of volume of specific test subjects, as was done here, may be necessary.

CHAPTER IX

HOW BODY MASS AFFECTS PUSH AND PULL FORCES

From the preceding chapters it has become clear that the body bulk is distributed on the body links in a way that may be reasonably well predicted. These masses, of course, are continually subjected to the acceleration of gravity. Accordingly, one may visualize the segmental masses as a related system of vertical force vectors. In addition, forces due to muscular tension or exterior forces other than gravity may operate on the system from various other directions. Forces acting on the body parts over a short interval may produce balanced torques with no resultant movement, or the masses may be accelerated along paths consistent with the kinematics of the linkages involved. Either dynamic or static considerations, or both, are involved in a body mechanism under such forces. Present concern, however, will be limited strictly to static situations.

Whenever the body segments are moved, the body masses acquire new positions in space. For any such static posture the several masses are balanced in the sense that torques involving both mass and leverage distances to the centers of gravity of the individual parts are in equilibrium; resultants may be figured from a torque analysis based on the various vectors and the distances between them.

Actually, a true balance of forces over a period of time is only approximated. Maintenance of a posture for a protracted period involves irregular volleys of muscular activity and the degree of steadiness depends upon how the forces fluctuate. The anti-gravity system of muscles thus is largely corrective in nature. In mere standing, for instance, the center of gravity of the body sways erratically over the support area with variations according to subject (Hellebrandt, 1938; Hellebrandt, et al., 1942, 1943; Franseen and Hellebrandt, 1943; Fries and Hellebrandt, 1943). Even though these periods of maintained posture truly involve dynamic behavior of muscles, the mean posture may be studied helpfully by static methods. The instantaneous posture record shown in a photograph may be analyzed statically, and such analyses have value if the photographed posture is representative of some mean body position.

Recent activity in the interest of increasing the efficiency of the man-machine system has directed attention to those postures and movements which will produce maximum operating forces with a minimum of effort and fatigue. A number of articles have been directed to force data on the hand and foot—often with the idea of determining optimum positions of a foot rest, back rest, or hand grip. Representative of these studies are reports on hand forces by Lehmann (1927), Garry (1930), Bedford and Warner (1937), Hugh-Jones (1944, 1945), Müller and Müller (1949), Wakim, et al. (1950), and Hunsicher (1954), foot pedal forces by Müller (1936), Koch (1941), Clark and Weddell (1944), Martin and Johnson (1952), and Rees and Graham (1952) and hand- and foot-pedal forces by Hugh-Jones (1947), Orlansky and Dunlap (1948), and McFarland, et al. (1953). On the whole, the approach to the above studies has been direct and the resulting data have been empirical. The transfer of derived experimental values even to situations that are apparently related is uncertain, since the principles of the body mechanics involved have not been clear.

This investigation was undertaken to determine how the body mass, exerting a vertical component, is utilized by the seated subject to effect horizontal push and pull forces in the midsagittal plane.

To avoid complicating factors, neither foot nor back rests were used in the standard series of experiments; these features, however, were not ignored. It was our purpose to study how the body uses its dead weight in effecting pushes and pulls. A priori it seemed that a basic principle was involved, yet this has been neglected in past researches. The present effort is little more than an introduction to one class of problem in force relationships; nevertheless, it presents a new approach which should result in a better understanding of the fundamentals involved in the application of forces by the seated operator.

We are prone to regard all forces which the subject produces as direct muscle force and to neglect completely the effect of body inertia and body dead weight in the effort. The distribution of body mass relative to its support area forms an anchorage for the body as the muscles operate. Either the anchorage or the muscular effort may be the limiting factor which defines the maximum force that the body produces. The body anchorage may be improved by designers who understand the principles involved in the operation of dead weight and the advantages of effective body supports and leverages.

The research methods involved in the present study were basically simple. Eccentric pushes and pulls, which would involve body twisting about a vertical axis, were avoided in favor of symmetrical two-handed actions, where forces could be resolved in a plane. Then all pertinent forces that were operative in the plane were measured at the same instant during a maximal body effort. These measurements included readings of both a hand dynamometer and six force gauges at the seat. All horizontal and vertical forces operative within the plane of action were recorded. Simultaneously, a side-view photograph was taken to freeze the body position. Measurements of heights and distances as well as the location of limb joints could be taken from the photograph.

The subject was nude; additional data on the bulk of limb segments and of the trunk were available. From joint centers and data on body mass, estimated positions of segment centers of gravity could be laid out on the photographs. Details of the procedures and apparatus were outlined in Chapter II, Item 42 and Figures 25-30. A number of repetitions, as outlined in the section on procedure, were averaged to provide the values in the tables to be discussed here.

In Figure 28 the six pull positions shown as stick figures represent different seated postures, involving pulls at a constant height above seat level. In the different figures the various segment masses have different positions in space. Initially the postures were selected to represent different patterns in the distribution of body mass consistent with a fixed height of pull. The vertical line of action of the center of gravity of the body is represented in each sketch by the arrow above the seat; its position relative to the front-to-back span of the seat is critical. The sequence of postures shown in the figure, as will be seen later, corresponds with the relative strength of pull found; in contrast, the relative distance of the center of gravity from the rear edge of the seat follows the sequence a-f-e-d-c-b.

The postures of Figure 28 may be described in a sequence based on center-of-gravity position. At "a" the subject simply leaned back passively while holding the hand grip; the feet dangled passively; the center of gravity was well toward the rear. Next, at "f" both the buttocks and feet made contact with the seat and the doubled-up posture was strained; the center of gravity was nearly as far back as at "a". At "e" the subject's trunk was tensed, his arms were flexed and held close to the body, and his knees were tensed and bent; the center of gravity was more forward in this posture. Sketch "d" shows a posture in which the center of gravity was only a little farther forward; the trunk was tensed and strongly inclined backward; the head was back also, and the knees were bent strongly. At "c" the subject sat upright in a strained position with the legs sharply flexed, to prevent pulling the body from the seat. The center of gravity was a full 3 cm farther forward than in the last position. Finally, at "b", the most forward position of the center of gravity, the subject leaned as far forward as he could and still get positive pull values.

Figure 29 shows push positions in a sequence of the strength values found. The mass distribution is superficially comparable with that of the pull positions, except that the tensed leg and trunk postures differ. In all of the postures muscular action holds the body members in a given spatial position. The individual segment masses are deployed in a characteristic pattern; a separate downward force vector acts at the segment center of gravity. For each posture the resultant force, termed here the whole body center of gravity, comes to have a specific location relative to the supporting surface.

When the original procedures were set up, the six pull and six push postures were assumed to be identical; later analyses showed that trunk and leg tensions altered the postures in the sense that may be seen by comparing "similar" postures in Figures 28 and 29. The relative closeness of the center of gravity to the rear edge of the seat follows the sequence c-b-d-e-f-a.

The relative locations of centers of gravity shown in Figures 28 and 29 are based on precise measurements and calculations of moments. For instance, the distances between the rear seat contact with the pressure gauges and the line of action of the body centers of gravity as calculated for Subjects A, B, and C are shown in the second columns of Table 27.

Procedures used in locating the body center of gravity have been outlined in Chapter II and Figure 30. The method was based on balancing of moments about the rear pressure gauge contacts.

In addition, common centers of gravity were located by an alternate method. From the cadaver data of Chapter VII (Table 15, Figure 94) a series of ratios was available on the distances of the segment centers of gravity from adjacent joint centers. In addition, measurements of segment bulk were available on the specific subjects of this experiment in line with procedures of Chapter VIII (Tables 22, 23, 24, 25). The problem called for locating centers of gravity on the photographs of the individual subjects in specific postures and the assignment of correct mass values to each.

On the photograph of the most nearly average posture in each group of 10 records joint centers were plotted as accurately as possible by inspection; these positions were checked by two anatomists acquainted with joint center data. Segment centers of gravity were plotted on the segment links on the photographs at appropriate distances based on the ratios derived from cadavers.

TABLE 27

DIMENSION AND FORCE DATA ON TWO-HANDED HORIZONTAL PULLS AND PUSHES

1	2			3			4			5		
Pull Positions	Distance from CG Line to Rear Gauge-seat Contact, cm			Distance from Effective Seat Contact to Rear Gauge-seat Contact, cm			Horizontal Distance from CG to Effective Seat Contact, cm			Maximum Horizontal Midsagittal Pull Force, kg		
	Subjects			Subjects			Subjects			Subjects		
	A	B	C	A	B	C	A	B	C	A	B	C
a	24.0	22.8	22.3	27.3	28.2	27.2	3.3	5.4	5.4	3.6	5.3	6.2
f	24.1	24.3	22.1	41.7	44.1	42.0	17.6	19.8	22.2	18.8	19.3	22.8
e	26.0	26.4	29.8	41.9	44.2	42.3	15.9	17.8	13.9	16.9	17.3	14.2
d	26.5	25.8	24.5	41.8	42.7	41.3	15.3	16.9	16.8	16.4	16.5	19.1
c	29.8	28.8	30.8	41.4	43.7	42.4	11.6	14.9	13.0	12.4	14.6	13.3
b	30.3	29.2	32.3	41.9	42.9	42.3	11.6	13.7	11.2	12.4	13.3	11.4

Push Positions	Distance from CG Line to Rear Gauge-seat Contact, cm			Distance from Effective Seat Contact to Rear Gauge-seat Contact, cm			Horizontal Distance from CG to Effective Seat Contact, cm			Maximum Horizontal Midsagittal Push Force, kg		
	Subjects			Subjects			Subjects			Subjects		
	A	B	C	A	B	C	A	B	C	A	B	C
c	19.6	22.8	25.0	10.4	10.3	10.9	9.2	12.5	12.5	10.8	13.0	15.5
b	19.8	24.5	21.9	11.9	14.9	13.4	7.9	9.6	8.5	9.2	10.2	9.3
d	23.3	29.3	32.4	11.6	13.4	16.3	11.7	15.9	16.1	13.6	16.9	17.6
e	25.6	29.8	31.9	12.0	13.1	13.6	13.6	16.7	18.3	15.8	17.6	20.1
f	31.6	38.0	38.7	12.4	18.1	17.7	19.2	19.9	21.0	22.4	20.9	23.2
a	33.1	35.8	34.9	29.3	29.8	29.8	3.8	6.0	5.1	4.4	6.3	5.7

At each center of gravity, vertical downward force vectors with magnitudes corresponding with segment mass were assumed to operate; additional data from the photographs on the horizontal distances of successive centers of gravity from some arbitrary point permitted the calculation of a common center of gravity. About this common center, clockwise and counterclockwise moments of the separate segment masses were in equilibrium.

The center of gravity calculated in this way in no instance was separated by more than 1 cm from the center of gravity as derived from the first method involving the balancing of moments about the rear gauge supports.

If the sketches of Figures 28 and 29 simply represented plaster dummies fixed in the various postures shown, but without hand grip contact, the center of gravity would act downward and there would be an equal and opposite reaction in the same vertical line. In the actual push and pull situation, however, the location of the reaction vector, termed here the effective seat contact, is not in the same vertical line as the whole body center of gravity. Chapter II and Figure 30 show that the location of the reaction vector to the body weight may be located at a distance of X_1 from the contact of the rear pressure gauge. The value of X_1 was calculated from mean force data for each subject from each series of 10 similar tests. Column 3 of Table 27 shows these values for each subject.

In pull position "a" (Figure 28), in which the subject grasped the hand grip and leaned back passively, the effective seat contact was close to the center of the seat. In all other pull positions, however, the subject strained backward and moved the location of the effective seat contact to the front edge of the seat. In push position "a" (Figure 29), the subject leaned forward passively against the hand grip; the effective seat contact was now several centimeters forward of the mid-point of the seat. In all other push positions the point of effective seat contact moved, in contrast, toward the rear edge of the seat. To effect this change, the subject ordinarily extended the knees and flexed the thighs from the seat. Thus, the subject moved the location of the effective seat contact forward to produce a maximum pull, and he moved the location of the effective seat contact to the rear to effect a maximum push.

We have taken the location of the vertical downward force vector as the subject's mass acting at his center of gravity; an equal and opposing vector is located at the effective seat contact. These two opposing vertical parallel forces of equal magnitude in the same plane, but not in the same line, form what is termed a couple. The two opposed coplanar forces, separated by a finite perpendicular distance, act upon a rigid body, to cause rotation in their plane of action. The vertical couple associated with these forces is diagrammed in the sketches of Figure 102. The figure at the right illustrates 10 superimposed tracings of side-view photographs, showing repetitions of pull position "d" at the moment of maximum effort; the heavy outline shows the selected average position. To simplify this force picture, we have substituted a wooden block for the subject. The vertical couple represented by the vertical force arrows tends to rotate the subject in a counterclockwise direction.

When the seated subject pulled backward on the hand grip, the hand dynamometer recorded an equal contrary horizontal force acting forward at shoulder level. In addition, a parallel force of equal magnitude which acted in the opposite direction, i.e., backward, was recorded by the gauge at the front of the seat, shown by cross-hatched arrows of Figure 102. The two opposing horizontal forces at the hand and at seat level form a couple which tends to rotate the subject in a clockwise direction.

The sense of this clockwise rotation due to the horizontal forces was opposed to that of the vertical forces mentioned earlier.

The tendency of a couple to produce rotation is expressed by the term moment of rotation or torque, and is derived by multiplying the magnitude of one of the forces of the couple by the perpendicular distance between the two forces. These couples have been illustrated in Figure 30, which represents the reaction forces recorded by hand and seat gauges; equal and opposing forces based on dead weight could have been alternately figured. For a pull force, the horizontal vector recorded by the hand dynamometer, F_4, or its reciprocal, recorded by the seat dynamometer, F_6, multiplied by the perpendicular distance (h) between them will be the moment of rotation produced by the horizontal couple. For a push force the horizontal vector recorded by the hand gauge, F_3, or by the seat dynamometer, F_5, multiplied by the distance (c) between them will be the moment produced by the horizontal forces. The moment produced by the vertical couple is the product of the mass of the subject (W) or the reciprocal reaction at the seat (R) multiplied by the perpendicular distance between their lines of action (a). A further discussion of forces, couples, and moments can be found in such texts on mechanics as Seely and Ensign (1945) and Timoshenko and Young (1940).

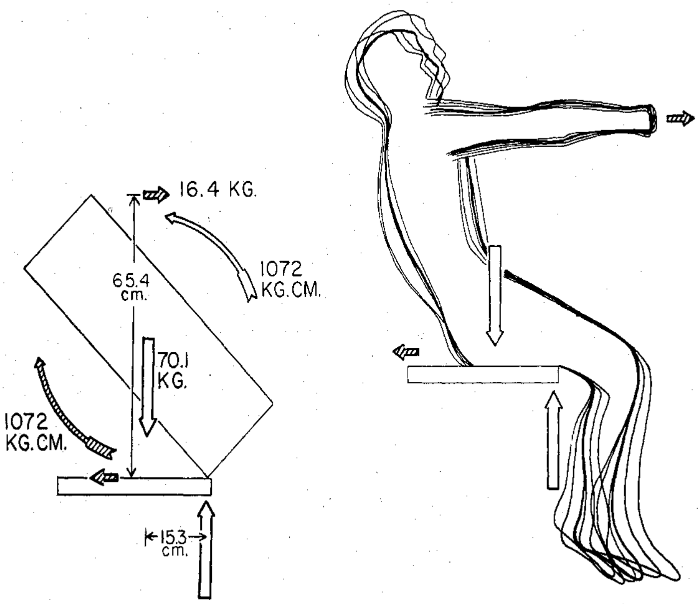

Figure 102. On the right are superimposed tracings showing body posture at the instant of 10 maximal horizontal pulls. These postures have been analyzed in terms of vertical force vectors (white arrows) and horizontal force vectors (shaded arrows). The block to the left shows an analogy to the body situation involving vertical couples (with forces and lever distances indicated) with the counterclockwise moment in kg cm; the opposed clockwise moment produced by the horizontal couple (shaded area) is shown also.

It follows from the above that any body action which lengthens the moment arm of the vertical couple for a constant force will necessarily increase the moment produced by the horizontal couple. When the subject strains and adjusts his position of effective seat contact relative to his center of gravity in such a way as to increase the moment arm of the vertical couple, he simultaneously increases the pull at a fixed height above the seat. An analysis of each of the standard pull postures showed relationships similar to those recounted here for one posture.

Figure 103 presents a similar analysis of push position "f"; the central outlined figure in the sketch at the right is the most nearly average position, and the stippled halo about this figure represents the range of position for 10 push repetitions. A block diagram analogy of this push posture appears at the left. Here, as in the pull force system, the two vertical forces form a vertical couple and the two horizontal forces form a horizontal couple. In contrast to the pull system, the line of action of the effective seat contact was to the rear of the line of action of the subject's mass, the vectors of the horizontal forces were reversed, and the moments of rotation produced by the couples were reversed.

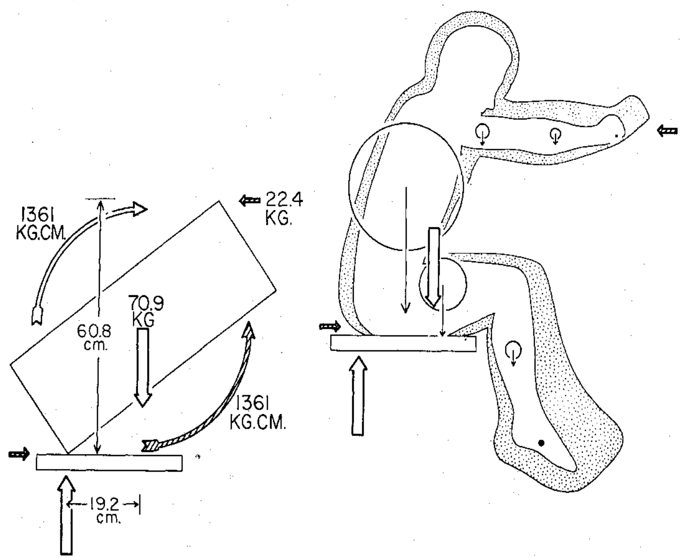

Figure 103. Balanced clockwise and counterclockwise moments are illustrated for a body-push position and for a block analogy. Circles and fine arrows on the sketch to the right represent the position and magnitude of segment-mass vectors which have as their resultant the broad downward arrow acting at the whole body center of gravity. The shaded halo about the figure shows the variability of the positions of body contours found in 10 repeated maximum pushes.

On the right hand sketch of Figure 103 circles represent the relative masses of individual body parts; arrows directed downward indicate the lines of action of these masses. The data were calculated from measurements of bulk made on the three subjects and located at centers of gravity (cadaver data). As explained earlier, data on segment mass provided a means of checking the accuracy of the calculated locations of action lines of whole body centers of gravity. A calculation of the counterclockwise moment produced by the mass of the trunk about the center of gravity should be equal and opposite to the clockwise moment produced by the sum of the masses of all other body segments. These moments for the situation illustrated were +342 kg cm and -340 kg cm, respectively. Similar calculations for all selected body positions were used to check the accuracy of the locations of whole body centers of gravity.

From analyses of force diagrams it is apparent that when the subject pushed or pulled, he increased the perpendicular distance between the action lines of the forces acting at his center of gravity and at the effective seat contact. He did this by tensing muscles in such a way as to adjust the point of weight application. In addition, he modified his posture to some extent by extending or pulling in his legs; this changed the location of the body center of gravity to favor either the push or the pull action. In other words, the subject by muscular action lengthened the moment arm of the gravity couple both by moving the effective seat contact and, to a lesser extent, the line of action of the gravity vector.

Figure 104 is a block analogy of our force system; the heavy solid line in the left sketch shows a block tilted forward and corresponding to a push position; in the sketch at the right the block represents a pull position (tilted backward). The stippled rectangle A in both drawings is the product of the length of one of its horizontal sides multiplied by the length of its adjacent vertical side; the area of the rectangle graphically represents the torque. The horizontal forces recorded for a push or pull are the horizontal sides of the rectangle and the distance between these two forces is the vertical dimension of the figure. The product of the horizontal and vertical dimensions is an area that corresponds in magnitude with the moment of rotation produced by the couple. Figure 104 is, therefore, a visual representation of the moments of rotation acting on the body. Area A is equal to area B in a balanced system. Thus the moment of the horizontal couple is the same as that of the vertical couple—the sense is opposite.

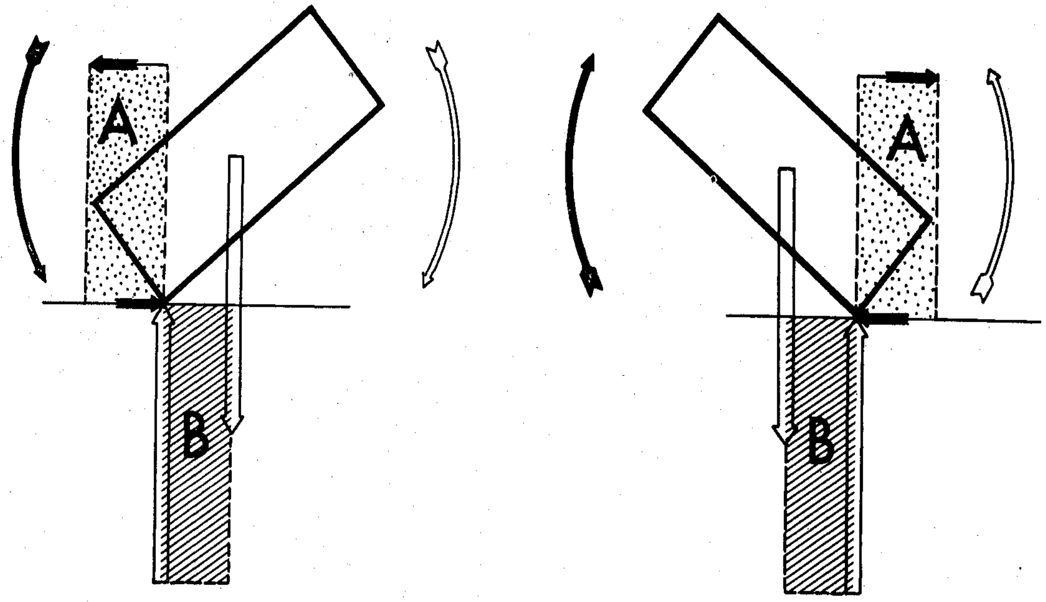

Figure 104. Block analogies illustrating the push force system at the left and the pull force system at the right; the rectangular area outlined in a heavy black line represents the block. Area B, cross hatched, is the movement produced by the vertical body-mass couple (white arrows) and is equal to area A, stippled, which is the pull or push movement produced by the horizontal couple.

Under the conditions of the experiments the distance between the line of pull at the hand grip and the line of opposing force recorded by the compression gauge at the front edge of the seat was fixed; the subject was not permitted to change the moment arm of this horizontal couple. Neither could he change the magnitude of his body mass; hence the size of the vertical counterforce was fixed also. The distribution of mass of the body parts was different in each of the six standard positions. For each posture the two vertical arrows in Figure 104 were separated by a characteristic distance. If the subject, or the block, tilted forward, moving the center of gravity forward, as in the left sketch of Figure 104, or, tilted backward as in the right sketch, the distance between the two vertical forces increased and area B became greater, its outline more closely approximating a square. If the force system is to be in equilibrium, there must be an equal increase in area A. Since the subjects were not permitted to change the horizontal level of push or pull, an increase in the magnitude of the horizontal push or pull force resulted, or the system was out of balance.

Column 4 of Table 27 lists the average values of the moment arms of the vertical couples for all push and pull positions. Data for each of the three subjects has been listed. In pull posture "a", in which the subject leaned back passively grasping the hand grip, and in push position "a", in which the subject leaned forward passively on the hand grip, the moment arm was minimal. Notice that the horizontal forces, column 5, were correspondingly small. This was in contrast to pull and push positions "f" in which both the moment arm of the vertical couple and the magnitude of the horizontal force was greatest. From the above explanation of the force system involved in dead weight push and pulls one should expect an increase in the magnitude of horizontal force, corresponding to an increase in the moment arm of the vertical couple.

An examination of columns 4 and 5 shows exactly this relationship, progressing from minimum values at position "a" through the sequence b, c, d, and e to maximum values at position "f". The moment arm for subject C was out of sequence for posture "e"; his horizontal force, however, was proportionally low also.

When the moment arms for any subject were plotted as ordinates against the related horizontal forces as abscissae, a straight line plot was produced in each instance, pull or push. The slope of the curves for either pushes or pulls indicated that subject A produced a greater horizontal force for a given moment arm than the other subjects; subject B consistently produced lower forces than subjects A and C. Subject A had a medium weight and a short trunk length; subject C was heavier but had a longer trunk length. Thus, to obtain equivalent pulls or pushes at shoulder level, it was necessary to increase the moment arm of the horizontal couple for subject C. This resulted in lower values for horizontal push and pull forces for a given moment arm than for subject A, despite the fact that C weighed more than A.

All the moment-force data on the three subjects thus were mathematically consistent. The magnitude of horizontal forces was proportional to moment arm for a given body mass. Larger mass for a given moment arm produced larger forces.

The data emphasize that there is a basic mechanical principle underlying the body use of dead weight in effecting horizontal forces. Further data on this point resulted from exploratory investigations using the foot rest and back rest. The sketch at the left of Figure 105 illustrates the force system underlying midsagittal pulls using a foot support. When the subject pulled a maximum, his buttocks were raised from the seat and all of the body weight was applied to the foot rest. In lesser pulls the buttocks were in contact with the seat so that weight was distributed on both the foot rest and seat. In the pull position illustrated the horizontal force at shoulder height was 47.7 kg, and its moment arm was 100 cm. The subject's weight was 68.2 kg, and it acted over a moment arm of 70 cm. The resultant moments of rotation produced by these forces showed that areas A and B were practically equal (i.e., 4770 kg cm = 4774 kg cm); hence, the system was in equilibrium.

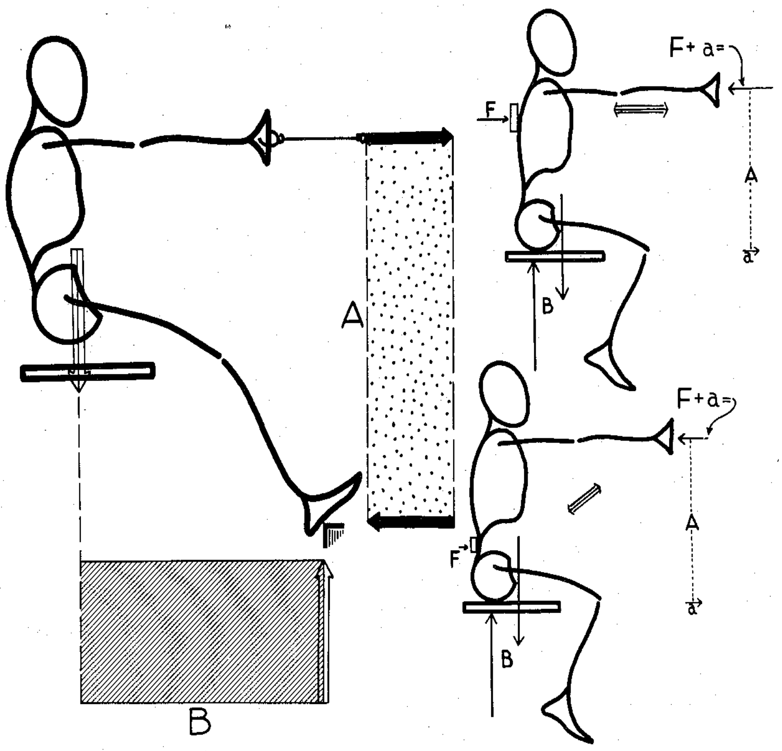

Figure 105. Diagrams showing force relations when a foot rest and back rest are utilized. Large figure: system of couples when a foot rest is employed for pulls; upper right, force system for pushes with a back rest in the upper thoracic region; lower right, force system for pushes with a back rest at the lumbar level.

The figure accordingly shows a force system identical in principle to that seen earlier. The advantage gained in using the foot rest was that the effective body contact moved a considerable distance beyond the front edge of the seat; in other words, the moment arm of the vertical couple involving body weight has become far larger than could be attained by the use of seat alone. This resulted in an increase in the horizontal force.

The increase in the pull force for the posture illustrated, however, was not as great as could be attained, since the location of the foot rest below seat level increased also the moment arm of the horizontal couple. For a more effective use of dead weight, the foot rest should have been located closer to the level of hand pull.

In push tests, the back rest was placed at sacral, waist, xiphoid, and shoulder levels. The horizontal forces effected were 19 kg, 30 kg, 33 kg, and 40 kg, respectively. Two of these positions, waist and shoulder, are shown by the sketches at the right of Figure 105.

When a back rest was utilized, forces were greater than when no rest was used. The same torques due to body moments still applied, but an additional factor calls for attention. The back rest supplied a counterforce against which upper limb and trunk muscles could operate to increase the magnitude of horizontal hand pushes. For the subject tested, this force, now involving back rest, was increased from 9 to 30 kg—an increase of 21 kg over that attained by the use of dead weight alone. In the lower right figure couple B balances couple A; in addition, the sum of force F at the waist plus "a" at the seat equaled the force F = a at the hand. Force F was produced by muscle tensions of the arm and back.

In the sketch at the upper right, the subject elevated his shoulder, arched his back, and tightened extensor muscles of the arm, to increase the compressive force acting across the strut between the back rest and hand grip. This muscle force, F, acting from the back rest plus force "a", owing to the weight couple, were equal to the horizontal force recorded at the hand. The couple "A", involving force "a", produced a rotatory action which contributed to the dynamometer reading. In addition, a direct compression force between back rest and dynamometer augmented the force value.

In the preceding discussion it was apparent that a basic mechanical principle underlies the use of dead weight in effecting midsagittal push and pulls. The addition of a foot rest and back rest do not alter this basic mechanism.

The hand pull, when a foot rest is used, is identical in principle to the pull without a foot rest; the push, however, is different. In addition to the rotatory mechanics using dead weight as analyzed above, the subject operates his muscles against a resisting contact and produces a direct compression.

ONE-HANDED PULLS IN THE SAGITTAL PLANE

The foregoing experiments in two-handed pushes and pulls in the sagittal plane, although calling attention to certain essentials, fall short of explaining the variety of mechanical problems which face the seated machine operator. Practical hand operations are usually asymmetrical, and analyses limited to the two dimensions of the sagittal plane necessarily ignore the third dimension. Oblique or eccentric pulls typically involve rotations about the vertical or anteroposterior axes in addition to actions in the sagittal plane.

A universal testing machine, which would give seat, hand, and foot forces in three dimensions, could be constructed, and simultaneous data in three mutually perpendicular planes could be derived. Factors that appear in the sagittal plane data, such as couples, effective mass centers, and fulcrum points, should be equally significant in analyses of the more complex three-dimensional system. When asymmetrical and oblique hand and foot forces are involved, the dimensions and placement of the base of support, foot rest, and seat back pose additional anchorage problems. Pivoting seats may be a partial solution for certain such problems.

An alternate plan, however, was adopted in this research as an extension of the data on symmetrical, horizontal, sagittal-plane hand forces. Seated test subjects were required to pull with one hand on a dynamometer, which was placed at various points in the space within hand reach; the pulls could be backward, upward, downward, or oblique; but they were always exerted in a sagittal plane. Pulls were made in the midsagittal plane, in sagittal planes 6, 12, 18 and 24 inches to the test limb side, as well as in a sagittal plane 6 inches beyond the subject's plane of symmetry.

A number of pulls in a selected plane were measured at a test; the pulls alternated with fatigue-preventing rest periods; successive pulls were oriented at random by changing the anchorage points of the dynamometer. The method and general setup, as presented in Chapter II, Item 43, and in Figure 31, may be consulted.

The special points of interest in the method are twofold: (1) the dynamometer was free to rotate about its attachment point, so that the subject unconsciously selected the best direction for a pull, when he was exerting maximal effort, and (2) the hand grip was free to rotate both about the axis of the pull and in the plane of the hand grip. Because of these two features, the hand grip orientation and the direction of pull became automatically best choices for the subject. The only restraint was that the pulls be directed in one of these selected sagittal planes. With the foregoing plan for experimentation the variability in maximum hand force could be assessed for various points within reach. The data, however, were strictly limited to sagittal plane pulls, since pulls oblique to this plane were beyond the scope of the equipment.

In addition, data on the preferred hand grip orientation for maximum sagittal pulls in the space within reach were obtained. Since the experiments were begun so late in the contract period of this project, data were obtained on only three subjects—they were reasonably complete on only one of these. Accordingly, the following account purports to be more qualitative and suggestive than quantitative in its information. The method warrants further exploration, and modifications looking toward problems of wider scope are feasible.

Data provided by the principal subject alone are presented here; the less complete records of the other subjects were in no way contradictory. Pulls by the subject ranged from 17 to 136 lbs. When the nearly 250 pulls were assorted into quintiles for simpler analysis, the distribution of equal-sized groups of pull values read as follows:

113-136 lbs, called very strong pulls
94-112 lbs, called strong pulls
73- 93 lbs, called average pulls
55- 72 lbs, called weak pulls
17- 54 lbs, called very weak pulls

Characteristically, the strongest pulls were downward pulls from overhead and downward-forward pulls from above and backward, where the subject braced himself against the seat back. The weakest pulls were from front to back, or from the rear directed forward. Upward, or upward and backward, pulls, where the seat formed a bracing, were ordinarily quite strong. Oblique, downward-backward pulls were strong-to-average.

If the directly-vertical downward pull vector is designated 0°, the angulation of pull in the forward quadrants ranged over a span of 168°, pulls from behind the body extended through a range of -102°; in other words, the pull angulations of choice for some 23 dynamometer attachments ranged through 270° of a 360° circle in the sagittal plane. Only the quadrant behind and below the seat was not explored.

Although a study of enlarged photo tracings showing pull vectors presented some variability, most pulls tended to be directed toward a center, or transverse horizontal line, about 18 inches above and 9-10 inches ahead of the "R" point of the seat. This line fell approximately at the level of the lower part of the sternal body about 3 inches ahead of the body profile. Strictly horizontal forward to backward pulls were directed toward this level, and with slight variability this was true also of oblique pulls in the 90-0° upper forward quadrant. The direct vertical downward pull vector passed entirely in front of the pelvis at a high thigh level and through the middle of the profile of the 15-inches-deep seat. Pulls in the first 60° of the upper rear quadrant, i.e., 0° to -60°, were similarly directed through a common center.

Backward-upward pulls in the lower forward quadrant tended to have force vectors directed lower and farther back through a region 6 inches ahead of, and 12-14 inches above, the "R" point of the seat. Forward pulls from the rear were similarly but erratically directed toward the lower center. These centers represented force vector intersections as projected on a common sagittal plane; they held equally well for situations where the hand grip distance was far from, or near to, the midplane of the body. If the pulls are arbitrarily regarded as directed toward a common center, the magnitude of pull may be treated graphically in terms of angulations of the force vectors and distances from the midline of the body.

The pulls were recorded for six different sagittal planes relative to the seated subject. Pulls from all angulations in each of the six planes (25-45 pulls for each plane) averaged 103 lbs for the midsagittal plane, 96 lbs at 6 inches right, 89 lbs for 12 inches right, 56 lbs for 18 inches right, 70 lbs for 24 inches right, and 97 lbs for 6 inches left, of the midplane. Although the number and angulations of the pulls were not always comparable—this was especially true of the 24-inch right sample—it was clear that the strongest pulls occurred in the midsagittal plane and in planes 6 inches right and left. The values decreased 12 inches out and were markedly less at 18 inches and 24 inches.

The drop in force values was not strictly proportional to what might be expected for moment values dependent upon the different distances, and one must assume that the bracing value of seat and foot rest positions varied from plane to plane. Clearly the sagittal band from shoulder to shoulder was markedly better for sagittal pulls than the region beyond; at elbow distance lateral to the midplane, i.e., 18 inches, pulls were weak.

A check through records of the 0 inch, 6 inches right, and 6 inches left groups of pulls showed that the strongest pulls typically were those where the subject pulled downward and forward, both bracing himself against the seat back and using his dead weight. This was especially effective in the midsagittal and 6 inches right planes. The bracing was less effective for the 6 inches left plane, where the subject's forearm crossed his neck or face. Straight downward pulls involving the partial lifting of the subject's dead weight were next in value; the lifting was partial since his buttocks and back were required to be in contact with the seat for a fair pull—the subject's weight was 151 lbs. Oblique downward and forward pulls were next in value, where foot stirrups and seat both formed a bracing. Pulls of flatter obliquity approached average values, while horizontal pulls were weaker.

In contrast, pulls 12 inches lateral to the midsagittal plane showed strong to very strong values when body dead weight could operate, and strong pulls for obliquely upward and backward and downward-backward vectors. More horizontal pulls were in the average-to-weak range, and this was true also of the forward and downward pulls, since bracing against the seat back was no longer effective at 18 inches and 24 inches. All these pulls ranged from average to very weak. In general, however, the vertical downward vectors were highest, and the horizontal pulls were lowest, but the differences in force magnitude were less consistently correlated with the direction of pull than for pulls closer to the midsagittal plane.

For purposes of data presentation the two factors discussed above, i.e., (1) differences in plane of pull and (2) differences in pull angulation, may be illustrated as shown in the model depicted in Figure 106. Surrounding the seat is a transversely-oriented cylinder. The model, when blown up to natural size, represents a 30-inch radius of curvature for the cylinder. Pull vectors normal to the surface and at different distances from the midsagittal plane point inward to intersect at the axis of the cylinder. As mentioned earlier this transverse axis was a reasonable, but not exact, approximation for the pre-sternal region of vector intersection found when side-view photographs of the subject were analyzed. A 0° overhead point may be visualized on the cylinder; plus angulations of pull to 90° relate to the upper forward quadrant. The lower forward quadrant continues with angulations beyond 90°. Negative values, 0° to -90° and beyond, were represented in the rear quadrants of the cylinder.

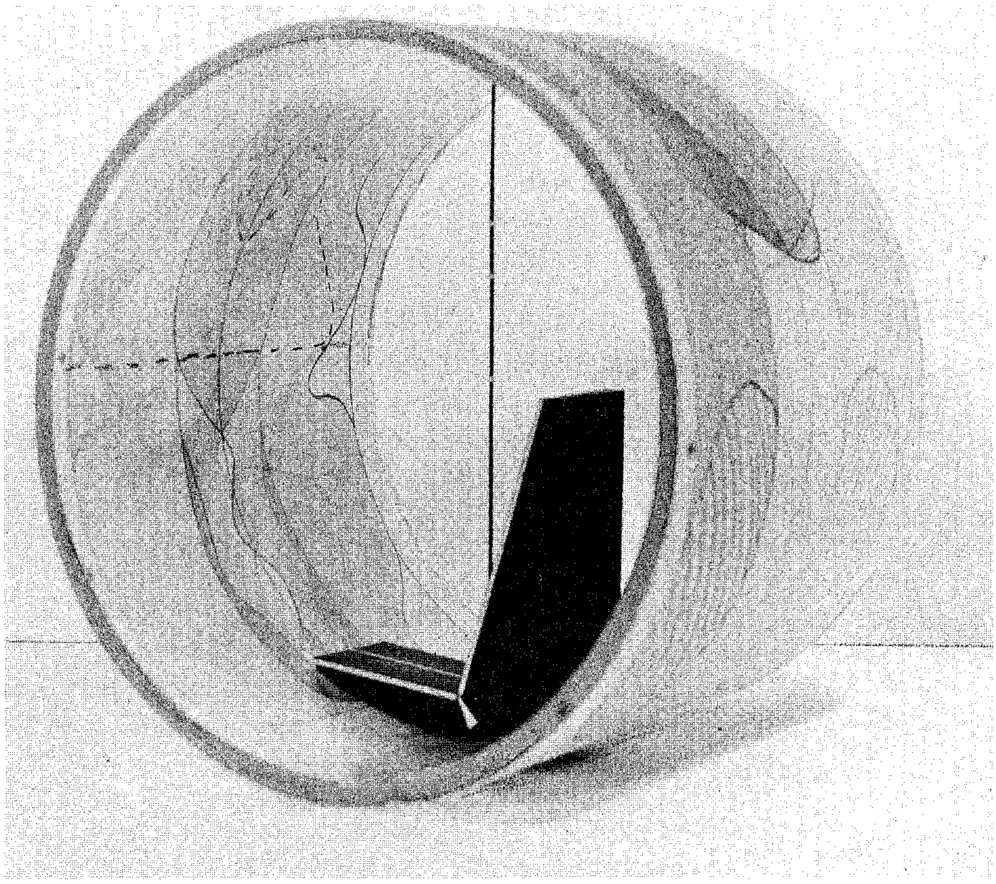

Figure 106. A method for illustrating the magnitude of hand forces or the preferred orientations of the grip for pulls in various sagittal planes. The model represents a transversely-set cylinder of 30-inch radius; plots at its surface show experimental data. In the following figure (No. 107) the graphs illustrate these plots of data as though they were unrolled from the cylinder.

Data capable of orientation on the cylinder are graphically presented as Figure 107-A. Consider that a cylindrical surface, as in the model of Figure 106, has been unrolled. The midsagittal plane appears as a central line, and the surface to the right and left is shown to scale. The 0° transverse line represents the overhead position; the 90° transverse line represents horizontal forward to backward pulls; beyond this is the lower forward quadrant for upward and backward pulls. Obliquely forward and forward pulls from the rear are shown as negative angles. Differently shaded areas are shown within the contours representing right hand pull values. As in a contour map, the shadings represent different magnitudes of maximal pull. Very strong, strong, average, weak, and very weak pulls (corresponding with the poundage ranges indicated earlier) are shown by different patterns of shading as shown by the code areas. Mirror-image pull values are shown as if for the left hand. The pull values in our experiments were recorded only for the right hand; the left hand should pull in comparable patterns, although, in general (Hunsicker, 1954), sinistral pull values tend to be about 10% less than dextral values.

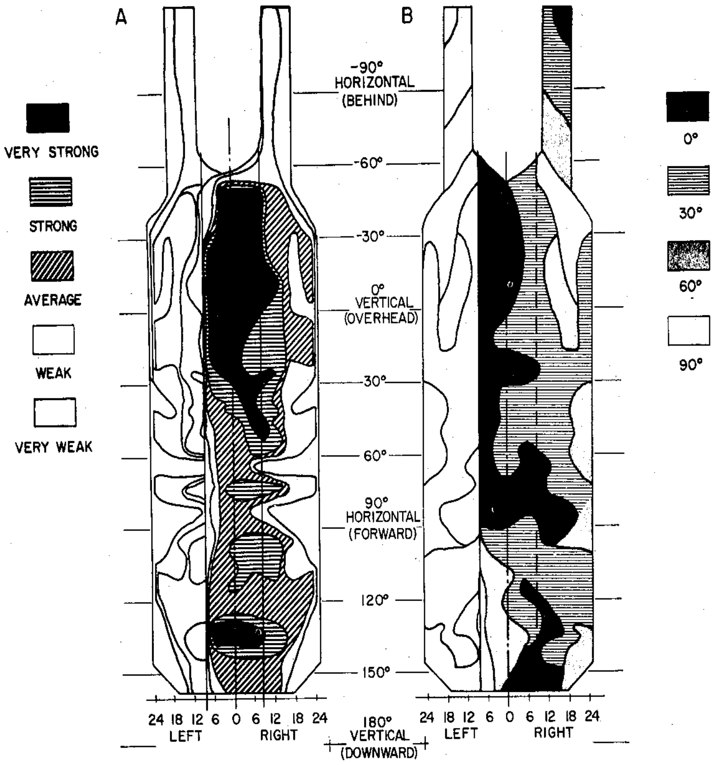

Figure 107. Plots of hand force magnitude and grip orientations for different regions of the work space for the seated subject. A-Five different magnitudes of sagittal hand pull are plotted relative to angle of pull and distance from the midline of the seat. B-Four classes of hand grip orientations are shown graphically relative to the angle of pull and distance from the midline of the seat.

The plot of maximal pulls in different sagittal planes clearly emphasized that pulls within a shoulder-to-shoulder span were stronger than more lateral pulls; it showed highest values overhead, where body dead weight added to the magnitude of downward pulls; it also showed very high values for upward and backward pulls at angulations from 50 to 60° below the horizontal. Pulls more lateral than 12 inches from the midsagittal plane tended to be quite variable, but generally low in magnitude.

Figure 108 shows a tracing of a representative pull record; line A-A represents and upward and backward pull vector; its magnitude was recorded in the dynamometer D. The seating surface and the foot stirrups and support cord (B) provided the bracing counter thrust. The x's in the upper limb call attention to joint centers (small circles) at the shoulder, elbow, and wrist. An arm link between shoulder and elbow centers and a forearm link between wrist and elbow were drawn in also.

Now it will be noted that the pull vector, as seen side view, passed through the wrist center and across the midportion of the arm link. It passed, in addition, through the common pre-sternal region of vector intersection, mentioned above. Very frequently for strong pulls from the different directions the force vector passed through the wrist center. If the positions of pull were natural and there were no encumbrances due to adjacent body parts, it was rare to find the force vector far from the wrist center; these rare pulls were invariably weak.

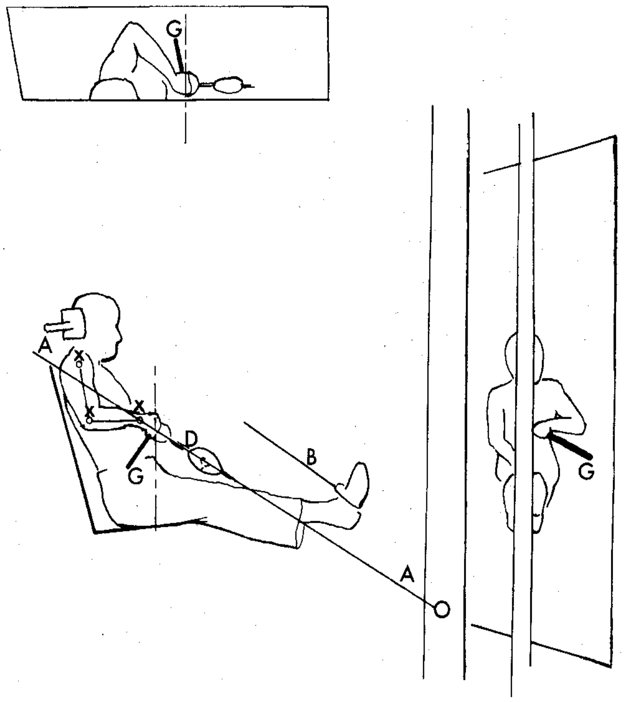

Figure 108. Tracing of a photographic record of the body posture during a maximal pull force including 45° mirror views from the top and front. A—A is the direction of the pull; B, the direction of counter force; D, dynamometer; G, rod showing grip angulation and also included in mirror views; the three X's indicate the position of joint centers for the shoulder, elbow, and wrist.

The pull vector illustrated in the figure intersected the arm link at a point where shoulder extension and elbow flexion were balanced. When both joints participate in a pull, muscular torques in the plane must be equal at the two joints. When the pull vector traverses the midregion of the arm link, or slightly below, maximal pull forces are greater than when the vector is closer to or above the shoulder, or closer to or beyond the elbow. The method of study provides a valuable tool for evaluating the contribution of muscles at adjacent joints and maximum efforts involving pulls and pushes by the limbs—but this avenue has not been explored sufficiently for reporting here.

Muscular effort per se is ordinarily a limiting factor to hand pulls, only when bracing, body support, and the use of body dead weight are maximally effective. Where body leverages and general stability are poor, the limiting value ordinarily resides in these factors rather than in the muscles. The present approach thus confirms the earlier results based on the analysis of midsagittal horizontal pushes and pulls.

The companion study to this research project (Hunsicher, 1954) on push and pull hand vectors presented numerous empirical values and ranges; other studies in the literature, as noted earlier, supplied additional data. Without analyses of bracing and dead weight, however, a critical judgment that would account for high values in one situation and low ones in another is difficult. A detailed knowledge of the body mechanics operative for each posture is needed. Unfortunately the force literature tends to slur over directions of force vectors in the sense of their obliquity and plane of action; it ignores data on the weight and posture of subjects, bracing and support areas, and it avoids problems of body leverage. Work in the future should be planned with attention to this wider scope.

PREFERRED HAND GRIP ORIENTATIONS

Figure 108 should be consulted again; the side view and mirror images show that the reference rod (G) attached to the hand grip was tilted obliquely, relative to the three planes of reference. Since the hand grip could rotate freely about the axis of the pull vector, and on an axis normal to this also, the hand grip was clearly in a preferred orientation for any sagittal pull.

The angulation of the reference rod to the x, y, and z coordinants and to the pull vector itself could have been measured accurately for each of the records. An alternate and quicker measurement, however, actually was employed after a superficial inspection of the record. Four classes of hand orientation, which included all of the hand grip angulations found, were set up: (1) grip parallel to the sagittal plane, i.e., 15 to 0 to -15°, with the thumb in a counterclockwise orientation, (2) perpendicular to the sagittal plane, i.e., 75-90-105°, with the thumb directed medially, and intermediate angulations (3) 30° (15-45°) and (4) 60° (45-75°). Angulations within a degree or two of 45° were recorded separately.

The measurement technique was simple. First, tolerance limits for reference rod length as seen side view, in the top mirror and in the front mirror, were determined for the four angulation classes mentioned; then measurements of rod length were made from the records. The side-view length, together with one or both mirror lengths, provided sufficient data to place the record in one of the angulation classes. Figure 107-B shows the regions where different classes of hand orientation were found.

Right-handed fore-to-back pulls most commonly had a sagittal hand grip orientation for a range of about 30° above the horizontal within a span of 12 inches to the right and 6 inches to the left of the midsagittal plane (darkest area, Figure 107-B). From 30° to directly overhead, midsagittal pulls more often involved 30° hand angulation; 6 inches beyond the midline they were still sagittal. Downward pulls behind the zenith were sagittal for both midplane and 6-inch left pulls. More laterally in both quadrants the grip angulation was 30° to the sagittal. At 24 inches lateral to the midline, oblique pulls favored a relatively flat hand-orientation. The flat (90°)

angulation predominated at distances of 18-24 inches lateral to the midplane for forward and downward pulls behind the vertical line. Forward pulls from the region behind the subject tended to have hand orientations of 45° obliquity or of flatter angulation.

In the forward quadrant below the horizontal a few grip angles were sagittal. In the midsagittal plane they varied through 30-60°; to the left of the midline grip angulations tended toward the prone. Six inches to the right and beyond, 30° grip angles predominated, though occasional 0° (sagittal) angulations were found.

The pattern of hand grip angulation, even though presented for one subject only, tends to be compatible with the geometry of the kinematic system of the upper limb. Changing orientations of the axis of the elbow joint have been shown for various spatial positions of the humerus (Figure 38). The fact that the right humerus is adducted, when the hand pulls in a plane 6 inches to the left of the midplane, favors the sagittal orientation overhead and oblique angulations below the horizontal. Conversely, when the humerus is abducted in pulls 12 inches to the right of the midline, flat grip orientations are favored for forward and downward pulls, oblique angulations are favored for downward pulls and downward and backward pulls, sagittal orientations are favored for backward pulls, and more oblique angulations again are preferred for upward-backward pulls.

The plot of Figure 107-B warrants study by a work space designer, since it relates not only to grip orientations per se, i.e., angles concerned in leverage, handles, cranks, and large knobs, but to finger orientations also. If the grip angulations imply efficient choices for pulls, they should also be mean-range comfortable positions for less strenuous activities involving the fingers.

When a rod of some sort—even a pencil—is held against the palm as an index of the grip angulation of the hand, a large coin or card may simultaneously be pinched between the thumb and index finger. Viewed endwise, the coin or card has an angulation of 45 or 50° outward from the grip angle; if the coin is pinched between the thumb and the first knuckle, nearly 30° more angulation is involved. Further attention along this line would show that pinch switches, thumb buttons, and finger pressure flip switches can be oriented relative to the grip angle, when the latter angulation is known. With due concern to the additional clockwise or counterclockwise movement required to operate a switch, one should be able to orient the axes of finger controls in relation to grip orientation data. This could well be an avenue for further research.

Our data as plotted in Figure 107 should be read as general gradients from regions of high to regions of low value (Plot A) or as tendencies toward upright, oblique, or flat grip orientations (Plot B). Although they pertain to data on one individual (or at most, three) and do not relate to a significant population sample, regions of high versus low magnitudes in different regions of the plots are believed to be mechanically or kinematically significant. The plots of Figure 107 show notable differences between a region above the lower sternal level, i.e., 18 inches above the "R" point, and a region below this level; they also show differences in sagittal planes near the midplane of the body in contrast to regions to the right and left. These features should be of general importance; the precise locations of contour lines which separate one grade of performance from another in the figure are unique to the subject on whom the data were plotted.

CHAPTER X

CONCLUSION—ASPECTS OF PRACTICAL CONCERN

This investigation was initially conceived as a study concerned with the fundamentals of body kinematics and it has in no way been dominated by a search for quick empirical or ad hoc answers to practical questions. Nevertheless, the seated subject and the range of potential activity of his limbs has been focal. Such a view is without meaning unless it can in some way contribute to an understanding of the ways in which human beings behave. This, in turn, should contribute to practical ends.

Kinematic and mechanical information on the body system should provide the behavioral picture with a structure and form comparable to that which an underpainting supplies to an artist's canvas; it supplies form and defines limits to the overlying colors of physiological and psychological knowledge. If the kinematic and mechanical aspects of the body are only pursued far enough, they cannot fail to contribute usable information to the field of human engineering.

Our study has related both to the man and to the space that he requires for his activities. The seated operator may twist about on a seat or he may reach to the side, behind, or above, or he may direct his feet sideways or turn them back under the seat; we have considered these postures secondary to purposeful activities oriented in the direction that the operator faces. Most manual operations of the seated individual are within the visual field of the subject or through slight movements of the head they come within the purview.

Consequently, as an initial exploration of the work space we have, like King (1948, 1952), seated our test subjects squarely and symmetrically on a standard seat and have determined a range of space necessary to include specific classes of hand and foot movements. The seat reference or "R" point has arbitrarily been taken as the midline point of the junction between the back of the seat and the seating surface. The moving point of reference for the hand has been the midline of the hand grip at the level of the third knuckle and for the foot it has been the heel point of the foot; in the latter instance, additional space as required for the foot and toe have been allowed for in our determination of space requirements.

Motions which the subject produced have been studied without the hampering effects of clothing, so that space envelopes which enclose movement patterns should be maximal. This is especially true for foot movements where the foot was held passively by the subject and its movements were effected by an assistant who moved the foot to its limits in all directions; for the hand, movements were voluntary; accordingly, they were more variable. Averaged data on hand movements were more variable because certain subjects were highly conscientious and exerted themselves, while other subjects were more saving of their energy. But this is also true in practical situations.

Figure 89 shows our conclusions on the envelope which encloses the work space that should suit an average-to-muscular male who directs his hand and foot activities forward; dimensions relative to the "R" point of the seat may be scaled off from the coordinates shown in the figure. This should fulfill all routine demands for space for the multitude of hand and foot movements involved in the operation of vehicles and of machinery or that are pertinent to the worker at a desk or bench. Contours that should aid in planning such an average space are shown in Figure 90. Additional allowance to include sufficient space for movements within the 95th percentile may be planned from the data of Figures 90 and 91-A. If the worker needs to bend his trunk forward, he will require still more hand space, as indicated in Figure 92; the forward and upward range for such a space envelope would more correctly be a simple curvature which would connect the forward contour of the foot space with the upper contour of the hand space without the intervening angular notch.

Figures 75 and 85 show a comparison of the volumes of kinetospheres involving various hand and foot orientations; the relative transverse areas for different distances ahead of and behind the seat "R" point (for the hand) or from the floor or seat "R" point (for the foot) are also shown. For the hand the largest transverse areas are between 12 and 24 inches ahead of the "R" point; the 15- to 18-inch range ahead of the "R" point is especially important for the vertical and prone orientations of the hand grip. For the foot the maximal range varies with foot tilt from an average of 6.5 inches below the "R" point for the 90° (flat) foot to 4.5 inches above the "R" point for foot orientations of 15°. (The average height of the "R" point from the floor for the selected subjects was 15.5 inches.)

But the average man is an abstraction. A population fluctuates about its average. The practical problem, as McFarland (1943 a and b) and McFarland, et al. (1953) emphasized, involves individual people, not population averages; it should be of interest to fit as many people in the population of concern as practicable. This might be interpreted as fitting perhaps 80 percent or 90 percent of the people as assorted by height, by weight, by arm length, by shoe size, or some other arbitrary measure.

Our median and muscular subjects corresponded well with common Air Force builds as to dimensions. Our criteria for work space dimensions were not based upon any arbitrary body dimensions, but upon the actual performance of these selected individuals. An inside and an outside measure of the space required for performance is shown in reference to a coordinate system in Figure 91. The larger space of the figure is 5 inches larger for the hand and 4 inches greater for the foot than the average dimensions; the smaller spaces are respectively 5 inches smaller for the hand and 4 inches smaller for the foot.

The design problem regarding the work space should center on (1) the provision of sufficient room so that an individual is not crowded, and (2) the placement of hand controls, pedals, or manipulated objects so that they are at a correct distance within the general range of reach for efficiency. This is a problem that calls for careful analysis both of the operative postures of subjects and of such other special requisites of the work space as visual displays, windows, multiplicity of controls, etc. Clearance space implies freedom of incumbrance for knees, shank, elbows, etc., especially for the larger individuals of the population selected for the operation.

Very commonly, in a vehicle for instance, it may be that sufficient space for unrestricted hand or foot movement (Figure 91-A) cannot be made available, and it is essential to know how to evaluate regions within the more extensive space. Figures 81, 82, and 83 show what regions of the total hand space are available for actions involving special orientations of the hand; in addition, they show a common region (shaded areas) where any of the eight orientations of the hand studied (or intermediate hand positions) may be used. Figure 87 shows comparable information for the foot in orientations from 90° (foot sole flat) to 150. The dimensions of these common regions may be scaled off from the figures.

In addition, these figures show the locations of the centroids of the several hand and foot kinetospheres. The mean positions of these points relative to the seat "R" point may be scaled off the figures. The centroids for each hand or foot orientation have a double importance. They are midrange or mean positions from which the end member may move in any direction to the limit of the kinetosphere; in addition, more than any other point within the available space, they pin down the location of the longest straight mean paths of end-member motion. Straight-line motions may of course begin at any point in the envelope of a kinetosphere and pass across to another point in the envelope; on the average these paths will be longer if they pass through the centroid than through any other point.

The front, or front and top views of the figures show the extent of right-left overlap for the various hand and foot positions. Actually, the precise overlap shown is nominal since only the left side was analyzed specifically in the present study. Apart from asymmetrical joint ranges in a limb for a given individual, however, the disposition of left-side patterns as if they were symmetrical right and left sides should be a minor discrepancy. It is pertinent to know that the amount of right-left overlap varies notably with hand orientations. When a given operation calls for two-handed performance or the crossing of one hand by the other, one may plan in advance for the space needed in the operation, if there is due concern for the hand postures which are preferred in the operation. Clearly, a knowledge of manipulative preferences for pulls, twists, one-handed acts, two-handed actions, etc., will contribute to the designer's background. It should be noted that because of the very small overlap for the supine and 90° sagittal orientation of the hand (Figures 81 and 82), the common region of right-left overlap for all possible hand orientations is very small.

We have referred here to six points in the organization of the work space: (1) the overall shape and size of the work space for all possible forward orientations of the hand, (2) to the relative volumes available for various hand and foot orientations, and to the distances from the "R" point of sections of wide range, (3) to regions of use for only special orientations of the hand, (4) to common regions where two, more than two, or all orientations of the end member are possible, (5) to regions of right-left overlap, and (6) to the centroidal regions for different hand orientations. The illustrations mentioned show coordinates, and with the aid of the scales employed the different regions and point positions may be laid out relative to a seat "R" point.

In addition to the six features mentioned, two others may be considered also. An additional, critical position is suggested by Figure 107 and the accompanying text, which shows that one-handed pull vectors at the midline and at different distances lateral to it tend to intersect on a transverse line just anterior to the lower sternal level. The general position of this line may be located in space relative to the "R" point on the basis of data presented; because of too limited a study sample, however, the locus should be regarded as tentative.

The limb segments have weight, and there are positions of rest in which the links hang freely in balance with low-order supporting forces provided by muscles. For instance, when the forearm is bent 90° to the humerus, and the limb is held easily, the humerus finds an oblique position behind or lateral to the vertical, and the forearm hangs obliquely (Fischer, 1895, 1897). The hand then is notably closer to the trunk and to the body midline than when the humerus is held stiffly vertical. The leg hangs from the knee joint in a comparable way, and the foot slants downward and forward when the lower leg hangs freely from the knee.

These comfortable rest positions should not be ignored in work-space planning, where the more distal limb parts are not otherwise supported. Muscular action is always called for, except when a distal part hangs freely or is passively supported, as the hand and forearm on a desk surface. The hand in the lap is a similar example of passive support. These rest positions have not been studied in this project, and specifications for positions relative to the "R" point cannot be made.

A distinction should be made between the active and resting phases of hand performance. The former require muscular energy and they are tiring; the latter contribute more to boredom than to fatigue. In general, the rest positions of the hand when unsupported will be notably closer to the body and lower than the controidal positions mentioned above. One may contrast the arm positions of a boxer in a defensive position or the ready position of a wrestler (examples of active upper limb postures) with postures seen in a crowd waiting for a bus (passive arm postures); our centroidal positions for the hand are seen in the former instances, while rest positions will predominate for the latter group.

Probably, if primary controls on which the hands may rest passively (cf. automobile steering wheel) are placed at or below the centroidal positions and a little nearer to the body, they will supply support for the upper limbs and obviate tiring; at the same time the hands will be in a ready position for properly-placed secondary controls.

For maximum pulls there are preferred orientations of the hand grip, suggested by Figure 107-B; for optimum efficiency the orientation of the hand controls in a work place should be correctly angled for different positions within reach. Clues to the problem are suggested in Chapter IX. In addition, it was pointed out that hand grip positions were correlated with pinch orientations and other finger postures. The latter involve an additional distance from the grip position and plus or minus angulations relative to the grip angle. For efficiency the placement and orientation of finger controls may be as important practically as the placement and orientation of hand grip controls.

It should be appreciated that the unique features of our basic approach to work space problems have depended upon analyses of the range of translatory motions which the hand or foot may show for specific orientations of the end member. The space circumscribed by a reference point on the moving member was in all instances related to an X, Y, and Z coordinate system originating at the seat "R" point. The space envelopes so outlined were worked out on groups of living subjects, and the data were superimposed, grouped, and averaged, to get representative patterns. Data on different body builds were compared, and information on those men who corresponded most nearly with the military population have been presented for possible use.

It should be appreciated that the present research has sought underlying principles that should be pertinent to work-space designs. Much development work and evaluation relative to specific operational situations must follow. Practical compromises must invariably be made in the designing of work spaces, and it should be kept clearly in mind in evaluating developments, whether the compromise was unwise or whether further principles and information are needed.

A second emphasis in this study has related to manikins that might represent the seated operator on the drafting board or which would present data pertinent to the design of test dummies. To this end, Chapter IV has explored the bones and joints of the limb systems to find what type of kinematic system the parts present in life. Chapter III has provided a discussion of the theory that is apropos.

Our work has explored (1) the degrees of rotational freedom permitted by limb joints, (2) joint curvature relations, (3) the axes of rotation, (4) the range of position of instantaneous joint axes, (5) link dimensions of the limbs, and (6) the range of motions at limb joints; in addition, it treated a variety of secondary problems. Virtually no attention was directed to special kinematic problems of the trunk regions. Proportions of trunk links (Figure 32) were derived from measurements on cadaver vertebral columns; the locations of hip and shoulder centers for the seated subject were based on study; and measurements of sternal and pelvic inclinations were made for various postures. Limb dimensions were geared to the 5th, 50th, and 95th percentiles of the United States Air Force flying personnel. (Hertzberg, Daniels, and Churchill, 1954).

Chapter V shows cut-out segment designs for drafting board use which can be scaled to any convenient reduction relative to natural size and assembled. The manikins relating to the seated figure may be made to represent average dimensions, or a pair of models representing the 5th and 95th percentiles may be constructed. Designs based on the use of both the large and small manikins should fit a larger segment of a population, such as the Air Force flying personnel, than those based on the average manikin alone.

Such models are only tools, and considerable care will be required to determine whether manikin postures are truly equivalent to those used in actual operations; sagittal plane models actually relate to a single sagittal or vertical fore-and-aft slice through the work space, and they will be increasingly less accurate, for each inch lateral to the hip and shoulder regions.

The plans for three-dimensional joint models may serve to direct the attention of engineers and designers to the complexity of body joints. Where test dummies for various practical purposes are required, our designs may show the engineer what type of problem he faces if joint movements are to be accurately built in. Our designs are merely inventions which duplicate reasonably closely the movements of the limb joints; when properly oriented in a chain, the terminal link will permit essentially lifelike motions. It should be underscored that the designs for artificial joints presented in Chapter V have no significance other than that of showing a type of artificial system which exhibits the typical range and amplitude of motion that would be expected from a male subject of given dimensions.

Our work with both living subjects and cadaver material has continually kept before us the proposition that important as kinematic systems of the body are in relation to the motion of parts, the biomechanical activity of the body is a reflection of forces of various sorts. The systems involve weighted parts, muscle tensions, and environmental forces. Both static and dynamic activity are concerned.

Work on this project has extended the available data on cadaver segment mass from five subjects to thirteen; certain refinements have been adopted, and a critical evaluation of the type of data obtained can be made on the basis of our experience. Segment masses, locations of segment centers of gravity, density data, and work on moments of inertia have been tabulated and presented in Chapter VII. Much of this information depends upon dismemberment and subsequent measurement, and the procedures are possible only upon dead individuals. The builds available for this are not those of young men comparable to those of military personnel, where applications should have real value.

Certain data on the distribution of body bulk based on volume measurements have been made on living subjects of different builds. Chapter VIII presents these data: measurements based on volumes and assumed densities may be substituted for cadaver masses when the age, general build, and size of our living subjects are closer to those for whom mechanical analyses are planned. Data on centers of gravity from cadavers should not be far wrong for the various body segments of living subjects, and both anatomical clues and ratios relating to mean joint centers have been presented.

It has been assumed that the principal applications of our data on mass constants would be directed to analyses of actual test subjects recorded by photography—possibly even motion pictures. Certainly torque analyses, checks on the location of over-all centers of gravity, and dynamic relations may be derived in this way from test subjects, if the experimental design and photography are carefully planned.

Our study of body forces has been a limited approach, touching on two-handed pushes and pulls and one-handed pulls, but certain principles have appeared that are often obscure in the more common empirical approaches to hand and foot forces. The study has emphasized the significance of counterforces, the value of stability and bracing, and the fact that body dead weight may be importantly concerned in the development of force couples. Pushes and pulls involve rotatory mechanics when the body is not adequately stabilized; direct pressures and tensions call for counter supports. Attention has been directed to leverages and to the desirability of pinpointing which features are limiting factors in the application of force. Chapter IX presents our data in this area.

A variety of methods have been employed in this work, and these have been directed either toward cadaver material or to living subjects. The latter have been subjected to a large battery of measurements, often uncommon or new measurements. In addition, the subjects have performed a variety of hand and foot movements, which have been photographed, measured, analysed, and grouped.

The subjects have been very rigorously selected to obtain four different body builds. Data from the different groups have been compared for trends regarding body type. Data for recommended dimensions, however, have not included information from highly rotund and very thin individuals. Subjects more representative of the builds found among Air Force flying personnel or which were dimensionally comparable were used as sources of data when practical recommendations were contemplated.

In many respects the present investigation has been directed to a fresh study of basic information that will be required for the study of general human biomechanics; older work has been consolidated and checked. It is hoped that a viewpoint has crept in; it is important that methods be continually evaluated and that the value of all data is not given the same confidence. There are probably no respects in which our work can claim to be exhaustive. Opportunity has been provided to make exploratory forays into certain areas involving body kinematics and statics. Principles have been sought throughout, and it is pertinent that the reader be clear in his own mind as to what areas are adequately documented, as to where arbitrary limits have been set up, and where suggestive ideas only have been presented.

Both the preoccupation with the research efforts presented above and the reading of a correlated technical literature have convinced the author that further investigative effort in this and related fields should be profitable. We should have a good understanding of the biomechanical problems which the body must solve in its purposeful activities, and we should have available a fund of knowledge that will contribute practically toward increasing the efficiency, safety, and comfort of workers. Further study along the lines of our investigation should add increased certainty or should qualify and extend the available information. In addition, there are related areas, such as the following, which should yield substantial results:

(1) There should be an exhaustive, well-planned study on the total range of movement at each body joint for well-defined population groups—male, female, special military groups, etc. This should be correlated with standard anthropometric data so that we may learn the relative importance to the individual of body dimensions versus the range of joint movement.

(2) There should be studies involving the kinematics and spatial requirements of specific types of work operations. Our studies have dealt with overall requirements, but how are the total body operations of desk workers, drivers of land vehicles, pilots, machine-operators, etc., effected, how do they differ, and how much space does each require? Frame-by-frame motion picture records of different individuals doing the same job should help. It should be important to explore different methods of getting this information so that new operations may be analyzed later to supplement basic data on key operations.

(3) More should be known about hand and foot forces and body reactions under a large variety of operative conditions. Body stability, bracing, leverages, the action of couples and the importance of dead weight should be correlated and a number of body positions should be compared. A search for the principles which underly all possible conditions should be sought. Force duration as well as maxima should be studied. The preferred orientations and posturing of parts and of the facilitating joints should be understood.

(4) Knowledge on the contribution of different body muscles to purposeful, static and dynamic activities is necessary. Muscle torques and leverages should be studied, and the cooperative actions at different joints should be known. The speed and duration of actions and fatigue relations are also pertinent.

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