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REACH CAPABILITY OF THE USAF POPULATION

PHASE I

THE OUTER BOUNDARIES OF GRASPING-REACH ENVELOPES FOR THE SHIRT-SLEEVED, SEATED OPERATOR

KENNETH W. KENNEDY

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FOREWORD

The work presented in this report was accomplished under Project No. 7184, "Human Performance in Advanced Systems," Task No. 718408, "Anthropology for Design." Statistical reduction was performed by the staff of the Anthropology Research Project at Antioch College, Yellow Springs, Ohio, under the provisions of Contract AF 33(616)-6792. Dates of research: January 1960 - January 1962.

The author is grateful to Messrs. H. T. E. Hertzberg and C. E. Clauser of the Anthropology Branch, Aerospace Medical Research Laboratories (AMRL), for their encouragement during the data-gathering phases of the program and for critically reviewing the manuscript.

The anthropometric illustrations were prepared by M. J. Kennedy, Yellow Springs, Ohio.

This technical report has been reviewed and is approved.

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ABSTRACT

This report contains descriptions of the outer boundaries of the Minimum, 5th-, 50th-, and 95th-percentile grasping-reach envelopes of seated, shirt-sleeved operators. The two most important are the Minimum and 5th-percentile envelopes. These envelopes have been calculated to permit 99+ percent or 95 percent of the Air Force population, respectively, to reach any point at their boundaries. The report contains a critical resume of previous investigations of arm reach, and a description of the AMRL Grasping-Reach Measuring Device. The data-gathering and statistical procedures are included, and applications of the reach envelopes are discussed. Horizontal contours representing the outer boundary of the Minimum, 5th-, 50th-, and 95th-percentile grasping-reach envelopes are presented for each 5-inch level beginning at 5 inches below SRP (Seat Reference Point) and extending to 50 inches above SRP. The Minimum envelope extends from 2.5 inches below SRP to 48 inches above; the 5th-percentile envelope from 4 inches below SRP to 48.75 inches above. Horizontal distances from SRP to the boundary of each envelope are given at 15° intervals.

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SECTION I

INTRODUCTION

This is the first of a series of reports concerned with the reach capability of the United States Air Force population. The purposes of this report are to describe the outer boundaries of the Minimum, 5th-, 50th-, and 95th-percentile grasping-reach* envelopes for the shirt-sleeved, seated operator, and to discuss the factors influencing his reach capability. Future programs will include more detailed studies of minimum and maximum grasping-reach capabilities of the seated and semi-supine operator in shirt sleeves and wearing a full-pressure suit. Reach capability of the unrestrained seated operator will also be studied. These studies will be presented as phase reports under the general title, "Reach Capability of the USAF Population."

The most important reach envelopes described in this report are the Minimum and 5th-percentile envelopes, whose boundaries are within thumb-and-forefinger grasp of 99+ and 95 percent, respectively, of the Air Force population as described by Hertzberg, Daniels, and Churchill (ref 16). Hand operated controls can be located in accordance with the limits of these envelopes with assurance that correspondingly high proportions of the population will be accommodated.

The stimulus to ascertain these envelopes came from the realization that similar studies in the literature failed to include adequate treatments of reach throughout the total range of capability. Acceptable reach data were available only for that sector of the reach envelope extending to the right from the mediam plane through 135°. Data to guide the placement of controls outside this sector were not available.

Most data previously reported were obtained on subjects whose torsos were virtually immobilized by means of a taut lap belt and shoulder harness or similar restraining device. Whereas this condition of restraint was common during World War II, reach capability under such conditions proved to be not characteristics of that of the pilot of modern high-performance aircraft where the shoulder-harness inertia reel is used.

All controls must be within easy reach of the pilot. Although the use of reach data like those of King, Morrow, and Vollmer (ref 24) will assure accommodation for a very high percentage of the Air Force population in the sectors of the envelope treated, the data tend to be unnecessarily conservative. It appears to reflect a condition of greater shoulder restraint than is now practiced.

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[*] In this report the term grasping-reach denotes grasp between the thumb and the second phalanx (middle segment) of the forefinger. See also Procedures.

In an emergency, the inertia reel may be locked manually, or it may be lock automatically under rapid deceleration or when the canopy is jettisoned prior to ejection. The pilot is not required to tighten the shoulder harness further, and he retains an appreciable amount of his original shoulder mobility after the reel is locked. Hence the reduction in his reach capability is far less than that which usually occurs after manual adjustment of the older type of shoulder harness.

The requirement is stated as follows:

> "All controls essential to flight operation shall be easily operable by the appropriate crew member when seated with seat belt fastened and shoulder harness in place but not necessarily locked." (ref 30, par 4.1a.)

King, Morrow, and Vollmer (ref 24, p 11) have emphasized the requirement in human engineering terms:

> "It is not intended that a pilot be rigidly immobilized by his restraining devices throughout a long flight. It is reasonable, however, to require that a pilot be able to operate an aircraft without disturbing his normal sitting posture. Major movements may cause the pilot to shift his center of gravity, lose sight of his instruments momentarily, alter pressure on flight controls, and increase the difficulty in interpreting his orientation in space."

It is the shirt-sleeved reach capability under this condition of restraint that is described in this report.

In 1947, when King, Morrow, and Vollmer reported maximum fingertip reach capability, there were few comparable data in journal literature. The Anthropometric Unit of (the then) Aeromedical Laboratory, however, had done considerable workplace layout including placement of controls for aircraft cockpits and gun turrents as early as 1942. Although specific data were not available regarding man's reach throughout his range of capability, statistical data on the dimension "Functional Reach" was available. The reach envelope was estimated, using the 5th-percentile value for Functional Reach and using other anthropometric data gathered on the Army Air Corps, and used in valuations and layout of work stations. Most of these investigations were documented in reports for distribution primarily within the Army and did not find their way into the open literature. Most of their work, however, was summarized in 1946 in <u>Human Body Size in Military Aircraft and Personal Equipment</u> (ref 35). Since then, there have been sporadic efforts in various countries, and it is now fruitful to review the literature to date.

King, Morrow, and Vollmer determined the maximum fingertip reach capability for the right arm at 15°, 45°, 75°, and 105° to the right and left of the mid-line (0°) from 8 inches below Seat Reference Point (SRP)* to 52 inches above it. The combined reach envelope was presented in the form of horizontal sections at 6-inch levels. The sample consisted of 139 male Navy personnel. The subjects were restrained by a conventional aircraft lap belt and shoulder harness. The investigators calculated the means, standard errors of the means and standard deviations for maximum fingertip reaches, and from them determined a fingertip reach envelope within which 93 percent of their sample could reach all points on its boundary and 98 percent could reach any single point on its boundary. It extended from 2 inches below SRP to 46 inches above SRP. Although right-arm reach was measured throughout 210°, ie, 105° to the right and 105° to the left of the median plane, only that segment extending 75° to the right of the median plane was considered in the derivation of this envelope. The dimensions of this envelope appear in table 1.

In a later paper King (ref 23) reported essentially these same data but with additional information on the characteristics of the fingertip reach envelope when the subjects were permitted to flex their torsos 18 inches forward. In 1948, King and Swearingen (ref 25) used the reach data reported by King, Morrow, and Vollmer (ref 24) to determine the adequacy of placement of controls in the DC-3 and DC-4 aircraft.

In 1949, Swearingen (ref 41) described an adjustable cockpit mockup consisting of 15 vertical frames, mounted at 15° intervals to 105° right and left of the median plane (0°). Each frame supported 15 horizontal measuring members. Twenty-one vertical measuring rods were located in the ceiling of the mockup. Altogether 246 points could be located in space to simulate different sizes and shapes of workspaces. This device appears to have been used primarily in evaluations of existing or experimental workspaces rather than for the derivation of basic reach data.

Dempsey (ref 6) described a "workspace measuring device" with which the "maximum, minimum, and optimum space requirements of Air Force Pilots when seated in the cockpit situation" could be determined. Intended as a simplification of Swearingen's device, this equipment consisted of a seat and an overhead rack mounted in a vertical plane through SRP. Ten horizontal measuring-sticks were mounted at 6-inch intervals on the forward vertical member of the rack. Five similar measuring-sticks were mounted vertically on the horizontal overhead member. Each horizontal measuring-stick was calibrated to indicate the distance from a knob on its near end to a vertical axis through SRP. The vertical measuring-sticks were calibrated to indicate the distance to the horizontal plane through SRP. The seat was mounted on a platform which could be

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* Seat Reference Point (SRP) is the point of intersection of the mid-line of the seat with the mid-line of the seat back.

TABLE 1

THE MAXIMUM DISTANCE AT VARIOUS POINTS IN THE BOUNDARY AREA FOR OPERATION OF MANUAL CONTROLS*

ANGLE	0°	R15°	R45°	R75°
Level from Seat Reference Point (Inches)				
46	11.6	13.7	15.0	17.0
40	18.9	20.5	22.4	24.1
34	22.9	24.9	26.6	28.0
28	25.5	27.1	29.1	30.1
22	26.7	28.2	30.3	31.4
16	26.6	28.0	29.7	31.6
10	25.3	27.0	29.3	30.4
4	22.6	24.2	26.4	27.9
-2	17.5	19.7	21.8	22.8

*The maximum distance (inches) at various points in the boundary area for operation of manual controls which can be reached by 97.93% of the population at each position and 92.9% of the Naval Medical Research Institute (NMRI) series at every position: N= 139. (From King, Morrow, and Vollmer, ref 24.)

rotated about the vertical axis through SRP. Reach data could be taken at any interval as far as 135° to the right or left of the mid-line.

Utilizing this device, Dempsey and Emanuel in 1953 determined the 5th and 95th percentiles for "absolute maximum" reach (equivalent to Dempsey's "maximum"), "normal maximum" (Dempsey's "minimum") and for "optimum" functional reaches. Information was taken only to the right of the mid-line throughout 135° at 15° intervals, from 6 inches below SRP through 48 inches above it. Grasping-reach data were obtained for the shirt-sleeved condition and with the subjects wearing T-1 and S-2 partial-pressure suits, first uninflated and later inflated. The subjects were securely restrained by a lap belt and shoulder harness in all conditions. The shirt-sleeved results of this study were not published until 1963, when they were reported in Human Engineering Guide to Equipment Design

(HEGED) (ref 20, pp 546-550). The 5th-, 50th-, and 95th-percentile values are given. Unfortunately, however, the drawings accompanying the data illustrate handgrip reach instead of thumb-and-forefinger reach.

Sandberg and Lipshultz (ref 37) studied the maximum reach limits on flat vertical surfaces for application to the layout of radar consoles and communication panels. Fingertip reach capability was determined in frontal planes at distances of 10, 15, and 20 inches from the operators' eyes. Although useful for the purposes intended, such information has only limited application to the seated position for the placement of hand operated controls.

Dempster (ref 7) and Dempster, Gabel, and Felts (ref 8) present a completely different approach to the description of arm-reach capability. Their interest was on specific hand orientations in the "more forwardly-directed positions" (ref 7, p 159). Dempster determined the space "in which the hand could range up, down, forward, sidewise, etc, in straight, oblique, or curved paths . . . with the palm and grip angle . . . constantly the same relative to the space of the observer" (ibid, p 160). Eight orientations of the hand were studied (fig. 1). These were maintained through the use of a special handgrip device. The range of hand positions for each hand orientation was determined for the left hand.

Dempster used the term "kinetosphere" to denote the envelope of the maximum movement possible for a single hand orientation. Each kinetosphere was defined relative to the SRP. By combining kinetospheres for hand orientations in a single plane (vertical or horizontal group, fig. 1), patterns of motion called "strophospheres" were derived. A strophosphere describes the maximum movement of the hand when permitted three degrees of translatory freedom and one degree of rotatory freedom (at the wrist). Dempster developed two such strophospheres for the hand, one including four angles of forearm pronation-supination in transverse (frontal) planes (vertical column, fig. 1) and another for five angles of radial and ulnar flexion of the wrist in sagittal planes (horizontal group, fig. 1).* The magnitude of translatory motion of the hand was limited only by the restrictions on arm-segment mobility resulting from the necessity to maintain specific handgrip orientations. The mean kinetospheres were illustrated by means of horizontal, transverse and sagittal sections through their centers of gravity (centroids). Sections through the kinetospheres for each family of hand orientations were then superimposed (figs. 2 and 3). From these data the authors were able to construct a workspace floor plan in the form of horizontal contours at 12-inch intervals, each related to SRP (fig. 4).

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*Vertical (0°) grip angle is common to both planes; therefore it is represented in both strophospheres.

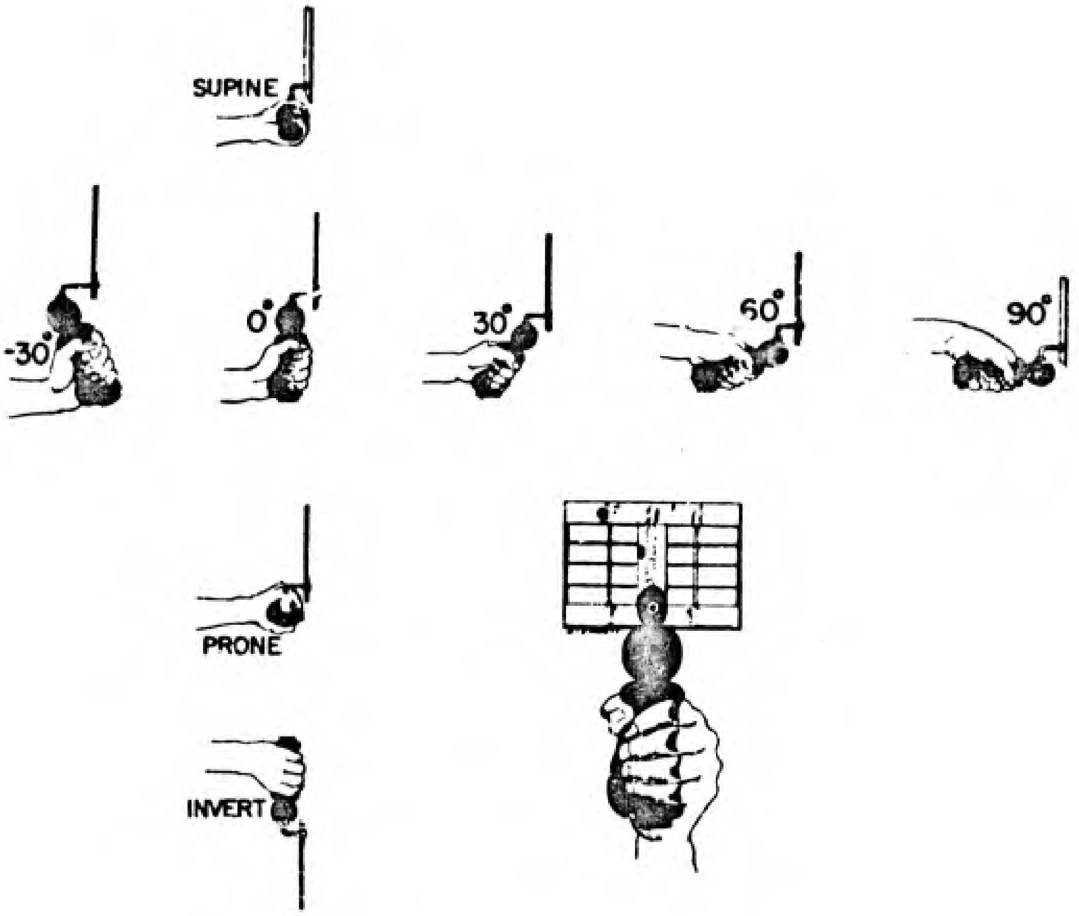

Figure 1. The Eight Hand Orientations Used by Dempster and by Dempster, Gabel, and Felts in Their Treatment of Reach Capability

The handgrip and reference grid used to maintain the hand orientations during recording periods is illustrated. (Modified from Dempster, Gabel, and Felts, ref 8, p 294.)

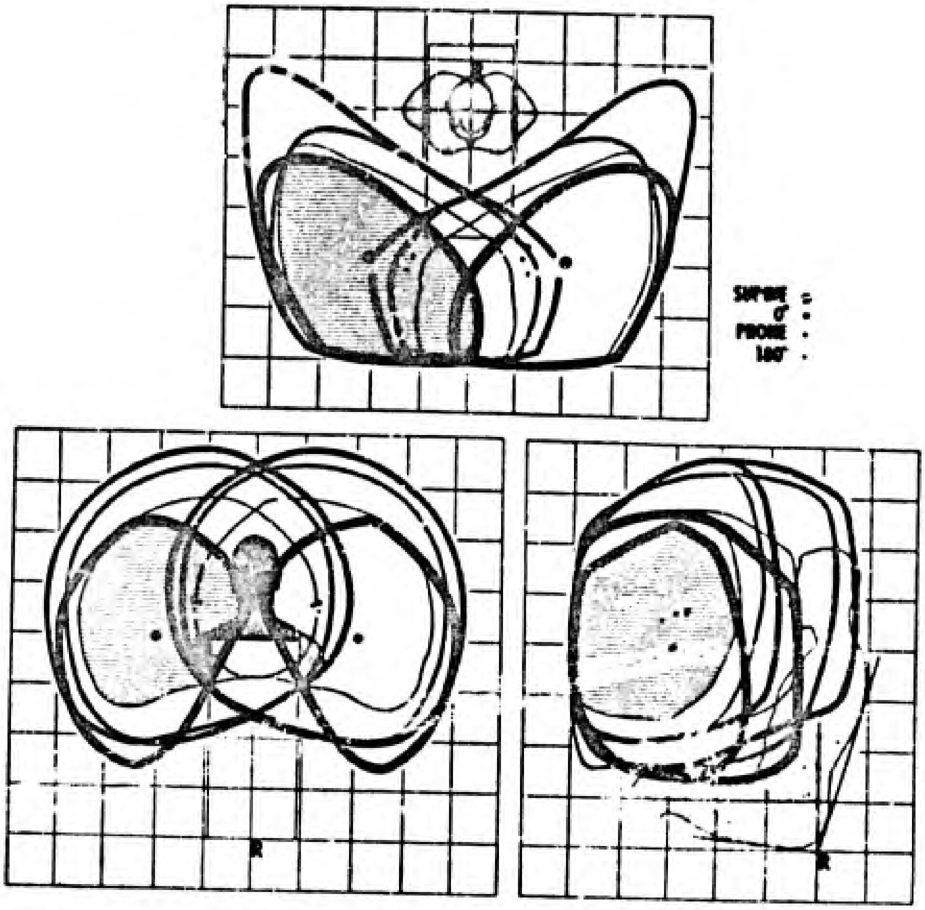

Figure 2. Superimposed Kinetospheres for Grip Orientations in the Transverse Plane

Shaded areas are those common to all kinetospheres. Dots represent the centroids of the various kinetospheres. (From Dempster, ref 7, p 169, and Dempster, Gabel, and Felts, ref 8, p 309).

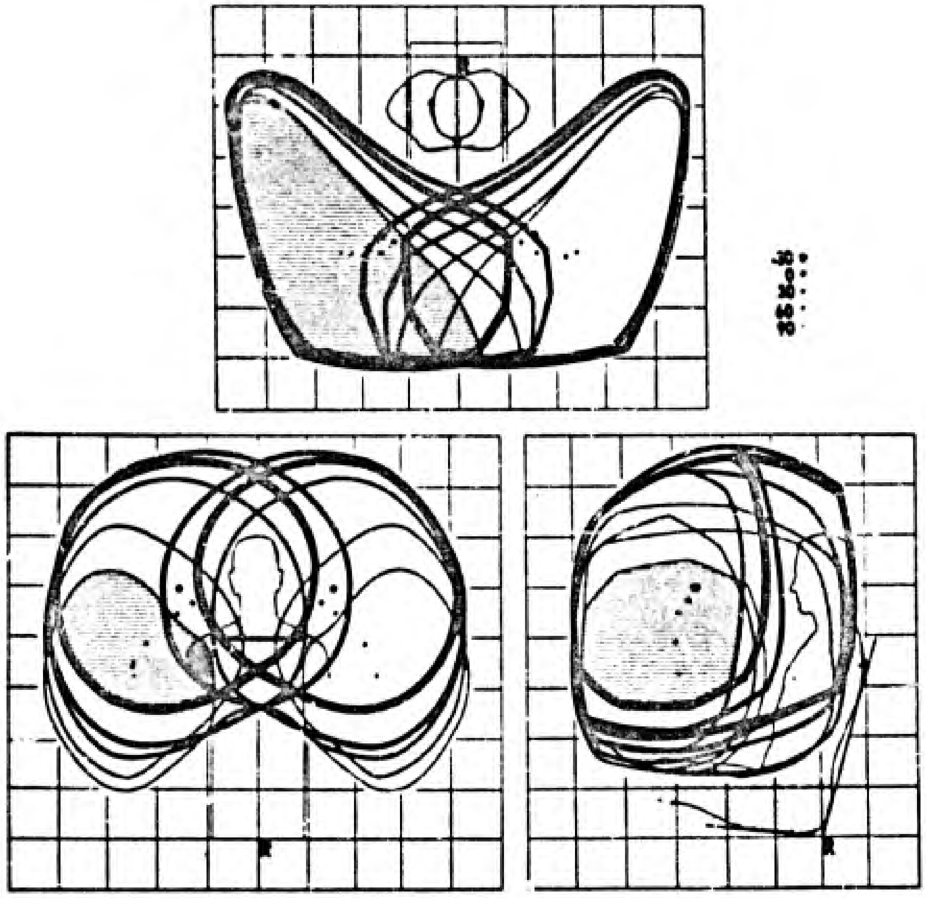

Figure 3. Superimposed Kinetospheres for Grip Orientations in the Sagittal Plane

Shaded areas are those common to all kinetospheres. Dots represent the centroids of the various kinetospheres. (From Dempster, ref 7, p 168, and Dempster, Gabel, and Felts, ref 8, p 308.)

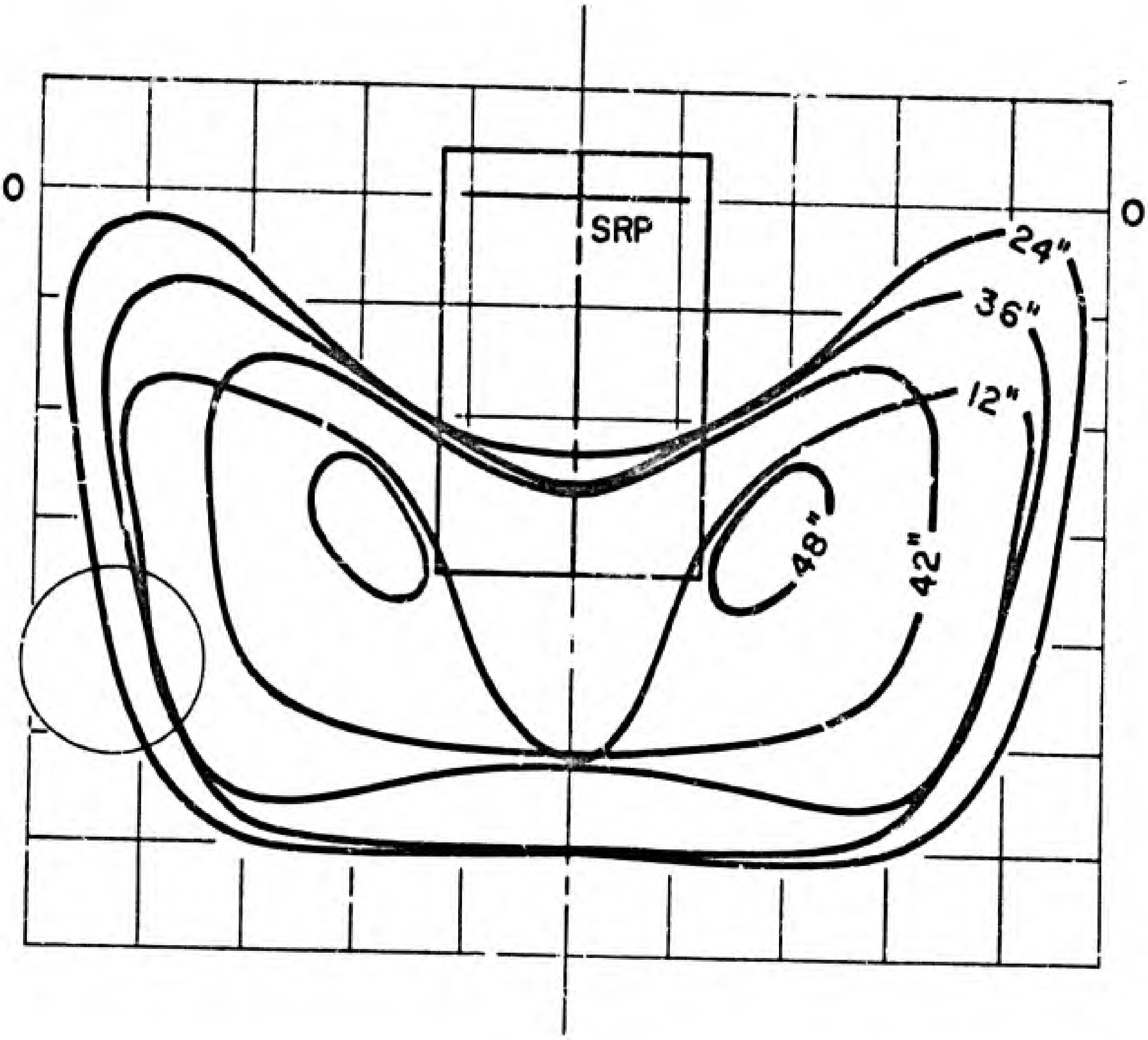

Figure 4. Floor Plan of Workspace Relative to the Standard Seat

Shown by 12-inch contours. The grid squares are 6 inches. The 12-inch, 24-inch, 36-inch, etc, levels are above SRP level. The radius of the circle represents a width to be added or subtracted from the different curves to include the 5th and 95th percentiles of movement. (Modified from Dempster, ref 7, p 179.)

These studies by Dempster, et al of the reach requirements for the seated operator were not primarily for the purpose of specifying actual dimensions, but rather to "develop an indirect approach to a functional anthropometry," and secondarily, "to present data which, if intelligently handled, should contribute to the designing of more effective work places, cockpits and driver compartments" (ref 8, p 310). Their sample was not representative of a specific using population but consisted of 22 young university men of muscular to median body configuration. Similar treatments to include dorsal and palmar flexion of the wrist in the forward sector as well as these orientations and those reported by Dempster in the sectors to the sides, above, below, and to the rear of the operator, are needed for a complete description of the ranges of hand motion for the seated operator.

In the Joint Services Human Engineering Guide to Equipment Design (ref 9, Chapter V, p 19 and ref 20, Chapter VII, p 289), Ely, Thomson and Orlansky describe "a vertical, fore-aft cross section through the optimum manual area, bounded by four points (each represented as the center of the operator's fist)" (ref 9, p 19). The plane of this cross section passes vertically through the operator's right shoulder. These points are described as follows (ibid):

"Near Low: operator's elbows next to body, forearms horizontal.

"Near High: operator's elbows next to body, forearms flexed forward about the elbow 15°. (This means 15° above horizontal, to 75°. The forearm swings through 105°.)

"Far High: operator's arm extended horizontally from shoulder, operator sitting erect.

"Far Low: operator's arms extended and lowered until hand is at level of elbow in Near Low position."

Sections were determined at seven back angles ranging from 0° (vertical) through 60° (fig. 5).

The information that can be extracted from any single section is limited. These are fore-and-aft vertical sections through a segment of the total arm-reach capability, and are not necessarily representative of the total segment. When the elbow is flexed to form an angle of 90° in the manner described for obtaining the Near Low point, the forearm can be swung laterally throughout an angle of approximately 80° by rotation of the upper arm around its long axis. If the elbow is flexed an additional 15° to 105°, to attain the Near High point, the upper-arm rotatability is not greatly affected, since its position does not change with respect to the shoulder, where rotation occurs. The upper arm can be swung medially through 10° or 20° with the elbow flexed at 90° or 105°, without materially altering its position with respect to the side of the body.

When the arm is outstretched to reach the Far High and Far Low Points, however, the upper arm is no longer rotated about its long axis to move the forearm through the horizontal plane; rather the outstretched arm is swung horizontally

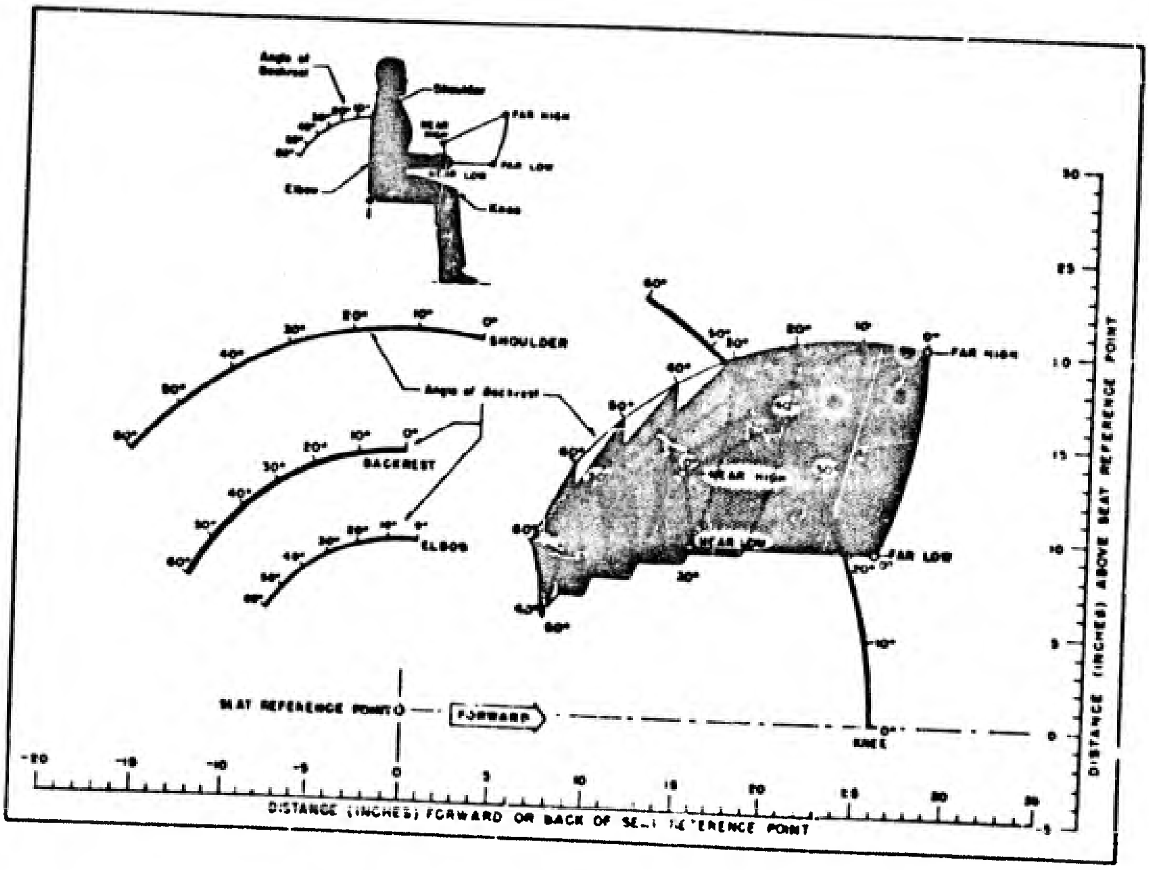

Figure 5. Optimum Manual Areas for Seated Positions (vertical cross sections)

(From Ely, Thomson and Orlansky, refs 9, 20.)

(horizontal adduction and abduction) about the shoulder. In such movements, the upper arm has a much greater range of angular motion. The mean angle for horizontal adduction (movement toward the median plane) of the upper arm is 134° (ref 2), exceeding lateral rotation of the upper arm around its long axis by approximately 54°. The mean angle for horizontal adduction (movement toward the median plane) of the upper arm is 48° (ibid), exceeding medial rotation of the upper arm by approximately 28°. As the hand is moved from the Near points to Far points, rotation of the upper arm around its longitudinal axis becomes less necessary to move the hand through a horizontal arc, and horizontal adduction and abduction of the upper arm gradually become necessary. The increased capability to swing the arm horizontally through the Far points produces medial and lateral areas, which may be called "wings." These medical and lateral wings are not represented by the vertical cross sections in figure 5. Rather, the cross sections are representative of a wedge-shaped central segment of approximately 100°, equal to the range of capability of rotating the upper arm around its long axis when obtaining the Near points. That part of the envelope created by the ability to swing the upper arm through a greater angle in a horizontal plane when reaching to the Far points is not considered.

Ely, Thomson and Orlansky present maximum fingertip reach curves for the seated and standing positions in the form of scaled charts (fig. 6). Seven back angles between 0° and 60° are treated. Data are presented as capability curves within different planes, each of which courses through the longitudinal axis through SRP. The planes considered are at 0° (the median plane) and 12.5°, 38.5°, and 66° to the subjects' right.

It appears likely that some readers may experience difficulty in utilizing the arm-reach data as they are presented in figure 6. Although the data represent planes through SRP, they are illustrated, with exception of the 12.5° plane, in the form of fore-shortened curves. Information that can be obtained from these charts is limited to the distances from points along the reach curves to the frontal and transverse planes through SRP. The distances from the median plane, however, can only be determined by triangulation. Furthermore, the authors give no body-size information concerning the test sample from which they determined their "optimum area" cross sections and "maximum fingertip" reach curves. Consequently, there is no means by which a designer can judge the representativeness of the curves for his using population.

The authors refer to the angular positions of the reach-curve planes as though they are equal to the angle that the arm forms with the median plane. Since the joint center of the operator's shoulder is seldom found in the vertical reach-curve planes through SRP (see fig. 7), it is not often possible for the reach-curve planes to coincide with the arm angle. With the arm outstretched to the 12.5° position, it is approximately parallel to the 0° (median) plane. With the arm in this position, the angle indicated necessarily refers to the reach-curve plane. As the arm is swung laterally, the angular difference between the reach-curve plane and the arm becomes less until the reach curve plane runs through the axis of shoulder rotation. The angle at which this occurs depends upon the relative positions of the SRP and the center of shoulder rotation. In figure 7 they coincide at about 90°. It is only at such a point that the angles of the reach plane and arm will be identical.

Pierce and Murch (ref 34) provide a treatment of arm reach (and strength) as influenced by wearing a full-pressure suit (Goodrich, Mark IV). Reach information was obtained on only one small subject* in the "launch position" (supine), with

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*Age, 31; Stature, 67 inches (20th percentile); Functional Reach, 29.6 inches (5th percentile). Values for other dimensions are not reported.

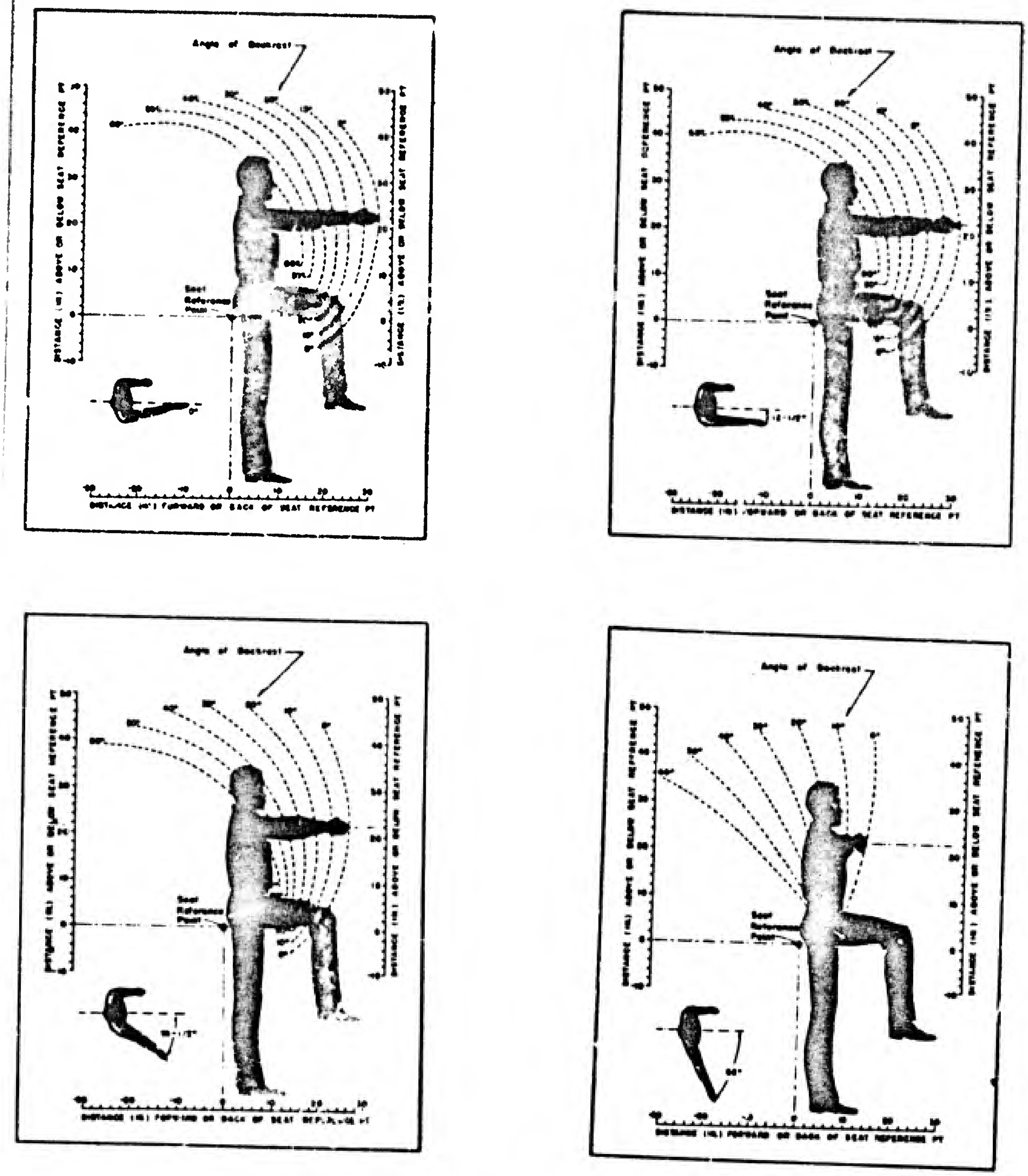

Figure 6. Maximum Fingertip Reaches for the Seated and Standing Positions at 0°, 12.5°, 38.5°, and 66°

(From Ely, Thomson, and Orlansky, ref 9, pp 26, 27, 28, and 29)

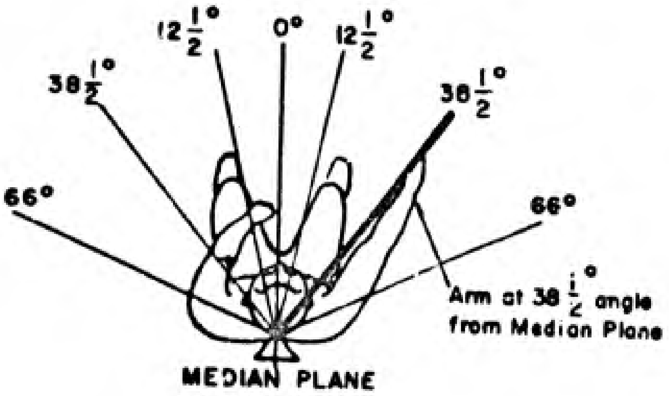

Figure 7. Angles at Which Maximum Fingertip Reaches Were Measured

(For the seated and standing positions illustrated in figure 6, from Ely, Thomson, and Orlansky, ref 9, p 25)

the suit uninflated, and during the "orbit position" (seated), with the suit inflated to 3.5 psi. All reach data were referred to SRP. With his suit inflated, the subject's arm reach was "considerably restricted particularly in the vertical dimension, in which he could reach only to the level of the top of his helmet." Unfortunately, data were not obtained for the shirt-sleeved condition.

Zinser, Farley, and Rohles (ref 48) determined the "optimum manual performance areas" for a population of 13 chimpanzees. Arm-reach information of the same type as reported by Ely, Thomson, and Orlansky (ref 9) was determined on these primates. These authors were aware of the necessity to consider accommodation for a large percentage of their using population. The segment of the performance area which was within the capability of all their subjects was determined. The authors obtained the maximum reach curves for the chimpanzees in vertical planes through SRP in a manner similar to that described by Ely, Thomson, and Orlansky, but at a greater number of angles. They avoided the ambiguity in terminology involving the angles of the arm and of the reach-curve planes.

P. Frankenstein and Sons (ref 29) described a mobility-measuring device and a method of data presentation by which decrements (or increments) may be portrayed. They designed the device for measuring the status of mobility of the shoulders and arms among patients undergoing orthopedic therapy, and for measuring reach decrement resulting from wearing pressure garments. Wright (ref 47) also described the device in 1963. It consists of a semicircular bar carrying a movable measuring rod. The bar, supported on tripods in front of and behind a chair, is capable of being rotated over the chair. (See figure 8.) Linear reach measurements are made by touching the end of the measuring rod to the tip of the forefinger.

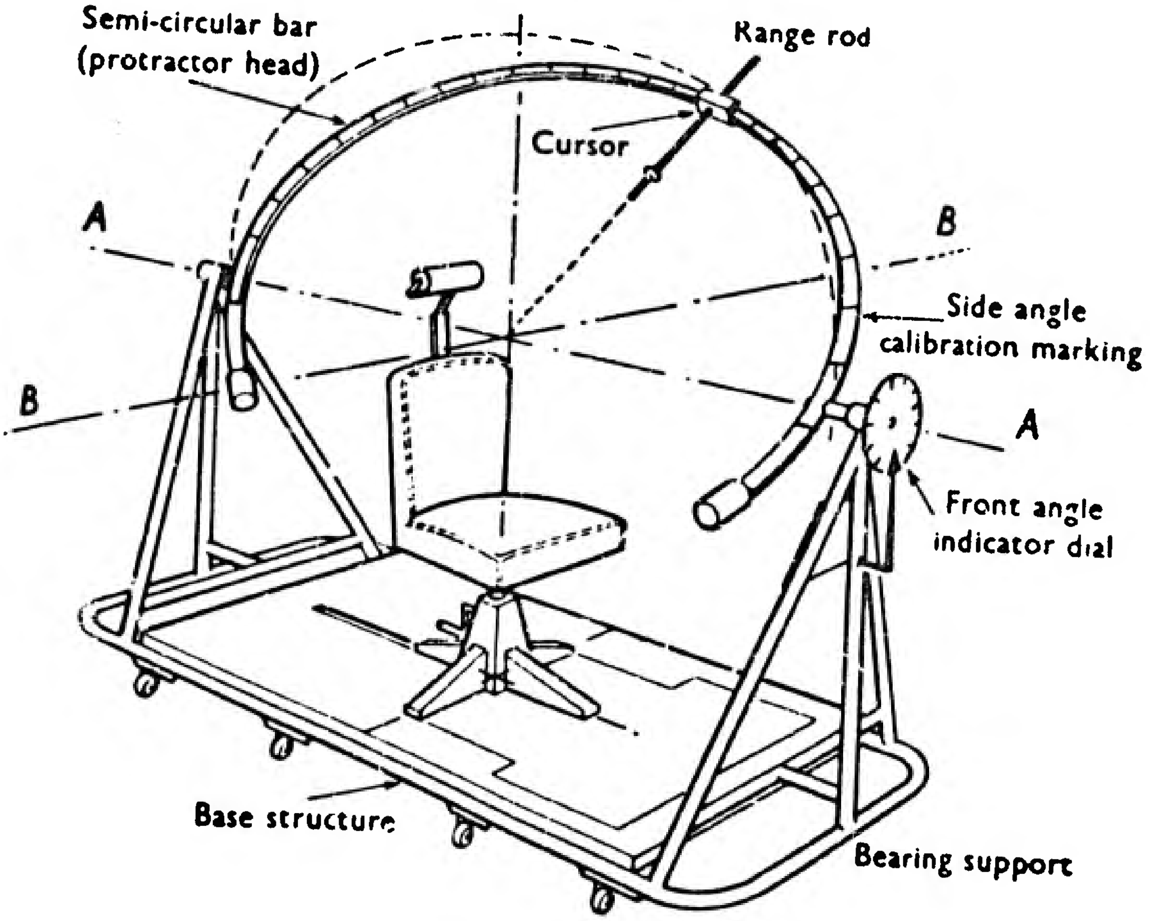

Figure 8. The Frankenstein Anthropometric Measuring Apparatus

(From Wright, ref 47, p 35.)

Both reports present data as polar graphs (fig. 9). In these graphs, reach to a point in space is located by means of the "front angle" (inclination of the semicircular bar), the "side angle" (location of the cursor), and the length of the range rod (calibrated to show length of reach). The angular extremes of reach are defined by plotting front angle against side angle. The distance along these azimuths (recorded relative to front angle) define the limits of reach. The entire sector of the "sphere" thus described is within reach. The apparatus, then, is used primarily as a mobility-measuring device rather than as one to ascertain the complete reach envelope. It is, however, sufficiently versatile to be used for the latter purpose as well.

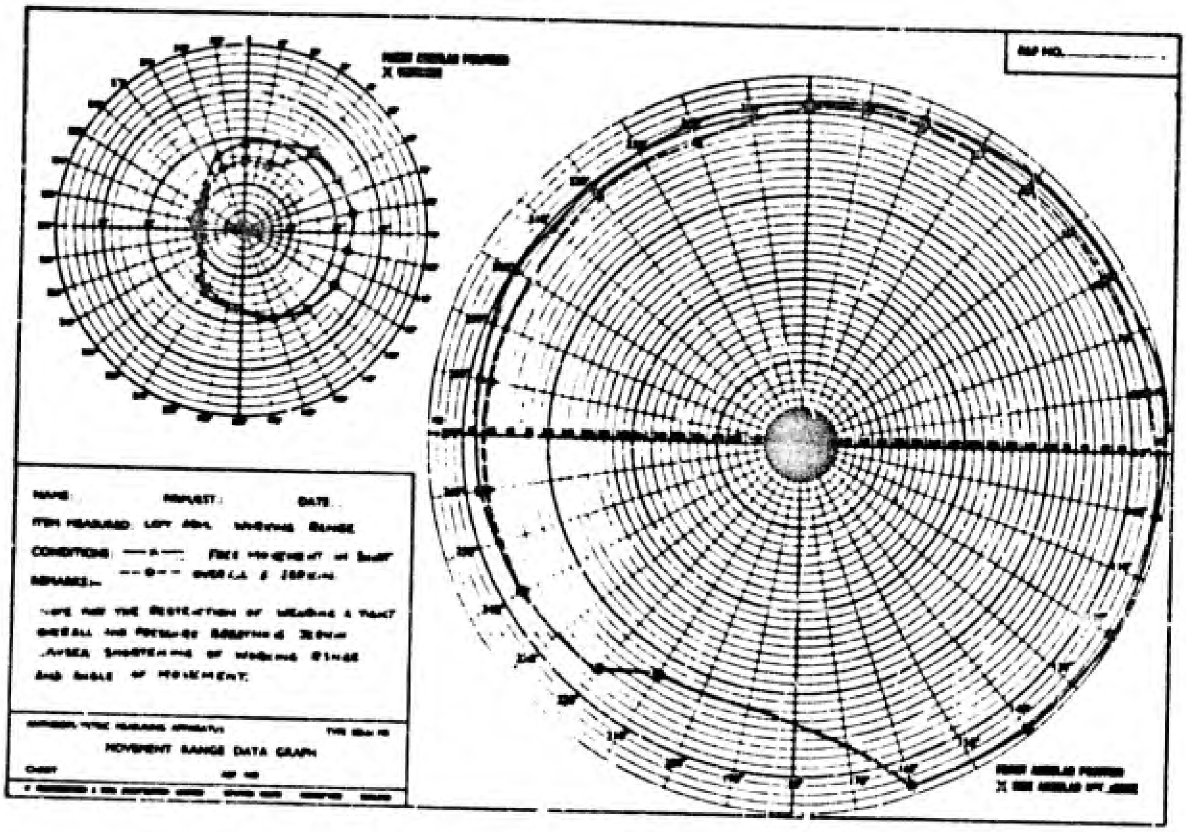

Figure 9. Movement Range Data Graphs Obtained from the Frankenstein Anthropometric Measuring Device

Front angle is plotted against side angle, and against linear distance from a central datum point (From Wright, ref 47).

From this summary of available techniques and data on arm reach, it can be seen that, although several investigators have described various aspects of the general problem, none has attempted to describe the complete outer boundary of the reach envelope. Hitherto, emphasis has been placed on the sector of the reach envelope to the subjects' right front.

Reach capability to the rear of the frontal plane through SRP has been ignored. Granted that this is a relatively unimportant region, in that few hand controls and items of equipment are located there, greater understanding of reach into this egion can lead to its more efficient use.

Those sectors of the total envelope which include right-hand reach capability to the left of the median plane, and left-hand reach to the right, have not been determined. Should a designer wish to locate a critical control so that it is operable with either hand, especially in the event of injury or emergency, he would find very little statistically treated information available to guide him. A thorough understanding of reach into all sectors is of extreme importance.

The only study lending itself to convenient use by designers is that of King, Morrow, and Vollmer (ref 24). It is concerned primarily with maximum fingertip each into the sector forward of the frontal plane through SRP. Although all subjects could reach with the right hand to 105° each side of the median plane at most levels, only right-hand reach in the sector between 0° and R75° was considered in the determination of an envelope within which a high percentage 98%) can be accommodated. Reach capability of the left hand was assumed to be a mirror image of that for the right hand.

In all investigations of shirt-sleeved reach capability treated herein he subjects' torsos were effectively immobilized by some method of restraint. Reach capability under such conditions of restraint is not characteristic of that which the pilot experiences during emergency periods of flight, as when preparing or ejection or a collision. It is excessively conservative. Obviously, any control that must be operated during such periods must be within the pilot's reach when he is restrained in his seat. Controls of this nature are comparatively few in number and are usually integrated with seat structure.

Controls are operated mostly when the shoulder harness is not tightened. With relative looseness in the shoulder harness, there is less decrement to mobility at the shoulder; reach capability approaches the natural, unrestrained state. It is his reach capability that the majority of control locations should accommodate. No tudy of arm reach, taking into consideration this extent of freedom in shoulder mobility, has hitherto been reported. This investigation of grasping-reach capability hroughout 360° in each of the three cardinal planes is an attempt to correct this situation.

SECTION II

APPARATUS

To derive information on reach capability, the AMRL Research Measuring Device was designed and fabricated (figs. 10, 11). It consists of a rotatable seat mounted on a platform beneath an arch, so that the centerline of the seat's vertical axis lies in the plane of the arch. The arch contains friction-held measuring staves (or slats) radiating at 15° intervals, so that each slat points to the center of the arch. Each slat is calibrated to indicate the distance from the center of the arch to the mid-point of a knob at the inside end of the slat.

The center of the arch is an important point for the entire device. The vertical axis about which the seat rotates passes through the center of the arch; and the SRP of the seat lies 10 inches* to the left of the arch center, and 23 inches† below it. Thus, the center of the arch lies close to the joint-center‡ of the right shoulder, and remains fixed with respect to the subject as the seat is rotated. For convenience, the center of the arch will hereafter be referred to as PO (Point of Origin). The vertical line through PO will be referred to as POV.

This design permits the subjects to push the scaled slats along lines radiating from the right shoulder, regardless of the orientation of the seat. Consequently, slat angle from the shoulder is not a significant factor in making any one slat more or less convenient to push.

The basic dimensions of the seat are in accordance with the specifications of those in stick-controlled aircraft (ref 15). The values for these dimensions (SRP-to-Heel Rest Line, SRP-to-Heel Rest Point, Back Angle, and Seat-pan Angle) are underlined in the side view of the seat in figure 12.

The maximum grasping reach that can be measured on the device is 38 inches. This limit was chosen after noting that the 99th-percentile value for Functional Reach in the U.S. Air Force is 36.4 inches (ref 16). An excess of approximately 1-1/2 inches was considered adequate, as was subsequently found to be the case.

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*Ideally, this distance should have been 7.9 inches, half of the mean value for Biacromial Diameter (ref 16). In practice, however, this distance was not adequate, since it determines the plane of the system of radiating measuring slats which in turn must clear the right side of the seat. The need to accommodate a large Hip Breadth, Sitting, in the chair demanded the utilization of this larger distance.

† Approximately the mean value for Acromial Height, Sitting (ibid).

‡ This term is used for the sake of convenience, even though Dempster (ref 7) has shown that there is no such thing as a pin-center of rotation for the shoulder, or any other joint.

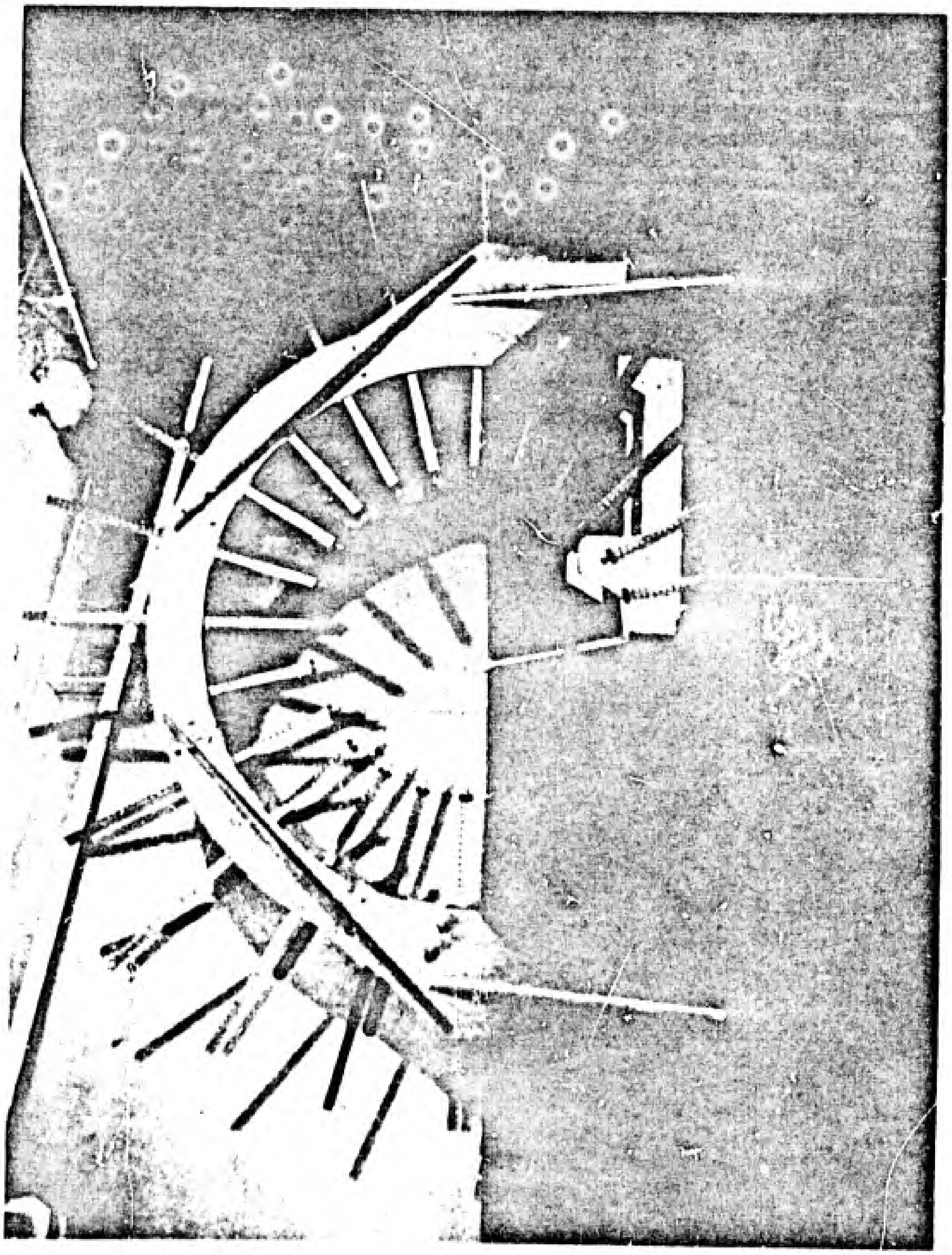

Figure 10. The AMRL Grasping-Reach Measuring Device

Through the use of this apparatus, grasping-reach capability was determined throughout 360° in the three cardinal planes.

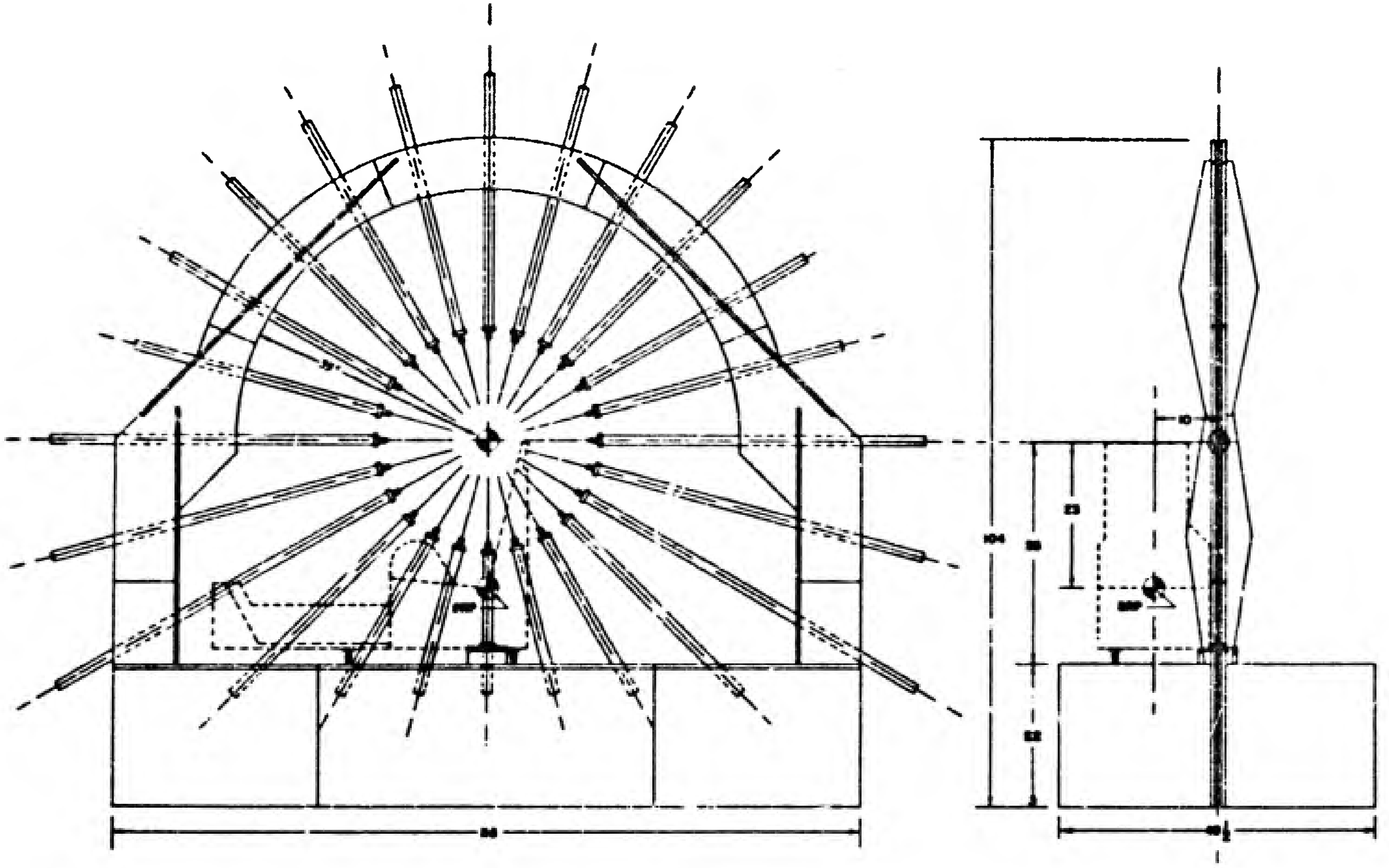

Figure 11. Plan of AMRL Grasping-Reach Measuring Device Platform and Arch

The axis of seat rotation is within the plane of the arch and its measuring slats.

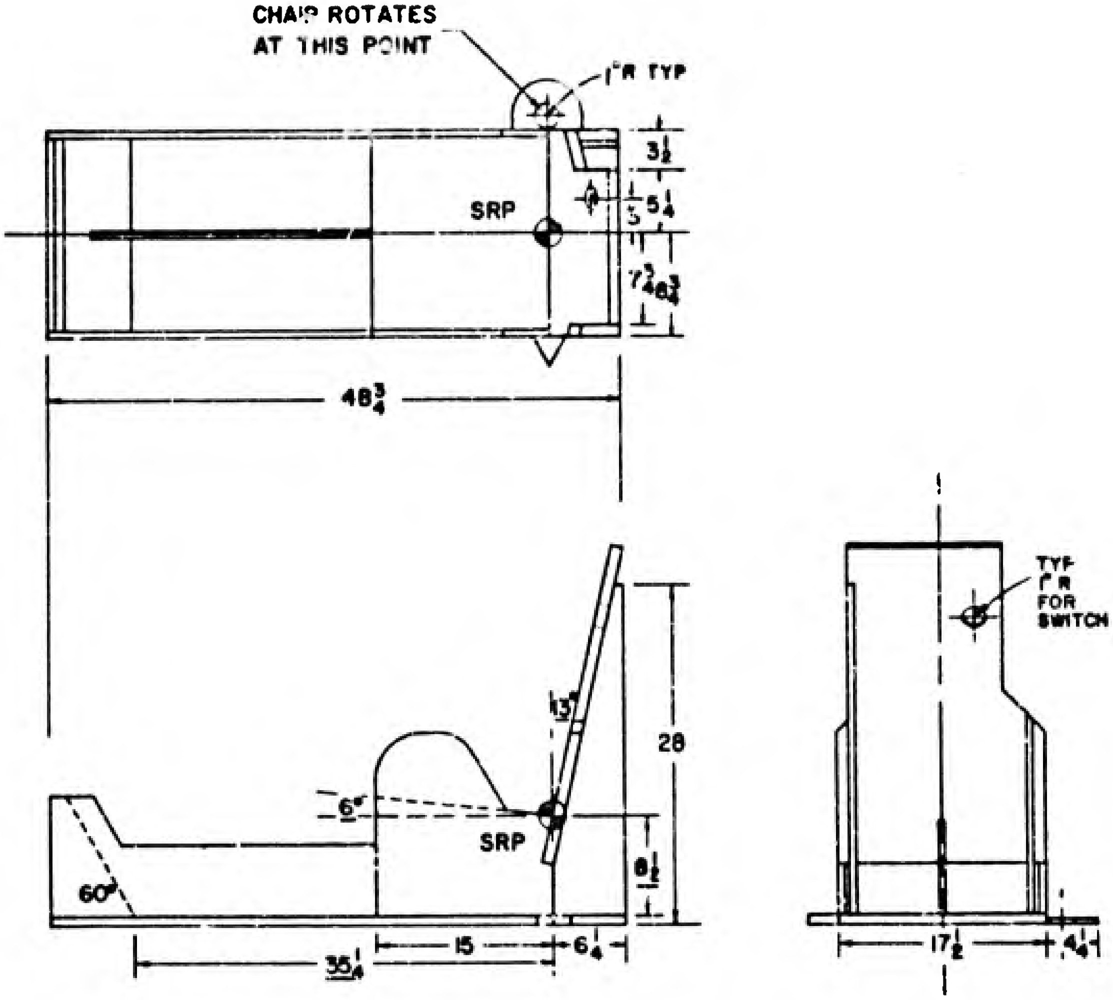

Figure 12. Plan of Seat for AMRL Grasping-Reach Measuring Device

Underlined measurements are those that are in accordance with HIAD, Vol III, AD 1, sheet 1 (ref 15).

Casters attached to the bottom of the seat faciliatate its rotation. They are about 2 inches in diameter so that the bottom of the seat can clear the ends of the slats when these are thrust as far as possible into the body of the platform. Two circular bands of sheet metal are fastened to the surface of the plywood platform to provide a track on which the seat casters can roll (fig. 13). Without tracks, the casters would quickly wear a rut in the surface of the platform. The casters are located on the bottom of the seat so that they can roll between the ends of the slats.

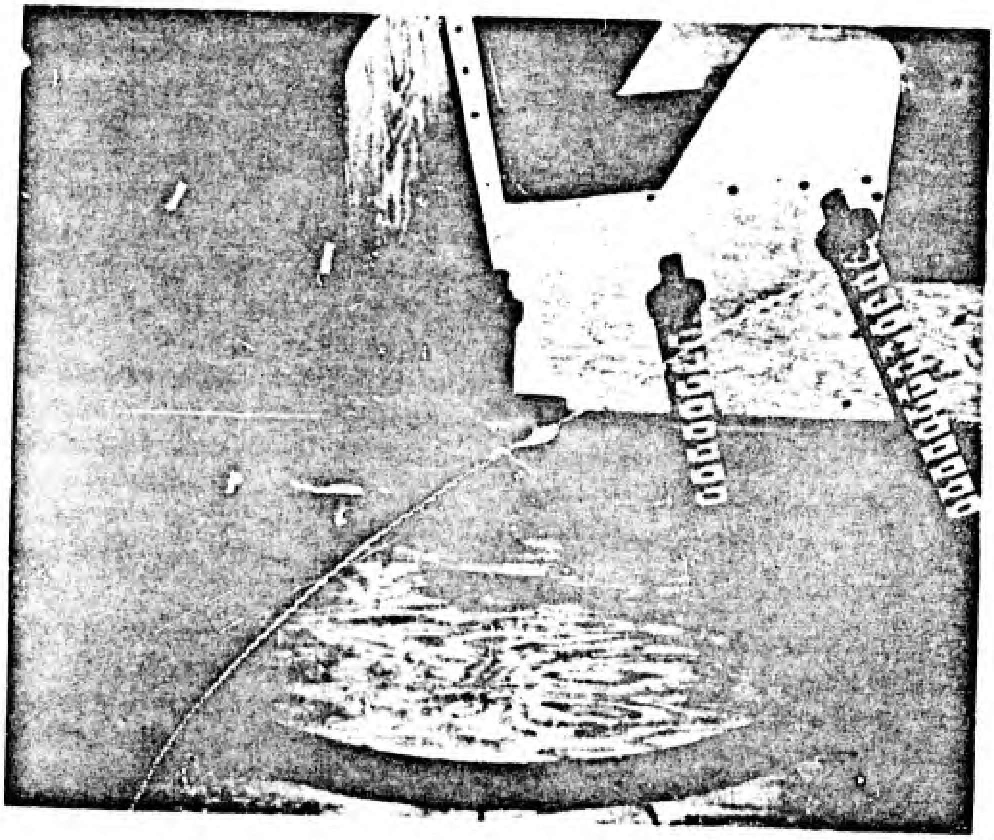

Figure 13. The Axis of Seat Rotation

The axis of seat rotation is within the plane of the arch and the calibrated slats. Segments of the circular tracks and the seat protractor (lower right) are visible. The wire emerging from between the two halves of the platform and entering the seat structure serves the back switch and light.

A circular scale marked at 15° intervals is painted on the platform around the pivot of the seat. A pointer on the left side of the seat indicates the seat orientation with respect to the measuring plane. To maintain seat orientation while reach information is taken, wedges are blocked under the casters.

A large, button switch, lightly spring-loaded, is installed in the back of the seat, 18 inches above SRP and 3 inches to the right of the seat-back midline (fig. 14). When the subject is seated with his shoulder in the correct position, the weight of his back presses the button and causes a small bulb to glow at his feet. If his shoulder moves out of position, the spring breaks the light circuit (fig 15). If the light goes off, the subject knows he is out of position and has to repeat the reach motion. The switch and light function together as a warning primarily during establishment of the forward half of the arm-reach envelope.

When necessary, the arm-reach measuring device can be quickly disassembled into relatively small parts and moved to a new location.

Figure 14. The Back Switch

With the subject correctly seated, the backswitch is depressed and the light (fig. 15) is "on." A break in contact between the dorsal surface of the right shoulder and the seat back releases the switch and "turns off" the light.

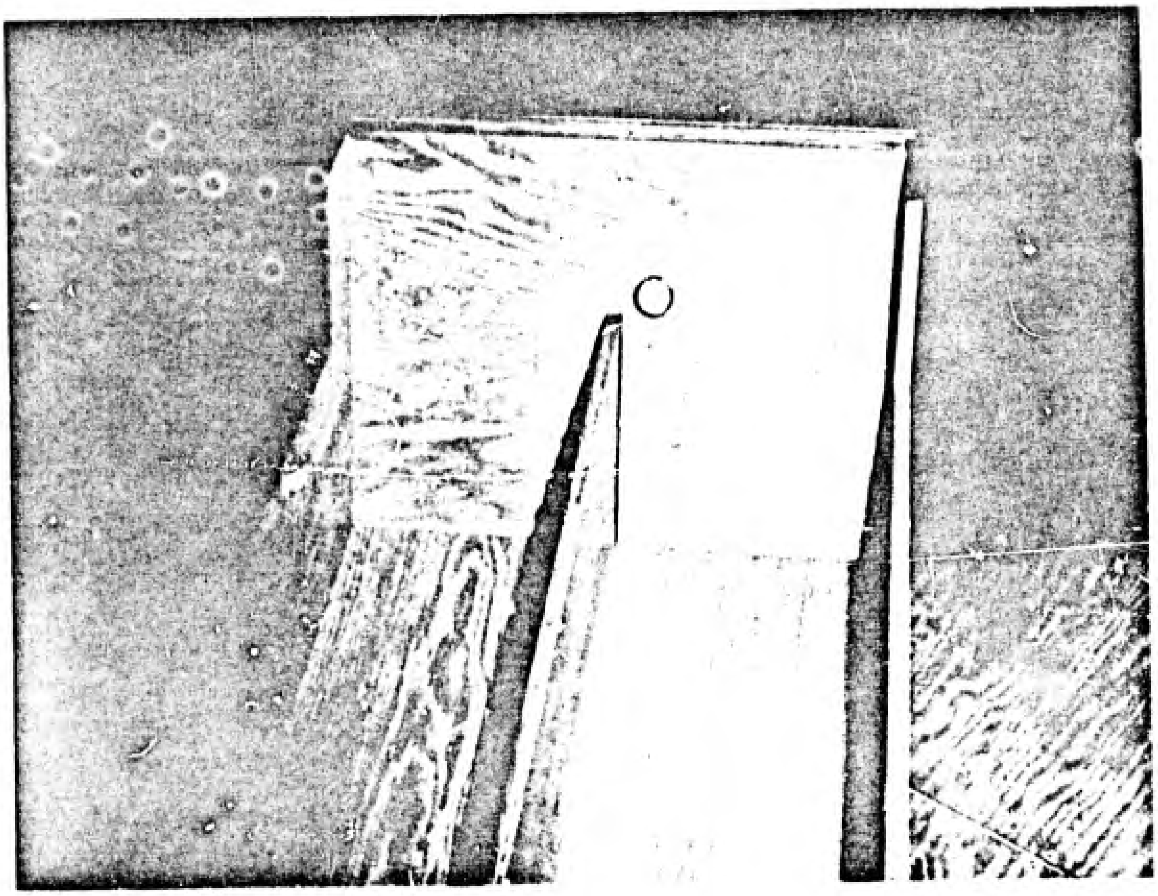

Figure 15. Footrest Area Showing Position of Warning Light

The subject looks toward the footrest area and, by opening and closing each eye alternately, centers himself in the seat so that he can see equal amounts of the sides of the brace that runs down the center of the footrest.

SECTION III

PROCEDURE

Prior to each measuring session, the subject* was handed an instruction sheet explaining the purpose of the study, the workspaces in which the data would most likely be used, the mechanics of operation, and the approximate length of time to complete the "run." After reading the instructions, the subject was encouraged to ask questions concerning any procedure about which he was unsure, such as how to grasp the knobs of the measuring slats, how to center himself in the seat, and how far to push the slats. If the subject did not ask questions concerning the procedures, the operator made certain they were clear by discussing them. The essential points were as follows: After sitting in the seat the subject was requested to look down toward the footrest area and, by opening and closing first one eye and then the other, to center himself with respect to the brace that runs the length of the footrest, so that he could see equal amounts of its sides with each eye. With the full length of his back leaning firmly against the seat back, he was then to center his torso on the seat. At this point, his position was examined by the investigator and, if necessary, corrections were made. He was asked to memorize this position and to check it prior to each reach. The subject was reminded that this was not a contest, that the slats should be pushed away only until the arm was fully extended without pulling the right shoulder away from the seat back, and that if he pushed a measuring slat and the light on the footrest went off, that particular reach would be retaken. Each subject was cautioned to take his time, so as to prevent unnecessary fatigue. He was then allowed a few minutes to manipulate the measuring slats and to practice orienting himself in the seat. Each run lasted approximately one hour.

The initial or 0° position of the seat in every series of measurements is illustrated in figure 16. With the seat in this position, with its sides parallel to the arch, reach information was taken throughout a vertical (sagittal) plane through PO (not SRP) and designated the 0°-180° plane (forward is 0°; rear, 180°) (see figure 18a). After the reach data had been gathered for this position, those measuring slats interfering with seat rotation were inserted as deeply as possible into the platform, and the seat was rotated 15° to the right. Reach data were then taken throughout the vertical plane designated L15°-R165°. This procedure was repeated until the seat had traversed 165°, to the L165°-R15° vertical plane. Tests with the seat at 180° would simply have duplicated the original position.

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*An anthropometric description of the subjects is included in the Appendix.

Figure 16. The Initial Seat Position: For Measuring Grasping Reach in the 0°-180° Plane Through the Shoulder

Each subject first pushed slat No. 19 directly forward of his right shoulder. He then pushed all slats within reach below and above this level.

To compare the performance at the beginning of a run with that at the end, the seat was occasionally rotated to the 180°-0° position and mirror image was taken of the vertical plane obtained in the first position, 0°-180°. The subject's performance at that position was always without realization that he was repeating. The data derived from each were then compared. Variations found were infrequent and seldom greater than 1/2 inch from the values obtained in the first seat position Most of the variations were in the form of slight increases in angular capability to the rear of the frontal plane. It seems likely that these were due to a "loosening-up" of the shoulder.

In handling the data, it was more convenient to think of the reach plane turning about the subject than vice versa. Thus, when the seat was turned 15° to the subject's right, the reach distances were recorded as though the vertical plane of reach had rotated 15° to the subject's left. This plane was referred to as the L15°-R165° plane. The seat position to obtain the L90°-R90° plane illustrated in figure 17.

Figure 17. The Seat Position Necessary to Determine Reach Capability Throughout the L90°-R90° Vertical Plane

SECTION IV

METHOD

It does not necessarily follow that a device designed for accuracy and ease of operation will yield data that are immediately convenient for analysis and application. The data may have to be transformed; and that was true in this case.

The reach-measuring device was designed to measure grasping-reach at 15° intervals in vertical planes through PO at the right shoulder. A 0°-180° vertical plane appears in figure 18a. However, illustrations showing 12 vertical planes through a point (PO) and data regarding them are difficult to visualize and apply. Hence it was necessary to convert the data to represent horizontal sections through the reach envelope—a form much easier to use.

In accomplishing the conversion, the first step was to plot the 12 planes on paper. Thereafter, horizontal lines (fig. 18a) were drawn to scale at 5-inch levels beginning at 5 inches below SRP and continuing to 55 inches above SRP. Distances then measured along each horizontal plane from POV to the reach boundaries were appropriately recorded.* From such measurements, the outer boundary of each subject's reach envelope was reconstructed in the form of horizontal contours. Figure 18b is a horizontal contour through the subject's reach envelope at 25 inches above SRP. Since PO was the reference point from which reach distances were taken to establish the vertical planes, POV must be used as the reference to establish the horizontal sections.

Even though the PO for a given subject was always stationary with respect to the seat and measuring device, its position relative to the subject depended upon his body size and proportions. For a subject whose dimensions of Shoulder (Acromial) Height, Sitting, and Biacromial Diameter are both toward the upper ends of the ranges, the PO will be located above and to the right of Acromion of the subject who is at the lower end of the ranges of these dimensions. Because of this, PO is inconvenient as a reference point in laying out a workspace, and has made it necessary to transfer the point of reference from the POV to SRV. This achieves a family of reference points that are stationary with respect to the seat and the operators as well. They are also much more convenient to use in laying out workspaces. The transfer is accomplished as follows.

Diagrams similar to figure 18c were made by overlaying the horizontal contours through POV (fig. 18b) with a system of radiating lines, the axis of which coincided

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*The PO (and POV, a vertical line through PO) and SRP (and SRV, a vertical line through SRP) lie in the L90°-R90° vertical plane. Consequently, they appear as a single line in figure 18a, a view from R90°.

with SRV, 10 inches to the left of POV. Distances were measured from SRV along all radial lines to the envelope boundary. To prevent the loss of portions of reach curves ending between lines, the angular locations of the ends of the curves were measured with a protractor and recorded with other measurements for that level. Individual contours similar to figure 18d were then constructed.

Having extracted data for all levels, we arrive at a suitable time to derive the Minimum, 5th-, 50th- and 95th-percentile* grasping-reach envelopes. Referring for a moment to the method of measuring Functional Reach (see Appendix), it can be imagined that instead of the subject being measured, he is reaching for a control. A control located for a subject whose Functional Reach is at the 5th percentile will be well within the capability of all those with greater reach, or 95 percent of the population. Conversely, a controller located at the 95th-percentile distance for Functional Reach will be beyond the reach of the subjects,with 5th-percentile Functional Reach.

Turning from such a straightforward linear dimension as Functional Reach, we shall now utilize essentially the same rationale in determining the grasping-reach percentile envelopes. This is accomplished by determining: (1) the percentile angular limits of reach capability, and (2) the percentile linear-reach distances at 15° intervals throughout the inclosed angle.

To determine the percentiles of angular-reach capability, the maximum medial and lateral angles which the subjects were able to reach were listed in ascending order separately for each level, thus reflecting an increasing capability. The first value in each series represented the bottom of the range or minimum angle of capability. All subjects demonstrated the capability of reaching throughout this arc. All such values were used to describe the minimum reach envelope. The second value in each series defined the angular boundaries of the 5th-percentile envelope. Nineteen subjects (95 percent) could reach to each extreme of this angle. One subject (5 percent) could not reach to the medial extreme of this angle and one (a different subject) could not to the lateral extreme. The arithmetic mean of the 10th and 11th values in each series defined the angular boundaries of the 50th-percentile envelope. Ten subjects (50 percent) demonstrated reach capability at each boundary of this angle and ten did not. However, not all 10 subjects reaching to one angular boundary could reach to the other. The 19th value in each series defined the boundaries of the 95th-percentile envelope. Only one (5 percent) could reach beyond these boundaries. The last value in each series described

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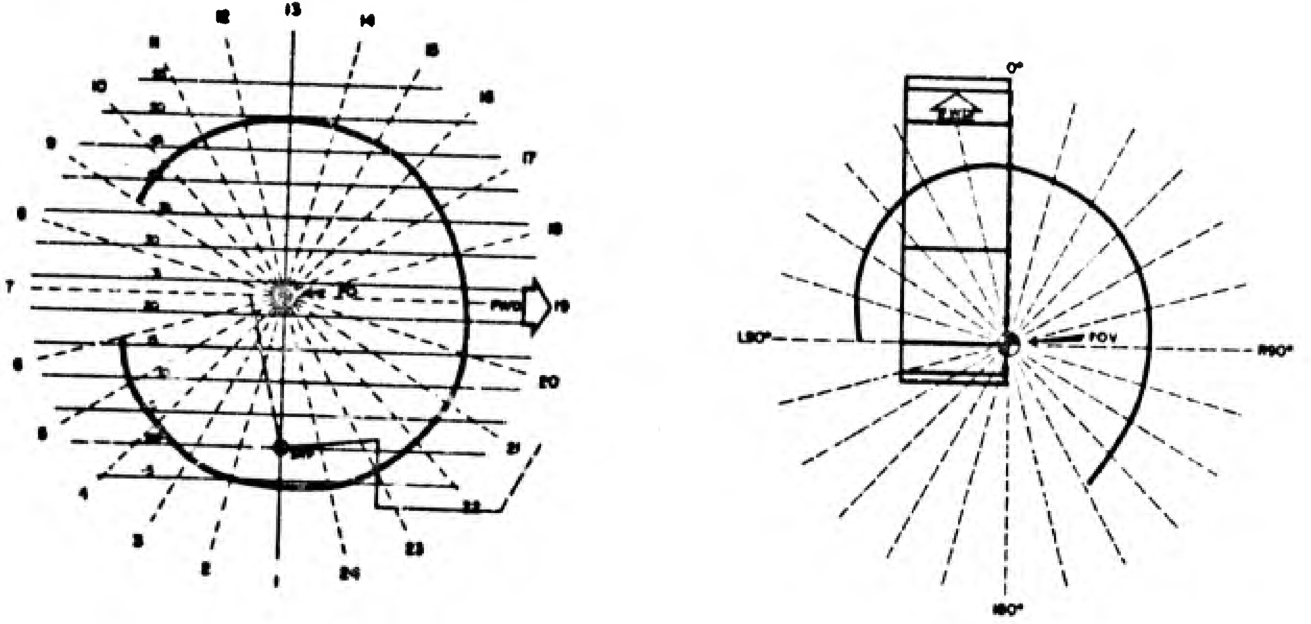
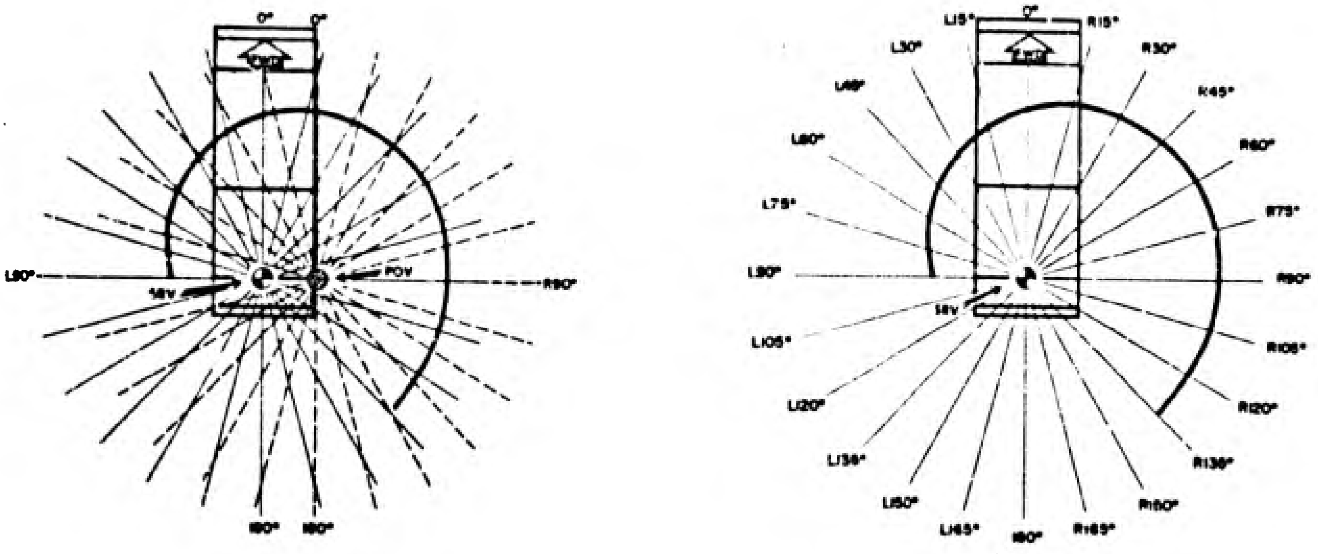
*In a series of values, the 5th-percentile is that value which is greater than 5 percent of the total number of values and is smaller than 95 percent of the total number of values. The 50th-percentile is that value at the midpoint of such a series. This value divides the series exactly in half: 50 percent are smaller than this value and 50 percent are larger. Similarly, the 95th-percentile is that value which is greater than 95 percent of the total number of values and is smaller than 5 percent.



a. Side view of the vertical section at 0°-180° (through PO) through the grasping-reach envelope of one subject. Horizontal lines are at 5-inch intervals from SRP level.

b. Top view of the horizontal section through the grasping-reach envelope of one subject at the 25-inch level, referenced to POV.



c. Diagram showing method used to transfer reference from POV to SRV. Indentical system of radiating lines is superimposed so that its center is over SRP. Distances from SRV along line to envelope boundary are measured.

d. Top view of the horizontal contour through grasping-reach envelope at the 25-inch level, referenced to SRV.

Figure 18. Method Used to Convert the Vertical Planes Measured about POV to Horizontal Contours Based on SRV

the top of the range of angular reach. Usually, the subject who could reach to the lateral extreme of this angle could not reach to the medial extreme unless the arc traversed a full 360°.

The percentile values for linear-reach capability were determined in a manner that was the reverse of that used in the determination of percentiles of angular reach capability. Since some subjects could not reach through as wide an angle as others, there was a decrease in the number of subjects who could reach along the angles near the extremes. It was convenient, then, to list the reach distances so as to reflect a descending order of capability. Since this is the reverse of the order used in determining angular percentiles, the first value in each series is established as the top of the range. This is the distance to which only one subject could reach, the one with the greatest linear-reach capability. The second value is the limit of the 95th-percentile envelope. Only one subject (5 percent) could reach beyond this distance. The arithmetic mean of the 10th and 11th values is the 50th-percentile boundary. Half of the subjects could reach beyond this distance and half could not. The 19th value in each series defined the boundary of the 5th-percentile envelope. Nineteen subjects (95 percent) had reach capability in excess of this distance. The last value in each series defined the boundary of the minimum envelope. None of the subjects demonstrated a lesser capability.

Whether or not an envelope reflected reach along any specific angle depended on the number of subjects able to reach along that angle. If all subjects could reach along any selected angle, the minimum envelope included that angle. If 19 subjects were able to reach along any selected angle, a 5th-percentile linear-reach value could be determined and that angle was within the 5th-percentile envelope. If as many as 10 subjects were able to reach along any angle, that angle was within the 50th-percentile envelope. Finally, if two subjects were able to reach along any angle, that angle was within the 95th-percentile envelope. When the linear and angular data were "fitted" together, contours portraying minimum and percentile capabilities for each level were drawn. This information for each 5-inch level is presented in section V.

SECTION V

RESULTS

The results of this investigation are embodied, beginning on page 35, in the ntours for each 5-inch level through the outer boundaries of the Minimum, 5th-, th-, and 95th-percentile grasping-reach envelopes. It is understood, of course, t there are inner boundaries that represent the least distances that can be reached. nce the contours for the inner boundaries were not ascertained, all contours tween 5 inches below SRP through 30 inches above SRP are incomplete. At levels ove 30 inches some of the contours are complete (see the 35-inch Contour).

The actual distances along the various angles from SRV to the outer boundary each reach envelope can be found in the table at the upper left of each data page ginning on page 35. The values for the Minimum and 5th-percentile envelopes ve been outlined with a solid line to emphasize their importance. The medial and teral angular limits of each contour can be found in the table in the lower left rner of the page. A discussion of each level is included. Means and Standard viations can be found in Appendix I.

To establish the lower and upper limits of each envelope, the lowest and hest points to which each subject could reach were measured, and the Minimum h-, 50th-, and 95th-percentile values were determined in the usual manner. The nimum envelope extends from 2.5 inches below SRP to 48 inches above it, through istance of 50.5 inches. The 5th percentile envelope extends from 4 inches low SRP to 48.75 inches above it, through a distance of 52.75 inches; the 50th- centile envelope extends from 5 inches below to 52.25 inches above SRP through istance of 57.25 inches; and the 95th-percentile envelope extends from 7 inches ow to 54.25 inches above SRP, through a distance of 61.25 inches.

The Minus 5-Inch Contours*

Ten of the sample of 20 subjects could reach below the—5-inch level. Capability at this level was quite variable. One subject could reach to this level only along angles R45° and R120°, leaving a gap in his reach pattern. Another subject could do so only through a smaller arc between R63° and R118°, thus falling completely within the first subject's gap in reach. The arcs for the seven remaining subjects were arranged between R30° and R145°, with the maximum an arc encompassing 105° and the minimum, one of 55°.

The Minimum and 5th-percentile envelopes are not represented in the—5-inch contour, since they extend only to 2.5 and 4 inches, respectively, below SRP level. The 50th- and 95th-percentile envelopes, however, are represented at this level. The 50th-percentile envelope extends just to this level, the 95th-percentile envelope to 2 inches below it.

At this level, reach is restricted by factors other than natural limitations of mobility in the shoulders and arms. At the forward ends of the curves, the side of the seat formed a block to arm and hand movement for every subject. As a result, the forward ends of the 50th- and 95th-percentile boundaries terminate at the right side of the seat.

Arm movements were also inhibited by seat structure at the rear. All reaches along angles beyond approximately R120° were accomplished by reaching around the right rear of the seat. Whereas the rear end of the 50th-percentile contour terminates at the side of the seat, the 95th-percentile contour extends somewhat around this obstruction.

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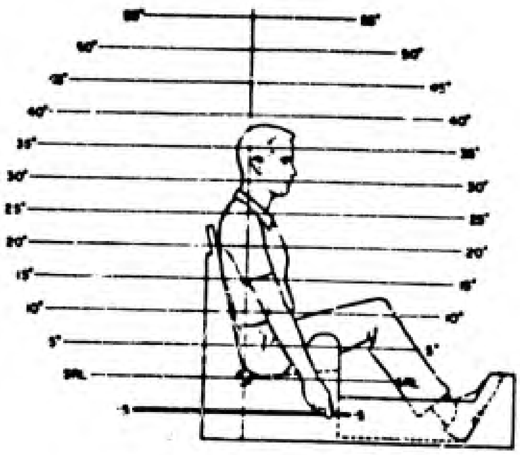
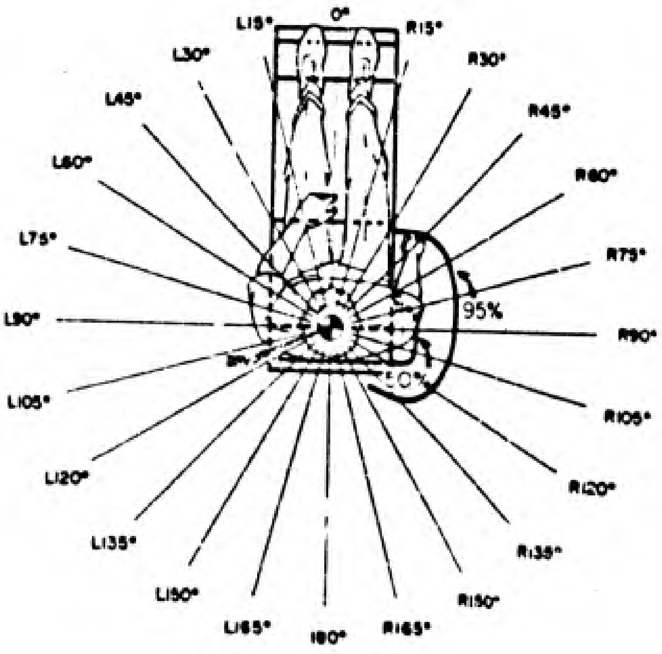
*For convenience this will be written "—5-inch contour or level."

Linear Data for Grasping Reach (in inches)

Angle	N	Min	Percentiles 5th	50th	95th
L165°					
L150°					
L135°					
L120°					
L105°					
L 90°					
L 75°					
L 60°					
L 45°					
L 30°					
L 15°					
0°					
R 15°					
R 30°	1				
R 45°	6				19.00
R 60°	8				19.75
R 75°	10			11.50	18.75
R 90°	10			12.50	18.25
R105°	10			12.50	18.00
R120°	8				17.25
R135°	3				14.50
R150°					
R165°					
180°					

Minus 5-inch Contour





Angular Reach from SRV at the -5-inch Level

Minimum	- - - - - - -
5th %ile	- - - - - - -
50th %ile	R69°* to R116°
95th %ile	R33°* to R145°

* Right side of Leg Support

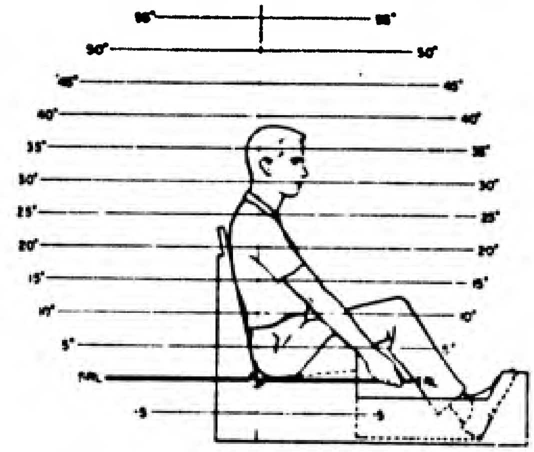
The Seat Reference Point Contours

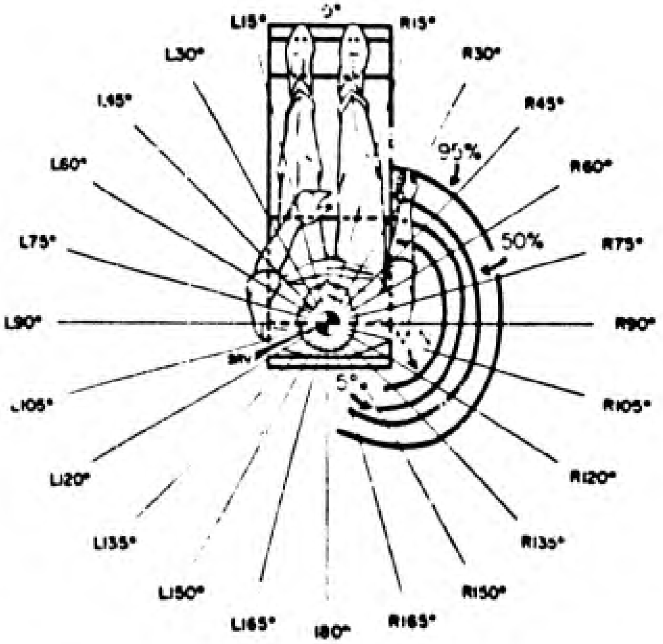
The plane of the SRP contours is the lowest of those ascertained that passes through all three envelopes. The Minimum envelope extends down to 2.5 inches below this level, the 5th percentile to 4 inches below. The 50th- and 95th-percentile envelopes extend to 5 and 7 inches below SRP level. The discussion concerning the fore- and -aft terminations of the 50th- and 95th-percentile contours at the —5-inch level is applicable to all envelope contours at this level. The reach boundaries for all subjects are confined within the angle formed by R20° and R170°. The smallest angular capability is 103° and the largest, 150°.

Linear Data for Grasping Reach (in inches)

			Percentiles		
Angle	N	Min	5th	50th	95th
L165°					
L150°					
L135°					
L120°					
L105°					
L 90°					
L 75°					
L 60°					
L 45°					
L 30°					
L 15°					
0°					
R 15°					
R 30°	19		17.50	20.75	25.00
R 45°	20	16.25	19.50	21.75	26.00
R 60°	20	17.50	20.50	22.25	26.25
R 75°	20	17.25	20.00	22.25	26.00
R 90°	20	17.00	19.50	22.25	25.50
R105°	20	16.25	18.75	22.00	25.25
R120°	20	15.00	18.25	20.75	24.50
R135°	20	13.00	16.50	19.00	23.50
R150°	19		14.00	16.50	20.25
R165°	13			13.00	17.00
180°					

Seat Reference Point Contours





Angular Reach from SRV at the SRP Level

Minimum	R37°* to R140°
5th %ile	R30°* to R151°
50th %ile	R26°* to R166°
95th %ile	R21°* to R175°

* Right side of Leg Support

The 5-Inch Contours

At this level the forward ends of the reach boundaries terminate at the right side of the knees. The rearward termination of the contours at this level are primarily governed by obstruction from seat structure. Since the section of the seat-back immediately behind the right arm has been removed, arm movement to the rear is only moderately affected by the seat back.

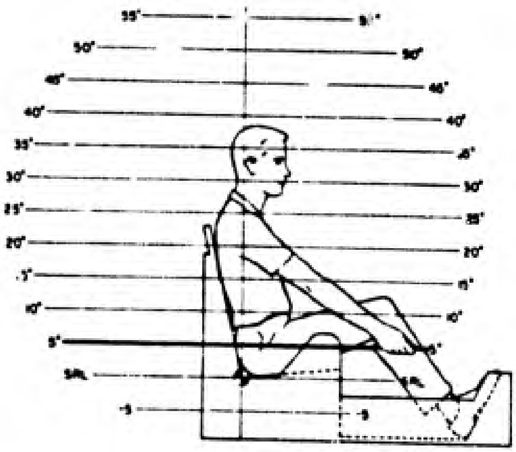
A greater range of variation in rearward angular reach capability is found at this level than at the SRP level. This movement requires abduction of the upper arm, a clockwise rotation as seen from above. The range of rearward angular reach between the 5th- and 95th-percentile is 40° at this level. The same range at the SRP level is 24°.

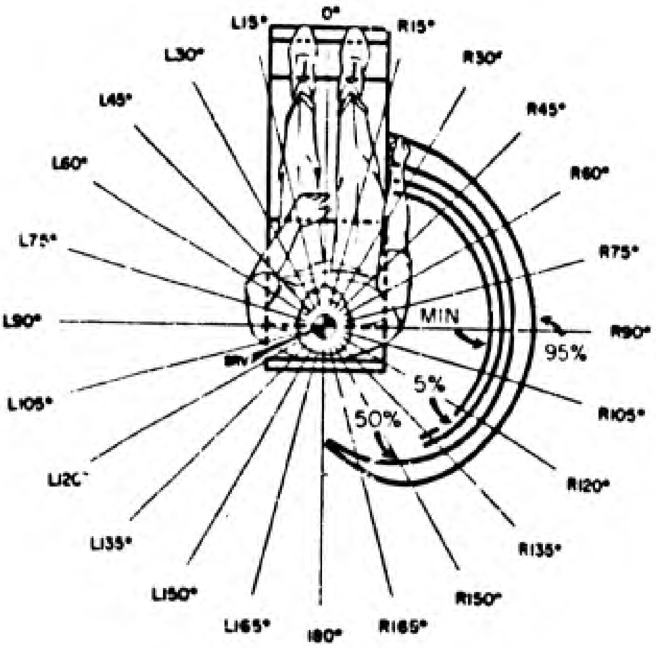
When comparing the envelope boundaries at the SRP and 5-inch levels, we find that at the 5-inch level, the rear ends of the 50th- and 95th-percentile boundaries have shifted a few degrees in a clockwise direction. This end of the Minimum and 5th-percentile boundaries has shifted in a counterclockwise direction.

Linear Data for Grasping Reach (in inches)

Angle	N	Min	Percentiles 5th	50th	95th
L165°					
L150°					
L135°					
L120°					
L105°					
L 90°					
L 75°					
L 60°					
L 45°					
L 30°	1				
L 15°					
0°					
R 15°					
R 30°	20	22.00	23.75	26.00	29.50
R 45°	20	23.50	25.25	27.25	30.00
R 60°	20	23.75	25.75	27.75	30.00
R 75°	20	24.00	25.75	27.50	30.25
R 90°	20	24.00	25.75	27.50	30.75
R105°	20	23.75	25.25	27.00	30.00
R120°	20	23.00	24.50	26.50	29.00
R135°	20	21.50	22.75	25.00	28.00
R150°	18			22.25	25.75
R165°	8			19.25	21.25
180°					

5-Inch Contours





Angular Reach from SRV at the 5-inch Level

Minimum	R25°* to R137°
5th %ile	R23°* to R139°
50th %ile	R20°* to R178°
95th %ile	R18°* to R179°

* Right side of knees

The 10-Inch Contours

At the 10-inch level, all subjects experienced varying degrees of obstruction due to the protrusion of their knees into the reach envelope as high as 13 inches above SRP. Because of this, there are no data for the median plane (0°) forward of the body at this level.

For the first time, a certain amount of reach capability for the right hand appears in the area to the left of the median plane (0°). Fifteen subjects could reach into that sector at this level. Consequently, Minimum and 5th-percentile capability are not represented in that sector at the 10-inch level.

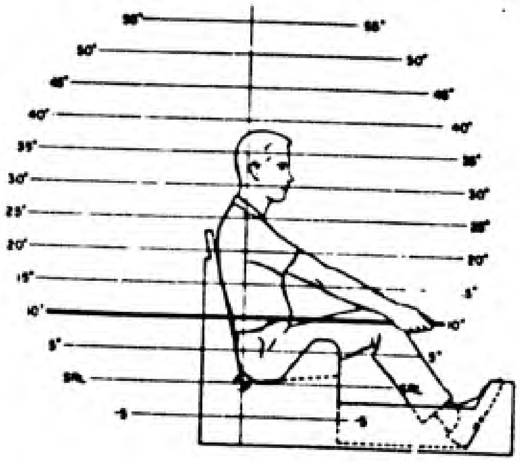
An unforeseen characteristic of the reach-measuring device was its inability to measure capability for the right hand in the area immediately above the right half of the leg support. Since the knees create an obstruction which is nearly symmetrical, and 50th- and 95th-percentile capability can be detected in the area above the left half of the leg support, it might be assumed that capability also extends into the space immediately above the right half of the leg support. Although not indicated in the 10-inch contours it might also be assumed that the extent of penetration into this area is similar to that into the region immediately above the left half of the leg support. The Minimum and 5th-percentile envelopes are not picked up in the region immediately above the left side of the footrest by the 10-inch contour. There are no means of judging the extent they might penetrate this sector above the right side of the footrest. All contours at this level are assumed to have terminated at the right side of the leg support.

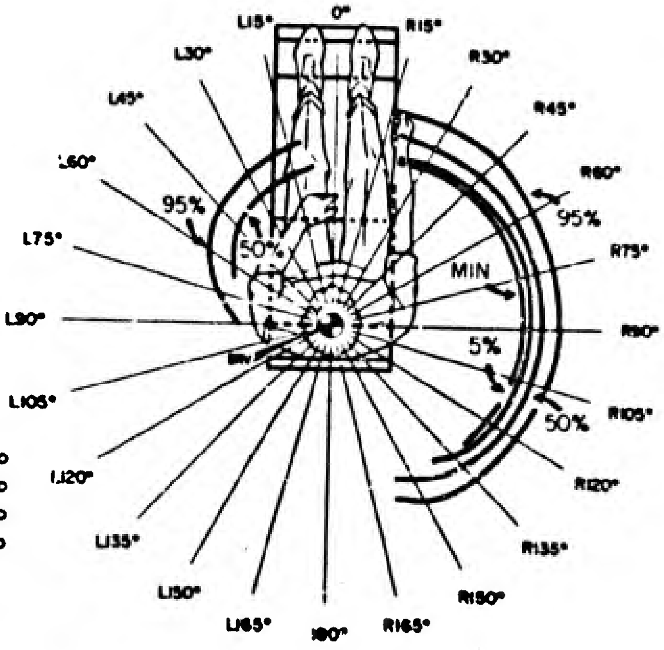
The Minimum and 5th-percentile angular capabilities to the right rear have not changed significantly from those indicated by the 5-inch contour. The ends of the 50th- and 95th-percentile contours, however, have shifted 23° and 22°, respectively, in a counterclockwise direction. Study shows that the close angular positions of the rearward ends of the 50th- and 95th-percentile boundaries at the 5- and 10-inch levels is the result of an extremely skewed distribution of angular values at these levels. The reason for a skewed distribution is that movement of the hand through this level is obstructed by the right edge of the seat back.

Linear Data for Grasping Reach (in inches)

Angle	N	Min	5th	50th	95th
L165°					
L150°					
L135°					
L120°					
L105°					
L 90°	4				13.50
L 75°	4				17.25
L 60°	14			16.50	21.00
L 45°	15			19.50	23.25
L 30°	15			21.00	24.75
L 15°	10			22.00	26.25
0°					
R 15°					
R 30°	20	26.25	27.00	29.25	33.00
R 45°	20	27.25	28.25	30.50	33.75
R 60°	20	28.00	29.00	30.75	33.50
R 75°	20	28.25	29.25	30.75	33.50
R 90°	20	28.25	29.25	31.00	33.50
R105°	20	27.75	28.75	30.50	32.75
R120°	20	26.75	27.75	29.75	31.50
R135°	19		26.25	28.25	30.75
R150°	14			25.25	28.75
R165°	1				
180°					

10-Inch Contours





Angular Reach from SRV at the 10-inch Level

Minimum	- - - -	R21°** to R130°
5th %ile	- - - -	R20°** to R141°
50th %ile	L65° to L 7°* and	R18°** to R155°
95th %ile	L90° to L11°* and	R16°** to R157°

* Left side of knees
** Right side of knees

The 15-Inch Contours

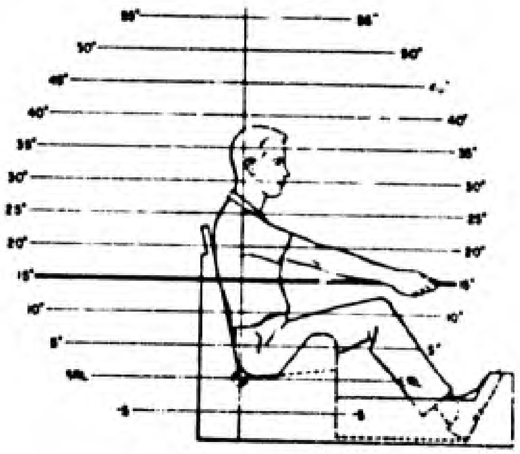
Whereas the 50th- and 95th-percentile capabilities to the left front were represented as "islands" of capability at the 10-inch level, they have enlarged at this level in a clockwise direction and united with those expanding into the area from the right. The Minimum and 5th-percentile contours were absent at the fore-left at the 10-inch level. At the 15-inch level they have not only made their appearance, but extend unbroken across the leg-support area.

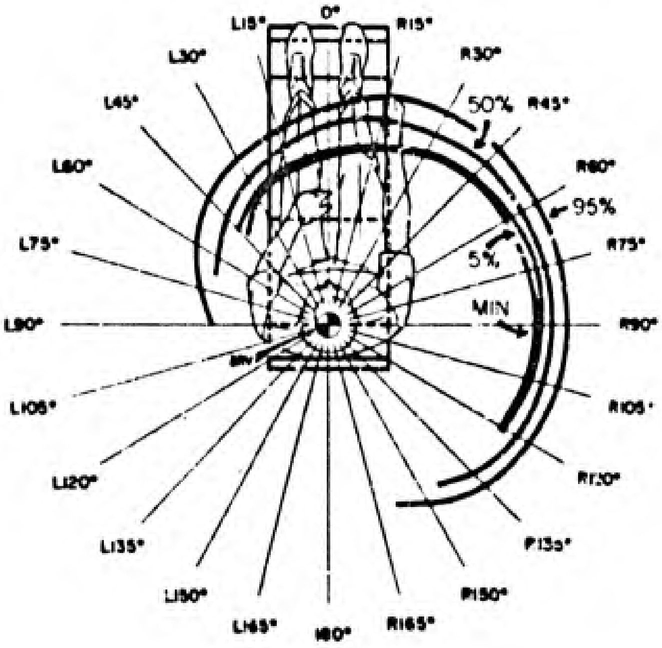
The angular positions of the left ends of the 50th- and 95th-percentile contours have not migrated appreciably in comparison to those at the 10-inch level. On the other hand, the ends of the contours to the right rear have undergone some change in relative position. Whereas the end of the 95th-percentile contour has remained essentially unchanged, the Minimum, 5th- and 50th-percentile terminations have receded in a counterclockwise direction 9°, 19°, and 10°, respectively. The end of the 50th-percentile contour has migrated away from that of the 95th-percentile, indicating that opposition to arm movement has been decreased.

Linear Data for Grasping Reach (in inches)

			Percentiles		
	N	Min	5th	50th	95th
Angle					
L165°					
L150°					
L135°					
L120°					
L105°					
L 90°	8				17.50
L 75°	8				20.00
L 60°	16			19.25	23.00
L 45°	19		19.00	21.50	25.75
L 30°	20	21.00	21.75	24.00	27.25
L 15°	20	22.50	23.25	26.00	28.75
0°	20	24.25	24.75	28.75	31.00
R 15°	20	26.00	26.50	30.50	34.00
R 30°	20	28.25	28.50	31.50	35.00
R 45°	20	29.50	30.00	32.75	35.50
R 60°	20	30.00	31.00	32.50	34.75
R 75°	20	30.00	31.50	32.50	34.75
R 90°	20	30.25	31.00	32.50	34.75
R105°	20	30.00	30.75	32.25	34.50
R120°	20	29.00	29.50	32.00	33.75
R135°	18			30.00	32.50
R150°	3				29.50
R165°					
180°					

15-Inch Contours





Angular Reach from SRV at the 15-inch Level

Minimum	L43° to R121°
5th %ile	L45° to R122°
50th %ile	L67° to R145°
95th %ile	L90° to R159°

The 20-, 25-, and 30-Inch Contours

The most obvious change occurring at levels from 20 to 30 inches above SRP is the steady progression of the 95th-percentile contours toward completion, or closure, behind the subject. This trend is most pronounced between the 25- and 30-inch levels. Between the 20- and 25-inch levels the left end of the contour advances 25° toward closure. The right end, however, recedes 10°. The ends of this contour actually approach each other by only 15°. At the 30-inch level the ends of this contour advance again, the right end by 13° to a position a few degrees beyond its position at the 20-inch level, the left end advances through 50°. The gap in the 95th-percentile envelope at the 30-inch level is approximately 15°.

The positions of the left and right ends of the minimum and the 5th- and 95th-percentile envelopes do not change significantly throughout these levels.

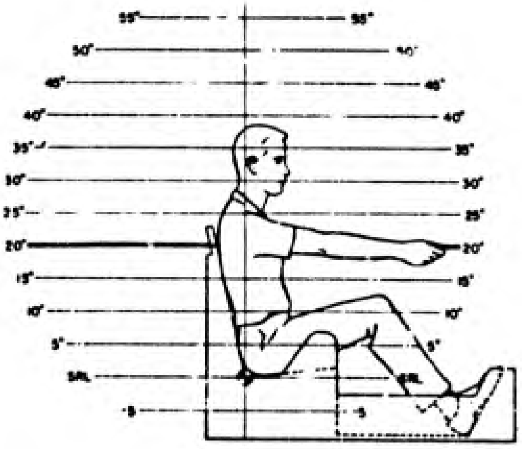
Beginning at the—5-inch level, we have seen a general increase in linear distances from SRP along the various angles to the reach envelopes. At approximately 23 inches above SRP, the maxima for these distances are attained; at higher levels, they again become progressively smaller.

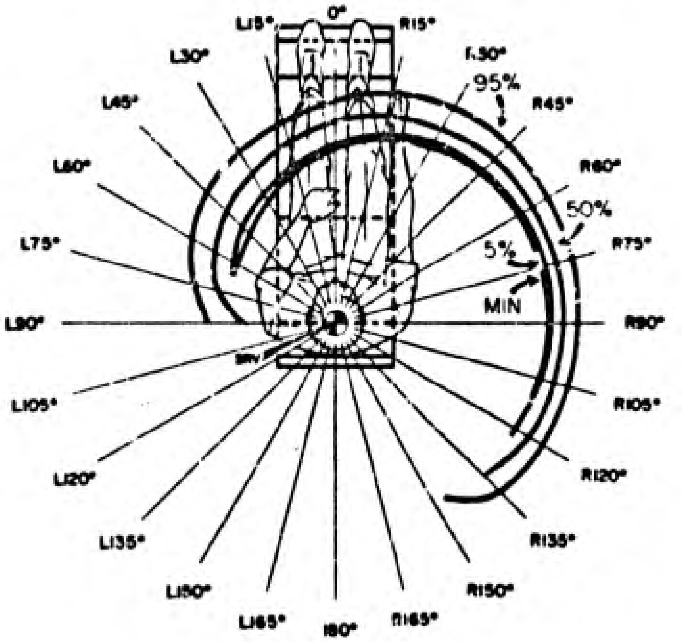
A new factor also enters here. Where the arm swings horizontally about the shoulder the trace of the fingers is usually thought of as perfectly smooth, because the extended arm is a radius. This is especially true for that sector of the envelope between L30° and R120°. When the radius of the envelope is reduced, the trace exhibits a depression which, in the globographic view, is a furrow or a groove in the total reach envelope (see Discussion on pages 57 and 60). Such a change in the envelope becomes obvious here, and can be seen further at higher levels.

Linear Data for Grasping Reach (in inches)

Angle	N	Min	5th	50th	95th
			Percentiles		
L165°					
L150°					
L135°					
L120°					
L105°					
L 90°	11			14.00	18.75
L 75°	16			18.00	21.50
L 60°	20	17.00	17.50	20.50	24.50
L 45°	20	18.25	19.50	22.75	26.75
L 30°	20	20.25	21.50	24.75	28.25
L 15°	20	22.50	23.50	26.75	29.75
0°	20	25.00	25.50	28.75	31.75
R 15°	20	27.25	28.00	30.50	34.00
R 30°	20	29.00	30.00	32.00	35.75
R 45°	20	30.50	31.00	33.50	36.25
R 60°	20	31.50	32.00	33.75	36.25
R 75°	20	31.50	32.25	34.00	36.50
R 90°	20	31.75	32.25	34.00	36.00
R105°	20	31.50	31.75	33.50	35.75
R120°	19		30.50	33.00	35.50
R135°	9				34.50
R150°					
R165°					
180°					

20-Inch Contours





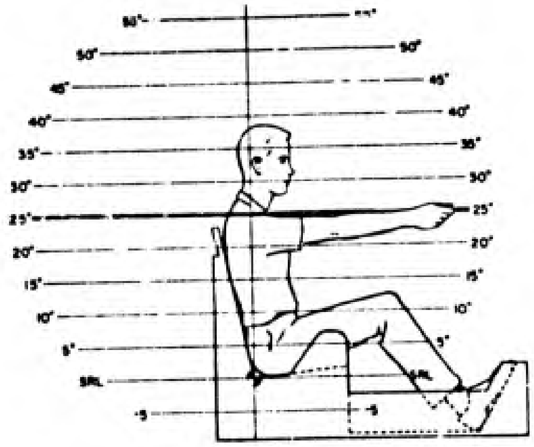
Angular Reach from SRV at the 20-inch Level

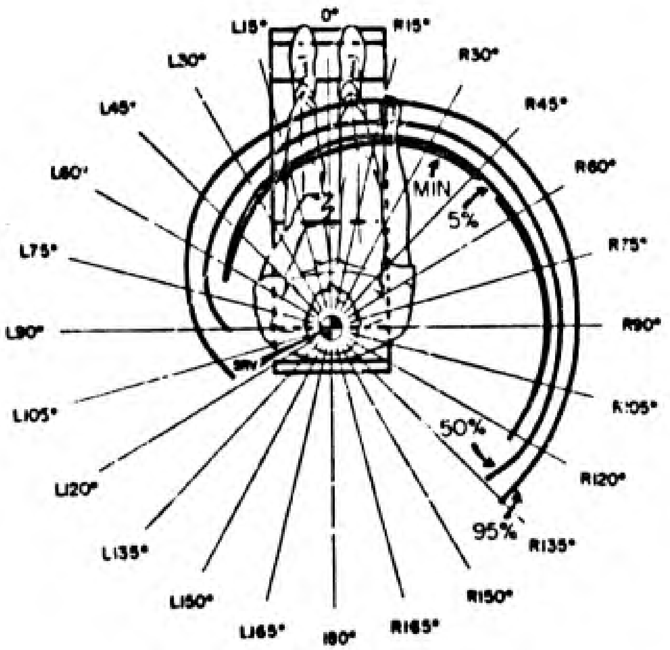
Minimum	L65° to R110°
5th %ile	L66° to R122°
50th %ile	L90° to R134°
95th %ile	L90° to R146°

Linear Data for Grasping Reach (in inches)

Angle	N	Min	5th	50th	95th
			Percentiles		
L165°					
L150°					
L135°					
L120°					
L105°	3				17.75
L 90°	12			15.75	20.25
L 75°	17			19.25	22.25
L 60°	20	17.75	18.25	21.50	24.75
L 45°	20	19.25	20.00	23.25	27.25
L 30°	20	21.50	22.50	25.00	28.50
L 15°	20	23.25	24.00	27.00	29.75
0°	20	25.00	26.25	28.50	31.50
R 15°	20	27.25	28.25	30.25	33.50
R 30°	20	29.25	30.25	32.50	35.25
R 45°	20	30.50	31.00	33.50	35.75
R 60°	20	31.00	31.50	33.75	37.00
R 75°	20	31.50	32.00	33.50	36.50
R 90°	20	31.75	32.25	33.75	36.25
R105°	20	31.25	31.50	33.50	36.00
R120°	19		30.50	33.25	35.50
R135°	5				35.00
R150°					
R165°					
180°					

25-Inch Contours





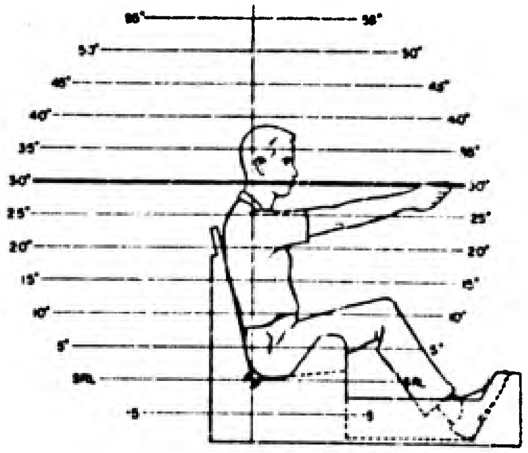
Angular Reach from SRV at the 25-inch Level

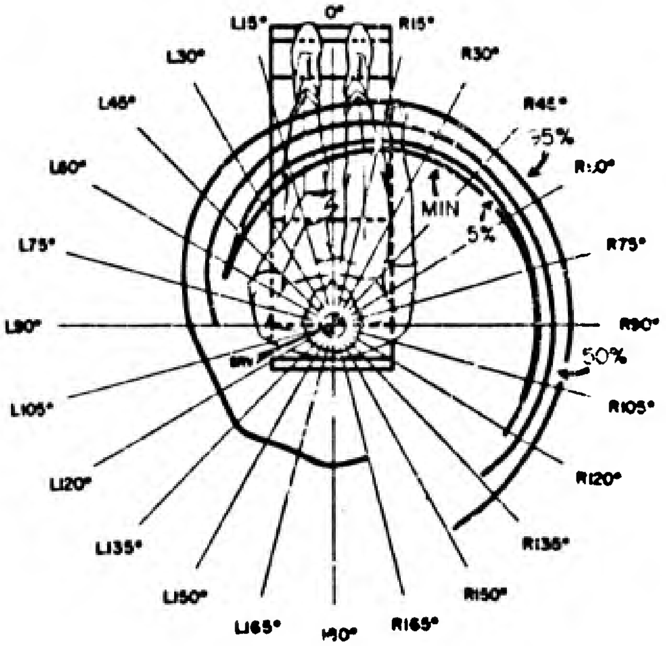
Minimum	L 66° to R111°
5th %ile	L 66° to R122°
50th %ile	L 90° to R134°
95th %ile	L115° to R136°

Linear Data for Grasping Reach (in inches)

Angle	N	Min	Percentiles 5th	50th	95th
L165°	4				18.75
L150°	4				19.25
L135°	6				20.00
L120°	7				18.75
L105°	9				19.00
L 90°	16			16.75	20.75
L 75°	18			18.75	22.50
L 60°	20	17.00	17.25	20.75	24.50
L 45°	20	18.25	19.00	22.50	26.50
L 30°	20	19.75	21.50	24.50	28.25
L 15°	20	22.00	23.75	26.75	29.50
0°	20	23.75	25.50	28.50	31.00
R 15°	20	26.00	27.25	29.75	33.00
R 30°	20	27.75	29.00	31.50	34.25
R 45°	20	28.75	30.25	32.25	34.75
R 60°	20	30.00	31.00	32.75	35.75
R 75°	20	30.75	31.25	33.00	35.50
R 90°	20	31.00	31.25	33.25	35.75
R105°	20	30.75	31.00	33.00	35.25
R120°	19		30.25	32.50	34.75
R135°	9				34.50
R150°	1				
R165°	2				19.50
180	2				20.25

30-Inch Contours





Angular Reach from SRV at the 30-inch Level

Minimum	L 67° to R111°
5th %ile	L 67° to R122°
50th %ile	L 90° to R134°
95th %ile	R165° to R149°

The 35- and 40-Inch Contours

The 95th-percentile contour is complete at the 35-inch level. At the 30-inch level, the linear distance along R165° to the 95th-percentile contour is appreciably less than that along R149° at the other side of the gap. At 35 inches the distance along 180° has increased, whereas that along R165° and R150° has remained approximately the same. As a result, a groove in the 95th-percentile contour is indicated at the 35-inch level. It begins to disappear at the 40-inch level.

The 50th-percentile contour begins, at 30 inches, essentially the same pattern of closure that the 95th-percentile boundary began at the 20-inch level. The left end of the contour plays the "active" role, while the right end remains relatively stationary. It lacks only 13° of closure at the 40-inch level.

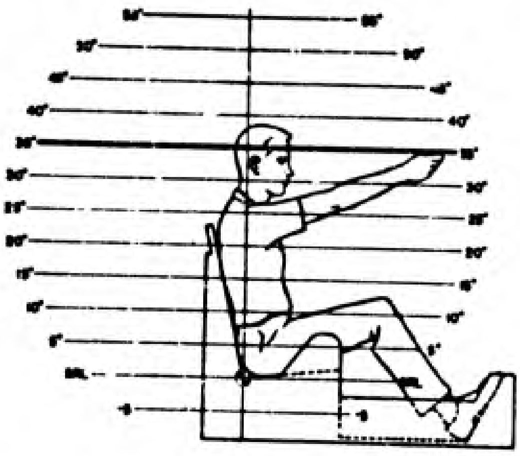
The 5th-percentile boundary appears to exhibit the same pattern of closure between the 30- and 35-inch levels, though the boundary ends remain essentially in the same positions between 35 and 40 inches.

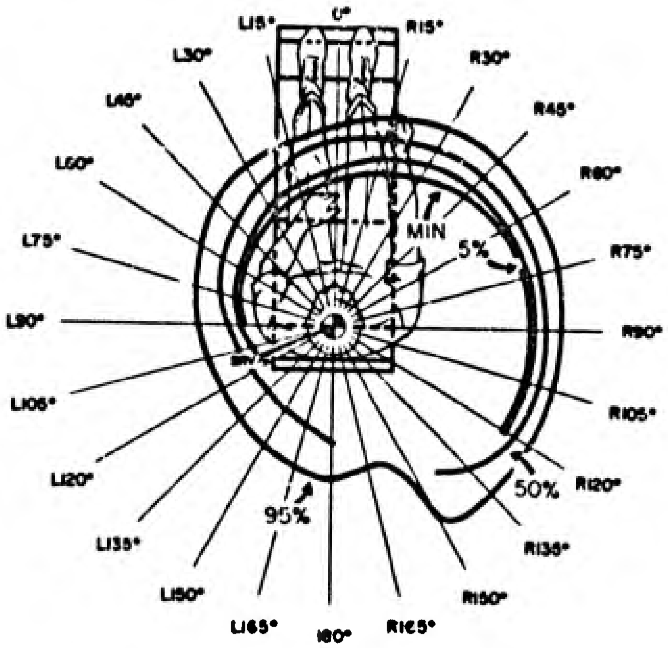
The pattern of closure of the Minimum contour is not so distinguishable, since it does not go to completion. It appears, however, to foreshadow the closure pattern at the 40-inch level.

Linear Data for Grasping Reach (in inches)

Angle	N	Min[1]	5th	50th	95th
			Percentiles		
L165°	10			14.75	21.00
L150°	12			13.75	20.00
L135°	14			13.25	19.00
L120°	19		10.75	13.25	18.75
L105°	19		12.25	14.00	18.75
L 90°	20	12.75	13.75	15.50	20.00
L 75°	20	14.25	15.00	17.25	21.00
L 60°	20	15.25	16.00	18.75	21.50
L 45°	20	16.25	17.25	20.50	24.75
L 30°	20	18.00	19.25	22.50	26.25
L 15°	20	19.25	21.00	24.75	27.00
0°	20	20.75	22.25	26.50	28.50
R 15°	20	22.75	24.75	27.75	31.00
R 30°	20	24.50	26.75	29.25	32.75
R 45°	20	26.75	28.25	30.50	33.75
R 60°	20	28.00	29.00	31.00	33.75
R 75°	20	28.75	29.50	31.25	34.00
R 90°	20	29.00	29.75	31.25	33.50
R105°	20	29.00	29.75	31.50	33.50
R120°	20	28.50	29.00	31.00	33.50
R135°	15			28.50	33.50
R150°	3				31.50
R165°	5				21.75
180°	10			16.50	22.25

35-Inch Contours





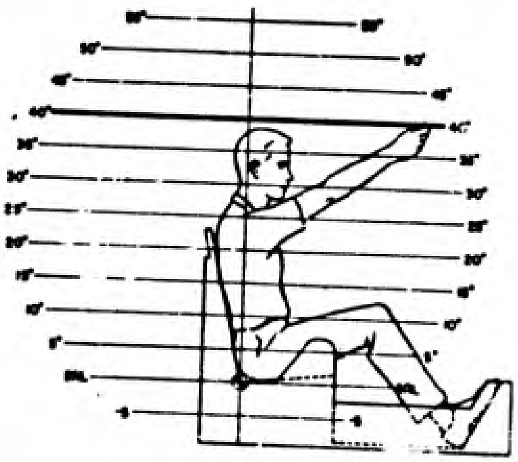
Angular Reach from SRV at the 35-inch Level

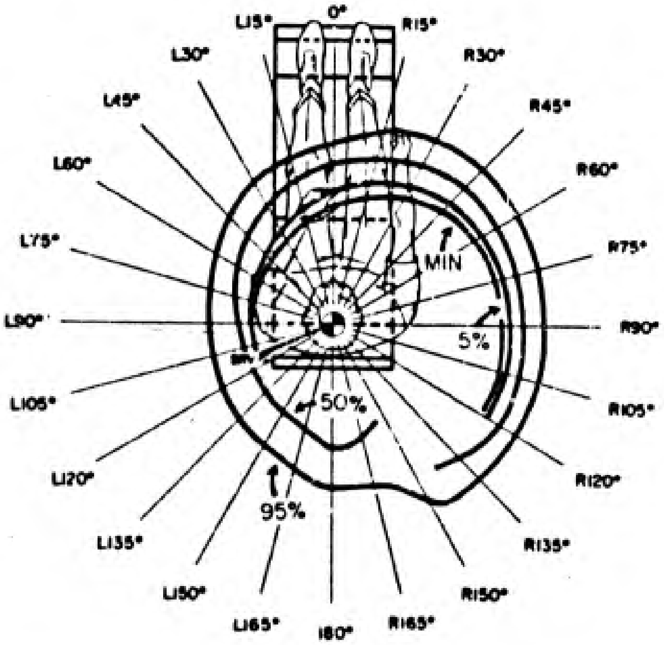
Minimum	L 90° to R121°
5th %ile	L120° to R121°
50th %ile	R178° to R143°
95th %ile	360°

Linear Data for Grasping Reach (in inches)

			Percentiles		
Angle	N	Min	5th	50th	95th
L165°	14			15.50	21.50
L150°	13			14.75	20.00
L135°	15			14.00	19.25
L120°	19		11.25	13.25	18.50
L105°	19		11.75	13.25	18.25
L 90°	20	12.00	12.25	13.75	18.25
L 75°	20	12.25	12.50	15.00	18.75
L 60°	20	12.50	13.25	16.25	20.00
L 45°	20	13.00	14.00	17.75	21.50
L 30°	20	13.75	15.50	19.50	23.50
L 15°	20	15.25	17.00	21.25	24.50
0°	20	17.00	19.00	23.00	25.75
R 15°	20	18.75	21.00	24.50	28.50
R 30°	20	21.00	22.75	26.25	30.50
R 45°	20	23.25	24.75	27.75	31.50
R 60°	20	24.25	25.50	28.00	31.25
R 75°	20	25.00	26.00	28.00	31.50
R 90°	20	25.00	26.25	28.25	31.50
R105°	20	25.75	26.75	28.50	31.75
R120°	19		26.25	28.75	31.50
R135°	16			27.00	31.00
R150°	8				29.25
R165°	10			16.75	23.75
180°	10			17.75	23.50

40-Inch Contours





Angular Reach from SRV at the 40-inch Level

Minimum	L 90° to R119°
5th %ile	L120° to R120°
50th %ile	R156° to R140°
95th %ile	360°

he 45- and 50-Inch Contours

The groove in the 95th-percentile-reach contour to the rear has, at 45 inches, ssentially disappeared. All that remains is a flattened area between 180° and 145°, where the groove was located. At 50 inches, all traces of the groove have lisappeared.

The groove in the 50th-percentile envelope which is beginning to become vident in the 40-inch contour has essentially disappeared when this reach contour raverses 360° between 40 and 45 inches.

The 5th-percentile contour closes just below the 45-inch level. Though the ap in capability at 40 inches is great, 120°, the distance from SRV along L120° is uch less than that along R120°, and there is evidence of the familiar contour attern caused by a groove in the envelope below the level at which closure occurs. he last remnant of this depression is picked up at the 45-inch level. The 5th-ercentile envelope extends to 48.75 inches above SRP. Therefore it is not epresented in the 50-inch level.

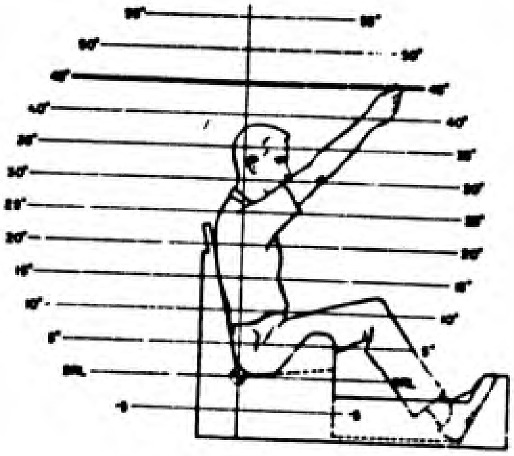
The Minimum-reach envelope shows early signs that a groove exists in its urface beginning at the 40-inch level. This is evidenced by the difference between he distances along L90° and R119° to this reach boundary. The groove appears to egin formation first in the form of a gap between L155° and R146° at the 45-inch evel. This envelope, however, extends only to 48.0 inches above SRP and is herefore not represented in the horizontal section at the 50-inch level.

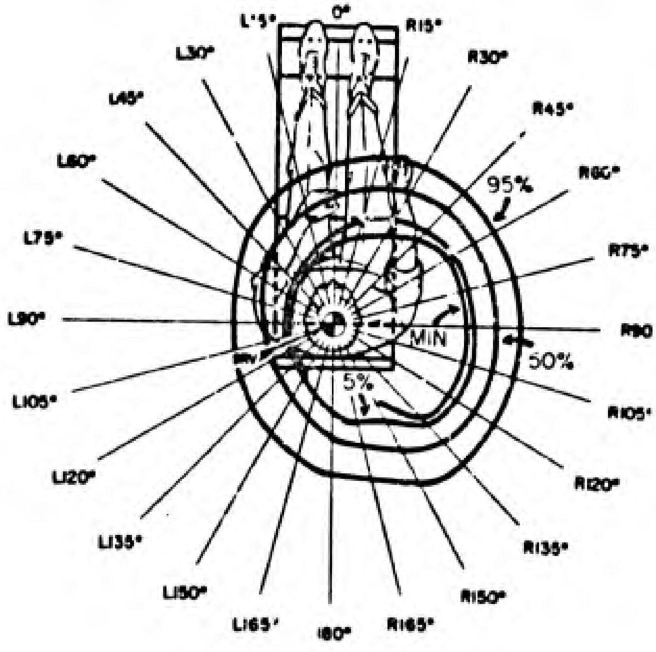
The 50th- and 95th-percentile envelope contours remain completed through the 0-inch level. The former envelope extends to 52.25 inches above SRP, the atter to 54.25 inches.

Linear Data for Grasping Reach (in inches)

Angle	N	Min	Percentiles 5th	50th	95th
L165°	19		10.50	14.00	20.00
L150°	20	8.50	8.75	12.25	18.25
L135°	20	7.50	7.75	11.00	16.75
L120°	20	7.00	7.50	10.50	15.50
L105°	20	6.75	7.25	10.25	15.00
L 90°	20	6.75	7.25	10.50	15.00
L 75°	20	6.75	7.50	11.00	15.25
L 60°	20	7.00	7.75	12.00	16.25
L 45°	20	7.50	8.50	13.50	18.25
L 30°	20	8.50	9.50	15.00	19.75
L 15°	20	10.00	11.00	16.50	21.25
0°	20	11.25	12.75	18.25	22.75
R 15°	20	13.00	15.50	20.00	24.75
R 30°	20	14.75	17.50	22.00	26.25
R 45°	20	17.25	19.00	23.50	27.00
R 60°	20	19.25	20.50	24.00	27.25
R 75°	20	19.50	20.50	24.00	27.50
R 90°	20	19.75	21.00	24.25	27.75
R105°	20	20.25	21.50	24.50	28.00
R120°	20	19.75	21.25	24.50	27.75
R135°	20	18.75	20.00	23.25	27.75
R150°	19		15.50	20.75	26.00
R165°	19		14.75	18.00	22.75
180°	19		12.75	16.50	21.50

45-Inch Contours





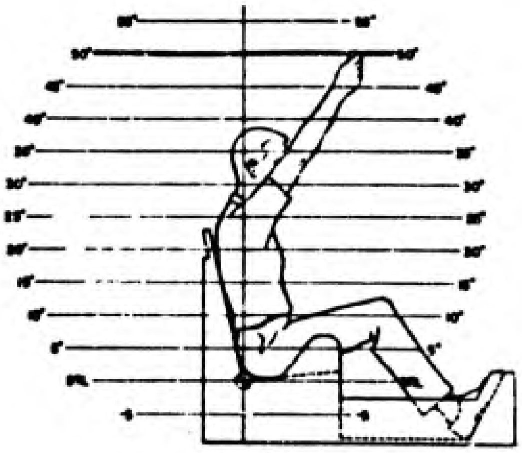
Angular Reach from SRV at the 45-inch Level

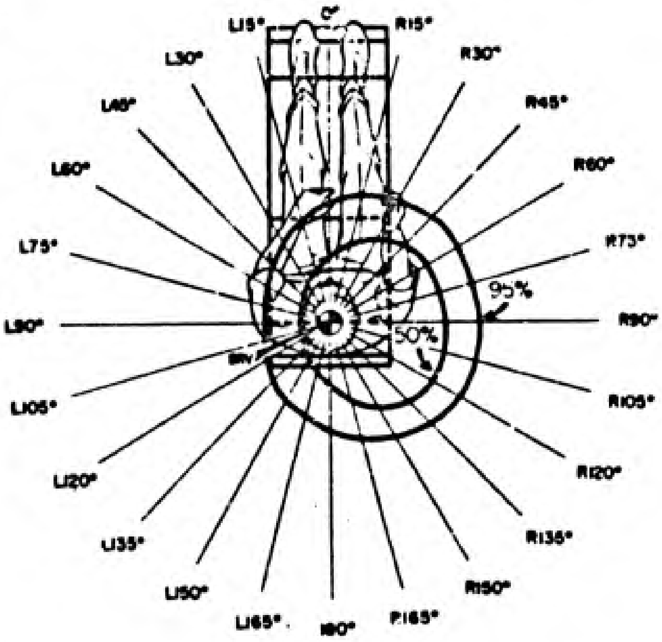
Minimum	L155° to R146°
5th %ile	360°
50th %ile	360°
95th %ile	360°

Linear Data for Grasping Reach (in inches)

			Percentiles		
	N	Min	5th	50th	95th
Angle					
L165°	17			7.50	13.75
L150°	17			6.00	13.00
L135°	17			5.00	12.00
L120°	17			4.50	10.75
L105°	17			4.25	9.75
L 90°	17			4.25	9.50
L 75°	17			4.25	9.75
L 60°	17			4.75	10.25
L 45°	17			5.25	11.50
L 30°	17			6.50	13.25
L 15°	17			7.75	15.00
0°	17			9.50	17.25
R 15°	17			11.75	18.75
R 30°	17			14.00	20.00
R 45°	17			15.75	21.25
R 60°	17			16.75	21.75
R 75°	17			16.75	21.75
R 90°	17			17.25	22.25
R105°	17			17.50	22.25
R120°	17			17.50	22.00
R135°	17			16.50	20.75
R150°	17			14.25	19.00
R165°	17			11.50	17.25
180°	17			8.75	15.50

50-Inch Contours





Angular Reach from SRV at the 50-inch Level

Minimum	- - - - - - -
5th %ile	- - - - - - -
50th %ile	360°
95th %ile	360°

SECTION VI

DISCUSSION

The two most important factors influencing the size and shape of the grasping-reach envelope are (1) the distance from the center of shoulder rotation to the tip of the thumb, and (2) the characteristics of motion of the shoulder joints. The lengths of the links of the arm and hand are responsible in part for the variable radii of the reach envelopes (see ref 7, pp 121-133). These influences, and others, should now be considered.

Because of the great flexibility of the shoulder, it is impossible to distinguish a stationary center of rotation for more than a very limited range of movement. Any joint center of the uninhibited shoulder is temporary and migrates as the shoulder performs. Dempster (ibid) charted the centers of shoulder rotation for a series of arm positions and found that no point could be considered a joint-center for more than about 10° of movement. The migration of the center of shoulder rotation makes it extremely difficult to determine the distance from the mean shoulder joint-center to the tip of the thumb at any arm position. It is convenient, then, to substitute the dimension Functional Reach for this distance. Although Functional Reach is only an approximation of the true distance, it is easily obtained and is one on which data have been reported for a large U.S. Air Force sample (ref 16).

The influence of Functional Reach on the size and shape of a reach envelope is obvious: the greater the value, the farther one tends to reach.

In any discussion concerning the mobility of the shoulder, it should be noted that references carrying the implication that the shoulder is composed of a single joint are misleading. The shoulder is comprised of four separate joints: (1) the glenohumeral, between the humerus and the scapula, or shoulder blade, (2) the scapulothoracic*, between the costal (inside) surface of the scapula and the thorax, (3) the acromioclavicular, between the lateral end of the clavicle (collar bone) and the acromial process of the scapula, and (4) the sternoclavicular, between the medial end of the clavicle and the sternum. The movements of the shoulder are a result of synchronous participation of these four joints. In elevating the arm in the medial or lateral plane, for example, movement occurs at all four joints, the most obvious movement being at the glenohumeral joint.

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*Dempster (ref 7) does not consider scapular movement in his treatment of mobility of the shoulder. The scapulothoracic joint is unusual in that the relationship between the two primary skeletal parts, the thorax and the scapula, is not of the intimate nature found in most other joints. Whereas the two primary skeletal parts of a joint such as the glenohumeral are separated by articular cartilages and enclosed by the articular capsule, these accoutrements are absent in the scapulothoracic; hence the scapula is free to glide, within limits, over the deep muscles of the back. For treatments of the mechanics of shoulder movement, see also Inman, Saunders, and Abbott (ref 22) and Steindler (ref 40).

Inman, Saunders, and Abbott (ref 22) report that during the first 30° of elevation of the arm in the frontal plane (abduction) and the first 60° of elevation parallel to the median plane (flexion), participation of the scapulothoracic joint is variable. Higher elevations, however, are invariably accompanied by simultaneous movements of the scapula. They found that when the scapula is fixed, the arm may be raised actively to the horizontal position and passively through an additional 30°. Further movement is obstructed mechanically by the greater tubercle of the humerus striking the acromial process of the scapula.

During these movements of the arm, the clavicle follows as a stabilizing strut and permits elevation of the scapula through rotation of its sternal and scapular joints. These investigators found that by manually preventing rotation of the clavicle around its long axis, the arm could be elevated in the median and frontal planes to just above shoulder level, through about 110°. Since the mean for shoulder flexion is 188° (ref 2, p 9), the result is a reduction in mobility of as much as 78°. Thus, when any of these joints is rendered inoperable, a significant reduction in mobility at the shoulder results.

It is of special interest to note that the method employed by Inman, Saunders, and Abbott to fix the scapula consisted of a harness resembling the standard Air Force crew shoulder harness and lap belt. When scapulae are jammed against the seat back and the shoulders held down by the shoulder harness, the ranges of movement for the scapulae and clavicles are reduced. Obviously, such restriction in shoulder mobility will result directly in reduced reach capability.

Other dimensions playing smaller roles in generating the arm reach envelopes are: (1) the distance between the joint-center of the glenohumeral joint and the sitting surface (for which Acromial Height, Sitting, minus 1.5 inches* is here substituted), (2) one-half the distance between the right and left glenohumeral joint-centers (approximately one-half Biacromial Diameter), and (3) the lengths of the segments of the arms and legs.

The value for Acromial Height, Sitting,† minus 1.5 inches will closely approximate the height of the joint-center of the glenohumeral joint when the arms are relaxed at the side. Since the shoulder invariably rises when the arm is brought to the forward and lateral horizontal positions, the levels at which the maximum forward and lateral reaches are attained can be expected to be somewhat higher than the center of rotation at the shoulder when the arm is down. To estimate this difference, Acromial Height was measured in the conventional manner on a series of 10 men, then with the subjects' right arms forward, and then out to the side.

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*Dempster (ref 7, p 125) found that the joint-center for the glenohumeral joint is approximately 3.5 cm (about 1.5 inches) below Acromion.

† For convenience, in future references to Acromial Height, Sitting, the term "Acromial Height (S)" will be substituted.

With the arm forward, Acromion rises approximately 1.25 inches; when in the lateral position, it rises about 2 inches. It follows that the center of rotation of the shoulder will rise by similar amounts when reaching in these directions. The individual levels of maximum forward horizontal reach, then, can be expected to cluster at about 23 inches above SRP: ie, mean Acromial Height (S) (23.24 inches) minus 1.5 inches (Dempster's estimate of the location of the glenohumeral joint-center) plus 1.25 inches (rise of the joint-center when the arm is brought to the forward horizontal position). The level of maximum lateral horizontal reach can be expected to cluster at about 23.75 inches above SRP: 23.24 inches, minus 1.5 inches, plus 2 inches (rise of the joint-center when the arm is brought to the lateral horizontal position). The data support these conclusions.

The distance between the right and left glenohumeral joint-centers (for which Biacromial Diameter is substituted) has relatively little influence on the size and shape of the reach envelope. It does, however, contribute to the lateral emplacement of the individual envelopes through a distance approximating half the variability for this dimension, or about 2 inches. With Functional Reach, this distance influences lateral reach at shoulder level by a similar amount. In determining the size and shape of the sector of the reach envelope between L30° and R120°, total arm length is, of course, very important. Variations in the lengths of the segments of the arms are relatively unimportant. Between the 15- and 35-inch contours we find a gradual shortening of the radii of the arcs beginning at L30° and R120°. At points along the reach curves where the curve radii begin to shorten, the shoulder may be considered to have rotated (adducted and abducted) maximally, and reach at angles beyond these points is gained through the mobility of the elbow and wrist.

The lengths of the lower limbs play a role of some importance in influencing the reach envelope for the seated position. At the 5- and 10-inch levels, the subjects' knees protrude into their reach envelopes and restrict movements of the hand at the 5- and 10-inch levels. The space above the knees becomes available to all subjects at the 15-inch level (see p 43).

Here it is appropriate to ask, "What anthropometric similarities, if any, can be found among those individuals whose reach capability is near the upper end of the range, and among those whose reach capability is near the lower end of the range?" Such information would be of great value in promoting a greater understanding of those body characteristics that do contribute to the size and shape of the arm-reach envelope, and likewise those that do not.

Before this question can be answered, however, it is necessary to establish the criteria that will permit us to recognize and classify greater and lesser reach capability. If we needed only to deal with capability into some limited sector of the total envelope, eg, the sector immediately forward of the shoulder, the basis for judgement would be limited to that aspect of total reach capability. Hand-operated controls, however, may be situated virtually any place within the reach envelope between L135° and R135° and at a few carefully selected locations to the rear of this sector. Therefore, we must consider reach capability into all regions of the envelope.

The reach envelopes can be thought of as having several natural areas or sectors. Reach capability forward of the shoulders and at the same level is the most important. The point thus reached can be thought of as the center of the forward sector. This sector merges at the operator's right-front with another sector which has its center at a point lateral to the shoulders and at the same level. The axis through the center of the lateral sector is orthogonal to that for the forward sector, the right arm acting as a radius with a variable center of rotation. Additional sectors may be similarly constructed to include any part of the envelope. For the purpose of dividing the total envelope into parts, however, it is sufficient to delimit two additional sectors, each orthogonal to the axes of the forward and lateral sectors. One of the latter sectors is centered vertically above the right shoulder, the other below. Mirror-images of these sectors may be distinguished for the reach envelope of the left hand.

Having described the forward, lateral, overhead and downward reach sectors for the right arm, it is possible to rank the subjects' capabilities of reaching into them. Table 2 presents a ranking of the subjects' reach distances along the axes of each sector. It is immediately noted that, although an individual ranks high in his capability in one sector, he may rank relatively low in another. Subject No. 8, for example, ranks 5th or 6th in his capability in the Downward Sector (see table 2, footnote *). In the Overhead Sector, however, he ranks 18th. Subject No. 10 demonstrated the least capability of all subjects in reaching forward, yet ranked 11th or 12th in the lateral direction (see table 2, footnote †). These inconsistencies in intrasubject capabilities result in part from real differences in reach capability and to a minor extent to differences in subject motivation. Because of them we are forced to derive an estimate of overall capability, ie, a single value with which to compare anthropometric measurements. If we could consider each of the four sectors equally important in such a determination, the overall capability could be estimated by calculating the mean of the individual subject's ranks in all sectors, and then rank these means. Such a procedure, however, would be erroneous, because the sectors are not of equal importance. With the obviously greater importance of the forward and lateral sectors, insofar as control placement is concerned, reach into them must receive greater emphasis. Of these two, the forward sector must be considered more important. Hence, to assign appropriate weight to reach capability into the four sectors, the actual distance reached toward the center of the forward sector for each subject was arbitrarily multiplied by three; the distance to the center of the lateral sector by two*; and that to the centers of the overhead and

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*Since the canopy and fuselage of fighter aircraft remove all of the reach envelope except that which is within about 15 inches on each side of the median plane, lateral reach capability, in its application to such workspaces, should not receive the emphasis given it here.

downward sectors by one each. The sum of these values, when ranked, represents an estimate of rank in overall reach. This, of course, is an example of the weights that may be assigned to these sectors for a very generalized workspace. Specific workspaces would likely require a different ranking system. In a theoretical treatment of arm reach, no sector should be considered of greater or lesser importance in such an estimate.

TABLE 2

RANKING OF REACH CAPABILITY OF SUBJECTS IN THE FOUR MAJOR SECTORS OF THE ENVELOPE, AND IN OVERALL REACH
(One is greatest, 20 is least)

Subject Number	Forward*	Lateral†	Downward‡	Overhead	Overall Reach
1	7,8,9	6	5,6	8	8
2	6	7	10	7	6
3	11,12	8	13	11	11
4	16,17	15,16	17	12	15
5	13,14,15	11,12	19	10	13
6	19	17	15	19	20
7	2	5	4	6	4
8	11,12	14	5,6	18	14
9	16,17	19,20	16	20	18
10	20	11,12	14	15	16
11	13,14,15	13	12	14	12
12	1	2	1	2	2
13	18	18	18	17	19
14	10	15,16	8	13	10
15	5	9,10	7	4	5
16	7,8,9	9,10	9	9	9
17	3	1	3	1	1
18	4	3	2	3	3
19	13,14,15	19,20	20	16	17
20	7,8,9	4	11	5	7

*Equal distances were reached in this sector by subjects 1, 16 and 20; 3 and 8; 4 and 9; and 5, 11 and 19.

†Equal distances were reached in this sector by subjects 4 and 14; 5 and 10; 9 and 19; 15 and 16.

‡Subjects 1 and 8 reached the same distance in the Downward Sector.

With the establishment of a method of ranking the subjects in terms of overa capability, it is now possible to compare anthropometrically those subjects demonstrating greater capability with those of lesser capability. To make such comparisons, five subjects with greatest overall reach and five with the least, we extracted from the sample and the mean values for pertinent anthropometric dimensions were calculated for each group. These were then compared with the means for the total sample. Table 3 substantiates what is already obvious, that i most anthropometric dimensions, the subjects with greatest overall reach capabili are larger; those with the least capability are smaller.

To gain a thorough understanding of the influences contributing to variation in arm reach capability, it is instructive to divide anthropometric dimensions into three groups, based on the nature of their influence. In group I we can list those dimensions that cannot vary without producing a corresponding variation in the siz shape or displacement of the reach envelope. In addition to conventional anthropometric dimensions, shoulder mobility must be included in this group. Those immediately recognizable are listed below.

Functional Reach
Acromial Height (S), Sitting
Biacromial Diameter
Shoulder Mobility

Variability in these dimensions affects reach capability in a different manner and t a different extent. The manner in which any one variable affects the envelope is determined by the role played by the body parts measured and also by the range of variation of that dimension. Functional Reach, for example, approximates the radius of the envelope, and hence variations in this dimension are reflected in the radius of the reach envelope. Of the linear dimensions in group I, Functional Reach has the greatest range of variation. Because of these two characteristics (direct influence and great range of variation), Functional Reach is, as we shall s the most highly related anthropometric dimension. Variations in Acromial Height (and Biacromial Diameter also directly influence the nature of the envelope, but to lesser extent than Functional Reach, and in a different manner. Whereas the valu for Functional Reach has a great effect on the size of the envelope, the values for Acromial Height (S) (approximating the center of arm mobility at the shoulder) and one-half Biacromial Diameter (approximating the lateral displacement of the cente of arm mobility) do no more than locate the center of arm mobility.

Variability in shoulder mobility also influences the size and shape of the reach envelope. As was stated previously, the point on the boundary of the reach envelope where the radius begins to shorten coincides with the angle of maximum upper arm rotation through a horizontal plane. Angular reach beyond this point is accomplished by utilizing the mobility of the elbow and wrist. The amount of subcutaneous fat deposited about the shoulders, torso and upper arm very probabl reduces mobility of the shoulder and can affect the angular displacement of this point. There is little variation, however, in the curvature of the reach boundaries beyond these points. This is explained in part by the relatively small range of variation in the lengths of arm segments.

TABLE 3

MEAN VALUES* FOR VARIOUS ANTHROPOMETRIC DIMENSIONS: COMPARISONS BETWEEN THE FIVE SUBJECTS WITH GREATEST OVERALL REACH AND THE FIVE SUBJECTS WITH LEAST OVERALL REACH

		Weight	Height	Sitting Height	Functional Reach	Acromial Height, Sitting	Shoulder-Elbow Length	Forearm-Hand Length	Biacromial Diameter	Hand Length
Five Subjects with Greatest Overall Reach	Mean	183.0	72.3	37.0	33.6	24.6	15.2	19.9	15.6	7.6
Total Sample	Mean Standard Deviation	165.8 20.62	69.56 2.63	36.33 1.36	31.95 1.52	24.16 1.70	14.42 0.62	19.03 0.74	15.71 0.75	7.55 0.23
Five Subjects with Least Overall Reach	Mean	159.6	67.0	35.4	30.4	23.4	13.7	18.2	15.6	7.4

*All values are in inches, except weight, which is in pounds.

Dimensions of group II describe body parts that play a passive role in producing variability in the size and shape of the reach envelope. A list of such dimensions would include leg segment lengths and torso breadths and depths. The amounts of body fat and muscle may be considered members of this group. Variations in the values of this group influence the size and shape of the reach envelope only by influencing the function of the body parts that play an active role in producing variability in reach. As stated previously, the height of the seated operator's knees affects the size and shape of his reach envelope. Obviously the knees of a long-legged subject will protrude farther upward into his reach envelope than those of the shorter-legged subject. In effect, a larger sector of the envelope is rendered inaccessible. In a similar fashion, the mere presence of the operator's torso within the envelope removes from reach that space occupied by it. Obviously, the presence of a large torso removes more of the envelope than does the smaller one. The effect of torso size and shape on the reach capability of the short, stocky subject is much different than on that of a tall, slender subject. It can hardly be doubted that the proportions of the torso affect the facility with which the subject can reach to the left side of his body with his right hand. He must reach around his own body; and if his torso is broad and round and his are short, he finds his torso a formidable obstacle when attempting to reach into this sector of the envelope.

In group III we find those dimensions that, due to high correlations with dimensions of groups I and II and various measures of reach capability, appear to play a role in producing variability in reach capability. Examples of these include Stature and Sitting Height. Whereas neither of these dimensions directly influences the size and shape of the reach envelope, they do correlate significantly with various measures of reach capability, and with dimensions of groups I and II.

As we have shown, reach capability into any sector of the envelope is affected by body and segment dimensions and by the capabilities of movement in the involved joints. Consideration of these as independent influences, however, will not lead to an accurate estimate of their true character. Rather, it is only through an appreciation of their combined effects that a genuine understanding can be reached.

Estimates of the relationships between selected anthropometric dimensions and various measures of reach capability can be gained by studying their intercorrelations These are reported in table 4. Relationships between anthropometric dimensions and between aspects of reach capability may also be estimated. A high correlation does not necessarily indicate a direct relationship. Therefore, caution must be exercised in the interpretation of these correlations. Only the correlations between the anthropometric dimensions of groups I or II, and the different measures of reach capability can be considered to reflect direct relationship. Artificial but significant values can be derived (by addition or subtraction of specifically defined dimensions), such as Functional Reach-plus-Acromial Height (S), Functional Reach-minus-Acromial Height (S), and Functional Reach-plus-One-half-Biacromial Diameter. Because these values are derived from dimensions of group I, they are considered to belong to that group. The high correlations between aspects of reach capability and dimensions of group III do not indicate a corresponding level of direct influence, but result from the correlations between dimensions of group III and values of groups I or II—those that do have an influence.

TABLE 4

CORRELATION MATRIX
ANTHROPOMETRIC DIMENSIONS versus MEASURES OF REACH CAPABILITY
.549 SIGNIFICANT AT THE .01 LEVEL
.433 SIGNIFICANT AT THE .05 LEVEL

	1	2	3	4	5	6	7	8	9	10	11	12	13
1. Functional Reach		.396	.294	.874	.685	.977	.746	.428	.737	.667	.831	.744	.807
2. Acromial Ht (S)	.396		.043	.791	-.397	.351	.613	.648	.379	.337	.383	.149	.494
3. Biacromial Diam	.294	.043		.172	.329	.492	.323	.372	.171	.006	.460	.130	.291
4. Funct R + Ac Ht (S)	.874	.791	.172		.245	.835	.820	.627	.724	.621	.755	.573	.800
5. Funct R - Ac Ht (S)	.685	-.397	.329	.245		.697	.258	-.086	.485	.398	.526	.625	.411
6. Funct R - ½ Biac D	.977	.351	.492	.835	.697		.756	.476	.758	.608	.862	.705	.801
7. Stature	.746	.613	.323	.820	.258	.756		.849	.826	.749	.825	.588	.880
8. Sitting Height	.428	.648	.372	.627	-.086	.476	.849		.534	.471	.556	.172	.725
9. Overall Reach	.787	.379	.171	.724	.485	.758	.826	.534		.965	.912	.921	.890
10. Forward Reach	.567	.337	.006	.621	.398	.608	.719	.471	.965		.781	.787	.799
11. Lateral Reach	.831	.383	.460	.755	.526	.862	.825	.556	.912	.781		.814	.884
12. Downward Reach	.744	.149	.130	.573	.625	.709	.588	.172	.921	.787	.814		.618
13. Overhead Reach	.807	.494	.291	.800	.411	.801	.880	.725	.890	.799	.884	.618	

Contrary to the findings of King, Morrow, and Vollmer (ref 24, p 5), repeated by McFarland, et al (ref 27, p 29), that "no significant correlation had been found between a single anthropometric measurement and arm reach," this study revealed a number of significant and relatively high correlations between such dimensions and various measures of reach capability. Functional Reach, Functional Reach-plus-Acromial Height (S), and Functional Reach-plus-One-half-Biacromial Diameter are significantly correlated at the 1% level with reach capability into all four sectors of the reach envelope. One would expect to find that the highest of these correlations would be between Functional Reach and Forward Reach. The contrary, however, is indicated. Of all the correlations involving Functional Reach with the measures of reach capability, that with Forward Reach is the lowest. The relatively low correlations of Acromial Height (S) and Biacromial Diameter with measures of the reach envelope probably result from their relatively limited range of variability which, in turn, has limited effect on reach capability. When relatively gross measurements, like those of the reach envelope, are correlated with precisely-measured dimensions of limited variability, such as Biacromial Diameter, an existing high correlation may not be revealed.

The highest correlation involving Acromial Height (S) and measures of reach capability is that with Overhead Reach. Those subjects who could reach the highest level are more likely to be those with a higher shoulder than those who reached the greatest distance downward, forward or laterally. However, the opposite situation, that those subjects who had the greatest Downward Reach have lower shoulders, does not appear to be true. Greater capability in each of these sectors seems to be primarily due to a longer arm, since in both instances Functional Reach has higher correlations.

Functional Reach-plus-Acromial Height (S) is most highly correlated with Overhead Reach. It is understandable that those subjects who can reach to the highest level are those with the highest shoulder joint-center (Acromial Height (S)) and the longest Functional Reach.

Functional Reach-minus-Acromial Height (S) is most highly correlated with Downward Reach. The distance below SRP Level that the arm extends determines the lowest level to which a subject can reach.

Functional-Reach-plus-One-half-Biacromial Diameter, as we might now expect, has its highest correlation with Lateral Reach. Since SRV is in the subject's medial plane, the distance laterally that he can reach depends on the sum of Functional Reach and half of his Biacromial Diameter.

We have seen that in three of four cases, anthropometric dimensions of group I have been found to be most highly correlated with capability into the specific sector of the reach envelope on which they most logically would have the greatest influence. Under the conditions of this study, Functional Reach-plus-Acromial Height (S) seems to have its greatest effect on Overhead Reach; Functional Reach-minus-Acromial Height (S) on Downward Reach; and Functional Reach-plus-One-half-Biacromial Diameter on Lateral Reach. Functional Reach appears to have its greatest effect on

Lateral Reach, also, rather than on Forward Reach. Lateral Reach appears most affected by Functional Reach-plus-One-half-Biacromial Diameter.

The final factor of group I to be considered here is shoulder mobility. During forward reach in the horizontal plane, full flexion of the shoulder can increase reach capability by 4 to 6 inches. Elevation of the shoulder can account for a similar increase when reaching overhead. Understandably, given two subjects with the same Arm Length, the subject with greater shoulder mobility will find that he had greater forward reach than the one with lesser shoulder mobility. For similar reasons the subject with greater capability to adduct and abduct his upper arm will probably have greater angular reach capability. From joint-range data in Barter, Emanuel and Truett (ref 2), it is possible to calculate the 5th (mean minus 1.65 SD*) and 95th percentile (mean plus 1.65 SD*) values for upper-arm abduction, adduction, and other joint movements. For horizontal adduction of the right upper arm from a saggital plane through the shoulder, a value of 33° was obtained for the 5th percentile and 63° for the 95th percentile. The point on the envelope boundary where the radius begins to shorten will be farther to the left of the median plane for the subject with 95th-percentile capability in adducting his upper arm than for the subject with 5th-percentile capability in this movement. The former subject will likely have greater reach capability to the left of the median plane. The 5th percentile for total horizontal abduction of the upper arm is 106° and 95th percentile is 162°. Again, those subjects with capability in the upper percentiles can be expected to have greater angular reach to their right rear. Although these data apply specifically to movements in the horizontal plane at shoulder level, comparable capability can be expected when the arm is at an angle above or below the horizontal.

The subject with great muscular development or heavy deposition of fat about the shoulder, chest and upper arms is likely to have less capability to adduct his upper arm than the subject with lesser amounts of these tissues. Although Fisk and Colwell (ref 11) state that this is not true†, it must be remembered that their investigation of joint mobility treated only one class of movements of the upper arm, namely rotation of the humerus about its longitudinal axis at selected elevations of the arm. In these rotatory movements of the humerus, there is virtually no interference between the tissues of the torso and the upper arm, and hence a decrement in mobility due to such opposition would not be expected. In consideration of the possible opposition of body tissues to joint movement, this one class of movements is not representative of others of the upper arm such as adduction and abduction. The

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*Distribution is assumed to be normal.

† "The development and the patient's physique had no bearing on . . . range of movement . . . at the shoulder. Coal heavers and sedentary office workers showed the same components in all movements." (p 152)

latter motions at the shoulder are by far the most important in determining the size and shape of the reach envelope. In adducting the arm across the front of the body, for example, at some point the upper arm is physically blocked in its movement by the collision of the arm with the torso, especially when these tissues are excessive.

Barter, Emanuel and Truett (ref 2) ranked the mean mobility values for twelve motions, including upperarm adduction, and related them to physique. They found that in all motions, the rotund group had the least mobility. In seven movements, there was a progressive increase in mobility from the rotund group through the muscular, median and thin groups. The rotund group had capabilities in the lower percentiles, and the thin group in the upper percentiles.

After an investigation of the movement of joints in relation to sex and constitution, Sinelnikoff and Grigorowitsch (ref 38, p 24) reported that the asthenic* type males had significantly greater mobility in their joints than did the muscular types. Also, "the movement of joints in male pyknic† types is less than in male muscular types." They also found that in those instances in which the female had less capability than males, these could be "explained by reference to fat layers in this sex."

The rotund subject is likely to be in the higher percentiles of torso depths and breadths since the correlation coefficient for Weight and Chest Depth is .757, and that for Weight and Waist Depth is .755 (ref [illegible]). We can expect, then, an inverse relationship between joint capability (ie, shoulder adduction) and certain anthropometric dimensions (ie, torso depths). This means the rotund subject will probably approximate the 5th percentile of medial angular arm reach than the opposite extreme The thin subjects are likely to have greater mobility and, consequently greater angula reach than the rotund or muscular subjects. The capability of the thin subject will approach the 95th percentile. A similar but less pronounced situation can be expecte regarding other movements of the upper arm.

Because of the tendency for high values for certain body dimensions to reduce reach capability either by limiting the mobility of certain critical joints or by rendering some of the reach envelope inaccessible, the term "5th percentile reach envelope" cannot be considered descriptive of the reach capability of the often misused "5th percentile man."

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*Asthenic (slender)

†Pyknic (rotund)

SECTION VII

APPLICATION

Anthropometric percentiles are a very useful tool to designers of workspaces and equipment. They are readily understood and applied. They provide a scale whereby the magnitude of a dimension can be immediately recognized. When one specifies the 5th percentile for a dimension, for example, he immediately announces that it is a comparatively small value, near the low end of the range of values for that dimension, and that exactly 5 percent of the total number of values are smaller and that 95 percent are larger. When considering the 95th percentile for a given dimension, we know that it is a large value, near the top of the range, that 95 percent of the population are smaller in this dimension and 5 percent are larger. These simple properties make the percentile an important factor in choosing the optimal size of any space within which man is to work, or of any equipment which is to be handled or worn. When used in an appropriate manner, accommodation for a large segment of a population can be assured.*

Let us consider typical design situations in which various percentile values are used to assure accommodation for 90 to 95 percent of the using population. In determining the optimal length of a seat pan for such a large percentage of people, the distance from SRP to the forward edge of the seat should afford reasonable comfort to most members of the using population. With the subject sitting back in the seat, his legs, in effect, wrap around the forward edge of the seat. Should the seat pan be too long, many users will experience pressures in the popliteal and calf regions of their legs. To prevent this it is necessary to use a small value (usually the 5th percentile) for Buttock-Popliteal Distance† as the basic dimension† from which the functional distance is determined. Use of this value can assure that a very large (95) percent of the population will not feel the discomfort of a seat that

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*Caution must be exercised when sizing personal equipment and workspaces to accommodate limited ranges of body dimensions. Establishing even a 5th- to 95th-percentile range for a series of 10 dimensions can reduce the numbers of an otherwise eligible population by as much as 33 percent. The designer must limit himself to those few body dimensions that are most critical.

†Buttock-Popliteal Distance: The subject sits erect, his feet resting on a surface so that the knees are flexed at right angles. The Buttock-Popliteal Distance is the distance from the rearmost point of the right buttock to the popliteal region within the angle formed beneath the knee, along a line parallel to the axis of the thigh.

†In laying out workspaces, consider the manner in which dimensions have been measured. Since anthropometric dimensions are measured on the nude subject, consider the functional change (decrement or increment) in the dimensions resulting from personal equipment (including clothing) and other components of the workspace. A functional value is determined after consideration of these factors.

is too long for the thighs. Should it become necessary to accommodate the entire using population* in the manner described, the value at the bottom of the range must be used as the basic seat dimension. In prescribing a definite distance from any hand-operated control to a point on the seat back behind the shoulder (and ultimately to SRP), when the controller is in front of and at the level of the shoulder, particular attention should be given to those prospective operators with a shorter reach. A control placed just within the reach of the small subjects will automatically be within the reach of those with greater capability. Here either the minimum or the 5th-percentile value of reach capability should be selected as the basic value from which the distance to controls in this segment of the envelope is determined. If the former is used, all the population will be accommodated; if the latter, 95 percent will be accommodated.

Examples in which the 95th-percentile value for a dimension is used as the basic value will now be considered. In fighter aircraft, the distance from SRP to the canopy, and the distance between SRP and the ejection-clearance line, must be specified so as to accept at least 90% of the flying population. If a smaller percentil is used, the percentage accommodation will be reduced below 90 percent.

Should it be required that a controller be grasped between the thumb and forefinger by the shirt-sleeved operator, the dimensions of the minimum and the 5th-percentile envelope may be used as they are given. Push-button controls may be positioned as much as 2½ inches outside the 5th percentile envelope. For information concerning muscle force capability within the reach envelope, see Caldwell (refs 3 and 4), Hunsicker (ref 20) and Pierce and Murch (ref 34).

The 50th- and 95th-percentile envelopes are of small practical value, but they do have their uses. For example, should it be necessary to locate an infrequently-operated device such as a telescope, periscope, or other instrument on a movable boom or telescoping arm within the workspace, it would be advantageous to locate it at the outside edge of all operators' reach capability so as not to interfere with other activities. When it becomes necessary to use such a device, the operator need only to reach for it, use it and return it to the perimeter of his reach capability where it is out of the way, yet available for use at any time.

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*Accommodating the entire population is not always practical from the standpoint of design or logistic economy. In equipment and systems that must be sized, whether it be personal protective gear or work areas, it is generally accepted that if the entire population cannot be accommodated without excessive cost or inconvenience provisions will be made whereby 90 to 95 percent will be accommodated. For example to accommodate the entire USAF population in fighter aircraft and capsule workspaces, the necessary ranges of adjustability in some instances would be so great as to cause severe design and engineering problems. (See Hertzberg, ref 17.)

In applying any anthropometric data, the designer must be fully aware of the conditions under which they were derived. Heretofore, investigators of arm reach have used lap belts and shoulder harnesses that were pulled taut to maintain the subject's position in the seat. The reduction in shoulder mobility under such a condition of restraint has been previously noted. Since any reduction in shoulder mobility causes a reduction in reach capability, the data so taken tend to be conservative. Although Morant and Ruffell Smith (ref 29) rightly insist that controls must be operable from the restrained position, the extent of restraint has since been considerably reduced. The shoulder harness and inertia reel, which was subsequently introduced, allows more flexibility of movement in his shoulders and, consequently, greater reach capability.

In the Handbook Maintenance Instructions, Airframe Group (ref 43, p 5) the purpose of the shoulder harness and inertia reel is stated as follows: "The shoulder harness and inertia reel are designed to prevent the crewmen from being thrown forward when the airplane rapidly decelerates or when the seat is ejected but still allow the crewmen a limited amount of forward shoulder movement in normal flight." It is further stated that in the B58, the inertia reel "automatically locks when the ejection handgrips are raised to jettison the canopy. The reel, when locked, holds the shoulder harness taut, thus preventing any forward shoulder movement by the crewmen."

Thus the inertia reel restrains the pilot's torso with either automatic or manual locking. Preparation procedures always involve sitting back into the seat before the reel is locked. After the reel is locked, the pilot finds that he still retains a reasonable amount of mobility within the shoulders.

After locking-in his inertia reel, the pilot of high performance aircraft seldom has time to manually tighten the shoulder harness so as to immobilize his torso to the extent considered essential by some investigators of arm reach. Indeed, it is not necessary. Such controls as may be used during emergency periods are few in number and are usually integrated with the ejection-seat structure.

During normal flight, the pilot is permitted complete utilization of the mobility of his shoulders, since he need not lock his shoulder harness. Even though he is capable of essentially normal arm reach at these times, controls must be situated so that he need not disturb his normal sitting posture to operate them.

The reach envelopes reported herein are intended to be used only in seated shirt-sleeve workspace situations similar to that in which the data were gathered. In one respect, they can be considered baseline data for comparison with other reach envelopes reflecting the influences on reach that result from wearing personal protective and other equipment. It is important to understand the basic mobility of the shirt-sleeved man, before there can be a proper understanding of the encumbering effects of transitory items of personal equipment.

SECTION VIII

SUMMARY

Although several investigators have described various aspects of reach capability, none has heretofore attempted to describe the complete outside boundary of the reach envelope. Emphasis in the past has been placed on the sector to the operator's right and front. Reach capability behind the frontal plane, and for the right hand to the left of the median plane, have not hitherto been ascertained. Moreover, investigators have heretofore utilized a tight shoulder harness and lap belt, or other methods of effectively immobilizing the torso. Since the pilots of modern aircraft do not experience this degree of restraint, they have more shoulder mobility; and hence greater reach capability. Thus, any data gathered under a condition of extreme torso-shoulder restraint tends to be unnecessarily conservative and inappropriate to modern flying conditions.

To correct this situation, the present study attempts to ascertain the nature of reach capability as it is affected by the shoulder harness-inertia reel restraint system. Minimum, 5th-, 50th- and 95th-percentile grasping-reach envelopes have been ascertained. The Minimum and the 5th-percentile grasping-reach envelopes are of major importance since they describe the envelopes within which 99+ and 95 percent, respectively, of the Air Force flying population have grasping-reach capability. Situating controls within the workspace in accordance with these envelopes will assure a high level of personnel accommodation. The grasping-reach envelopes have been presented in the form of horizontal sections at 5-inch intervals, beginning at 5 inches below Seat Reference Point and extending to 50 inches above it.

The two most important factors influencing the size and shape of the grasping-reach envelope are (1) the distance from the center of shoulder rotation to the tip of the thumb, and (2) the characteristics of motion at the shoulder. The functional length of the arm approximates the radius of the envelope. Variability in the length of the arm directly affects the size of the envelope. The operator with greater mobility in his shoulders will tend to have greater reach capability. Other factors that influence reach capability have been discussed also.

High values (high percentiles) in certain anthropometric dimensions tend to increase grasping-reach capability; high values in certain others tend to reduce this capability. Therefore, the term "5th percentile grasping-reach envelope" cannot be considered descriptive of the reach capability of the hypothetical "5th percentile man." It is a level of grasping-reach capability calculated to accommodate 95 percent of the Air Force population.

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APPENDIX I

MEANS AND STANDARD DEVIATIONS OF LINEAR DISTANCES FROM SRV WITHIN THE MINIMUM GRASPING-REACH ENVELOPE

		LEVEL									
		SRP	5	10	15	20	25	30	35	40	45
L165	$\bar{X}$*										
	SD										
L150	$\bar{X}$										12.36
	SD										2.83
L135	$\bar{X}$										11.44
	SD										2.77
L120	$\bar{X}$										10.67
	SD										2.69
L105	$\bar{X}$										10.54
	SD										2.70
L90	$\bar{X}$								15.70	14.49	11.29
	SD								3.17	2.34	2.73
L75	$\bar{X}$								17.57	15.83	11.78
	SD								3.03	2.61	2.86
L60	$\bar{X}$					20.97	21.63	21.04	19.03	16.99	12.75
	SD					2.54	2.74	2.79	2.95	2.63	3.09
L45	$\bar{X}$					23.50	23.73	23.14	21.08	18.28	13.80
	SD					2.49	2.61	2.63	2.92	3.04	3.08
L30	$\bar{X}$				23.66	25.34	25.63	24.83	22.85	19.86	15.23
	SD				2.91	2.10	2.15	2.40	2.81	3.10	3.47
L15	$\bar{X}$				25.74	26.88	26.98	26.30	24.54	21.49	16.65
	SD				2.67	2.01	1.96	1.96	2.24	2.59	3.47
0°	$\bar{X}$				28.58	28.65	28.86	28.13	26.00	23.01	18.43
	SD				2.47	2.12	1.97	2.10	2.26	2.62	3.19
R15	$\bar{X}$				30.54	30.60	30.81	29.99	27.66	24.80	20.11
	SD				2.23	2.12	2.10	2.07	2.56	2.59	3.15
R30	$\bar{X}$		26.13	29.38	31.60	32.34	32.10	31.11	29.05	26.38	21.35
	SD		2.07	2.07	2.12	2.00	2.00	2.07	2.20	2.60	3.54
R45	$\bar{X}$	21.95	27.53	30.36	32.31	33.06	33.24	32.25	30.39	27.64	22.83
	SD	2.45	2.04	1.98	1.77	2.05	1.77	1.99	2.01	2.33	3.48
R60	$\bar{X}$	22.33	27.55	30.74	32.39	33.26	33.38	32.29	30.55	27.84	23.48
	SD	2.12	1.75	1.51	1.77	1.51	1.51	1.68	1.32	2.15	2.49
R75	$\bar{X}$	22.25	27.64	30.68	32.55	33.41	33.55	32.63	30.38	28.09	23.81
	SD	2.35	1.71	1.46	1.58	1.48	1.40	1.57	1.78	1.87	2.38
R90	$\bar{X}$	22.06	27.23	30.48	32.21	33.39	33.33	32.71	30.98	28.05	23.60
	SD	2.38	27.03	1.52	1.82	1.51	1.54	1.57	1.69	2.01	2.79
R105	$\bar{X}$	21.64	27.03	29.98	32.05	33.04	33.40	32.65	30.86	26.35	24.18
	SD	2.22	1.70	1.49	1.39	1.80	1.58	1.56	1.78	1.97	2.33
R120	$\bar{X}$	20.40	26.14	29.31	31.23				30.34		23.74
	SD	2.04	1.95	1.55	1.68				1.88		2.18
R135	$\bar{X}$	18.86	25.41								
	SD	2.52	1.37								
R150	$\bar{X}$										
	SD										
R165	$\bar{X}$										
	SD										
180°	$\bar{X}$										
	SD										

*N=20

APPENDIX II

THE SAMPLE: SUMMARY STATISTICS AND DESCRIPTIONS OF ANTHROPOMETRIC DIMENSIONS

In investigations of this type, it is essential that the end results be applicable to the using population. To accomplish this, it was necessary to select a group of subjects whose body sizes represented the general range of United States Air Force personnel. For our purpose, 10 dimensions were selected because their contribution to the arm reach envelope was likely to be greater than most others. The values for these dimensions were obtained on a sample of 20 subjects, 9 military and 11 civilian personnel. The degree to which this microcosm represents the Air Force population (ref 16) is shown in table 5.

Illustrations and descriptions of the anthropometric dimensions used in this study may be found on pages 77 through 81.

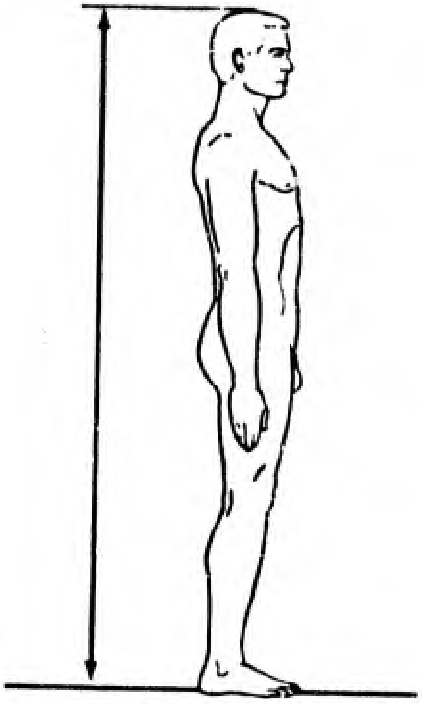
TABLE 5

ANTHROPOMETRIC MEANS AND STANDARD DEVIATIONS: COMPARATIVE DATA*

	Study Sample (N=20)		A.F. Sample (N=4000+)†	
	X	S.D.	X	S.D.
Functional Reach	31.95	1.52	32.33	1.63
Biacromial Diameter	15.71	0.75	15.75	0.74
Acromial Height, Sitting	24.16	1.20	23.26	1.14
Stature	69.56	2.63	69.11	2.44
Sitting Height	36.33	1.36	35.94	1.29
Shoulder-Elbow Length	14.42	0.62	14.32	0.69
Forearm-Hand Length	19.03	0.74	18.86	0.81
Hand Length	7.55	0.23	7.49	0.34
Weight	165.80	20.62	163.66	20.86
Age	27.90	5.41	27.87	4.22
Arm Reach from Wall	34.19	1.43	34.59	1.65
Max. Reach from Wall	38.22	1.54	38.59	1.90

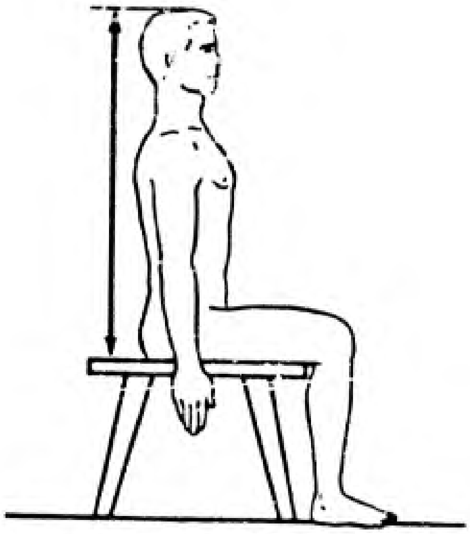
*All measurements are in inches, except for Weight and Age, which are in pounds and years, respectively.

†From Anthropometry of Flying Personnel - 1950, by Hertzberg, Daniels and Churchill (ref 16).



STATURE*

Subject stands erect, looking directly forward (head oriented in the Frankfort plane). With the anthropometer arm firmly touching the scalp, measure the vertical distance from the floor to the top of the head.



SITTING HEIGHT

Subject sits erect, looking directly forward (head oriented in the Frankfort plane), and his feet resting on a surface so that his knees are bent at about right angles. With the anthropometer arm firmly touching the scalp, measure vertically from the sitting surface to the top of the head.

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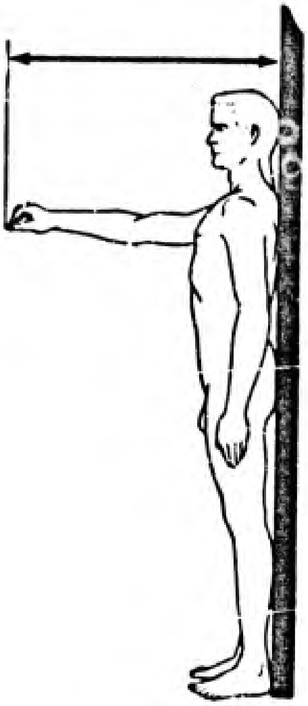
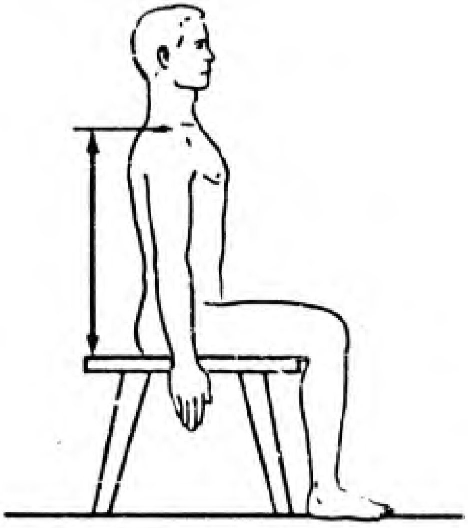
*All descriptions were taken from <u>Anthropometry of Flying Personnel-1950</u> (ibid).



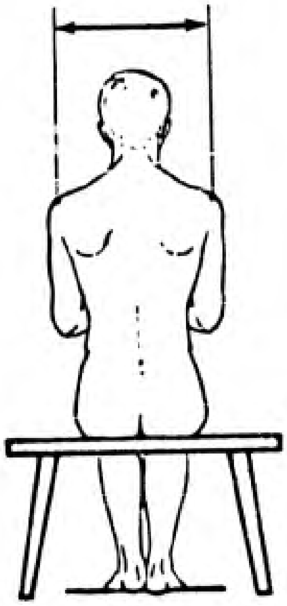


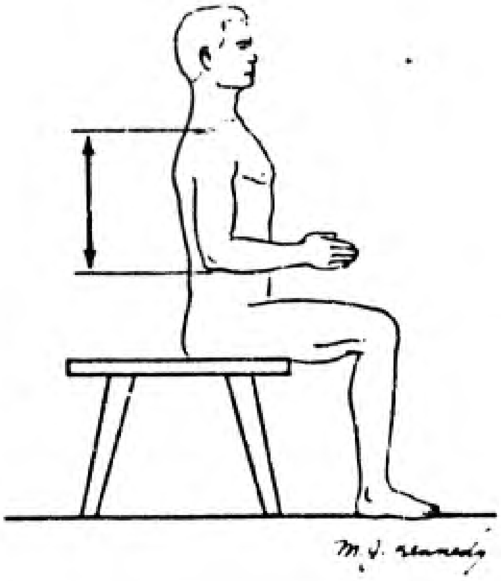
FUNCTIONAL REACH

Subject stands erect in a corner of the room, his shoulders pressed against the rear wall, his right arm and hand extended horizontally along the side wall, except that the tips of his thumb and forefinger are pressed together. Using the scale on the side wall, measure the distance from the rear wall to the tip of the thumb.

SHOULDER (ACROMIAL) HEIGHT SITTING

Subject sits erect, his feet resting on a surface so that his knees are bent at about right angles. Using the anthropometer, measure the vertical distance from the sitting surface to right acromion as marked.



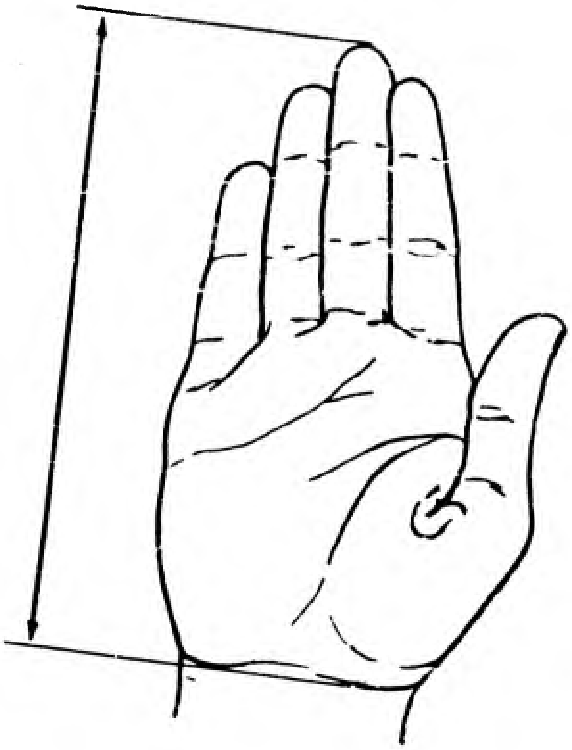


BIACROMIAL DIAMETER

ubject sits erect, his upper arms hangng at his sides and his forearms exended horizontally. Using the anthroponeter, measure between the points narked at the ends of the shoulders acromion to acromion).

SHOULDER-ELBOW LENGTH

Subject sits erect, his right upper arm hanging at his side and his forearm extended horizontally. Using the anthropometer, measure the vertical distance from right acromion as marked to the bottom of the elbow.

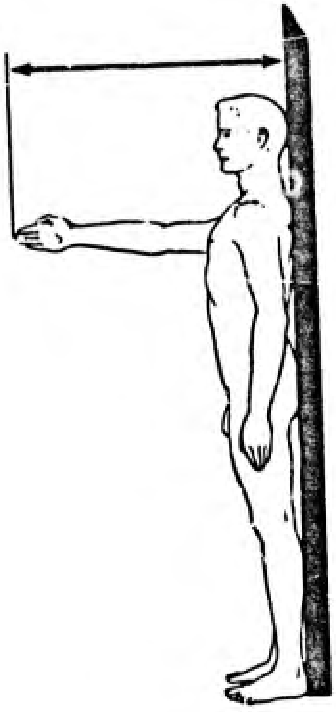


FOREARM-HAND LENGTH

Subject sits erect, his right upper arm hanging at his side, his forearm and hand extended horizontally. Using the anthropometer, measure the distance from the tip of the right elbow to the tip of the longest finger.

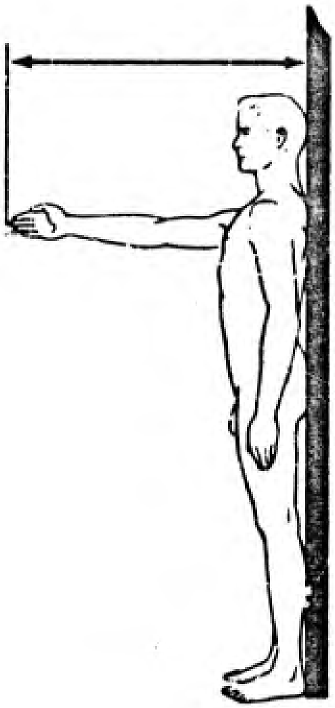
HAND LENGTH

Subject's right hand is extended, palm up. With the bar of the sliding caliper lying along his palm, measure the distance from the proximal edge of the navicular bone at the wrist to the tip of the middle finger.



ARM REACH FROM WALL

Subject stands erect in a corner of the room, his shoulders pressed against the rear wall, his right arm and hand extended horizontally along the side wall. Using the scale on the side wall, measure the distance from the rear wall to the tip of the longest finger.



MAXIMUM REACH FROM WALL

Subject stands erect in a corner of the room, his back pressed against the rear wall and his right shoulder thrust as far forward as possible, his right arm and hand extended horizontally along the side wall. Using the scale on the side wall, measure the distance from the rear wall to the tip of the longest finger.

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Security Classification

DOCUMENT CONTROL DATA - R&D

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Wright-Patterson Air Force Base, Ohio

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2b GROUP

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3 REPORT TITLE

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4 DESCRIPTIVE NOTES (Type of report and inclusive dates)

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5 AUTHOR(S) (Last name, first name, initial)

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Wright-Patterson Air Force Base, Ohio

13 ABSTRACT

This report contains descriptions of the outer boundaries of the Minimum, 5th-, 50th-, and 95th-percentile grasping-reach envelopes of seated, shirt-sleeved operators. The two most important are the Minimum and 5th-percentile envelopes. These envelopes have been calculated to permit 99+ percent or 95 percent of the Air Force population, respectively, to reach any point at their boundaries. The report contains a critical resume of previous investigations of arm reach, and a description of the AMRL Grasping-Reach Measuring Device. The data-gathering and statistical procedures are included, and applications of the reach envelopes are discussed. Horizontal contours representing the outer boundary of the Minimum, 5th-, 50th-, and 95th-percentile grasping-reach envelopes are presented for each 5-inch level beginning at 5 inches below SRP (Seat Reference Point) and extending to 50 inches above SRP. The Minimum envelope extends from 2.5 inches below SRP to 48 inches above; the 5th-percentile envelope from 4 inches below SRP to 48.75 inches above. Horizontal distances from SRP to the boundary of each envelope are given at 15° intervals.

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