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THE MANUAL WORK SPACE OF THE UPPER EXTREMITY AMPUTEE

A DISSERTATION

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THE MANUAL WORK SPACE OF THE UPPER EXTREMITY AMPUTEE

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CHAPTER I

INTRODUCTION

The loss of an extremity results in a great deficit in motor activity for the individual. He is restricted in ambulation, in his selection of an occupation and in recreation. He experiences difficulty in being accepted by a society that considers him as handicapped. The prosthesis is intended to replace this loss. However, even with a prosthesis the full range of motion of the normal extremity can not be matched. In the leg, the functions of weight bearing and locomotion are more easily replaced by a prosthesis than are the great numbers of motor activities that are accomplished by the normal hand.

Evidence of the first known amputee was found in Iraq in 1957. A skeleton, found by the Smithsonian Institute, was from an individual estimated to have lived 45,000 years ago (Wilson, 1963). The upper extremity showed a below elbow amputation which had occurred many years prior to death (Furman, 1962).

The earliest record of a prosthesis in use was described in the history written by Herodotus <u>circa</u> 484 B. C. (MacDonald, 1905; Garrison, 1916; Wilson, 1963). A Persian soldier named Hegesistratus, imprisoned in the stocks, escaped by amputating his own foot. According to the author, he later procured a wooden foot.

The oldest artificial limb that has been discovered was found in a tomb in Capua, Italy, in 1858. It was thought to have been made about 300 B. C. (Popp, 1939). This prosthesis, a leg, was destroyed during the bombing of the Royal College of Surgeons in London in World War II. The oldest artificial hand, is the Alt-Ruppin Hand which was unearthed in 1863. It dates back to 1400 (Garrison, 1916; Putti, 1925; Wilson, 1963).

Prostheses in the Renaissance were made of iron and used by knights. For example, an iron hand was made in 1504 for Goetz von Berlichingen (MacDonald, 1905; Garrison, 1921; Gourdon, 1924; Putti, 1925; Popp, 1939). Knights wished to conceal their mutilations and possible weaknesses. Their armorers thus became artificial limb makers. In 1529 Ambroise Paré described such an arm made of iron (Paré, 1840). Ambroise Pare was the most celebrated surgeon of this period of history. In his capacity as a French army surgeon during the Italian campaigns, he was able to modify the surgical techniques of amputations by using ligatures to stop the bleeding of blood vessels. He became directly responsible for increasing the number of individuals recovering from amputations. Paré, who was also interested in fashioning a lighter weight prosthesis, directed the fabrication of an artificial arm from tin.

Making an artificial limb which is suitable for cosmetic purposes does not present many difficult problems. However, developing a prosthesis which will take over functions of the normal limb presents an unending array of complications. In 1692, Lamzweerde constructed an artificial arm in which the fingers moved synchronously with motions at the elbow (Garrison, 1916). However, it was not until 1836 that Caroline Eichler devised an artificial arm that provided some function for activities such as sewing and writing (MacDonald, 1905). In 1844, Van Peetersen demonstrated before the Academy of Sciences in Paris a bilateral amputee who could perform complicated movements with a pair of artificial arms.

In the late nineteenth century prostheses were constructed that allowed movements through the use of straps and rings connected to the shoulder. Count de Beaufort (1867) devised an above elbow prosthesis in which the thumb was connected by a string to the hip. In 1877, Oscar Dalich manufactured a hand with an intrinsic mechanism which allowed finger movements (MacDonald, 1905).

In 1896, Vanghetti formulated the idea of connecting the mechanism of control of a prosthesis to a muscle (Wilson, 1963). The first surgery to accomplish this (cineplasty) was actually done by Ceci of Pisa in 1900 (Ceci, 1906). Sauerbruch, in 1917 according to Wilson (1963), was first to make a skin tunnel through a muscle for prosthetic purposes but this procedure was not introduced into the United States until 1939 by Dr. Henry Kessler (Furman, 1962). These techniques were greatly refined by Dr. Charles Bechtol (Furman, 1962).

Wars have always caused great loss of limbs. The first use of artillery at Crécy in 1346 resulted in increased numbers of amputees. The War of 1812 with Great Britain stimulated research on lower extremity prostheses. James Potts of London introduced the use of wood in the manufacture of prostheses for English amputees of this conflict. The Civil War (1861-1865) in the United States, which resulted in increased numbers of amputees, saw the formation of several of the first artificial limb companies. After World War I (1917-1919) research into prosthetics was stimulated with the establishment of the Surgeon General's Conference on Artificial Limbs in 1917. During World War II the first prosthetic research center was established by the Navy in 1943. In 1945 the Army Prosthetic Research Laboratory was formed. In 1948, further impetus to research was given by the passage of Public Law 729 which authorized the expenditure of one million dollars per year for artificial aids. In 1954, Congress passed Public Law 565, the Vocational Rehabilitation Ammendments Act. This permitted the Department of Health, Education and Welfare to pay for costs of research into prosthetics and training of the physically handicapped.

Amputations have also become more frequent with progress of modern high speed transportation and the introduction of more complicated high speed machinery into industry and agriculture. Advancements in operative techniques plus the introduction of aseptic surgery and anesthesia have resulted in higher rates of survival.

Interest in the surgical techniques of amputation, started by Paré in the sixteenth century, has not waned (Dupertius and Henderson, 1946; Jones and Ryan, 1946; White, 1946; Loon, 1960; Hall and Bechtol, 1968). The search for some external power to operate the prosthesis has also produced much experimentation (Livingstone, 1965; McKenzie, 1965; McLaurin, 1965; Wilson, 1965). The concept of myoelectric control of the prosthesis was particularly fruitful in creating many new ideas and adaptations (Kuitert and Vultee, 1954; Battye et al., 1955; Kobrinski, 1960; Bottomley, 1964; Popov, 1965).

Modifications of the prosthesis itself have been developed through research on terminal devices (Fishman and Berger, 1955; Fishman and Kay, 1964), cosmetic gloves (Dembo and Tane-Baskin, 1955; Carnelli et al., 1955), harnesses (Pursley, 1955; McLaurin and Sammons, 1963), and cables (Northrop Aviation, 1950). Work has also been done to find aids to help the amputee perform certain tasks (Smith and Fisk, 1963; Friedmann, 1965; Field, 1968).

Research has dealt with many problems of the amputee. Much statistical information has been collected as to the number, types, ages, and sex of amputees (Berger, 1958; Lambert and Sciora, 1959; Glattly, 1963). Other research has been concerned with their vocational efforts (Dietz, 1932; Shepherd and Caine, 1968) and their psychological adjustments (Randall et al., 1945; Hughes and White, 1946; Whittkower, 1947; Vultee, 1955; Dembo, 1956; Siller and Silverman, 1958).

Some studies have been completed concerning the actual functioning of the prosthesis. For example, in a study by Peizer (1958) amputees were evaluated on their abilities to perform normal everyday activities with their prostheses. In a study by Lambert and Sciora (1959) amputees were rated as to whether they had good, fair, or poor use of their prostheses.

Investigations into work space have evolved from engineering problems created by technological advances brought about by the machine age. Time and motion studies were started by Gilbreth at the end of the nineteenth century (Gilbreth, 1911). As a result of this research, engineers began to recognize the human factors in engineering.

Anthropological inquiries turned from determining simple body measurements (Gilliland, 1921; Glanville and Kreezer, 1937) to changing the design of the machine to accommodate both its purpose and the man who would operate it (Hugh-Jones, 1946; Randall et al., 1946; Darcus and Weddell, 1947; Morant, 1947; McFarland, 1951; King, 1952; Dempster, 1955; Dempster et al., 1959).

The field of athletic research has contributed the techniques of photography to the analysis of motion. Muybridge (1887) who investigated all types of normal motions and Marey (1895) who studied athletic motion were two pioneers of these techniques. Demeny (1902) used lights to analyze the abnormalities found in walking. By taking photographs in quick succession, he was able to obtain a path of the trajectories of locomotion.

Photographic methods were utilized by Gilbreth (1911) in an analysis of the fundamental elements of a series of motions which are used in performing a specific task. He used a motion picture camera which recorded the paths of lights attached to the moving subject. Dempster and his coworkers (1955; 1959) and Rozier (1970) adapted the methods of Demeny and Gilbreth to analyze manual work space. They attached lights to the arms of subjects and took time exposures of the light path as the subject moved his arm.

Anthropologists have developed the concept of manual work space as being the maximal volume that can be utilized for the operation of controls. King et al. (1947) measured the extreme anterior arm reach at different angles and levels. Barnes (1951) defined the manual work space as being determined by an arc made with the arm pivoted at the shoulder and with the hand sweeping across a table, but he did not recognize the three-dimensional aspects of the work space. Dempster <u>et al</u>. (1959) found the three-dimensional manual work space which he termed the kinetosphere. Rozier (1970) has described the three-dimensional manual work space with the scapula restricted.

Relatively little research has been carried on concerning the manual work space of the upper extremity amputee. Keller <u>et al</u>. (1947) employed a three-dimensional analysis of specific motions performed with the prosthesis and Kay and Peizer (1958) utilized a positioning test to determine the movements in which the prosthesis could be used to greatest advantage. A three-dimensional analysis of the entire work space has not been completed. Therefore, it has not been possible to design functional working areas for the amputee without these data.

The shape of the manual work space of the amputee with a prosthesis has not been defined. It is not known how the work space of the normal extremity differs from that of the extremity with the prosthesis or how the work space differs between above and below elbow amputees. It is the intent of this study to lay a basis for the definition of the limits of the three-dimensional work space of the upper extremity amputee. The basic differences between the work space of the above elbow and the below elbow prosthetic limb can then be visualized. The disability can also be assessed in terms of reduction in work space when compared to the normal extremity. Shifts in occupation may not be necessary for many amputees if more is known about their space limitations for motor activity.

CHAPTER II

MATERIALS AND METHODS

Materials

Twenty white male upper extremity amputees were selected from the general population. Eleven of the subjects were below elbow amputees and nine of the subjects were above elbow amputees. These subjects were volunteers. They either responded to letters asking for volunteers or they were asked to volunteer when they were present at various Oklahoma amputee clinics.

The equipment that was used in this study is shown in Figure 1. It will be helpful to refer to this figure when reading about equipment mentioned in the following paragraphs. Figure 1a shows the experimental chair and footrest. Figure 1b shows the mirror and frontal grid in relation to the chair and footrest. Figure 1c shows a subject performing a motion. Figure 1d shows the hand grid. The arrangement of this equipment is shown in Figure 2.

A wooden chair was devised for seating the subjects when the work space measurements were taken. Its seat dimensions were selected according to recommendations of Barnes

Figure 1. Experimental equipment and experiment in progress. A. A side view of the work chair and footrest. Note the position of the adjustable headrest. B. A front view of the equipment. A mirror is positioned at a forty-five degree angle with the chair. The footrest is placed directly in front of the chair. A stand suspends the frontal grid and a tape measure is attached to the floor at the side of the chair. The number on the footrest identifies the experimental subject. C. Front view of the subject completing an interval. The mirror provides the side view of the subject. D. Close-up view of the hand grid. The wrist is in the neutral position. Note the position of the light opposite the interphalangeal joint of the middle finger of the left hand.

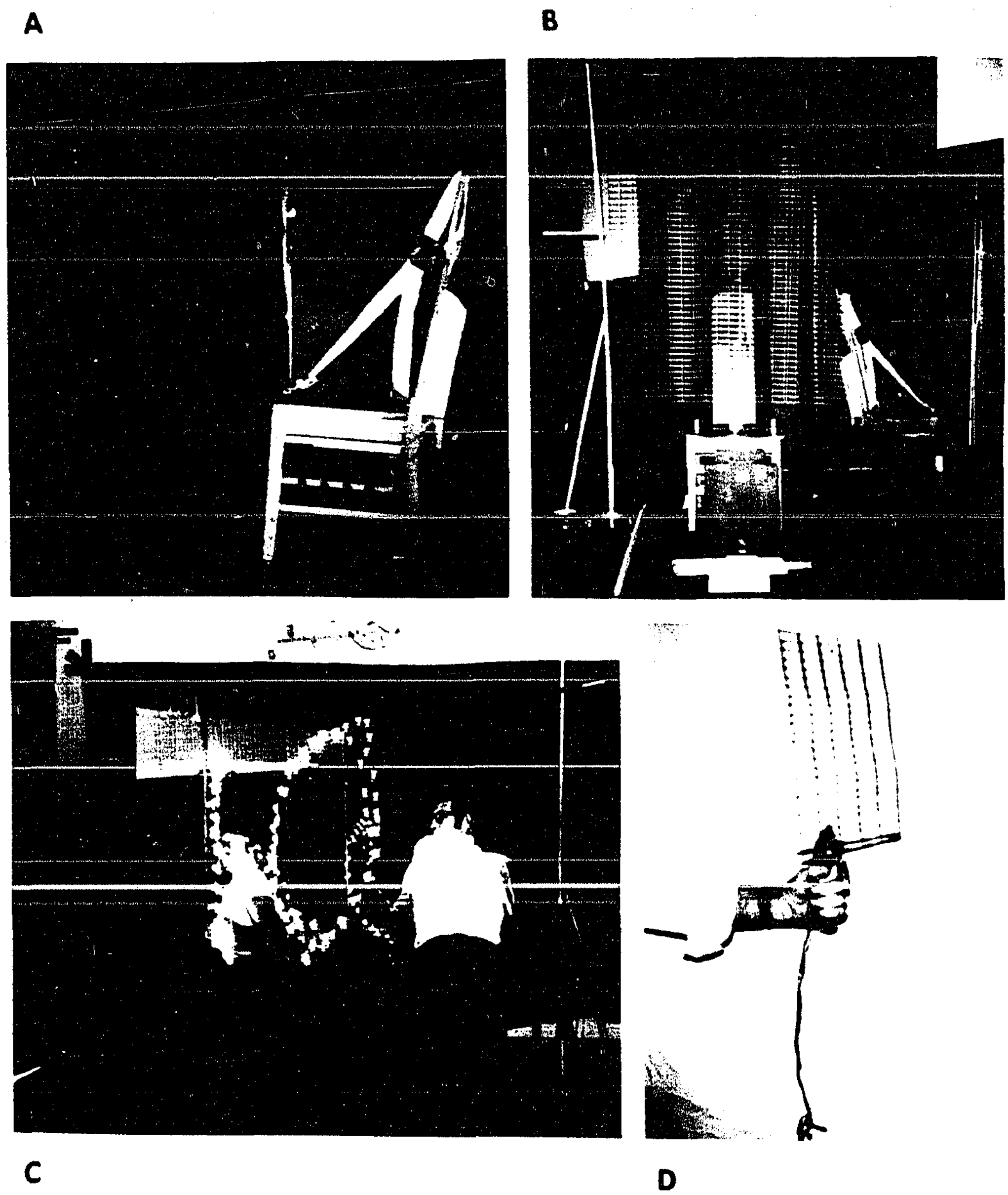


FIGURE 1

Figure 2. Diagrammatic view of experimental equipment in place. a. Work chair. b. mirror. c. frontal grid. d. footrest. e. electrical equipment for light system. e. camera. g. strobe light.

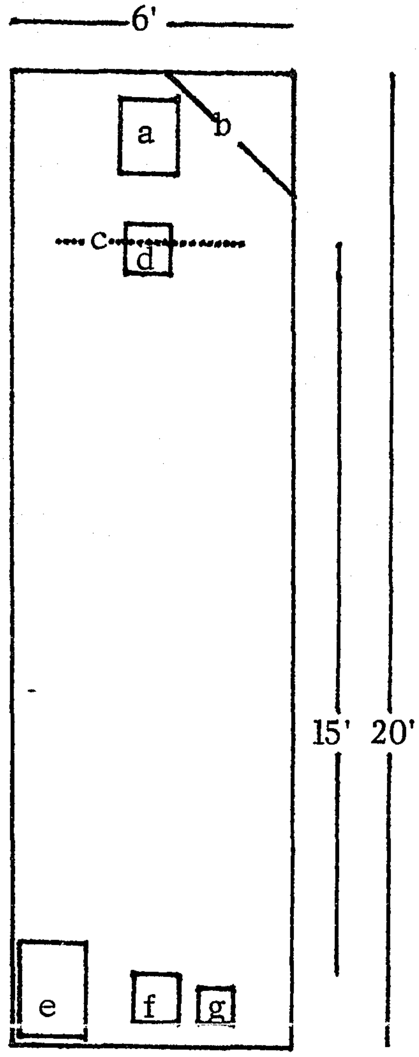


FIGURE 2

(1951). The seat measured fifteen inches in width by seventeen inches in length. This shallow seat permits the body to bend at the hip and not at the waist. It also does not impede the circulation of the blood near the knees. The back of the chair measured twenty-six inches in height by eleven inches in width. It was narrow so that the scapula and elbow were not impeded in movement. It inclined posteriorly to seventeen degrees as in the studies of Dempster et al. (1959) and Rozier (1970). The headrest of the chair held the head firmly and restricted movement of the subject. It was adjustable in forward, backward, up, and down directions to accommodate individual differences in height and girth.

The footrest was made of wood. It was placed in front of the chair and was adjustable in height. The position of the footrest was changed with each subject to insure that the legs were in the same position regardless of differences in leg length.

The frontal grid, over which the subject moved his hand or prosthesis, provided a fixed standard of reference for measurements made from the photographic negatives. It was made of one inch by two inch wire mesh, and cut in four strips measuring one foot by four feet. The grid was suspended from a horizontal bar which was attached to a movable stand. The height of the bar was adjustable and the stand was fitted with casters which permitted it to be moved easily. The grid was easily assembled and photographs could be taken through it.

The mirror was four feet square. This was large enough to give an image of the subject and his movements. The stand for the mirror was also fitted with casters which permitted it to be moved. The mirror afforded the important side view of the subject.

The hand grid furnished a flat surface which was moved in a parallel relation to the surface of the frontal grid. It was made of a square foot of the one inch by two inch wire mesh. The grip was made of wood which had been carved in a set position to insure that the hand grid was held in the same way by each subject. The hand of each subject grasped the grip in a position similar to that of the hand at rest when the arm is supported in a horizontal manner. This is called the neutral position. The hand grid was attached vertically above, and one inch in front of the holder. This allows for clearance between the knuckles and the frontal grid. It is absolutely necessary for the subject to hold the grid upright, keeping his wrist in the neutral position at all times.

The wooden hand grip could not be held in the prosthesis. Instead, a metal holder was made of a flat piece of metal two inches in length. A light was attached to the end of this holder. This holder could be held by the terminal device of the prosthesis.

A system of lights, composed of four 1/25 watt neon bulbs, was arranged in parallel and connected to a circuit. The circuit was intermittently broken causing the lights to flash. The rate of the flashing of the light could be changed to accommodate various speeds of movement of the subjects.

The following photographic equipment was used in obtaining photographs of the subjects. A 35 mm single lens reflex camera, manufactured by the Minolta Corporation, was attached to a tripod which was placed at a height of three feet. Plus X Pan film (ASA 125) gave fine grain negatives which could be enlarged without losing quality. The strobe light used was a Braum self-contained 110 volt unit. The enlarger was a Leitz Focomat Ic which allowed suitable enlargement of the 35 mm negatives to 1/6 natural size.

A straight arm goniometer was used to measure knee and hip angles when positioning the legs of the subjects on the footrest. A metal tape measure was used to record arm length and a cloth tape measure was fixed to the floor beside the chair as a guide to use when moving the frontal grid in relation to the subject. A Keuffel and Esser polar planimeter with a fixed tracer arm was used to record areas of tracings of movement patterns.

Methods

The experimental techniques used in this investigation were based on the research of Dempster and co-workers (1955; 1959) and Rozier (1970).

Experimental Equipment

The equipment was set up in a space twenty feet long by six feet wide. The walls adjacent to the equipment were covered with black plastic to provide a dark background and to prevent reflection. The chair was positioned at one end of this space, fifteen feet from the camera. The footrest was placed directly in front of the chair. The mirror was positioned at a forty-five degree angle to the left side. The frontal grid was placed perpendicular to the floor with its stand positioned to the side of the chair. This stand was moved at specific six inch intervals along a tape measure glued to the floor.

Measurements of Subjects

Measurements on each subject included height, weight, normal arm length, prosthetic arm length and length of stump. Joints of the upper extremities were examined for normal range of motion. The type of prosthesis was noted as well as the length of time that the subject had used the prosthesis.

A metal tape measure was used to measure normal arm length. This is the distance in inches from the acromion process to the distal interphalangeal joint of the middle finger. The length of the prosthetic arm was also measured.

This is the distance in inches from the acromion process to the end of the terminal device. The length of the stump was measured from the anterior border of the acromion process to the end of the humerus in the case of the above elbow amputees and from the olecranon of the ulna to the bony tip of the stump in the case of the below elbow amputees.

The subject was seated in the chair facing directly forward with the feet on the footrest. Using the goniometer the hips were positioned at a seventy-five degree angle and the knees were positioned at an 160 degree angle. The resting arm was placed at the side in a position that did not interfere with movement of the other extremity.

Experimental Procedure

When measuring the work space of the normal extremity the subject held the hand grid in his hand with the lights taped in position. The first light was secured over the proximal interphalangeal joint of the third finger. This was determined to be the center of the grip by Dempster *et al.* (1959). This point was used rather than the tip of the finger because the controls in a work space ordinarily cannot be operated at the end of the finger tips (King *et al.*, 1947). A second light was taped directly over the olecranon to show movement at the elbow. A third was taped over the acromio-clavicular joint to show movement of the scapula. According to Taylor and Blaschke (1951), there is only .25

inches of skin and flesh superficial to the acromio-clavicular joint. Also, there is little skin movement to disturb the relationship of the light to the joint. A fourth and final light was taped over the jugular notch of the sternum. This light was used to determine excessive movement of the trunk.

The subject was instructed in the proper procedure before beginning the experiment. The headrest was adjusted to fit the subject and the subject was instructed to refrain from moving the trunk laterally or forward. He was told to hold the hand grid in the same orientation without changing the way in which his hand was positioned on the hand grip. He was instructed to maintain the hand grid at a distance no greater than three inches from the frontal grid. He was to move the hand grid first in a full clockwise circle and then in a counterclockwise circle in the extremes of movement possible. Lateral rotation of the head was permitted to enable the subject to observe his hand motion. A trial movement was allowed and any mistakes or extraneous movements which were observed were corrected.

The experimental procedure was then begun. The room was darkened except for the lights attached to the subject's arm and body. The frontal grid was first positioned at the extreme anterior reach of the arm while the arm was at ninety degrees of forward flexion. A time exposure photograph was taken of the movement of the arm. A strobe light was flashed once during each exposure. This provided an image of the subject on the film. The frontal grid was repositioned at six inch intervals, moving it closer to the subject. The whole sequence was repeated at each interval. The grid was raised when necessary to give adequate clearance for the knees. Sections of the grid were removed when necessary to avoid contact with the trunk at positions close to or posterior to the subject.

The entire procedure was modified and repeated for the prosthetic extremity. The first light was secured in a metal holder which the subject held in the terminal device of his prosthesis. This light corresponded to the light over the proximal interphalangeal joint of the normal hand. A second light was taped at the elbow joint at the olecranon in the case of the below elbow amputee and at the joint of the prosthesis in the case of the above elbow amputee. A third light was placed over the jugular notch of the sternum. The light on the acromion could not be positioned due to interference with the shoulder harness of the prosthesis. The subject was instructed to grasp the metal holder in his terminal device in such a way that the holder and light were at right angles to the frontal grid. Other instructions remained the same as for the normal extremity.

In both the above and the below elbow groups of amputees the subject closest to the mean was chosen as well as the subjects with percentage differences on either extreme from the mean. The data from these subjects were used to make superimpositions of the interval tracings. The data were also used to make styrofoam models of the three-dimensional work space (Appendix). Tracings were then made from the styrofoam models in order to make drawings of frontal, horizontal and sagittal sections through the work spaces. Balsa wood models were also made of the work spaces of the above and below elbow amputees with the percentage difference values closest to the mean (Appendix).

Analysis of Photographic Measurements

The film recording of the light paths was developed by the usual photographic chemicals in the prescribed manner. The negatives were then projected in an enlarger to 1/6 natural size of the subject. Tracings were made of the paths of the light which was attached over the third finger. An orientation point was marked on each tracing which corresponded to the mid-point of the junction of the back and the seat of the chair. Dempster et al. (1959) called this point the "R" point. A line was also drawn marking a horizontal level at the shoulders. The "R" point and this stationary line were used as orientations when superimposing one tracing over another.

The tracings showed two circles, one representing the clockwise path and the other representing the counterclockwise path. A line was drawn between the two circles to represent the mean area tracing. Planimeter readings were then made on each tracing to find the area of the outline in square inches. A total of three tracings was made of each outline and then this sum was divided by three to obtain the mean or average area. In certain cases the outline was too large to be circumscribed at one time. This outline was divided into two parts, planimeter readings made, and the readings added. In all cases the area measurements were multiplied by six to return them to full scale, and then multiplied by six inches to find the volume of each interval in cubic inches. The full scale volumes of all intervals for a single subject were added to give the total work space volume. The above procedures were followed using the data obtained from the tracings taken from the normal arm and for the prosthetic arm.

Statistical Treatment

The difference in the normal and the prosthetic volumes was found and converted to a percentage difference in order to be able to compare differences among subjects. The means (averages), medians (middle values), standard deviations (variations from mean), and coefficients of variation (variability) were calculated for all measurements. The mean is generally the most reliable or accurate measure of central tendency (Guilford, 1956). The median was also found to indicate the skewness of the distribution. The standard deviation indicates a reliable degree of variability. The coefficient of variation indicates the existing variation in a series of data. It is equal to one hundred times the standard deviation, divided by the mean.

A Spearman rank correlation was worked out relating the normal volume to the difference volume, prosthetic volume, age, height, weight, stump length, time worn, and prosthetic extremity length. A second rank correlation coefficient was done correlating the prosthetic work space volume with the remaining data. A third rank correlation was done relating the difference volume to normal volume, prosthetic volume, age, height, weight, stump length, time worn, and prosthetic extremity length. The rank correlation coefficient is used here because, although there may appear to be a dependency between two variables, the distribution is unknown and there can be no assumptions made about population distributions.

According to Yamane (1967) Spearman's rank correlation coefficient is found with the formula:

$$r_s = 1 - \frac{6\ Ed^2}{n\ (n^2 - 1)}$$

The symbol "r_s" stands for the Spearman rank correlation coefficient. The symbol "E" means "the sum of", "d" is the difference between the ranks of the two numbers, and "n" stands for the number in the sample.

The Wilcoxin-Mann-Whitney u test was calculated to find the significance in the percentage differences determined for the left versus the right handed prosthesis wearers. The u test was also calculated to indicate the significance in the normal volumes, difference volumes, and percentage differences in the above elbow versus the below elbow group. This test was used because it is applicable to observations on two independent random samples which can be combined into a single ordered series. The formula used to find the sum of ranks, "T^1", of the number of observations in a group, "N", was according to Tate and Clelland (1957):

$$T^1 = N_1(N_1 + N_2 + 1) - T$$

The symbol N_1 is the number in one sample and N_2 is the number in the second sample. The symbol "T" is the sum of ranks of the smaller sample.

CHAPTER III

RESULTS

Body Measurements

Of the twenty subjects used in the present study, eleven were below elbow amputees and nine were above elbow amputees. The values of the measurements made on these two groups of subjects can be seen in Tables 1 and 2. The age of the twenty subjects varied from seventeen to sixty-six. The age of the group of below elbow amputees averaged 45.4 years, while in the above elbow group it averaged 33 years. The height of the twenty subjects ranged from 5 feet, 5 inches to 6 feet, 3 inches. In the group of eleven below elbow amputees, the height averaged 5 feet, 10.6 inches, while that of the above elbow amputees averaged 5 feet, 10 inches. The weight of the twenty subjects varied between 112 pounds to 255 pounds. The weight of the group of below elbow amputees averaged 186.6 pounds, while in the group of above elbow amputees it averaged 156.6 pounds.

In order to be able to compare above and below elbow lengths, the stump measurements were made as percentages of the total normal arm lengths. In the below elbow amputees,

TABLE 1

MEASUREMENTS OF BELOW ELBOW AMPUTEES

Subject	Age In Years	Height In Inches	Weight In Pounds	Stump Length In %	Time Worn In Years	Normal Arm Length In Inches	Prosthetic Arm Length In Inches	Harness
A[r]	40	73	220	20	3	32	30	Fig. 8
B[r]	24	74	190	36.6	6	31	30	Fig. 8
C[r]	51	72	165	23.7	8	30	29.5	Fig. 8
D[r]	66	68	175	25	20	27.5	28	Saddle
E[r]	46	69	200	29.3	6	30[m]	29[m]	Fig. 8
F	25	70	185	31.4	25	29	25.5	Ring
G	46	71	185[m]	27.6	25	31	29	Fig. 8
H	22	75	255	31	3	34	30.5	Fig. 8
I[r]	29	68	135	27[m]	3	28	24	Ring
J[r]	65	70	168	22.2	40	28	27	Saddle
K	43[m]	70[m]	177	22.4	20	30	29	Ring
Mean (Average)	45.4	70.6	186.6	26.9	14.5	29.9	28.4	

r = Right Extremity Amputee
m = median

TABLE 2

MEASUREMENTS OF ABOVE ELBOW AMPUTEES

Subject	Age In Years	Height In Inches	Weight In Pounds	Stump Length In %	Time Worn In Years	Normal Arm Length In Inches	Prosthetic Arm Length In Inches	Harness
A r	34	73	220	23.3	21	32.5	30	Ring
B	56	67	125	44	3.5	27	25	Saddle
C r	50	73	170	30 m	30	29.5	30	Fig. 8
D	41	74	215	32.8	8	31.5	29	Fig. 8
E r	47	67	150 m	32.1	23	27.5	26.5	Fig. 8
F	17	65	120	29.6	14 m	27	27	Fig. 8
G r	25	71	147	33.9	.08	29	28 m	Ring
H	48	70	150	18.9	25	31	29	Fig. 8
I r	47 m	70 m	112	16	10	29 m	25	Saddle
Mean (Average)	33	70	156.6	28.9	15	29	27.9	

r = Right Extremity Amputee

m = Median

the stumps, as measured from the olecranon to the end of the stump, averaged 26.9 per cent of the total length of the normal arm. In the above elbow group, the stumps, as measured from the acromion to the end of the stump averaged 28.9 per cent of the total arm length.

The amount of time that the amputees had worn prostheses varied from one month to 40 years. In the group of subjects with below elbow amputations the time worn averaged 14.5 years while in the above elbow amputees it averaged 15 years.

Normal arm length (distance from the acromion to the distal interphalangeal joint of the middle finger) varied from 27 to 34 inches in the twenty subjects. In the below elbow amputees arm length averaged 29.9 inches, while in the above elbow group it averaged 29 inches. In the twenty subjects the length of the prosthetic extremity (distance from the acromion to the end of the terminal device) varied from 24 inches to 32.5 inches. In the below elbow amputees the length of the prosthetic extremity averaged 28.4 inches compared to the above elbow group in which it averaged 27.9 inches.

There were three basic types of harnesses worn by the amputees in this study: figure eight, metal ring, leather shoulder saddle. In the group of below elbow amputees six subjects had figure eight harnesses, three had ring harnesses and two had leather shoulder saddle harnesses. In the above elbow group, five subjects had prostheses with figure eight harnesses, on three of which the elbow lock was regulated by the opposite shoulder. There were two ring and two leather shoulder saddle harnesses. On one of the prostheses with the leather shoulder saddle harness the opposite shoulder regulated the wrist mechanism and had no elbow lock.

The length of the prosthetic extremity was found to be shorter than the normal arm length in eighteen of twenty subjects. In the group of below elbow amputees the prosthetic extremity averaged 1.8 inches less. In the group of above elbow amputees the prosthetic extremity length averaged 1.7 inches less than the normal arm.

All twenty subjects were initially right handed and of these 60 per cent had their right arm amputated. In the below elbow amputee group, 63.7 per cent had the amputation on the right side whereas in the above elbow group 56 per cent had the amputation on the right side.

Various problems were encountered in the attempts of the subjects to complete the required intervals. The first interval refers to the position of the frontal grid when it is farthest from the "R" point of the seat. This distance will vary with each subject since the first interval is determined by the length of the anterior reach of the subject's arm. The second interval will be six inches closer than the first. Thus the frontal grid has been moved eighteen inches toward the "R" point at the fourth interval. It has been moved twenty-four inches at the fifth interval and at the sixth it is usually behind the "R" point.

The subjects differed in the amount of effort, or enthusiasm with which they completed the ranges of motion required. These amputees were much more interested and willing than the non-amputee subjects of the previous study by Rozier (1970). Many subjects had difficulty keeping the hand grid parallel to and three inches from the frontal grid and had to repeat sequences when measurements were made using the normal extremity. When moving the light with the prosthesis, the subjects had trouble keeping the light and metal holder pointing at right angles to and three inches from the frontal grid. Trunk movement was also observed in some subjects as they tried to reach the extremes of motion.

The subjects' range of movement varied to a great degree. Using the normal extremity thirteen of the subjects could complete all six intervals and six of the subjects could complete only the first five intervals with the normal extremity. In the eleven subjects with below elbow prostheses, five were able to complete only the first four intervals and the remainder were able to complete the first five. Of the nine subjects with above elbow prostheses one was able to complete only the first interval, one was able to complete only the first two intervals, two could complete only the first three intervals, three could complete only the first four and two could complete the first five.

It was noted that more time was needed for the subjects to complete the sequence of ranges with the normal arm than was needed to complete the sequence of ranges with the prosthesis. However, the speed of movement was usually constant when the normal arm was used. When the prosthesis was used, the subjects varied the speed as they changed from a clockwise to a counterclockwise direction. The subjects with above elbow prostheses had more difficulty controlling speed and tended to move very quickly.

It was also observed that when the subjects performed the sequences with their normal arms, more variability in shape was encountered between the clockwise and counterclockwise paths than when the sequences were performed with the prostheses. This was true for all intervals completed.

Analysis of Photographic Negatives

When the photographic negatives were enlarged, the distance from hand grid to frontal grid could be checked for correctness from the image in the mirror. The subjects, when using the normal arm, had difficulty staying close to the frontal grid in the lower parts of the circles of movement. When using the prosthesis the subjects had more difficulty pointing the metal holder at right angles to the frontal grid in the lateral part of the circles of movement. The clockwise and counterclockwise paths of light were much closer together when the prosthesis was used than when the circles were performed by the normal arm. Many of the subjects also tended to make a rectangular pattern with the prosthesis while making a more curved pattern with the normal extremity.

The light on the olecranon process of the normal arm made a smaller circle resembling the larger one made by the hand. In the intervals in which the subject's arm moved at the side of his body, this pattern of light at the elbow was an arc of a half circle with the convexity of the arc directed laterally. However, movement at the elbow could not be completely seen in the photographs. The light at the elbow of the prosthetic extremity, when viewed in the mirror, appeared to be moving closer to the body. It was also less visible in a frontal view.

Measurements of Light Paths

The tracings of the light paths which were taken from the enlargements of the negatives were measured for all subjects. The planimeter readings of these tracings yielded the areas of all the intervals of each subject. Areas of specific intervals were not comparable among subjects since the subjects started at different distances from the "R" point. First, the intervals of the smallest and the largest areas were determined for each subject. Secondly, the specific intervals were identified when the subject was able or unable to cross the hand grid or light in front of his body. Next, superimpositions of the light paths were made for the subjects in each group with the percentage difference closest to the mean, as well as for the subjects in each group at either extreme of the mean (Figures 3 through 14). Then the differences in the height and shape of the intervals were determined for these subjects.

When the subjects used their normal arms, the sixth interval had the smallest area in eighteen subjects. However, in two subjects the first interval had the smallest area. In two subjects the second interval had the largest area, in thirteen subjects the third had the largest and in five subjects the fourth had the largest.

When the subjects with below elbow prostheses were measured, in two subjects the first interval had the largest area, in eight subjects the second had the largest and in one subject the fourth had the largest area. When the subjects with above elbow prostheses were measured, in three subjects the first interval had the largest area, in three subjects the second, in two subjects the third, and in one subject the fourth had the largest area. The last interval had the smallest area in all cases. In subjects who could not complete all intervals the smallest interval was counted as the one posterior to the last interval completed. This interval was counted as having a value of zero.

Most of the subjects could not move the hand of the normal extremity across his body after the frontal grid had been moved twenty-four inches toward the subject. However,

Figure 3. Superimposition of the interval outlines for the normal extremity of the below elbow amputee with the percentage difference value closest to the mean. Front view. Note the position of the "R" point.

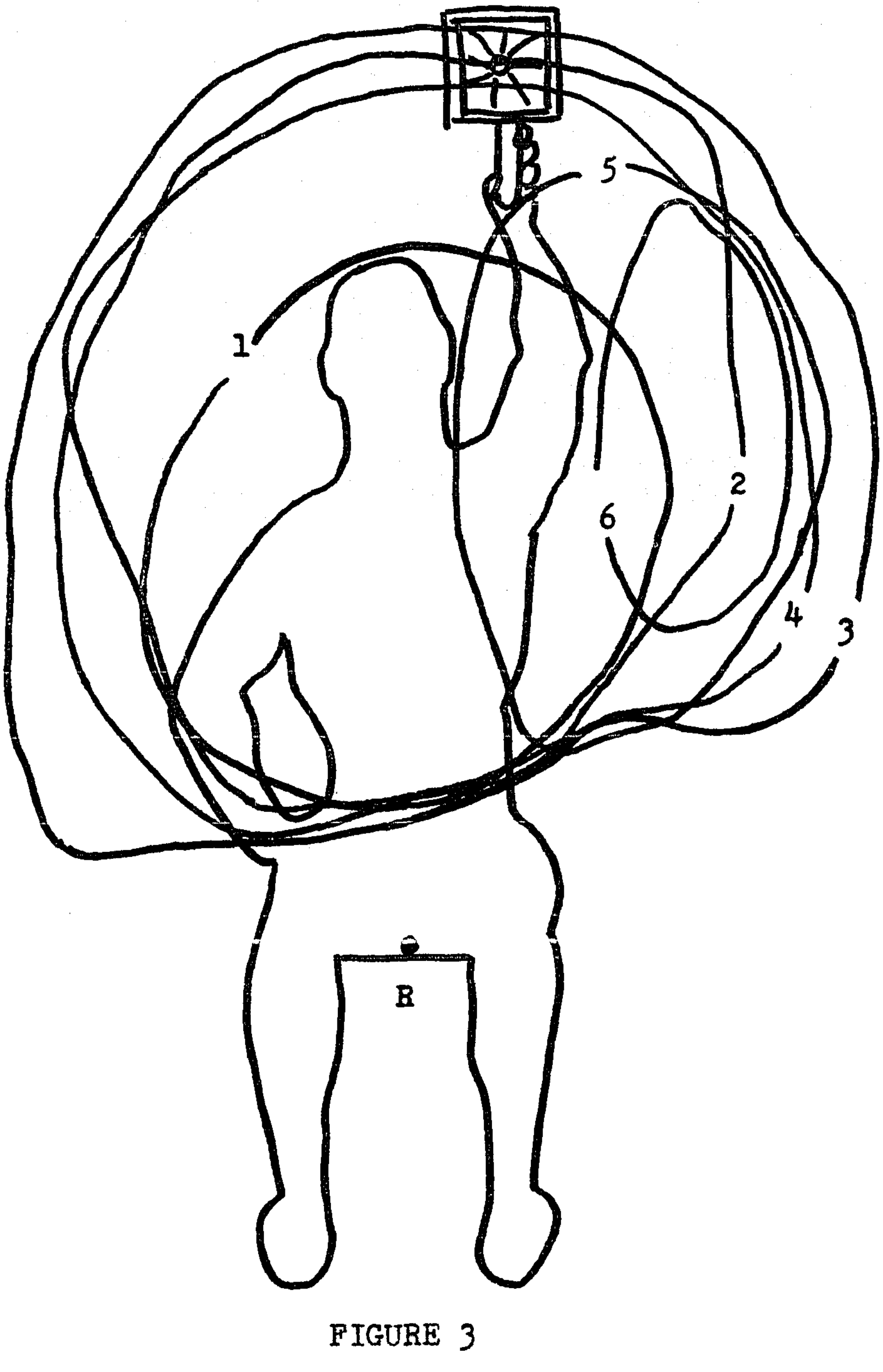


FIGURE 3

Figure 4. Superimposition of the interval outlines for the prosthetic extremity of the below elbow amputee with the percentage difference value closest to the mean. Front view. Note the position of the "R" point.

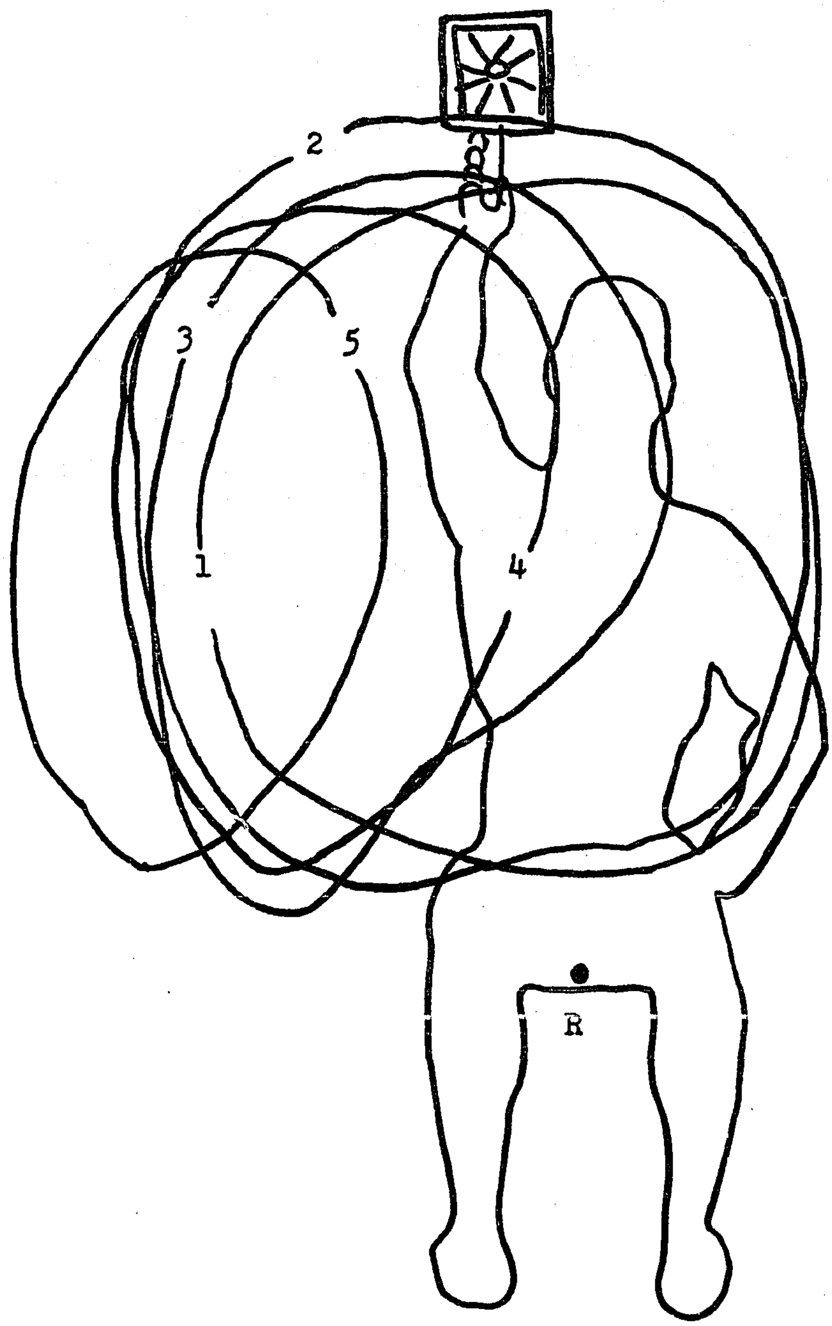


FIGURE 4

Figure 5. Superimposition of the interval outlines for the normal extremity of the below elbow amputee with the smallest percentage difference. Front view. Note the position of the "R" point.

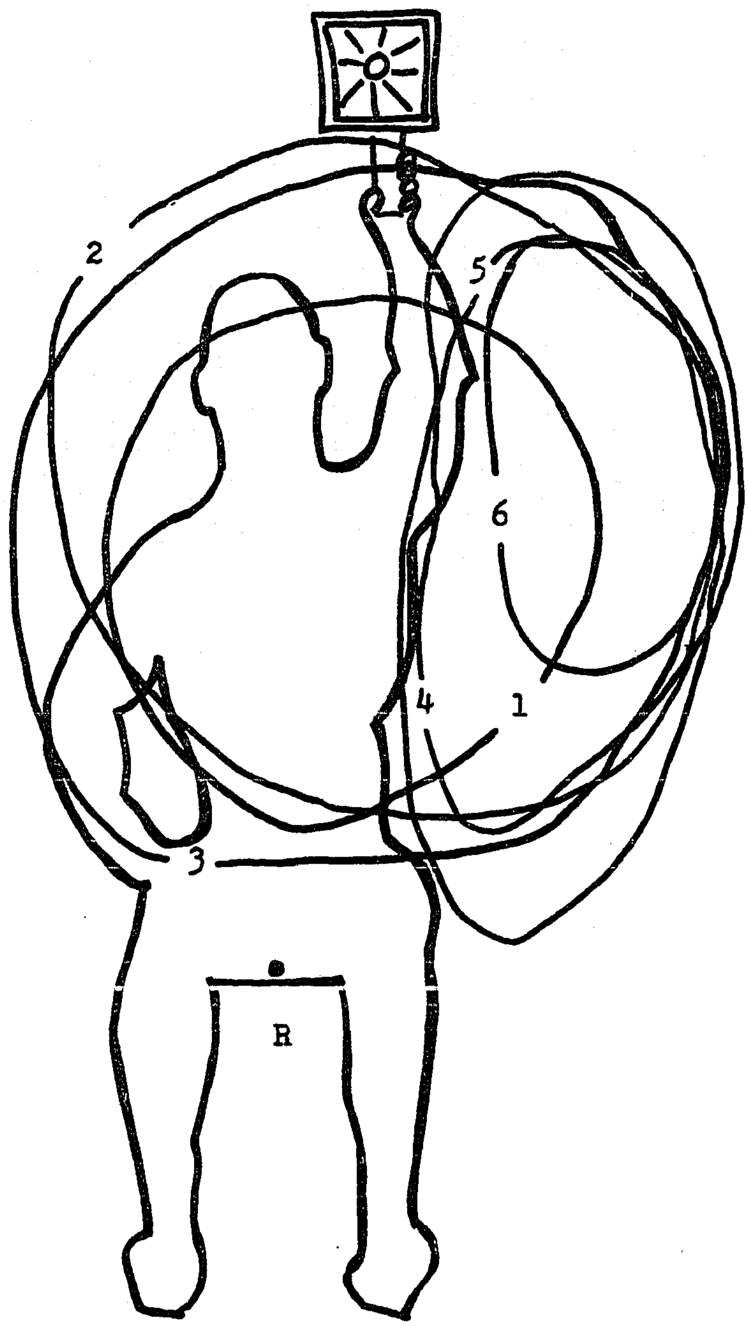


FIGURE 5

Figure 6. Superimposition of the interval outlines for the prosthetic extremity of the below elbow amputee with the smallest percentage difference. Front view. Note the position of the "R" point.

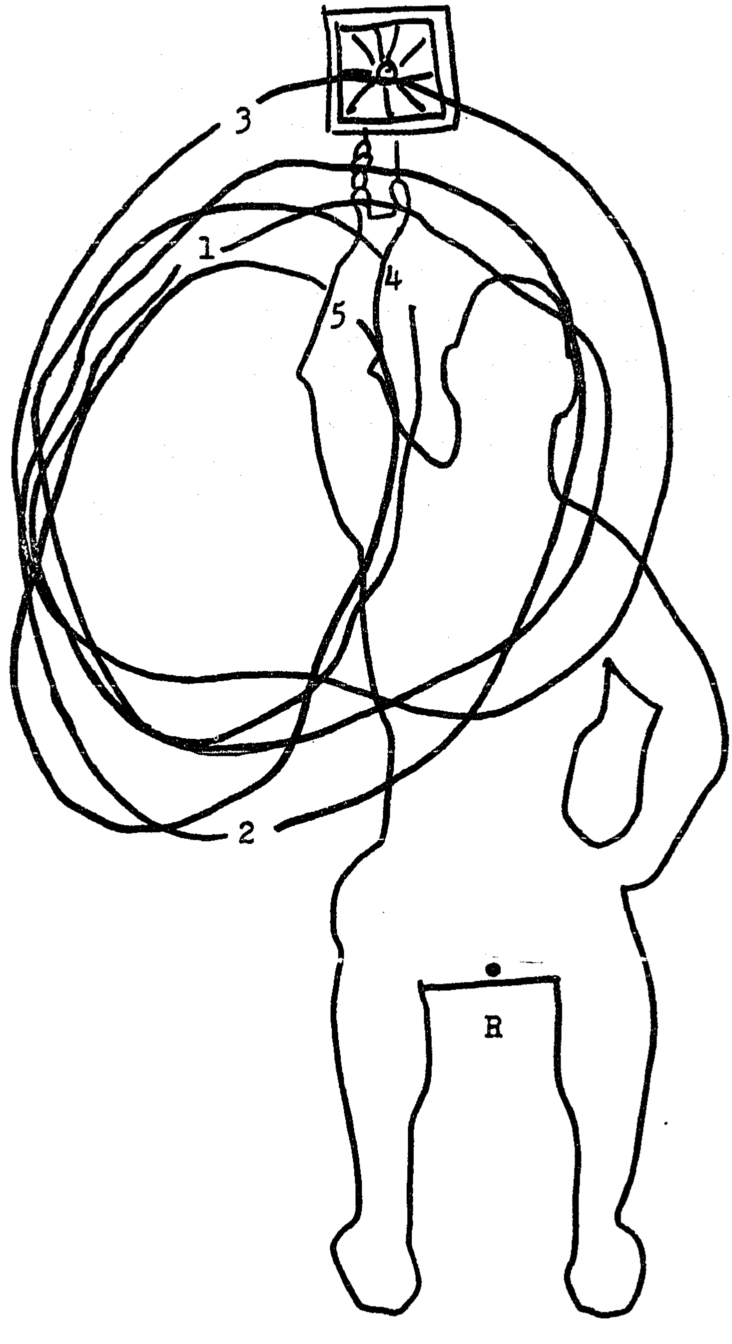


FIGURE 6

Figure 7. Superimposition of the interval outlines for the normal extremity of the below elbow amputee with the largest percentage difference. Front view. Note the position of the "R" point.

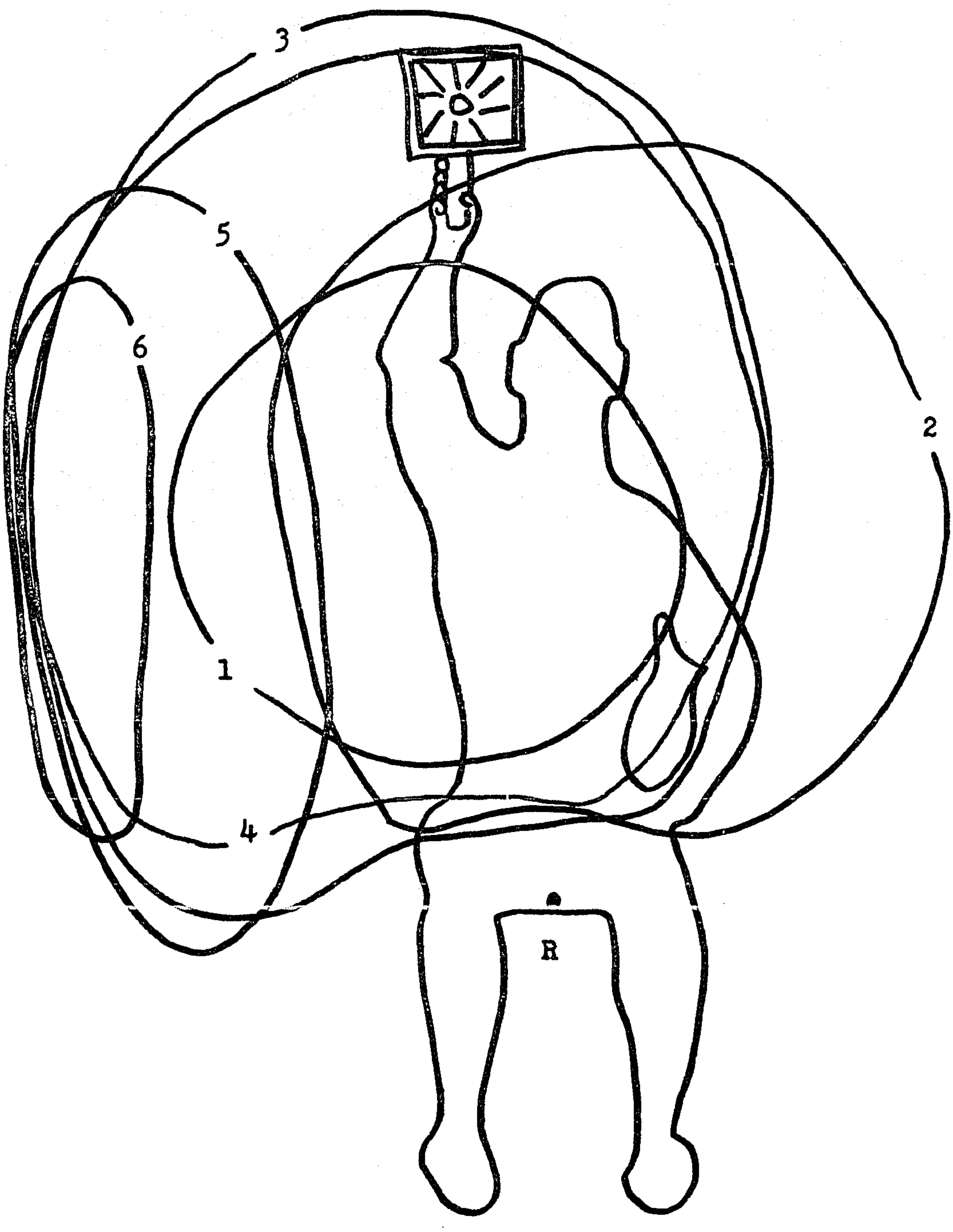


FIGURE 7

Figure 8. Superimposition of the interval outlines for the prosthetic extremity of the below elbow amputee with the largest percentage difference. Front view. Note the position of the "R" point.

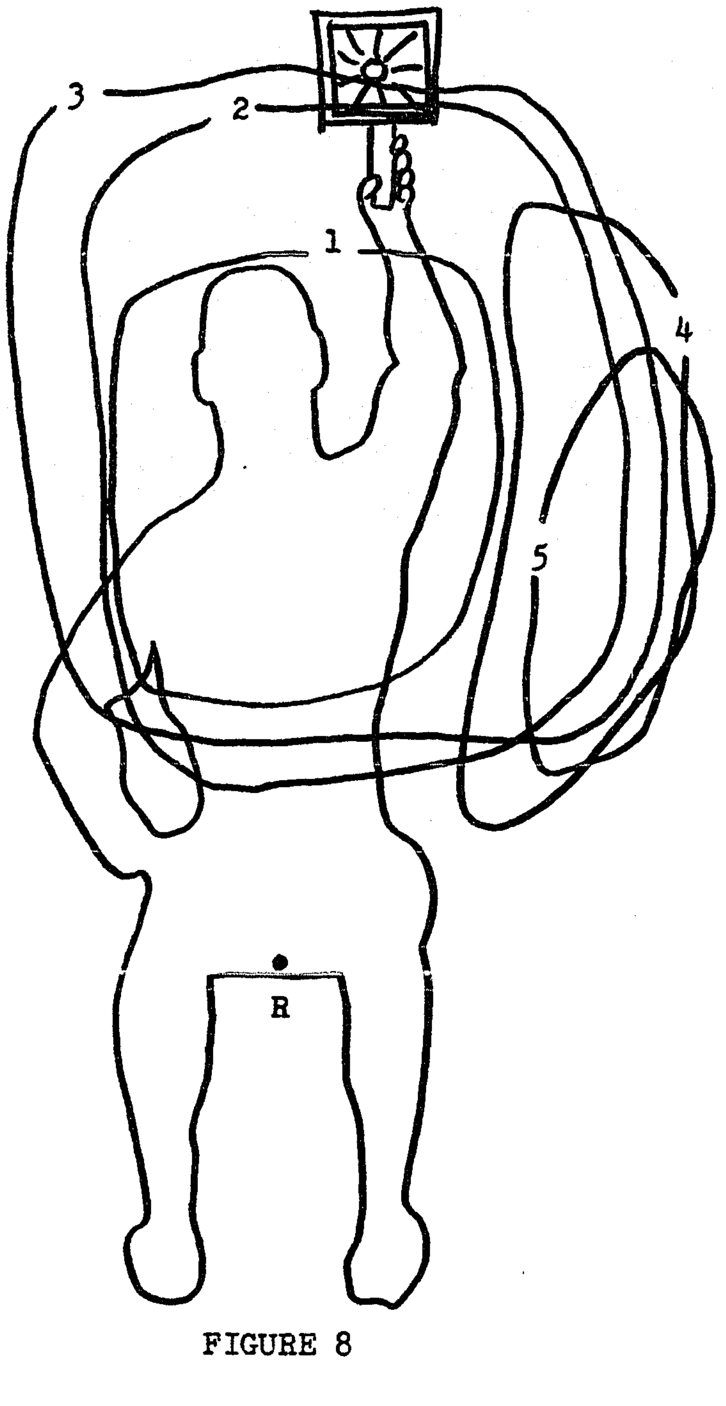


FIGURE 8

Figure 9. Superimposition of the interval outlines for the normal extremity of the above elbow amputee with the percentage difference value closest to the mean. Front view. Note the position of the "R" point.

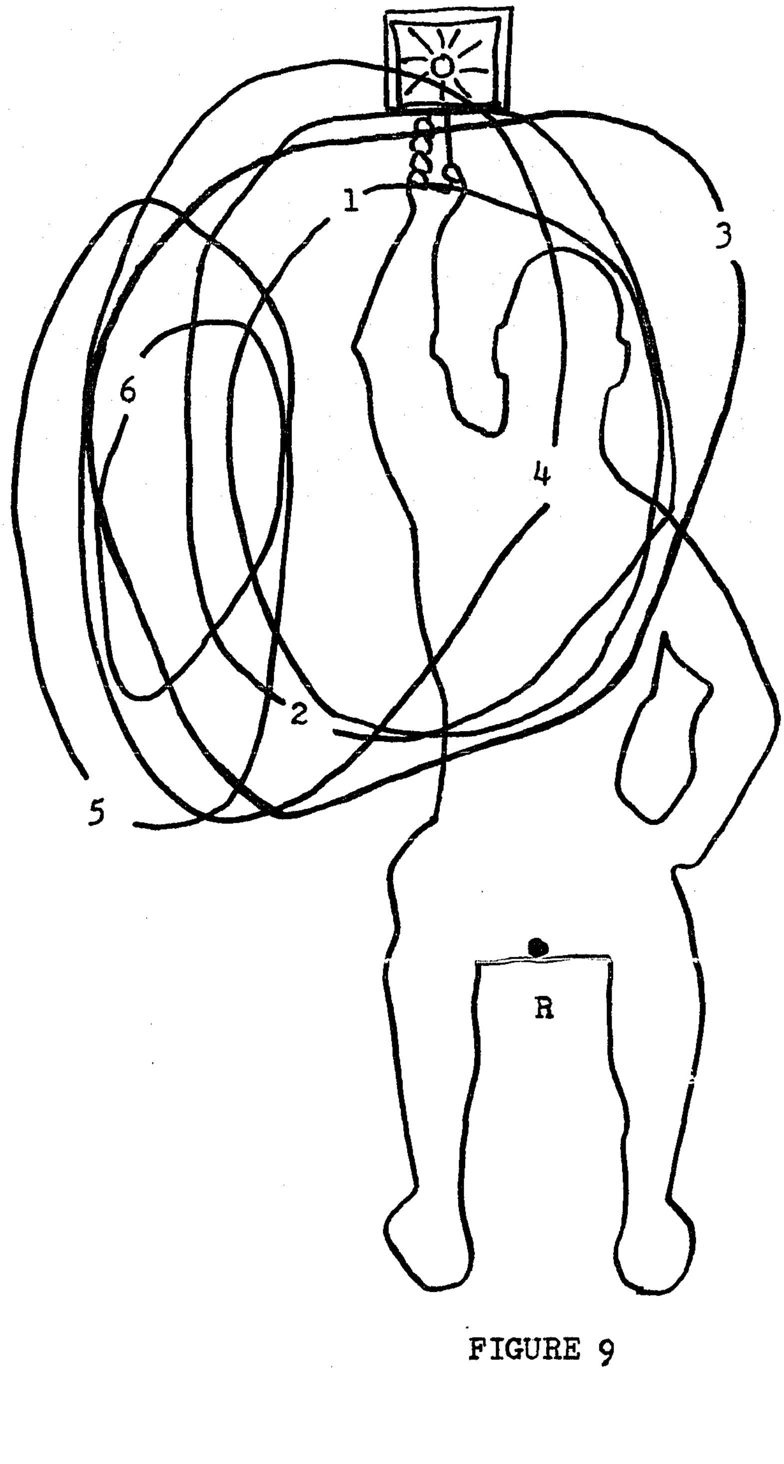


FIGURE 9

Figure 10. Superimposition of the interval outlines for the prosthetic extremity of the above elbow amputee with the percentage difference value closest to the mean. Front view. Note the position of the "R" point.

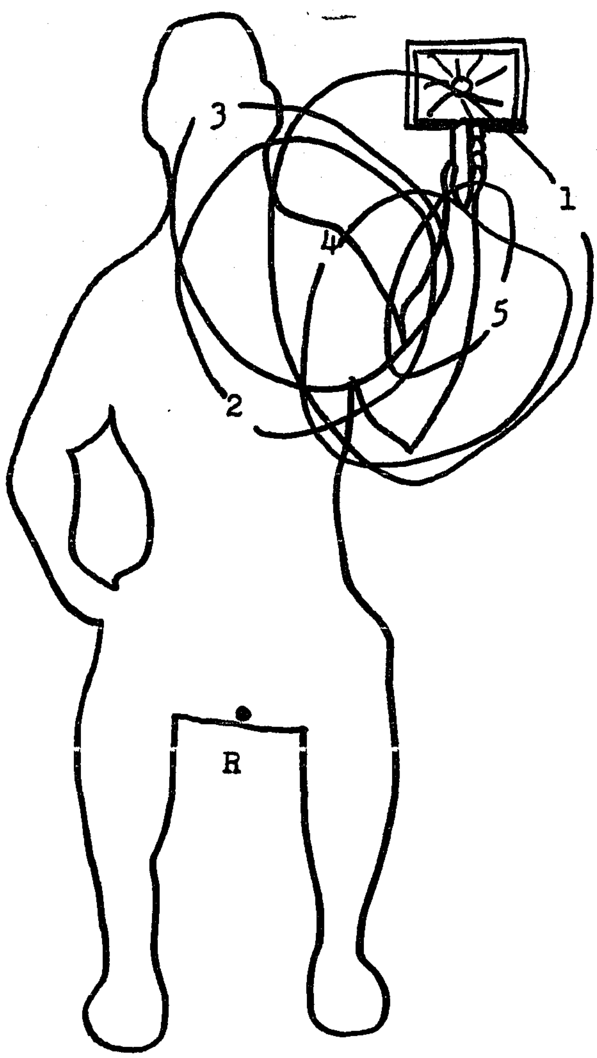


FIGURE 10

Figure 11. Superimposition of the interval outlines for the normal extremity of the above elbow amputee with the smallest percentage difference. Front view. Note the position of the "R" point.

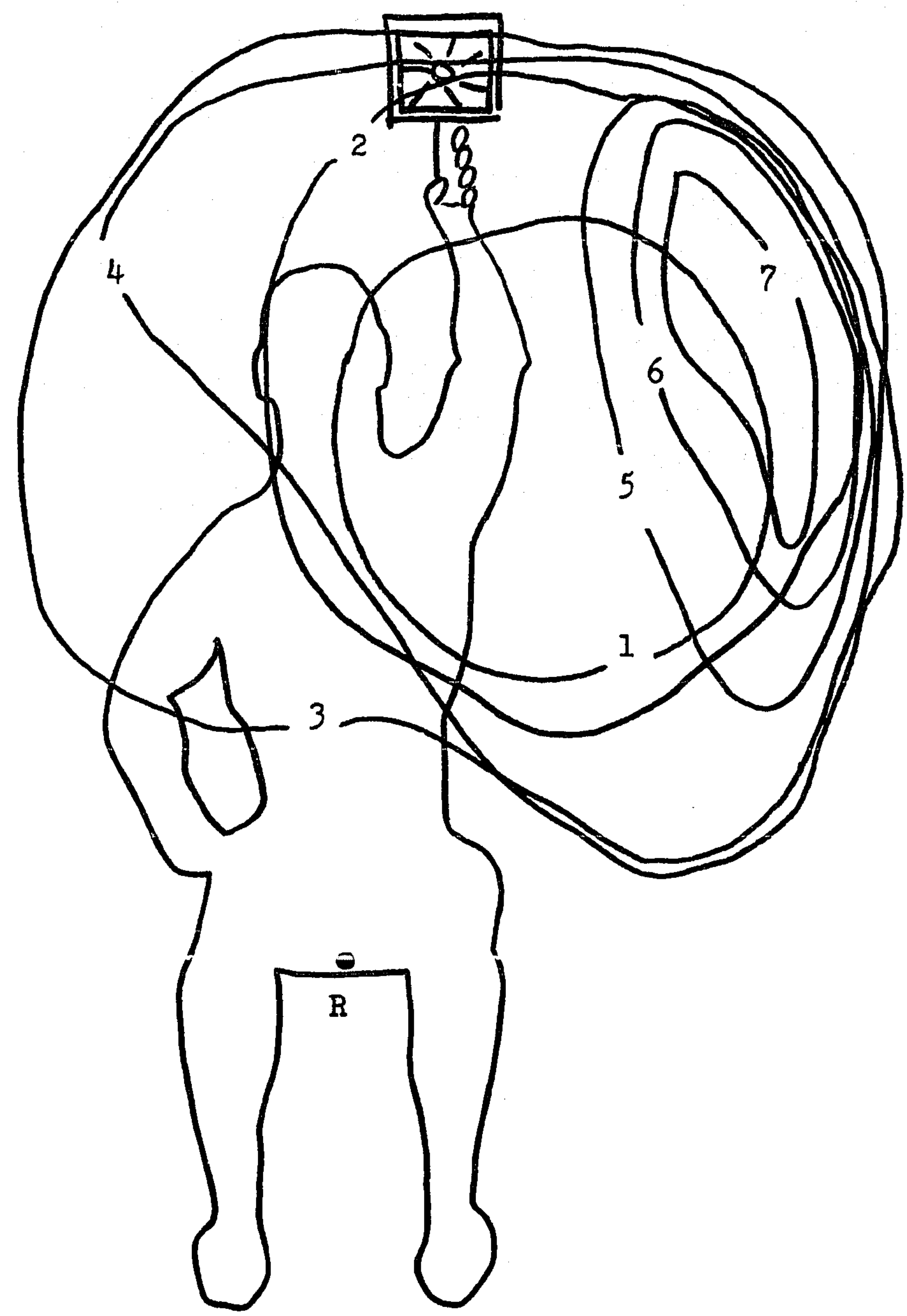


FIGURE 11

Figure 12. Superimposition of the interval outlines for the prosthetic extremity of the above elbow amputee with the smallest percentage difference. Front view. Note the position of the "R" point.

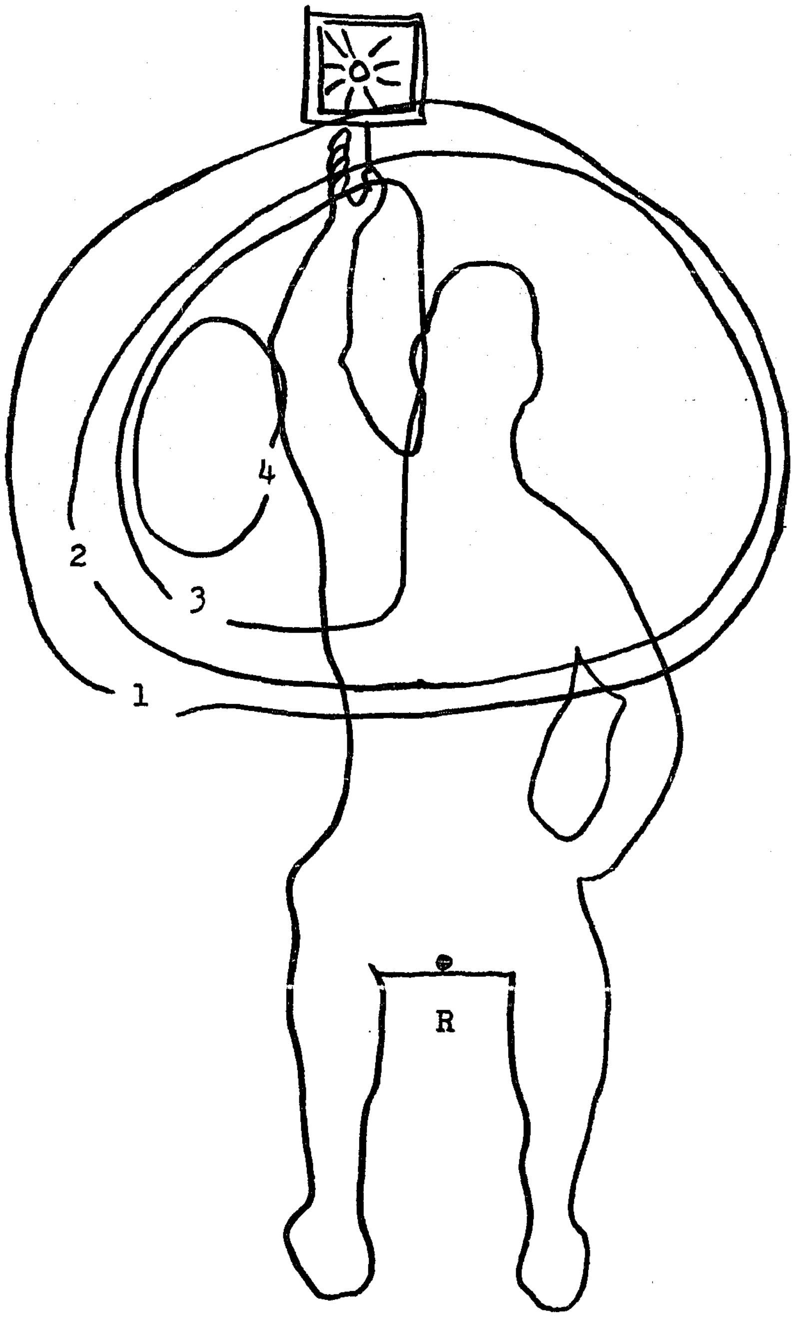


FIGURE 12

Figure 13. Superimposition of the interval outlines for the normal extremity of the above elbow amputee with the largest percentage difference. Front view. Note the position of the "R" point.

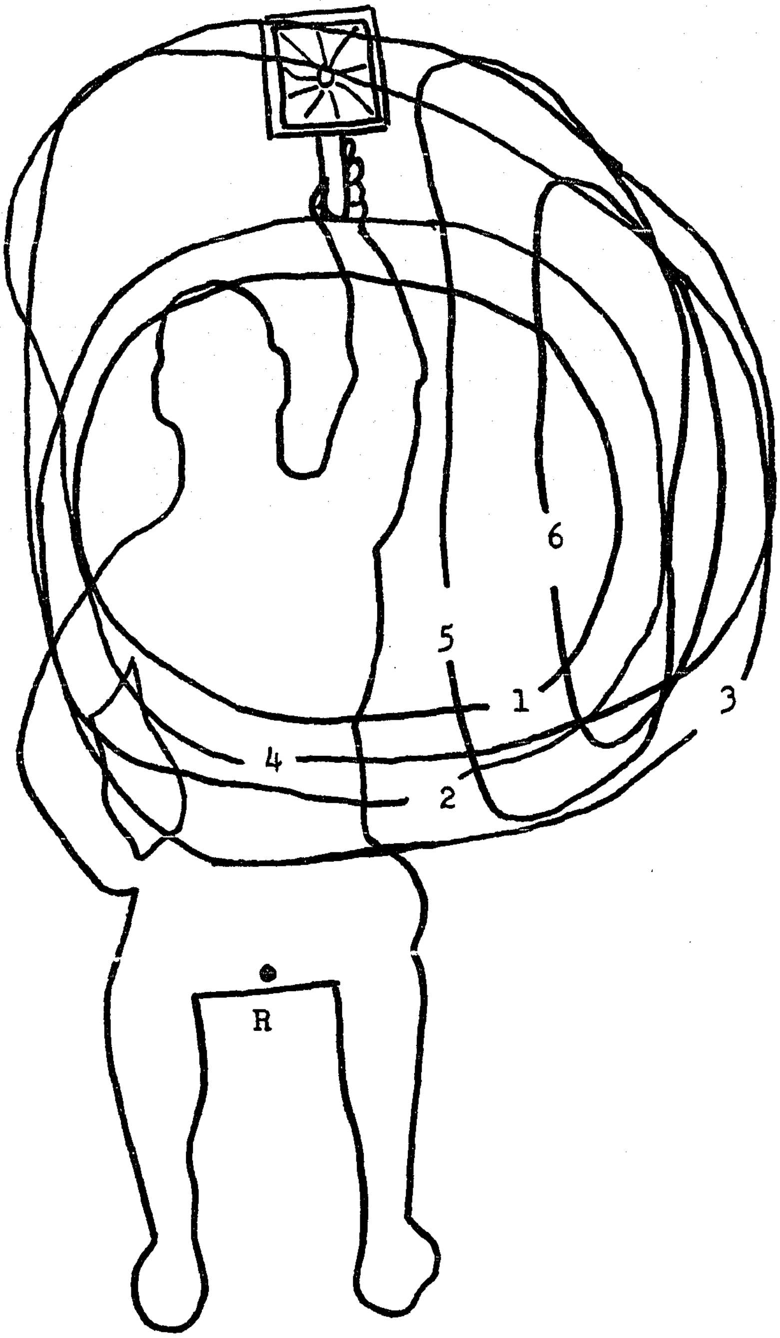


FIGURE 13

Figure 14. Superimposition of the interval outlines for the prosthetic extremity of the above elbow amputee with the largest percentage difference. Front view. Note the position of the "R" point.

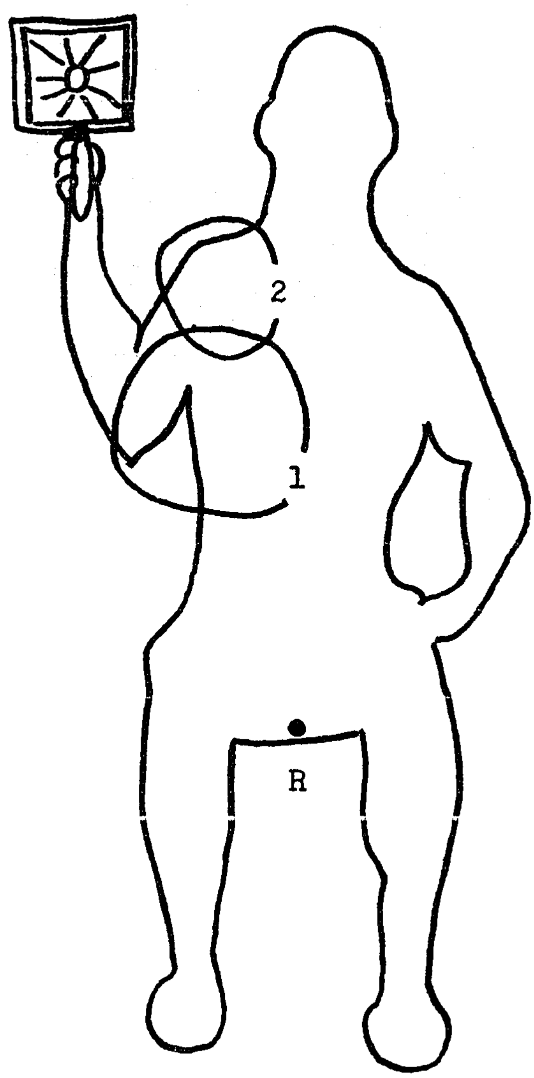


FIGURE 14

it was noted that one subject could complete this movement. In the group with below elbow prostheses five could not complete this movement at the third interval and six could not complete the movement at the fourth. In the above elbow group, one subject could not move the prosthesis across the body at the second interval and two could not complete this movement at the third interval.

The difference in areas for specific intervals were found and then the intervals with the smallest and the largest differences in area were indicated for both groups. In the group of below elbow amputees, the interval of the smallest difference between the normal arm and the arm with the prosthesis was the first interval in six subjects and the fifth in one subject. The interval with the largest difference was the first in one subject, the third in six subjects, the fourth in three subjects, and the fifth in one subject. In the above elbow group of amputees the interval of the smallest difference was the first in eight subjects and the sixth in one subject. The interval with the largest difference was the second in one subject, the third in six subjects, and the fourth in two subjects.

Differences in the size and shape of the areas of the intervals were apparent from the tracings taken from light paths of the normal extremities. Generally, the first interval was a circle with the upper border of the circle just above the level of the eyes of the subject. Two-thirds of this circle was directed laterally. Subjects were able to reach further medially and above head level in the second interval. The third interval was similar in shape to the second but larger. It also had a characteristic indentation due to the knees. The fourth interval lacked a definite outline of the knees. Here the majority of subjects could still move the hand across the midline of their body but did not have enough clearance between their body and the frontal grid to permit this movement. Some subjects could move the hand over the midline at the higher parts of the intervals but not in the lower. The fifth interval was, in the majority of cases, entirely lateral to the "R" point. The top of the outline was directed above the head with the vertical dimension greater than the horizontal one. The sixth interval was similar in shape to the fifth but with a smaller area.

The tracings of the intervals of the individuals using the below elbow prostheses were naturally smaller than the intervals of the individuals using their normal arms. The primary difference between the prosthetic and normal tracings was that the intervals of individuals using prostheses were not as large. The first interval was usually smaller and lower and did not project as far across the body. The second interval was smaller with the majority of the area lateral to the midline. The third interval was smaller than the second with no indentation due to the knees. The area of this interval was directly in front of the body. The fourth interval was at the side of the body and smaller than the third interval. The fifth and sixth intervals were entirely lateral to the body.

The tracings of the intervals of the individuals using the above elbow prostheses were generally much smaller, fitting well within the tracings of the normal arm. The first interval was extremely variable among subjects but was generally smaller and lower. It was also more laterally directed. The second and third intervals were smaller and directed laterally. The fourth and fifth intervals were entirely lateral to the body but not as far as those of the tracing for the normal arm.

When comparing the tracings of the above elbow group with the below elbow group, it was apparent that the tracings for the above elbow prostheses were much smaller and extended neither as high, as low, as far laterally, nor as far medially. These tracings showed that a larger percentage of the interval areas of each tracing were directed lateral to the midline.

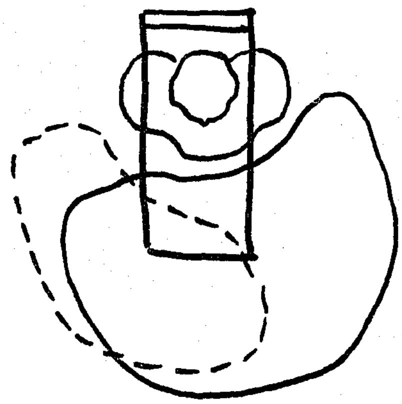
Representative subjects whose percentage difference values were closest to the mean and those on either extreme of the mean were used to provide data. The interval volumes of these representative subjects were used to make styrofoam models of the normal and the prosthetic work spaces (Appendix). These were then cut in horizontal, sagittal, and frontal sections and drawings made to show the three-dimensional aspect of the work space (Figures 15 through 20).

The three representative subjects for the below elbow group of amputees could not reach as far in any direction with their prostheses as they could with their normal arms. At the fourth interval close to the body the subject with the mean percentage difference could reach across the midline of his body but the remaining two subjects could not (Figures 15, 16, 17).

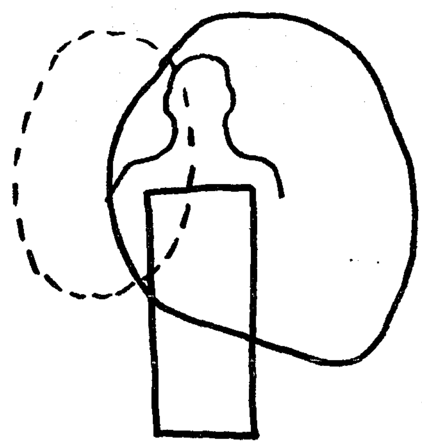
The three representative above elbow subjects could not reach as high, as far posteriorly or across their bodies as completely with their prostheses as they could with their normal arms (Figures 18, 19, 20). The subject with the smallest percentage difference could reach as low with his prosthesis as he could with his normal arm but the other two representative subjects could not. None could reach across the midline at the fourth interval.

When viewing the drawings of these representative subjects a bimanual area is seen (Figures 15 through 20). This is the area of overlap of the normal and the prosthetic work space in which both extremities can do work. The bimanual area does not extend as far as the fourth interval in either group of amputees. In the group of above elbow amputees the bimanual area is seen to be less than that for the group of below elbow amputees.

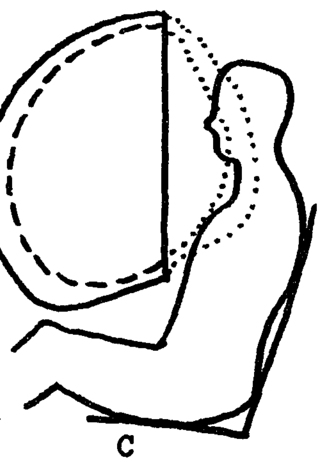
Figure 15. Sections through the manual work space of the below elbow amputee with the percentage difference value closest to the mean. The solid line represents the work space of the normal extremity. The broken line represents the work space of the prosthetic extremity. The area of overlap indicates the bimanual work space. A. Horizontal section at mid-chest level. B. Frontal section at the fourth interval. C. Sagittal section through the "R" point. The dotted line indicates the most posterior extent of the work space which projects lateral to the "R" point.



A



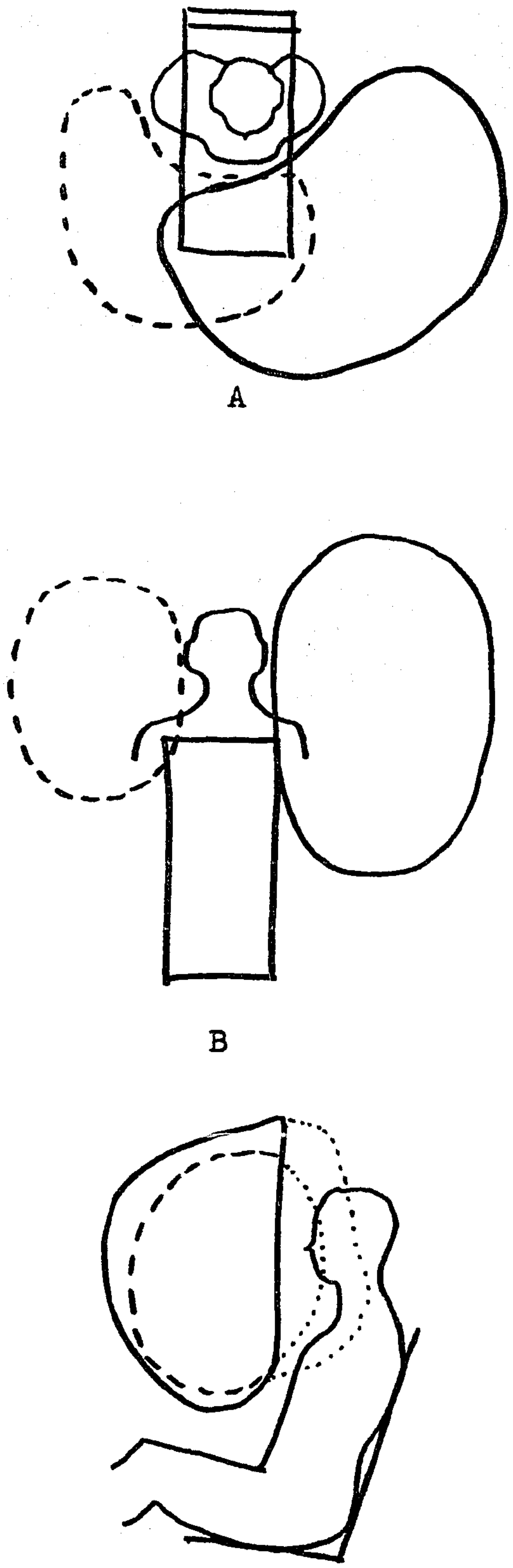
B



C

FIGURE 15

Figure 16. Sections through the manual work space of the below elbow amputee with the smallest percentage difference. The solid line represents the work space of the normal extremity. The broken line represents the work space of the prosthetic extremity. The area of overlap indicates the bimanual work space. A. Horizontal section at mid-chest level. B. Frontal section at the fourth interval. C. Sagittal section through the "R" point. The dotted line indicates the most posterior extent of the work space which projects lateral to the "R" point.



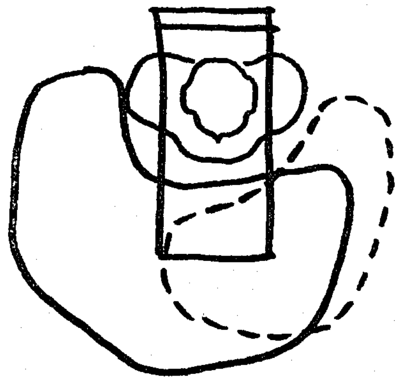
A

B

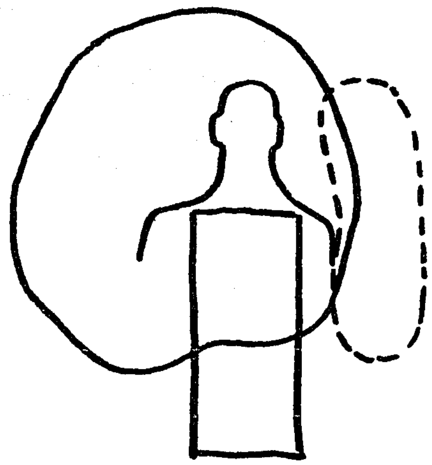
C

FIGURE 16

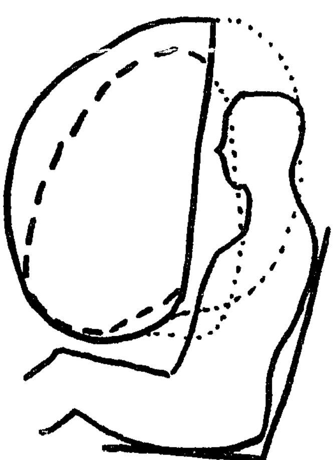
Figure 17. Sections through the manual work space of the below elbow amputee with the largest percentage difference. The solid line represents the work space of the normal extremity. The broken line represents the work space of the prosthetic extremity. The area of overlap indicates the bimanual work space. A. Horizontal section at mid-chest level. B. Frontal section at the fourth interval. C. Sagittal section through the "R" point. The dotted line indicates the most posterior extent of the work space which projects lateral to the "R" point.



A



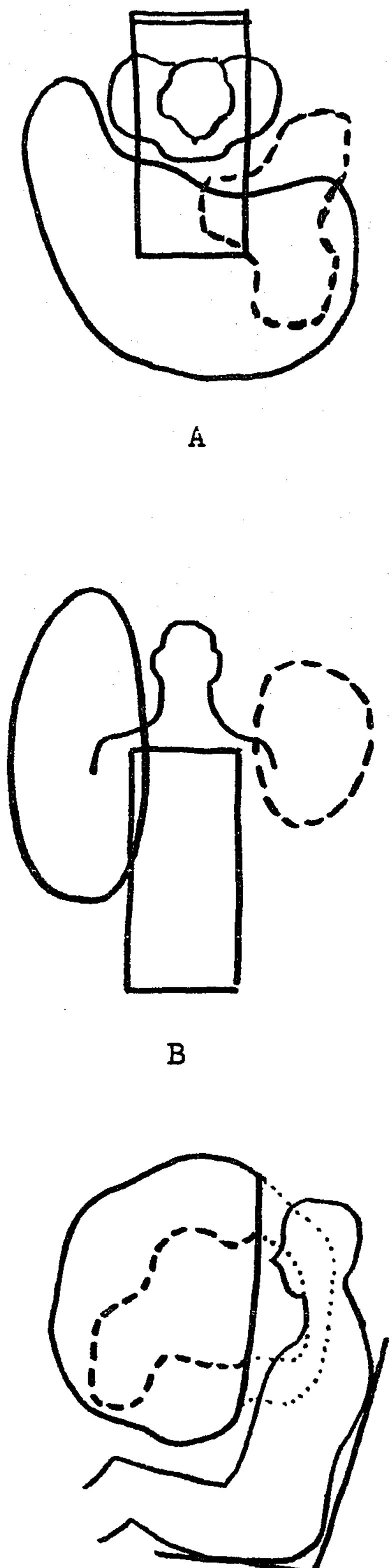
B



C

FIGURE 17

Figure 18. Sections through the manual work space of the above elbow amputee with the percentage difference value closest to the mean. The solid line represents the work space of the normal extremity. The broken line represents the work space of the prosthetic extremity. The area of overlap indicates the bimanual work space. A. Horizontal section at mid-chest level. B. Frontal section at the fourth interval. C. Sagittal section through the "R" point. The dotted line indicates the most posterior extent of the work space which projects lateral to the "R" point.



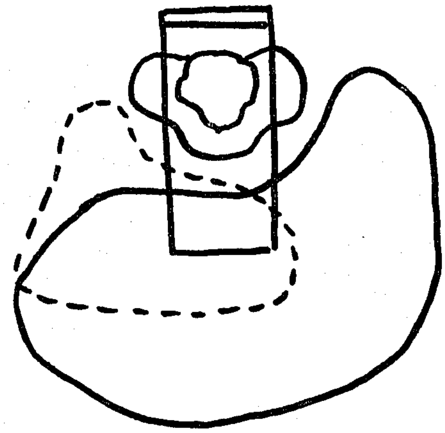
A

B

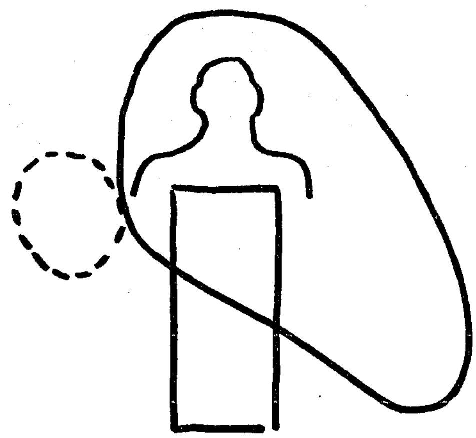
C

FIGURE 18

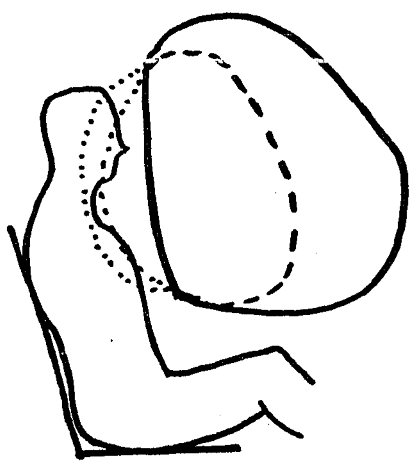
Figure 19. Sections through the manual work space of the above elbow amputee with the smallest percentage difference. The solid line represents the work space of the normal extremity. The broken line represents the work space of the prosthetic extremity. The area of overlap indicates the bimanual work space. A. Horizontal section at mid-chest level. B. Frontal section at the fourth interval. C. Sagittal section through the "R" point. The dotted line indicates the most posterior extent of the work space which projects lateral to the "R" point.



A



B



C

FIGURE 19

Figure 20. Sections through the manual work space of the above elbow amputee with the largest percentage difference. The solid line represents the work space of the normal extremity. The broken line represents the work space of the prosthetic extremity. The area of overlap indicates the bimanual work space. A. Horizontal section at mid-chest level. B. Frontal section at the fourth interval. C. Sagittal section through the "R" point. The dotted line indicates the most posterior extent of the work space which projects lateral to the "R" point.

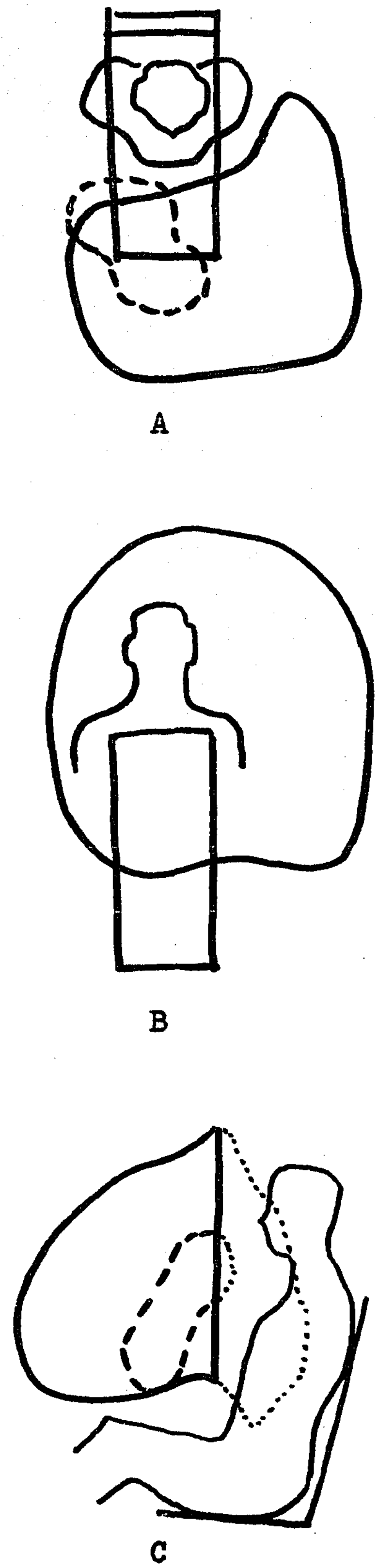


FIGURE 20

Statistical Analysis

After the areas of the intervals were determined, the volumes of the normal and prosthetic work space, the volume differences and the percentage differences of each subject were computed. These data are presented in Tables 3 and 4.

The work space volumes of the normal extremities of the eleven subjects with below elbow prostheses averaged 31,012 cubic inches. The standard deviation was 8,074 cubic inches. In the group of subjects with above elbow prostheses the work space volumes of the normal extremity averaged 30,156 cubic inches. The standard deviation was 11,497 cubic inches.

In the below elbow group the work space volumes of the prosthetic extremities averaged 17,241 cubic inches. The standard deviation was 6,145 cubic inches. In the group of above elbow subjects the work space volumes of the prosthetic extremities averaged 5,453 cubic inches. The standard deviation was 4,735 cubic inches.

The difference between the normal and the prosthetic volumes in the group of subjects with below elbow prostheses averaged 13,862 cubic inches. The standard deviation was 4,551 cubic inches. The percentage difference averaged 45 per cent. The standard deviation was 12 per cent. In the group of subjects with above elbow prostheses the difference in volume averaged 24,704 cubic inches. The standard deviation was 8,353 cubic inches. The percentage difference

TABLE 3

VOLUMES OF BELOW ELBOW AMPUTEES

Subject	Normal Volume Cubic In Inches	Prosthetic Volume Cubic In Inches	Difference in Volume Cubic In Inches	Percentage Difference In %
A	27,402	21,890	5,512	20.1
B	31,532	22,179	9,353	29.6
C	49,334	30,178	19,156	38.8
D	25,790	14,814	10,976	42.5
E	38,739	21,463	17,276	44.5^{m}
F	32,742	17,161	15,581	47.6
G	29,220^{m}	14,821^{m}	14,399^{m}	49.3
H	25,304	12,711	13,593	49.7
I	18,169	8,492	9,677	53.3
J	29,030	12,211	16,819	57.9
K	33,874	13,726	20,148	59.5
Mean	31,012	17,241	13,862	44.8
Standard Deviation	8,074	6,145	4,551	12

m = median

TABLE 4

VOLUMES OF ABOVE ELBOW AMPUTEES

Subject	Normal Volume Cubic In Inches	Prosthetic Volume Cubic In Inches	Difference in Volume Cubic In Inches	Percentage Difference In %
A	44,834	15,178	29,656	66.3
B	22,831	5,644	17,187	75.3
C	52,699	11,494	41,205	78.2
D	25,203^m	3,758	21,445^m	85.1
E	18,921	2,786	16,136	85.3^m
F	22,234	3,103	19,131	86
G	23,252	3,092	20,160	86.6
H	27,684	3,322^m	24,362	88
I	33,753	698	33,055	97.9
Mean	30,156	5,453	24,704	83
Standard Deviation	11,497	4,735	8,353	8.9

m = median

averaged 83 per cent. The standard deviation was 8.9 per cent.

The normal and prosthetic volumes of the subjects in both groups with the percentage differences closest to the mean and on either extremes of the mean are shown graphically in Figures 21 through 26. The interval volumes are plotted at six inch intervals from the "R" point. The difference in volumes is the area between the solid and broken lines.

The reductions in volumes due to the above or below elbow prostheses of these subjects are seen graphically in Figures 27 and 28. The work space volume of the normal extremity is compared to the work space volume of the prosthetic extremity. The shaded area represents the amount of work space volume that is lost when the prosthesis replaces the normal extremity. In Figure 27 the work space volumes for the three below elbow subjects shows that the subject with the smallest percentage difference lost 20 per cent of the normal work space. The subject with the largest percentage difference lost 60 per cent and the subject with the percentage difference closest to the mean lost 45 per cent. In Figure 28 the work space volumes for the three above elbow subjects shows that the subject with the smallest percentage difference lost 66 per cent of the normal work space. The subject with the largest percentage difference lost 97.9 per cent and the subject with the percentage difference closest to the mean lost 85 per cent.

Figure 21. A graph illustrating the normal and prosthetic interval volumes of the below elbow amputee with the percentage difference value closest to the mean. The interval volumes are plotted at six inch intervals from the "R" point. The solid line represents the work space volume of the normal extremity. The broken line represents the work space volume of the prosthetic extremity. The total normal work space volume is the area below the solid line (38,739 cu. in.). The total prosthetic work space volume is the area below the broken line (21,463 cu. in.). The area between the lines is the difference in volume (15,273 cu. in.).

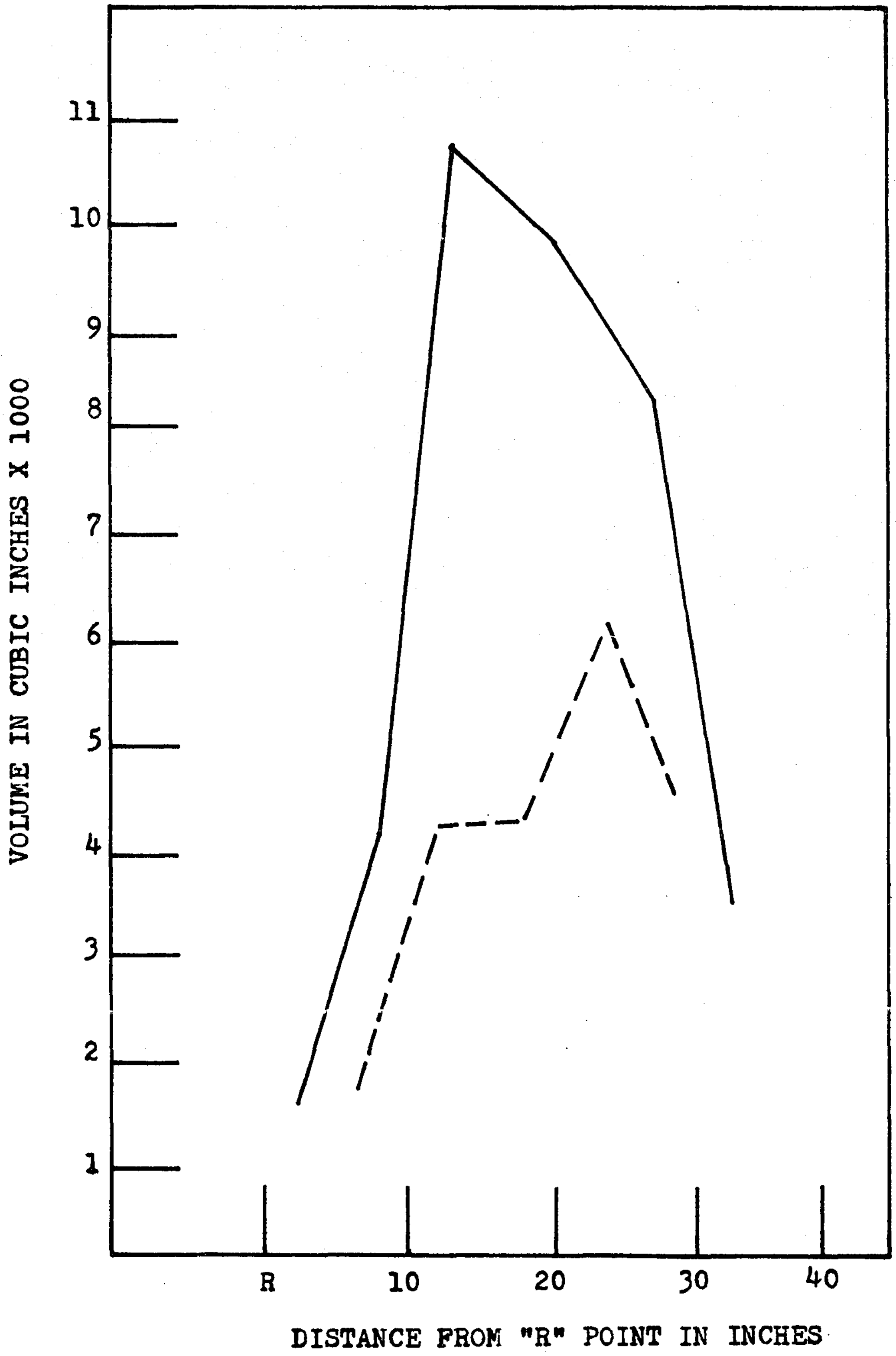

11
10
9
8
7
6
5
4
3
2
1
VOLUME IN CUBIC INCHES X 1000
R
10
20
30
40
DISTANCE FROM "R" POINT IN INCHES

FIGURE 21

Figure 22. A graph illustrating the normal and prosthetic interval volumes of the below elbow amputee with the smallest percentage difference. The interval volumes are plotted at six inch intervals from the "R" point. The solid line represents the work space volume of the normal extremity. The broken line represents the work space volume of the prosthetic extremity. The total normal work space volume is the area below the solid line (27,402 cu. in.). The total prosthetic work space volume is the area below the broken line (21,890 cu. in.). The area between the lines is the difference in volume (5,512 cu. in.).

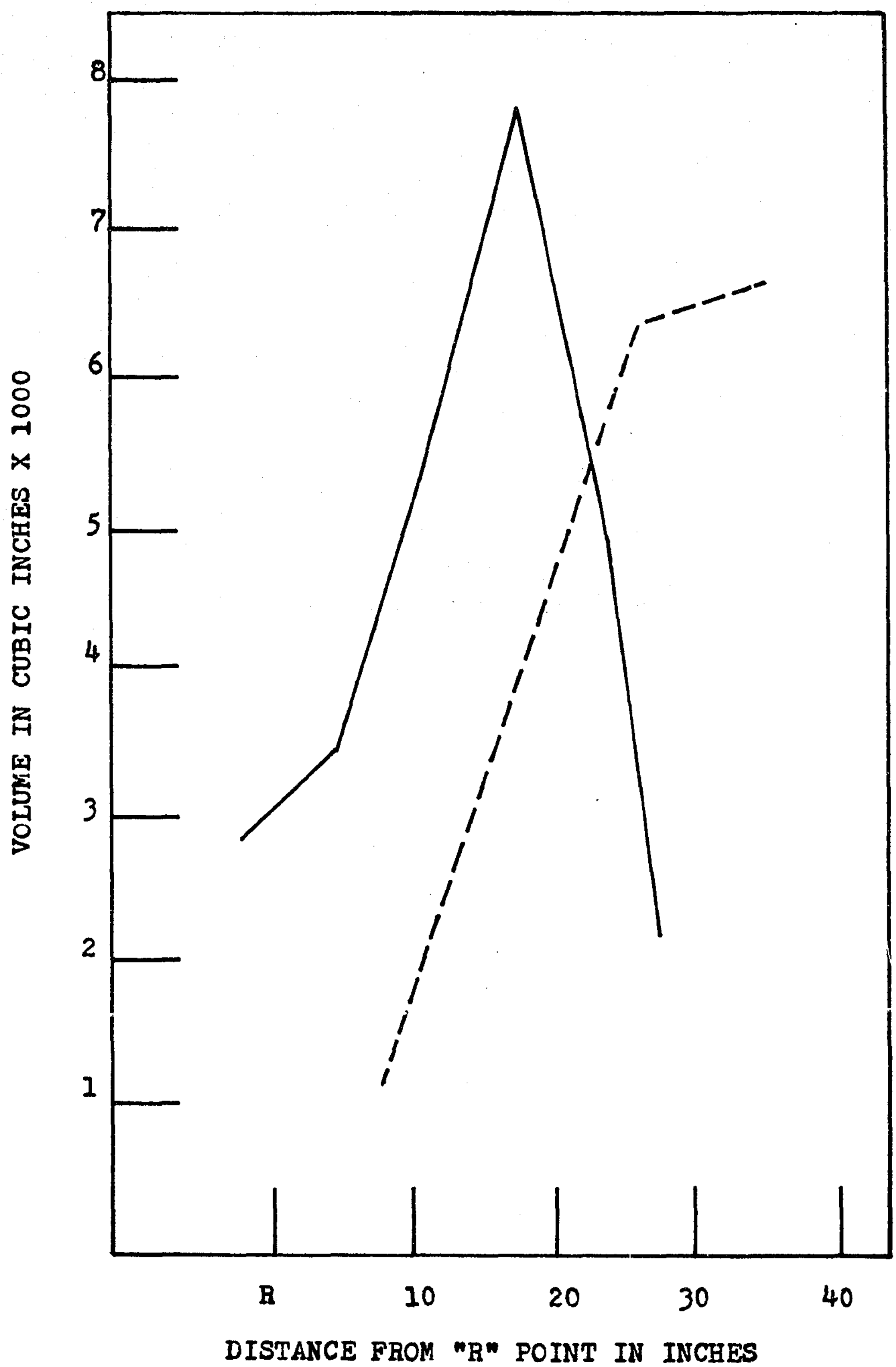

8
7
6
5
4
3
2
1
VOLUME IN CUBIC INCHES X 1000
R
10
20
30
40
DISTANCE FROM "R" POINT IN INCHES

FIGURE 22

Figure 23. A graph illustrating the normal and prosthetic interval volumes of the below elbow amputee with the largest percentage difference. The interval volumes are plotted at six inch intervals from the "R" point. The solid line represents the work space volume of the normal extremity. The broken line represents the work space volume of the prosthetic extremity. The total normal work space volume is the area below the solid line (33,874 cu. in.). The total prosthetic work space volume is the area below the broken line (13,726 cu. in.). The area between the lines is the difference in volume (20.148 cu. in.).

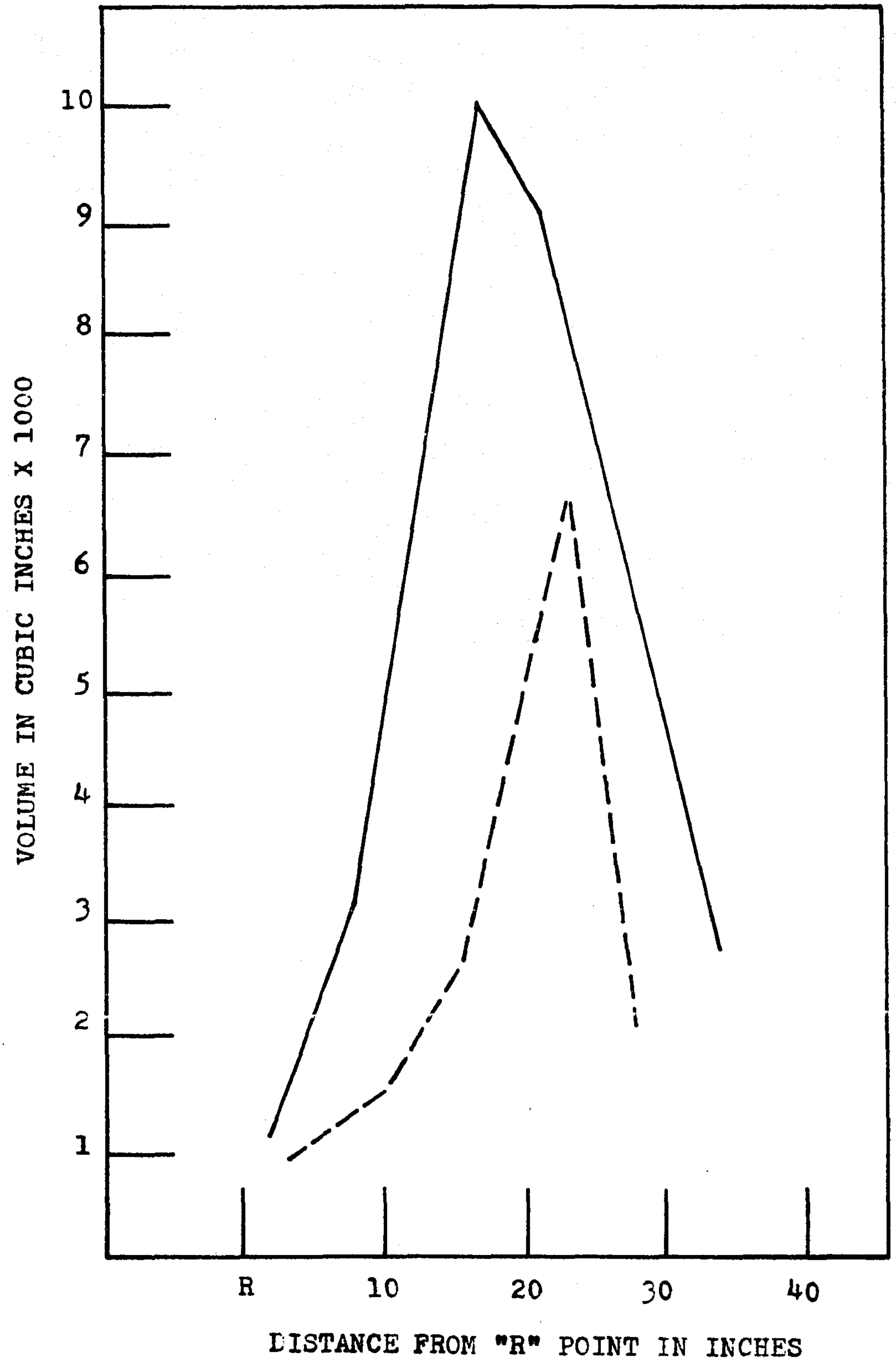

VOLUME IN CUBIC INCHES X 1000
10
9
8
7
6
5
4
3
2
1
R
10
20
30
40
DISTANCE FROM "R" POINT IN INCHES

FIGURE 23

Figure 24. A graph illustrating the normal and prosthetic interval volumes of the above elbow amputee with the percentage difference value closest to the mean. The interval volumes are plotted at six inch intervals from the "R" point. The solid line represents the work space volume of the normal extremity. The broken line represents the work space volume of the prosthetic extremity. The total normal work space volume is the area below the solid line (25,203 cu. in.). The total prosthetic work space volume is the area below the broken line (3,758 cu. in.). The area between the lines is the difference in volume (22,445 cu. in.).

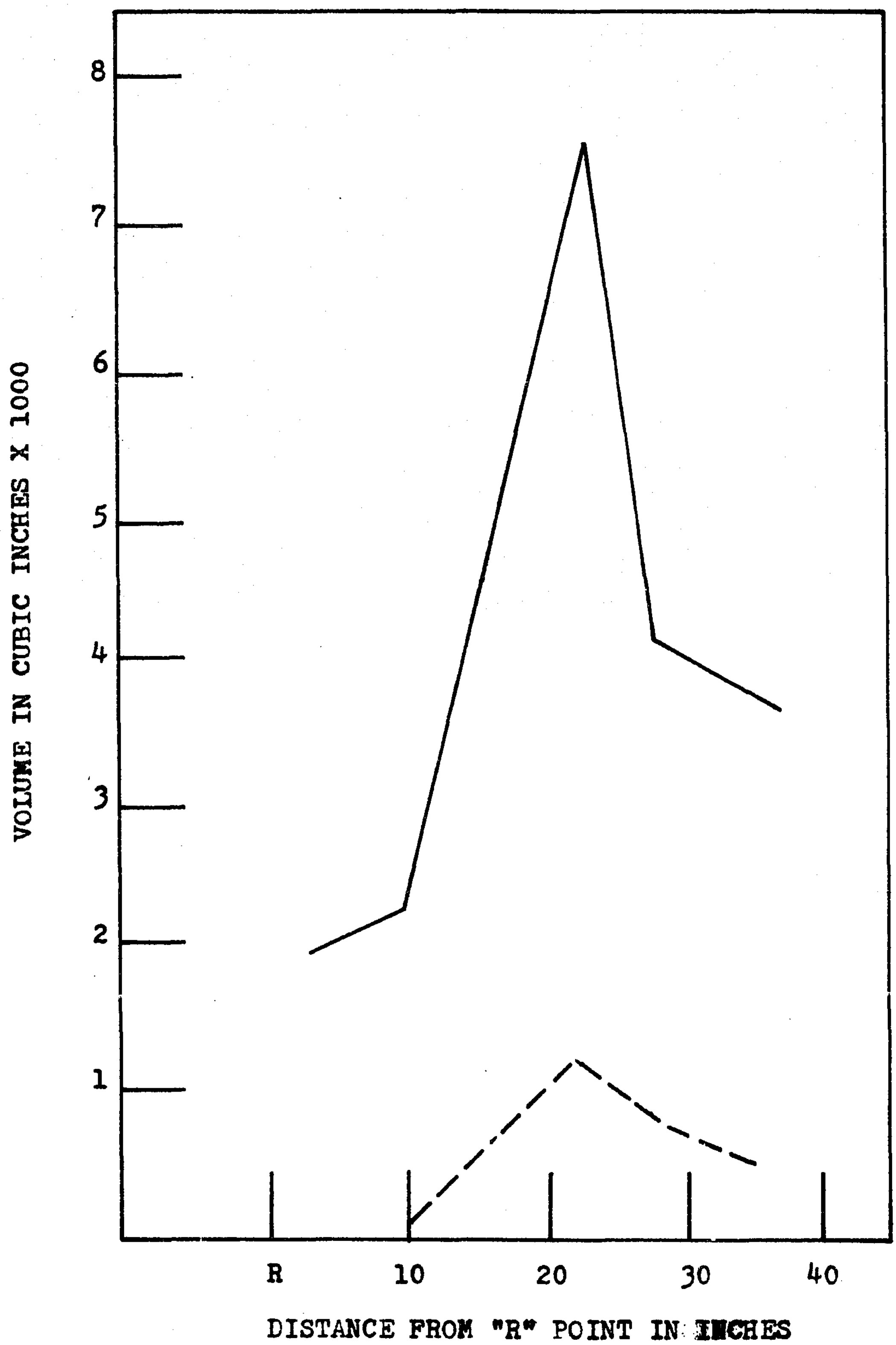

VOLUME IN CUBIC INCHES X 1000
8
7
6
5
4
3
2
1
R
10
20
30
40
DISTANCE FROM "R" POINT IN INCHES

FIGURE 24

Figure 25. A graph illustrating the normal and prosthetic interval volumes of the above elbow amputee with the smallest percentage difference. The interval volumes are plotted at six inch intervals from the "R" point. The solid line represents the work space volume of the normal extremity. The broken line represents the work space volume of the prosthetic extremity. The total normal work space volume is the area below the solid line (44,834 cu. in.). The total prosthetic work space volume is the area below the broken line (15,178 cu. in.). The area between the lines is the difference in volume (29,656 cu. in.).

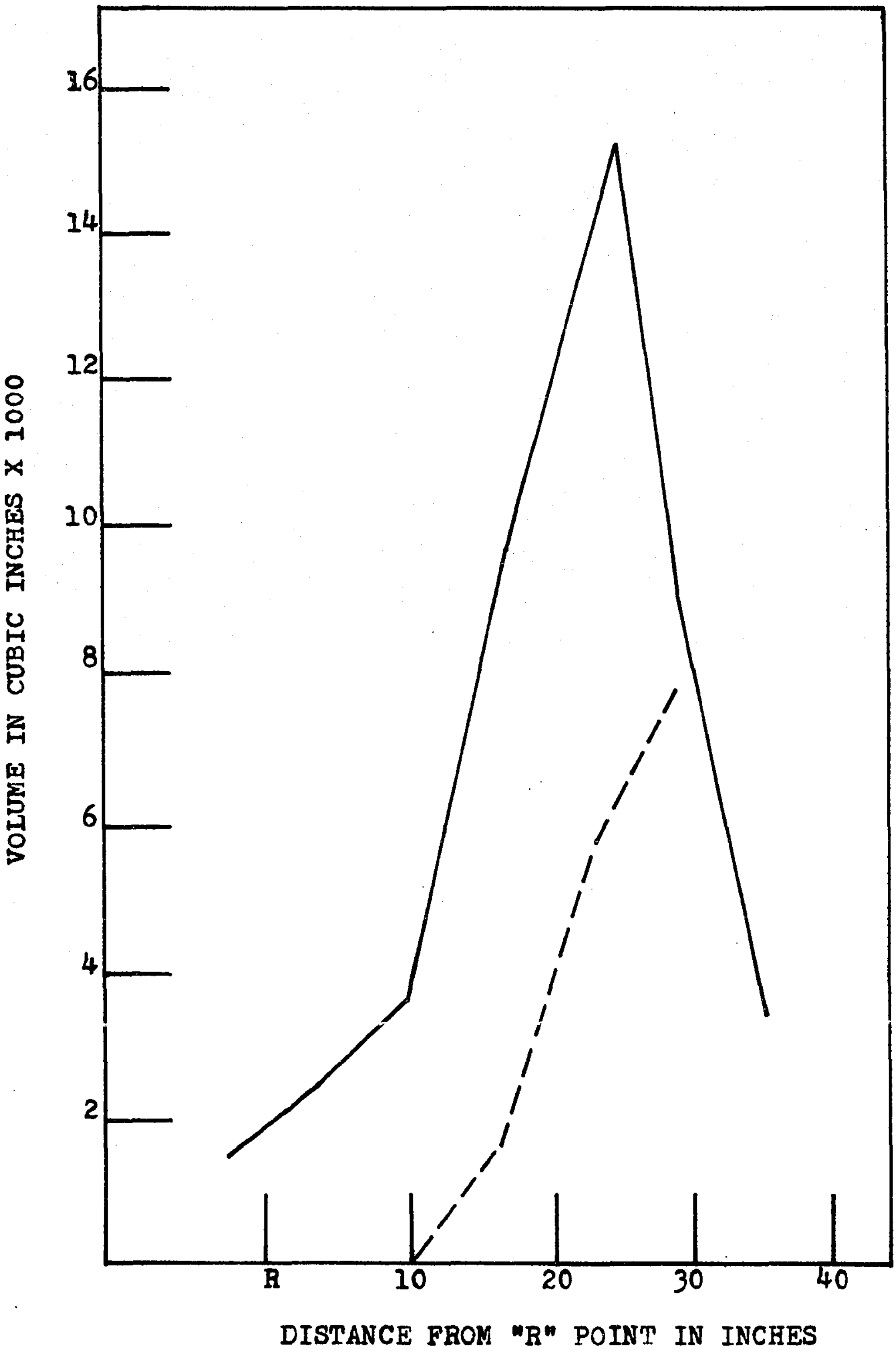

VOLUME IN CUBIC INCHES X 1000
16
14
12
10
8
6
4
2
R
10
20
30
40
DISTANCE FROM "R" POINT IN INCHES

FIGURE 25

Figure 26. A graph illustrating the normal and prosthetic interval volumes of the above elbow amputee with the largest percentage difference. The interval volumes are plotted at six inch intervals from the "R" point. The solid line represents the work space volume of the normal extremity. The broken line represents the work space volume of the prosthetic extremity. The total normal work space volume is the area below the solid line (33,753 cu. in.). The total prosthetic work space volume is the area below the broken line (698 cu. in.). The area between the lines is the difference in volume (33,055 cu. in.).

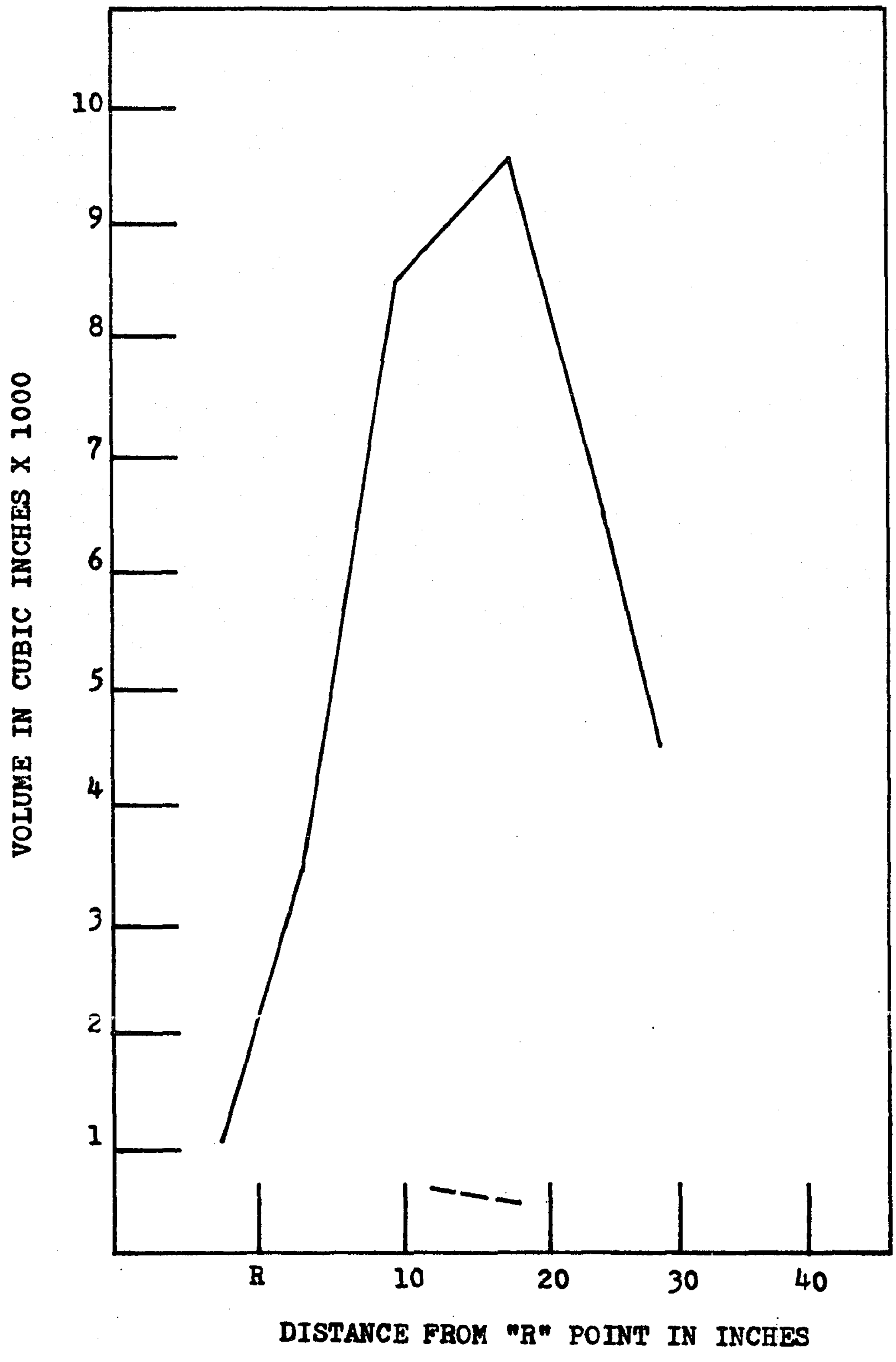

10
9
8
7
6
5
4
3
2
1
VOLUME IN CUBIC INCHES X 1000
R
10
20
30
40
DISTANCE FROM "R" POINT IN INCHES

FIGURE 26

Figure 27. A bar graph illustrating the normal and prosthetic work space volumes for the representative below elbow amputees. N stands for the work space volume of the normal extremity and P for the work space volume of the prosthetic extremity. The shaded area represents the amount of work space volume that has been lost when the prosthesis replaces the normal extremity. A. The volumes of the subject with the smallest percentage difference. The normal work space has been reduced by 20 per cent. B. The volumes of the subject with the largest percentage difference. The normal work space has been reduced by 60 per cent. C. The volumes of the subject with the percentage difference value closest to the mean. The normal work space has been reduced by 45 per cent.

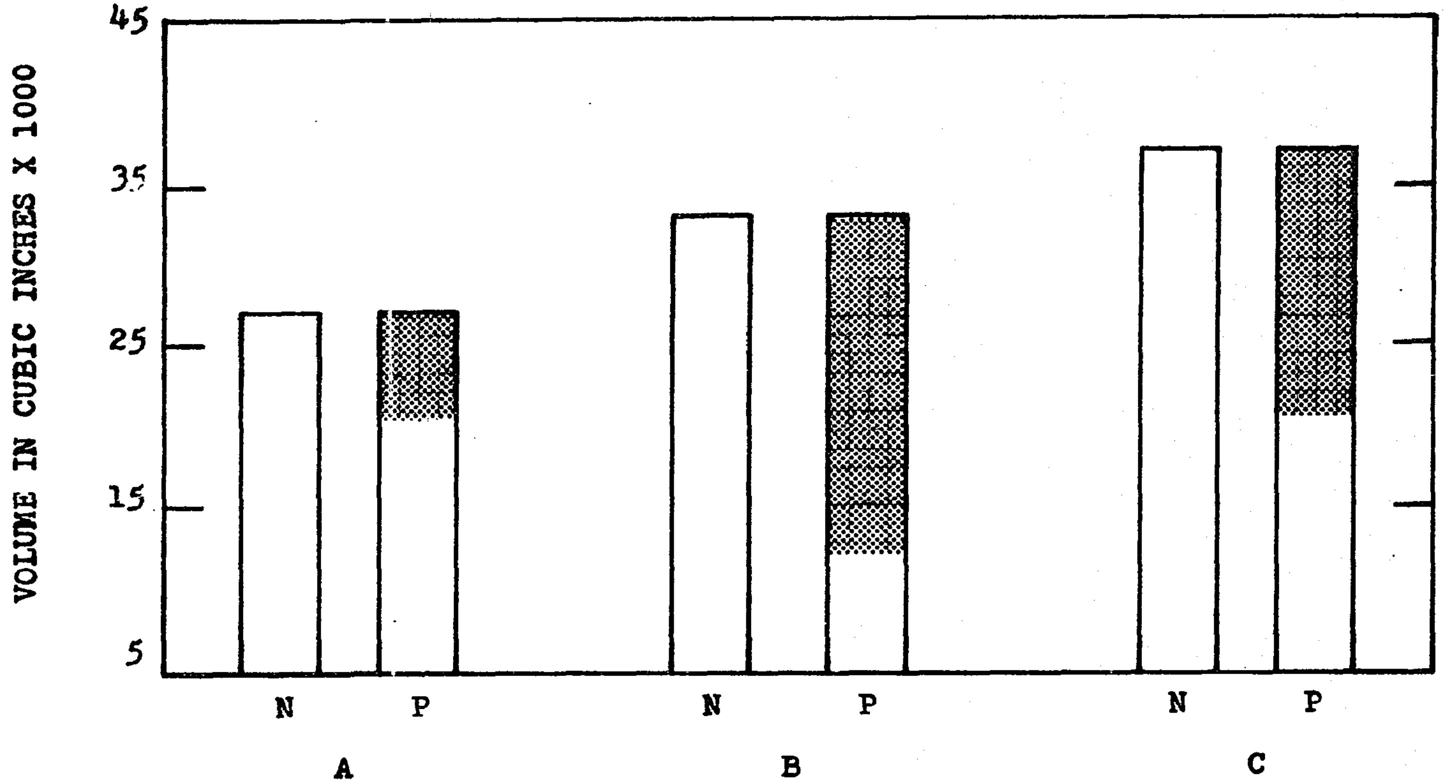


FIGURE 27

Figure 28. A bar graph illustrating the normal and prosthetic work space volumes for the representative above elbow amputees. N stands for the work space volume of the normal extremity and P for the work space volume of the prosthetic extremity. The shaded area represents the amount of work space volume that has been lost when the prosthesis replaces the normal extremity. A. The volumes of the subject with the smallest percentage difference. The normal work space has been reduced by 66 per cent. B. The volumes of the subject with the largest percentage difference. The normal work space has been reduced by 97.9 per cent. C. The volumes of the subject with the percentage difference value closest to the mean. The normal work space has been reduced by 85 per cent.

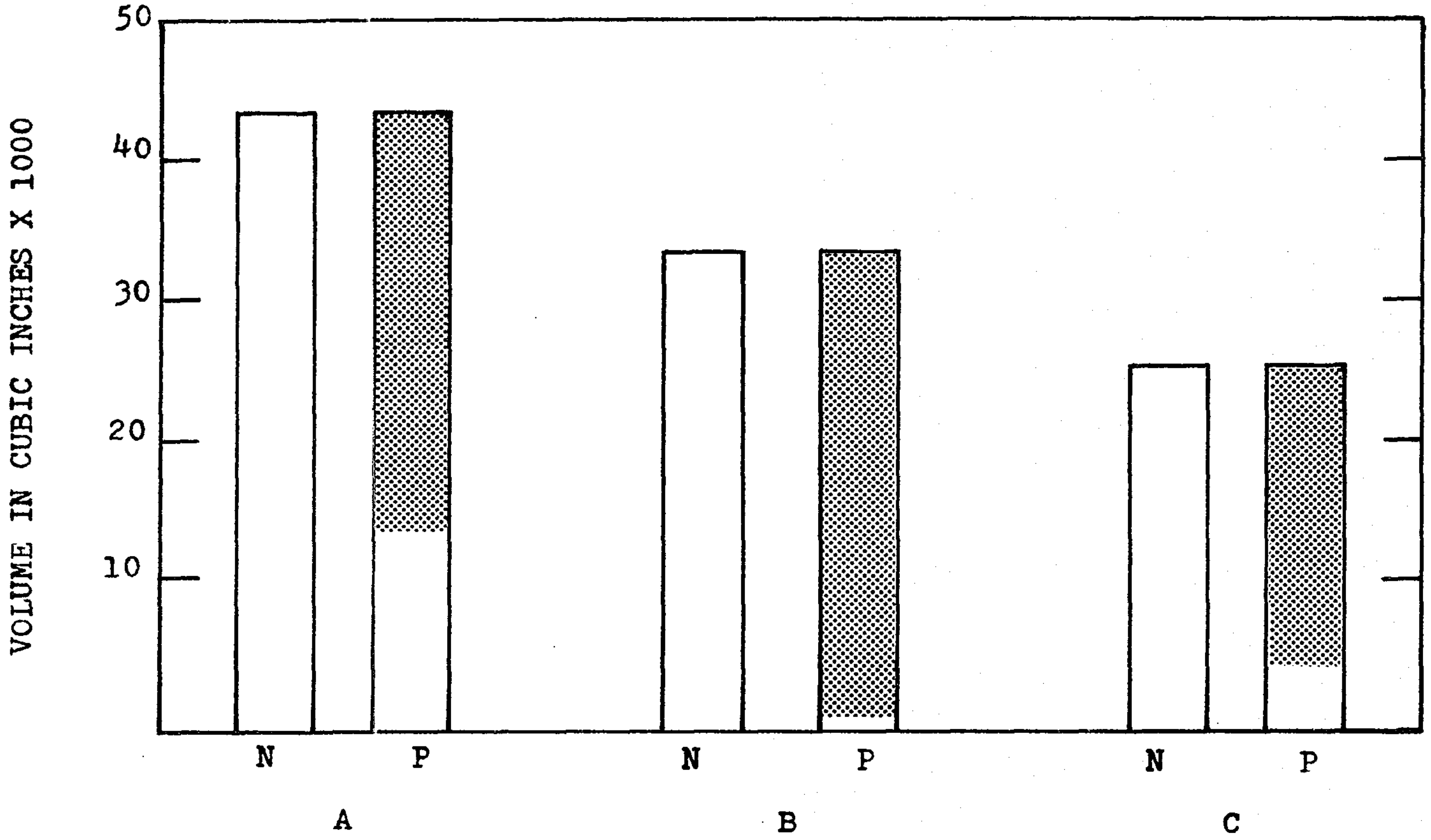


FIGURE 28

Coefficients of variation were computed from the data collected from all amputees. The coefficients of variation are expressed in per cents and the lower the numerical value the lower the variation. In the group with below elbow prostheses the prosthetic volume was slightly more variable than the normal volume. According to the coefficients of variation found for prosthetic extremity length compared to normal length, age, height, weight, stump length, and time worn, the time worn was the most variable and the height was the least variable factor (Table 5). In the group of subjects with above elbow prostheses, the normal volumes were less variable among subjects than were the prosthetic volumes. According to the coefficients of variation found for age, height, weight, stump length, time worn, and prosthetic extremity length (compared to normal length), the prosthetic extremity length was the most variable factor and the height was the least variable (Table 5).

The normal volumes were slightly more variable in the above elbow group. The prosthetic volume was much more variable in the above elbow group. The difference volumes were essentially the same in respect to variability. The percentage differences were more variable in the below elbow group. There was some difference in the variability of time worn and the stump length but in the other measurements there was no noticeable difference. In the below elbow group the time worn was more variable than in the above elbow group. The

TABLE 5

COEFFICIENTS OF VARIATION

Measurements	Below Elbow %	Above Elbow %
Normal Volume	26	38.1
Prosthetic Volume	35.6	86.8
Difference in Volume	32.6	33.8
Percentage Difference	26.3	10.7
Age	37.3	31.5
Height	3.3	4.5
Weight	16.7	18.5
Stump Length	18.2	29.4
Time Worn	84.9	69.2
Prosthetic Extremity Length (Compared to Normal Length)	77.8	71.5

stump length was more variable in the above elbow group.

In the group with the above elbow prostheses the rank correlation coefficient was found for the difference in volumes versus the normal volume, prosthetic volume, age, height, weight, stump length, time worn, and prosthetic extremity length (Table 6). There was a significant correlation between the difference in volume and the normal volume at the .01 level and for the difference in volume and the height at the .10 level. The rank correlation coefficient was found for the normal volume versus the age, height, and weight of the subjects (Table 6). The only significant correlation was for height which was significant at the .05 level. When the prosthetic area was correlated with the age, height, weight, stump length, time worn, and prosthetic extremity length, the only significant correlation was for weight at the .05 level (Table 6).

In the group with the below elbow prostheses, the difference volume was correlated with the normal volume, prosthetic volume, age, height, weight, stump length, time worn, and prosthetic extremity length (Table 6). The only significant correlation was for the normal volume at the .05 level. No significant correlation was found when the normal volume was compared to the age, height or weight. There was also no significant correlation when the prosthetic volume was compared to the age, height, weight, stump length, time worn, and prosthetic extremity length (Table 6).

TABLE 6

RANK CORRELATIONS

	BELOW ELBOW			ABOVE ELBOW		
	Difference Volume	Normal Volume	Prosthetic Volume	Difference Volume	Normal Volume	Prosthetic Volume
Normal Volume	0.71			0.97		
Prosthetic Volume	-0.02			0.30		
Age	0.40	0.22	0.00	0.14	0.23	0.24
Height	-0.21	0.42	0.42	0.63	0.71	0.47
Weight	-0.29	0.30	0.30	0.26	0.41	0.68
Stump Length	-0.15		0.15	-0.60		0.17
Time Worn	0.51		-0.09	0.38		0.23
Prosthetic Extremity Length	0.45		0.32	-0.33		0.00

The Wilcoxin-Mann-Whitney u test was applied to the percentage differences and the difference volumes between the above elbow group and the below elbow group. The differences between the percentage differences and the differences in volume in the two groups were found to be significant. The test was also applied to determine if the percentage difference varied significantly if the subject had a right or left prosthesis. For both the above elbow group and the below elbow group there was no significant difference according to the u test.

CHAPTER IV

DISCUSSION

The degrees of freedom of motion that the segments of the body possess are obtained by the summation of motion of two or more joints. The high degree of freedom of motion of the hand in relation to the trunk is a result of the freedom of motion of the joints of the various segments of the upper extremity. According to Brunnstrom (1962) the expression "degrees of freedom of motion" was originally coined by Reuleux in 1875 for use in engineering. It was adapted to biomechanics by Fischer in 1907. This freedom constitutes the mechanical basis for the performance of skilled manual activities. The freedom of motion of all the joints of the upper extremity is a very important factor in determining the work space.

The term "kinematic chain" is also applicable to the movement of the hand in space. This expression was also introduced by Reuleux. The term refers to a combination of several joints uniting successive segments. In an open kinematic chain the distal segment terminates free in space, while in a closed chain the end segments are united to form a ring or closed circuit. The hand represents the end member of an open kinematic chain and it has a great excursion due to the freedom of motion of all the joints in the kinematic chain of the upper extremity.

If movement of an individual joint is restricted, motion of the entire arm complex will be restricted, and the work space will be decreased. In the study by Rozier (1970) the scapula was restricted by shoulder belts to prevent upward rotation, elevation and protraction. This restriction caused a decrease in the manual work space of 54 per cent. In the present study the freedom of motion is drastically reduced by the loss of the joints of the hand, wrist and elbow. The prosthesis which is supposed to replace the lost joints does not re-establish the freedom of motion of the intact extremity. With a below elbow prosthesis there was an average decrease in the work space of 45 per cent and with an above elbow prosthesis there was an average decrease of 83 per cent.

Prostheses

The typical control system of a prosthesis consists of a cable with terminal fittings and a housing for the cable. One end of the cable is attached to a harnessed body control point and the other end is attached to the point of operation of the terminal device. The efficiency of the control is a critical factor in prosthetic operation.

The below elbow prosthesis provides substitutes for hand prehension, and wrist rotation. In below elbow amputations the functions of the hand and wrist are absent but those of the partial forearm, elbow, and shoulder remain. The harness serves to suspend the prosthesis and to provide the reaction point for control of its operation.

The unilateral below elbow harness consists of a webbing strap in a figure 8 pattern with an open end. The ring harness, a modification of the figure 8 harness, consists of a stainless steel ring at the back cross of the webbing strap. This serves as the distribution point for the four diverging webbing straps. The unilateral below elbow leather harness has a shoulder saddle instead of a front support strap to bear the bulk of the axial load. With this type of harness the wearer can carry heavier loads without suffering discomfort caused by concentration of pressure.

In above elbow amputations the functions of the shoulder and arm stump remain and the functions of the hand, wrist, forearm, and elbow must be replaced by a prosthesis. The harness must transmit power to flex the prosthetic forearm, lock and unlock the elbow, and to operate the terminal device. The above elbow harness depends upon the figure 8 pattern as the basic strap. A ring harness may also be used. Additional straps are required for socket suspension and integration. If the amputee is required to lift heavy loads the harness may cause painful pressure concentrations. As in the below elbow prosthesis, a leather shoulder saddle may be used to prevent these concentrations.

Due to the differences of the types of harnesses and control systems used by the subjects in this study a definite relationship could not be established between types of harnesses and the amount of prosthetic work space. There is a possibility that all of the harnesses in which the opposite shoulder is used as an anchor point may restrict movement of that shoulder. However, if we compare the average work space volumes of the normal extremities found in this study (30, 584) with those determined by Rozier (1970) (28,211), it appears that the shoulder harnesses used by amputees do not cause restriction of the work space.

In this study the terminal devices were not actually much of a variable factor in determining the work space. The subjects were limited to movement in one plane and they were not required to lift a load. This ruled out comparing the strength of the terminal devices except in the one plane. This may also have nullified the effect of some of the differences between the prostheses.

The prosthetic extremities were shorter than the normal arm for nineteen of the twenty amputees. The prostheses are made so that the terminal device corresponds to the grip of the normal extremity. Normal arm length was measured to the distal interphalangeal joint of the middle finger and not to the point of the grip. Thus the prosthesis would be shorter than the normal arm when looking at these measurements. When the subjects performed the movements with their prostheses the metal light holder added two inches to the total length. The prosthetic extremities averaged 1.75 inches shorter. The holder may have negated the difference in lengths. This difference was not found to correlate with the difference in volumes between the normal and prosthetic work spaces.

In the present study there was found to be a greater reduction in work space with the above elbow prosthesis. It is tempting to try to correlate this greater reduction with the lack of an elbow joint. However this can not be done because of other factors that differ between the above and below elbow prostheses. The above elbow prosthesis has replaced the normal elbow joint with a mechanical one that flexes and extends but the control of this movement is considerably decreased and more variable than the normal. The below elbow prosthesis limits motion at the elbow joint of the arm. There is actually no replacement of the radio-ulnar joints, but the terminal device can be manually turned to simulate supination and pronation. The above elbow prosthesis possesses a more complex control system which requires different body motions to control prosthetic movement. These are linked to different control points on the harness.

Measurements

The measurements of the age, height, and weight of the subjects in this investigation were much more variable than those in the studies by Dempster _et al_. (1959) and Rozier (1970). Subjects in the present study varied in age from 17 to 66 years with an average of 41 years. The ages of the subjects in the work by Rozier (1970) ranged from 19 to 31 years with a mean of 23 years and those in the study by Dempster (1959) varied from 17 to 33 years. The height of the subjects ranged from 5 feet, 5 inches to 6 feet, 3 inches with an average height of 5 feet, 10.5 inches. In the previous study by Rozier the height was restricted to a smaller range of from 5 feet, 7.5 inches to 5 feet, 10 inches with an average height of 5 feet, 8.5 inches. The height of the subjects in the study by Dempster was even less variable with an average height of 5 feet, 9 inches. Weight of the twenty subjects in this study varied from 112 pounds to 255 pounds with an average of 173.2 pounds, compared with that in the study by Rozier (1970) which ranged from 135 pounds to 165 pounds with an average of 152 pounds. Weight was not stated in the Dempster study.

Since there have been no anthropometric data collected on upper extremity amputees as a group, subjects with average values could not be selected for study. In the previous studies (Dempster _et al_., 1959; Rozier, 1970) it was desired to find the work space for the average male subject. Average subjects were used because the problem of the work space is one of placement of controls for efficient use.

The extremes of the work space are less frequently used by average subjects.

The variability of measurements on above and below elbow amputees is seen in Table 5. The height and weight of the subjects was only slightly different in variability between the two groups. Age was somewhat more variable in the below elbow group. The most variable measurement was the prosthetic extremity length in the above elbow group, but in the group with the below elbow prostheses the time worn was more variable.

When the rank correlation coefficients were determined (Table 6) the length of time that the subject had worn his prosthesis did not correlate significantly with the reduction in work space. When comparing the time worn with reduction in work space, there was a higher correlation in the below elbow group but this was not great enough to be significant. There was also no significant correlation of prosthetic extremity length with the reduction in work space but a higher value was seen in the below elbow group than in the above elbow group. This would seem to indicate that there is more possibility for different degrees of prosthetic movement with the below elbow prosthesis which perhaps was due to the increased variability of prosthetic extremity length and the time worn. This would also seem to indicate that the length of time that the amputee had worn his prosthesis did not necessarily contribute to an increase in the work space. There was no correlation between prosthetic extremity length, time worn, stump length, and work space volume for the prosthetic extremity. In both the above and the below elbow groups of subjects the stump length did not correlate with reduction in work space. Thus the conclusion can not be reached that the amputee with a longer stump will have a greater work space volume.

The results found with the group of above elbow amputees showed that height had a significant correlation at the .05 level with the normal work space volume. There was also a significant correlation at the .10 level with the reduction in volume. The weight of the subjects with above elbow prostheses correlated with the volume of the prosthetic work space at the .05 level. It was concluded that the taller the subject, the larger the normal but not the prosthetic work space. Therefore the difference in volumes is increased. The normal volume had a correlation with the difference in volume at the .01 level for the above elbow amputees. Therefore the increase in the normal volume caused the increase in the difference in volume. There was also a correlation of the normal volume and the difference in volume at the .05 level for the below elbow amputees. No other significant correlations were evident for the below elbow group.

The amputees used for this study were all initially right handed and of these, 60 per cent had their right arm amputated. According to a study of 1200 amputees by Glattly (1963) 50.8 per cent had right upper extremity amputations. In the present study the fact that the subject was a right or left amputee did not seem to have any effect on the reduction of the work space. This coincides with the theory that the joint range of one extremity is not significantly different from the joint range of the other extremity (Gilliland, 1921; Salter and Darcus, 1953; Dempster, 1959).

Work Spaces Compared

The interval volumes of the normal extremities in this study were compared with those in a previous study (Rozier, 1970) with regard to the intervals that were the largest and the smallest. In the present study of the interval volumes of the normal arm, the sixth interval was the smallest in 90 per cent of the subjects compared to the previous study in which it was the smallest in 85 per cent of the subjects. In the present study in 65 per cent of the subjects the third interval was the largest and in 25 per cent the fourth was the largest. In the previous study, the third interval was largest in 30 per cent of the subjects and the fourth was largest in 65 per cent of the subjects. The subjects used in this study were much more variable in height and weight than in the previous study and naturally more variation would be expected in the volumes of the intervals.

The above findings tend to indicate that the part of the work space to the side of and posterior to the body is the smallest in most normal subjects regardless of body build. The largest interval does seem to vary with body build and in the present study the third interval was predominantly the interval of largest area. The obese subject was unable to move across the midline in the interval closest to the body. This was the fourth interval.

The shapes of the intervals for the normal extremities in the present study compared favorably with those found by Rozier in 1970. However there were variations close to the body and around the knees due to the difference in ages, heights, and weights of these subjects.

In the previous study the reduction of the work space due to scapular restriction was 54 per cent of the normal volume. With the below elbow prosthesis the reduction was 45 per cent. The scapular restriction produced a greater deficit than the below elbow prostheses. This might be explained by the fact that the scapula occupies a more proximal position in the kinematic chain than does the wrist which has been replaced by the prosthesis. With the above elbow prostheses the reduction was 83 per cent. This greater loss of function is understandable since both wrist and elbow have been replaced.

Subjects with below elbow prostheses had difficulty reaching the area lateral to the trunk. Eleven subjects were unable to complete the sixth interval and of these, five were unable to complete the fifth interval. According to Dempster et al. (1959) and Rozier (1970), the posterior and lateral parts of the work space of the normal extremity are limited by maximal elbow flexion and scapular retraction. In the present study the prosthesis itself reduced the extremes of normal elbow flexion and further scapular retraction would not compensate for this. With the above elbow prosthesis there is even further limitation. One subject could complete only the first and second intervals, two could complete the first three intervals, four could complete the first four and two subjects could complete the first five intervals. This indicates that the elbow joint of the prosthesis definitely limits motion in the posterolateral areas. Also the lack of active supination and pronation of the forearm requires the shoulder and the scapula of the amputated extremity to be positioned differently than the normal arm so that full scapular retraction may not be possible.

When using a prosthesis individuals were less able to move the hand across the midline in the intervals close to the body than when using their normal limbs. In the above elbow group two subjects could cross the midline of the body at the third interval and in the below elbow group six could move across at the third interval. Evidently, as a result of limitations imposed by the prostheses, there is more reduction in work space in the areas just anterior to the body with the above elbow prostheses. This reduction was not only due to the inability to position the prosthesis correctly in these areas but also to the lack of ability to control the elbow joint in some subjects. The reduction in the anterior area was also caused by limitations of the wrist movement. The wrist could not be positioned in order to use the length of the forearm to increase the height of the areas as had been done by the subjects with scapular restriction (Rozier, 1970).

In the normal extremity the third interval was the largest. When the below elbow prostheses were used the second was predominantly the largest. When the above elbow prostheses were used the interval with the largest area varied from the first to the fourth with six subjects having the first or second interval as the largest. For all amputees the most posterior interval that could be reached was the smallest and this compared favorably to the normal extremity in which the most posterior interval was also the smallest.

The bimanual area as investigated by Dempster and Rozier refers to the area in which work with both hands can be performed without added movement of the trunk (Figures 15-20). This area in the subject with a normal extremity and a prosthesis has a somewhat different connotation. Here it also represents the area in which the normal extremity may perform tasks that would ordinarily be performed by the opposite extremity. The prosthetic work space is severely reduced and the normal extremity can do work in a large part of the work space of the prosthesis. The work space of the normal extremity encompasses more of the work space of the above elbow prosthetic extremity than it does of the below elbow prosthetic extremity. It is evident that without added trunk motion the normal extremity can reach the area in which the prosthesis can be used except for a small posterolateral part of the prosthetic work space.

The bimanual area is important when considering occupations for amputees. If the amputee is forced to use his normal extremity for most tasks, this will cause fatigue. Certain tasks and controls can be placed within the prosthetic work space for efficient use of the prosthesis. Tasks requiring two hands must be performed in the bimanual area. Rearrangement of the work space according to the above criteria will facilitate the performance of a job by the amputee.

The largest and smallest differences in volumes can be compared among subjects. In both groups of amputees the smallest reduction in the work space due to the prosthesis was the same, predominantly at the first interval, and the largest reduction was predominantly at the third. Even though the sixth or last interval was the smallest in volume in the above and the below elbow groups this was not the interval of largest difference because the sixth interval was also the smallest for the normal extremity. The third interval was predominantly the largest interval in both groups but this was not the interval of smallest difference because the third interval was also large for the normal extremity. The size of the intervals farthest from the body did not differ as much between the prosthetic and the normal side. The third interval and intervals right in front of the body showed the greatest reduction. Thus as the subject-to-grid distance decreased the reduction of the work space increased.

The shapes of the interval tracings naturally varied between normal and prosthetic extremities. There was also great variation between above elbow and below elbow prosthetic groups. In comparing the below elbow tracings with those of the normal arm the shapes of the intervals were not usually indented due to the knees. However, the lateral wing of the work space was present and the interval tracing of the fourth interval was usually directed lateral to the midline and not as high as the preceeding intervals. When comparing the shapes of the above elbow intervals to those of the normal extremity intervals, there was a striking difference. There was not a great amount of conformity among the above elbow subjects. The above elbow subject tended to move in a very limited way in the area that extended in front of his shoulder.

When comparing the shapes of the planes of the three-dimensional models of the above and below elbow prosthetic work spaces, it was evident that the below elbow prosthesis allows much more area for operation than does the above elbow prostheses. Also they demonstrate that the below elbow prosthesis allows more movement across the midline of the body and in the posterolateral areas.

As a result of the variability in age, height, weight, prosthetic extremity length, and stump length the actual volumes of the work space of the subjects could not be compared in terms of cubic inches. For instance, the volumes for normal extremities varied from 18,169 cubic inches to 52,699 cubic inches. The volume of the work space of the prosthetic extremity varied from 698 to 30,178 cubic inches. The difference in volume for the normal and prosthetic work spaces for each subject varied from 5,512 to 41,205 cubic inches. Therefore, the difference in cubic inches from the normal volume was converted to a percentage in order to compare subjects. For the group with the below elbow prostheses the percentage difference varied from 20 to 60 per cent. The subject with the largest percentage difference did not have the smallest prosthetic volume and the subject with the smallest percentage difference did not have the largest prosthetic volume. For the above elbow group, the smallest percentage difference was 66 per cent and the largest percentage difference was 97.9 per cent. The subject with the largest percentage difference had the smallest prosthetic volume and the subject with the smallest percentage difference did have the largest prosthetic volume. From these observations no conclusion can be made relating prosthetic extremity volume to percentage difference.

Variations of the normal extremity work space volumes were within a close range considering the variability of height and weight. There was, however, a slightly higher coefficient of variation (38 per cent) for the above elbow group compared to that (26 per cent) for the below elbow group.

The prosthetic volumes were more variable than the normal volumes. This could be expected because of the different types of prostheses that the subjects wore. As noted previously, there were not enough of each type of prosthesis to be able to compare volumes on the basis of the type of prosthesis used. The coefficient of variation for the above elbow prosthetic volumes was 86.8 per cent. This high coefficient was apparently due to the many different types of harnesses and control systems. The subject with the smallest prosthetic volume in the above elbow group had a prosthesis with no elbow lock. It was also observed that this subject had the largest reduction in work space volume. Those with harness-controlled elbow locks seemed to have more difficulty performing the movements and keeping the elbow locked than did those with manual locks.

In the group with the below elbow prostheses the coefficient of variation for the prosthetic volume was 36 per cent. This was thought to be due to the fact that the below elbow amputee has retained one more joint in the kinematic chain and there is less variability in types of prostheses in this group than in the above elbow group.

The coefficient of variation for the difference in normal and prosthetic volumes was 33.8 per cent for the above elbow group and 32.6 per cent for the below elbow group. However, when the prosthetic volume was calculated as a percentage of the total volume (that of the normal extremity) the coefficient of variation of the percentage difference was only 10.7 per cent for the above elbow group and 26.3 per cent for the below elbow group. These findings indicate that the above elbow prosthesis limits movement to such an extent that there is less opportunity for variation than with the below elbow prosthesis.

Sources of Error

A possible source of error in the experimental procedure was the difference in the efforts of the subjects performing the indicated movements. Some tried to perform the motions correctly while others were not as conscientious. However, it was noted that the amputees used in this study tried harder to perform correctly than did the subjects used in the previous study by Rozier (1970). Only those amputees who were genuinely interested in furthering research in the area of prosthetics agreed to participate. The amputees who were self-conscious about their handicap refused. The eagerness of the subjects might be reflected in the volume of the work space but this factor was not evident when percentage differences were computed. Overeager subjects moved eractically and this could be seen if the hand grid or light moved too far away from the frontal grid. Also, some subjects may not have reached their extremes of motion. However, all precautions were taken to insure that the movements were completed correctly.

Since these subjects were of various ages some had decreased joint motion. If there was a slight decrease in joint movement it might possibly be reflected in both extremities. Decreased joint range of only the normal extremity would decrease the volume of that work space. It would also decrease the difference in volume. If there were decreased joint range in both extremities a decrease would be seen in the normal and prosthetic work space. However, the variations between volumes also were affected by many other variables and the slight reduction in range of motion probably was not of great importance. It should be stated that if the decrease in joint range was apparent the data for that subject was not included.

It was assumed at the onset of the study that perhaps the length of time that the amputee had worn the prosthesis might contribute some source of error since some amputees had more practice in using the prosthesis. However, the amount of time that the subject had worn the prosthesis was not a major factor as far as the extent of movement was concerned. Also, the type of movements that were required of the subject were not of the type that the subject was accustomed to performing. The subject's proficiency with the prosthesis in other tasks was not a factor in determining work space volume.

Applications

Randall *et al*. (1945) found that 50 per cent of 32 upper extremity amputees changed occupations after the amputation. Berger in 1958 studied 1630 upper extremity amputees and found that 14 per cent of these had clerical type jobs before the amputation, while 64 per cent had this type of job after the amputation. Work space information in addition to providing information concerning the use of the terminal device of the prosthesis might prevent certain occupational shifts by showing that an amputee could perform the work as specified.

In this study characteristic manual work spaces for both types of amputees were defined. This information should encourage the rearrangement of the work space for the most efficient use of the normal and prosthetic extremities. For instance, tasks that require two extremities should be placed within the bimanual work space, tasks that can easily be performed with the prosthesis and those that require the normal extremity should be placed within the corresponding work spaces. Tasks that are out of reach of the prosthetic extremity could be moved closer or placed within the normal work space. This type of evaluation of the work space might be beneficial in indicating modifications for machinery, cars, and aircraft in order to accommodate the upper extremity amputee.

The results of this study showed the average decrease from the normal manual work space for the prosthetic extremity of the below (45 per cent) and above (83 per cent) elbow amputee. This reduction indicated that there is further need for improving prostheses in order to increase work space volume. An amputee must first be able to reach the task before his prosthesis is effective.

Methods used in this study may have an application in the development of new types of prostheses. These techniques can be used to determine the manual work space of an amputee using different types of prostheses and to indicate whether one prosthesis is more effective in increasing the work space than another.

CHAPTER V

SUMMARY

A photographic method was used to obtain tracings of movement of the hand of the normal extremity against a frontal plane at different distances (intervals) from the subject. The same procedure was also used to obtain tracings of the movement of the prosthetic extremities of above and below elbow amputees. The intervals were a fixed distance apart so that volume values could be calculated for each interval and for the total work space.

The freedom of motion of the upper extremity is drastically reduced by the loss of the joints of the hand, wrist and elbow. The prosthesis which is supposed to replace the lost joints does not re-establish the freedom of motion of the intact extremity.

The subjects with above elbow prostheses had an average decrease in the work space of 83 per cent. The largest reduction of the work space was seen at the third interval. The smallest reduction of work space was seen at the first interval. The interval of largest volume for the above elbow prosthetic extremity varied from the first to the fourth.

The interval of smallest volume was the most posterior interval. The above elbow prosthetic extremity moved in a very limited way in an area that extended in front of the shoulder. The majority of the work space of the prosthetic extremity can be reached by the normal extremity without added trunk movement.

The subjects with below elbow prostheses had an average decrease in the work space of 45 per cent. The largest reduction of work space was seen at the third interval. The smallest reduction of work space was at the first interval. The interval of largest volume was the second and the interval of smallest volume was the last interval. The normal extremity could not reach as much of the prosthetic extremity work space as it could in the case of the above elbow prosthesis.

For both the above and below elbow amputee it was observed that as the subject-to-grid distance decreased the reduction of the work space increased. The length of time that the subject had worn his prosthesis did not correlate significantly with the reduction in work space in either the below or above elbow amputees. The fact that the subject was a right or left amputee did not effect the reduction in the work space. It was also found that the prosthetic harness did not restrict the work space of the normal extremity.

The results of this study may be applied: (1) to the prevention of occupational shifts after an individual becomes an upper extremity amputee, (2) to the rearrangement of work to accommodate the reduced work space of the prosthetic extremity, and (3) to the improvement of prostheses to increase the work space.

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APPENDIX

Plate I. Styrofoam models of the normal and prosthetic work spaces for the below elbow amputee with the percentage difference closest to the mean. The models do not present a smooth contour due to the fact that each model is made up of scale interval outlines each of which is one inch in thickness. The dark lines on the models represent the planes in which the horizontal, sagittal, and frontal sections of the models were cut. A. Front view of the models of the prosthetic (1) and normal (2) work spaces. B. Top view of the models of the prosthetic (1) and normal (2) work spaces. C. Side view of the models of the prosthetic (1) and normal (2) work spaces. The front of each model faces the middle of the photograph. D. Rear view of the models of the prosthetic (2) and normal (1) work spaces. E. Horizontal sections of the models of the prosthetic (1) and normal (2) work spaces. F. Sagittal sections of the models of the normal (1) and prosthetic (2) work spaces. The top of each model faces the middle of the photograph. G. Frontal sections of the models of the prosthetic (1) and normal (2) work spaces.

PLATE I

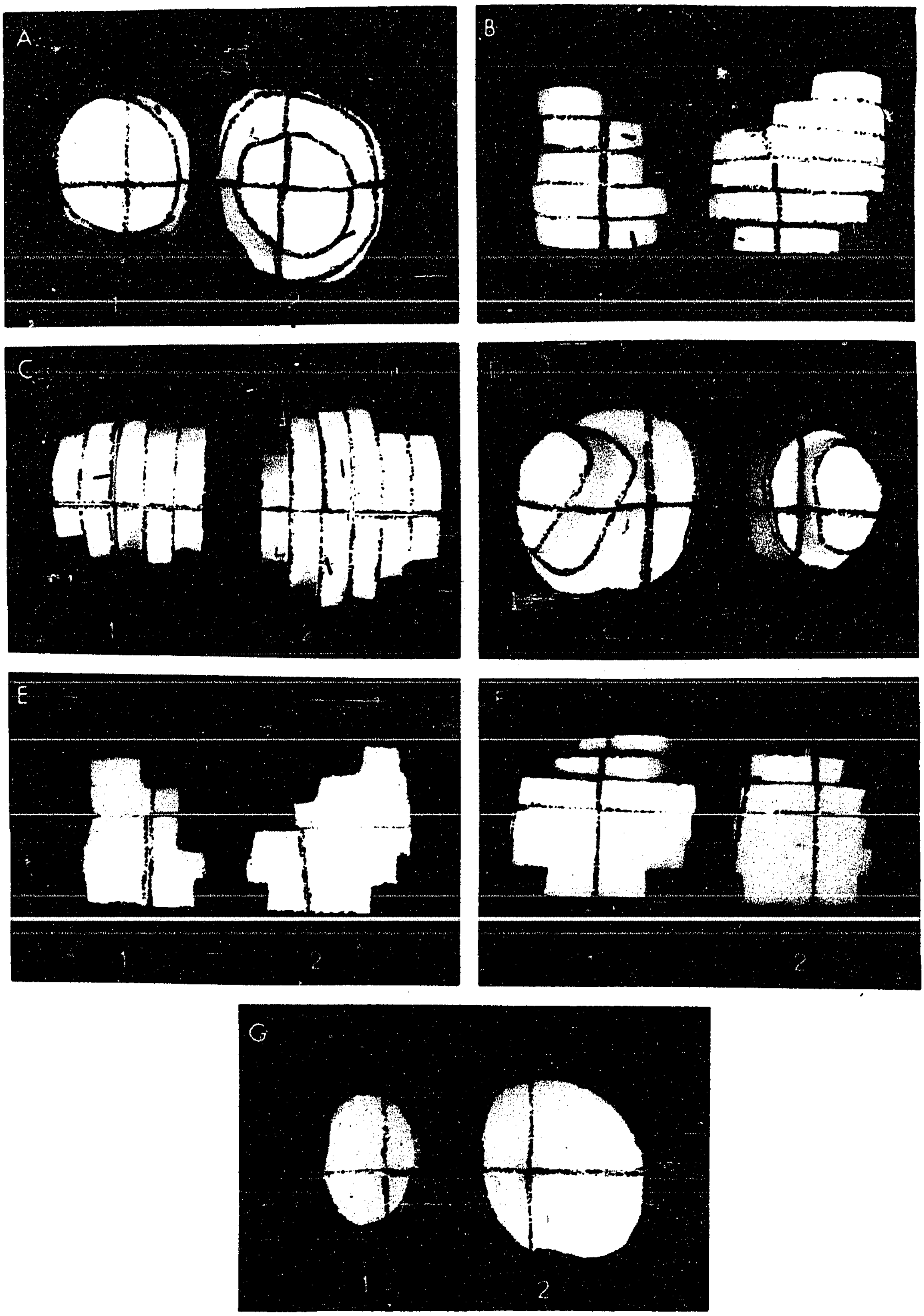

Plate II. Styrofoam models of the normal and prosthetic work spaces for the below elbow amputee with the smallest percentage difference. The models do not present a smooth contour due to the fact that each model is made up of scale interval outlines each of which is one inch in thickness. The dark lines on the models represent the planes in which the horizontal, sagittal, and frontal sections of the models were cut. A. Front view of the models of the prosthetic (1) and normal (2) work spaces. B. Top view of the models of the prosthetic (1) and normal (2) work spaces. C. Side view of the models of the prosthetic (1) and normal (2) work spaces. The front of each model faces the middle of the photograph. D. Rear view of the models of the prosthetic (2) and normal (1) work spaces. E. Horizontal sections of the models of the prosthetic (1) and normal (2) work spaces. F. Sagittal sections of the models of the normal (1) and prosthetic (2) work spaces. The top of each model faces the middle of the photograph. G. Frontal sections of the models of the prosthetic (1) and normal (2) work spaces.

PLATE II

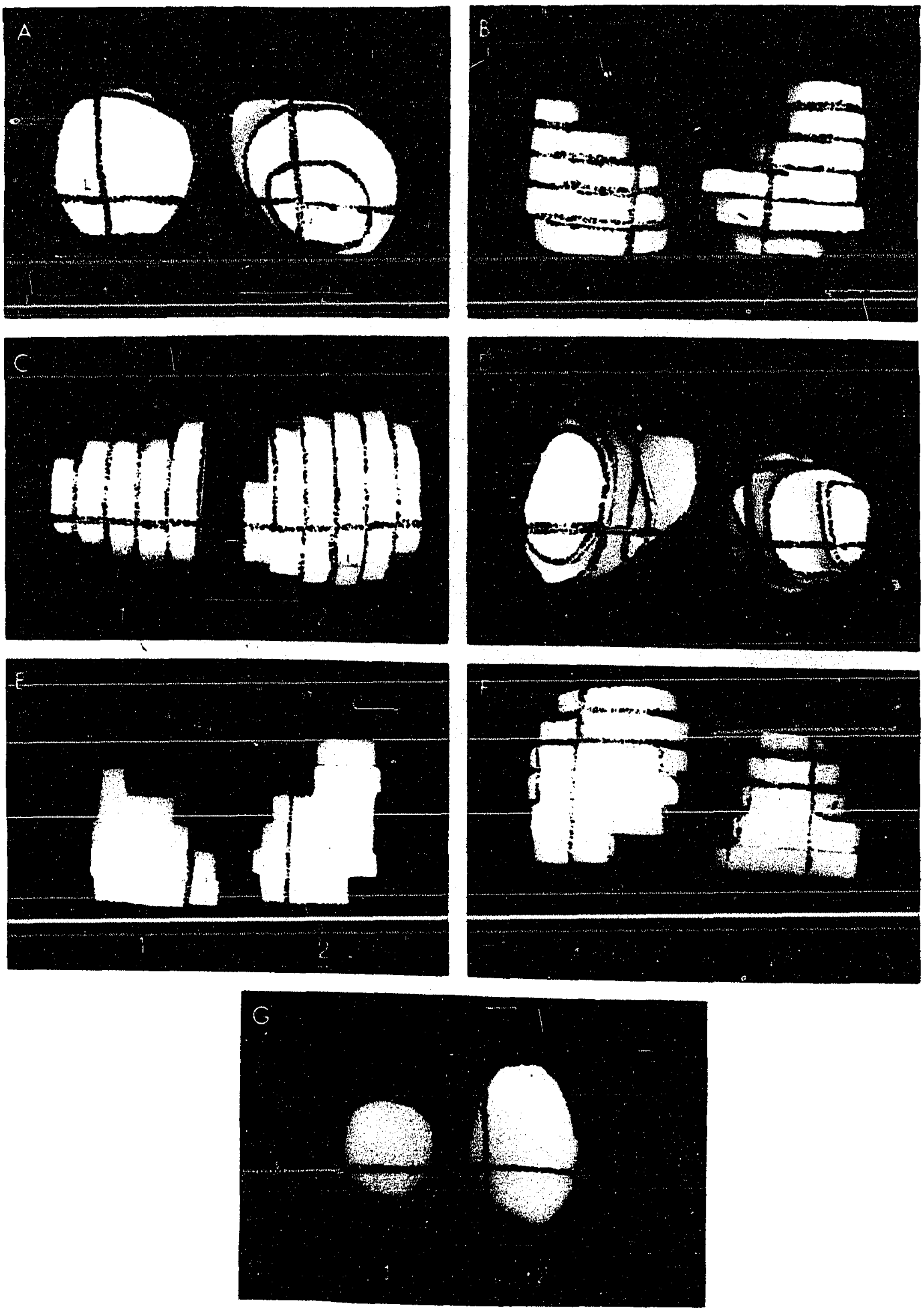

Plate III. Styrofoam models of the normal and prosthetic work spaces for the below elbow amputee with the largest percentage difference. The models do not present a smooth contour due to the fact that each model is made up of scale interval outlines each of which is one inch in thickness. The dark lines on the models represent the planes in which the horizontal, sagittal, and frontal sections of the models were cut. A. Front view of the models of the normal (1) and prosthetic (2) work spaces. B. Top view of the normal (1) and prosthetic (2) work spaces. C. side view of the models of the normal (1) and prosthetic (2) work spaces. The front of each model faces the middle of the photograph. D. Rear view of the models of the prosthetic (1) and normal (2) work spaces. E. Horizontal sections of the models of the normal (1) and prosthetic (2) work spaces. F. Sagittal sections of the models of the prosthetic (1) and normal (2) work spaces. Top of each model faces the middle of the photograph. G. Frontal sections of the models of the normal (1) and prosthetic (2) work spaces.

PLATE III

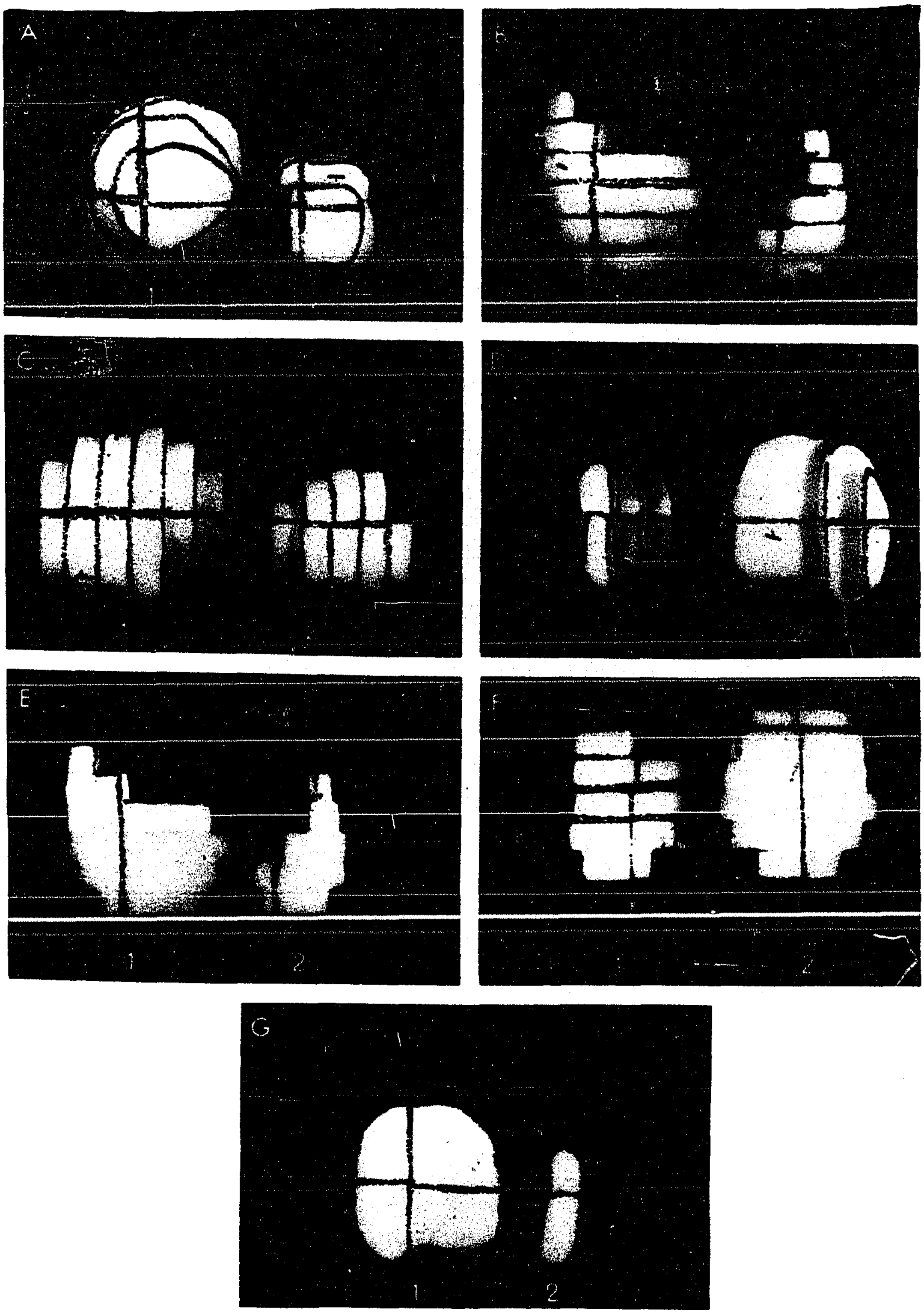

Plate IV. Styrofoam models of the normal and prosthetic work spaces for the above elbow amputee with the percentage difference closest to the mean. The models do not present a smooth contour due to the fact that each model is made up of scale interval outlines each of which is one inch in thickness. The dark lines on the models represent the planes in which the horizontal, sagittal, and frontal sections of the models were cut. A. Front view of the models of the normal (1) and prosthetic (2) work spaces. B. Top view of the normal (1) and prosthetic (2) work spaces. C. Side view of the models of the normal (1) and prosthetic (2) work spaces. The front of each model faces the middle of the photograph. D. Rear view of the models of the prosthetic (1) and normal (2) work spaces. E. Horizontal sections of the models of the normal (1) and prosthetic (2) work spaces. F. Sagittal sections of the models of the prosthetic (1) and normal (2) work spaces. Top of each model faces the middle of the photograph. G. Frontal sections of the models of the normal (1) and prosthetic (2) work spaces.

PLATE IV

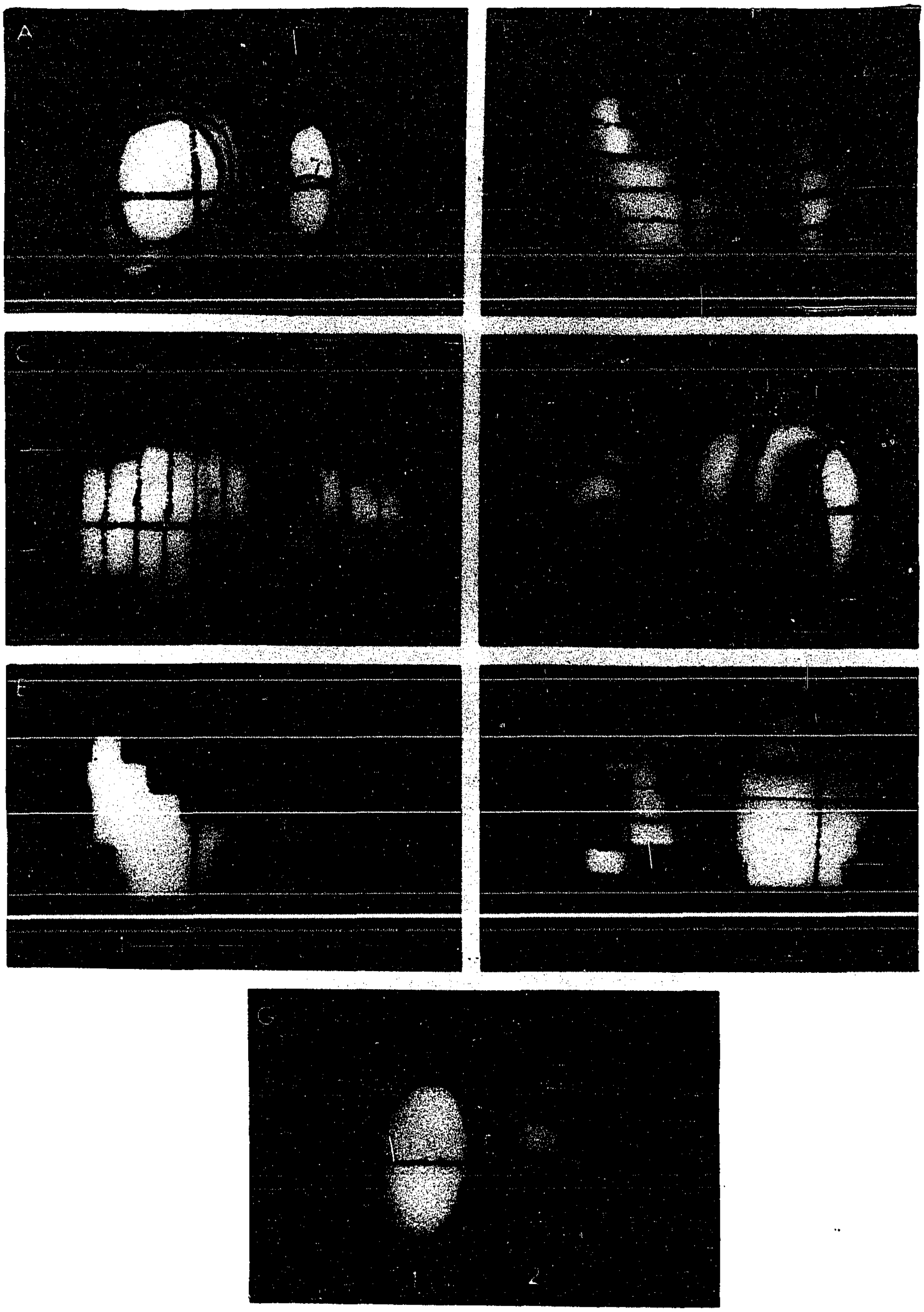

Plate V. Styrofoam models of the normal and prosthetic work spaces for the above elbow amputee with the smallest percentage difference. The models do not present a smooth contour due to the fact that each model is made up of scale interval outlines each of which is one inch in thickness. The dark lines on the models represent the planes in which the horizontal, sagittal, and frontal sections of the models were cut. A. Front view of the models of the prosthetic (1) and normal (2) work spaces. B. Top view of the models of the prosthetic (1) and normal (2) work spaces. C. Side view of the models of the prosthetic (1) and normal (2) work spaces. The front of each model faces the middle of the photograph. D. Rear view of the models of the prosthetic (2) and normal (1) work spaces. E. Horizontal sections of the models of the prosthetic (1) and normal (2) work spaces. F. Sagittal sections of the models of the normal (1) and prosthetic (2) work spaces. The top of each model faces the middle of the photograph. G. Frontal sections of the models of the prosthetic (1) and normal (2) work spaces.

PLATE V

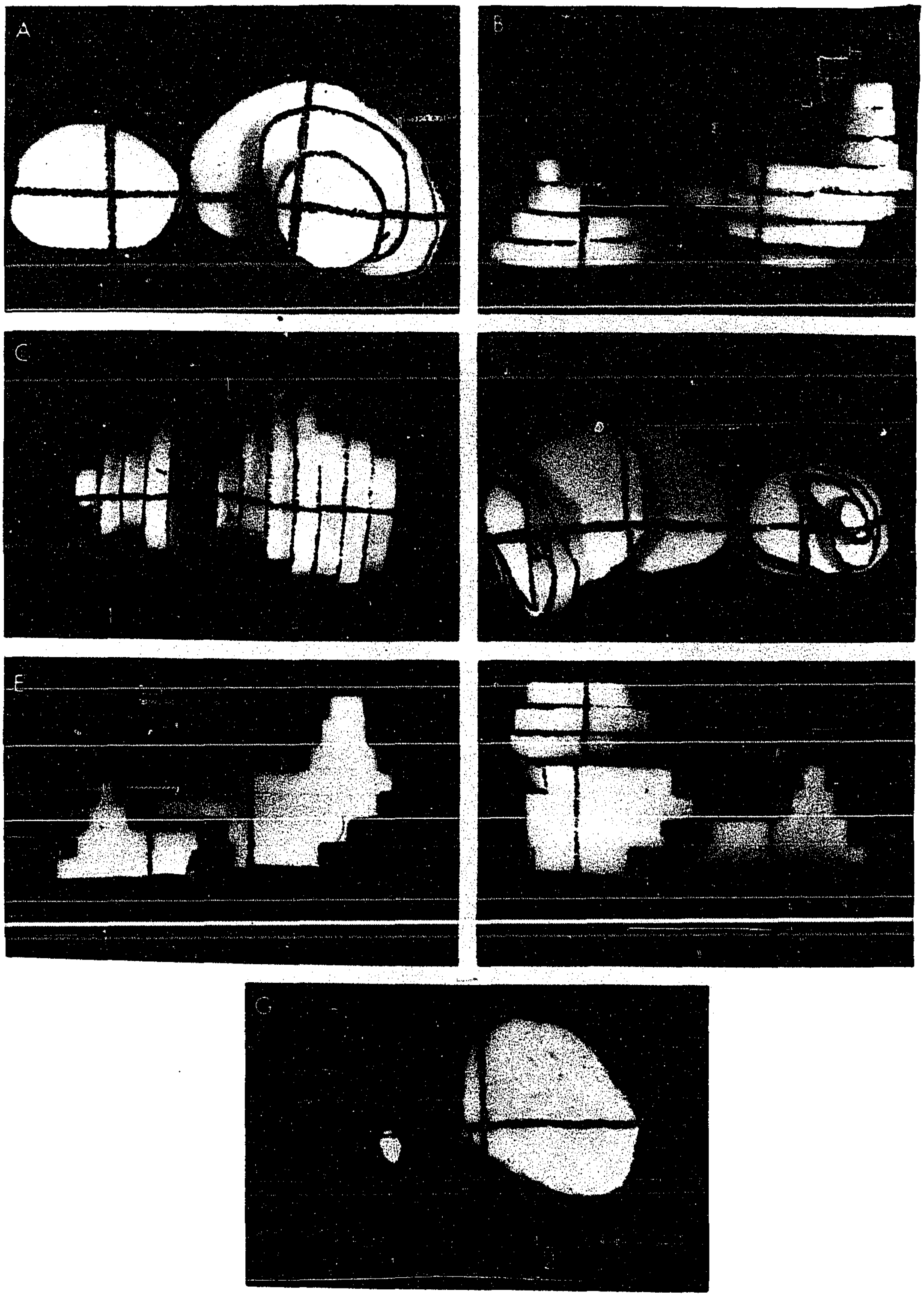

Plate VI. Styrofoam models of the normal and prosthetic work spaces for the above elbow amputee with the largest percentage difference. The models do not present a smooth contour due to the fact that each model is made up of scale interval outlines each of which is one inch in thickness. The dark lines on the models represent the planes in which the horizontal, sagittal, and frontal sections of the models were cut. A. Front view of the models of the prosthetic (1) and normal (2) work spaces. B. Top view of the models of the prosthetic (1) and normal (2) work spaces. C. Side view of the models of the prosthetic (1) and normal (2) work spaces. The front of each model faces the middle of the photograph. D. Rear view of the models of the prosthetic (2) and normal (1) work spaces. E. Horizontal sections of the models of the prosthetic (1) and normal (2) work spaces. F. Sagittal sections of the models of the normal (1) and prosthetic (2) work spaces. The top of each model faces the middle of the photograph. G. Frontal sections of the models of the prosthetic (1) and normal (2) work spaces.

PLATE VI

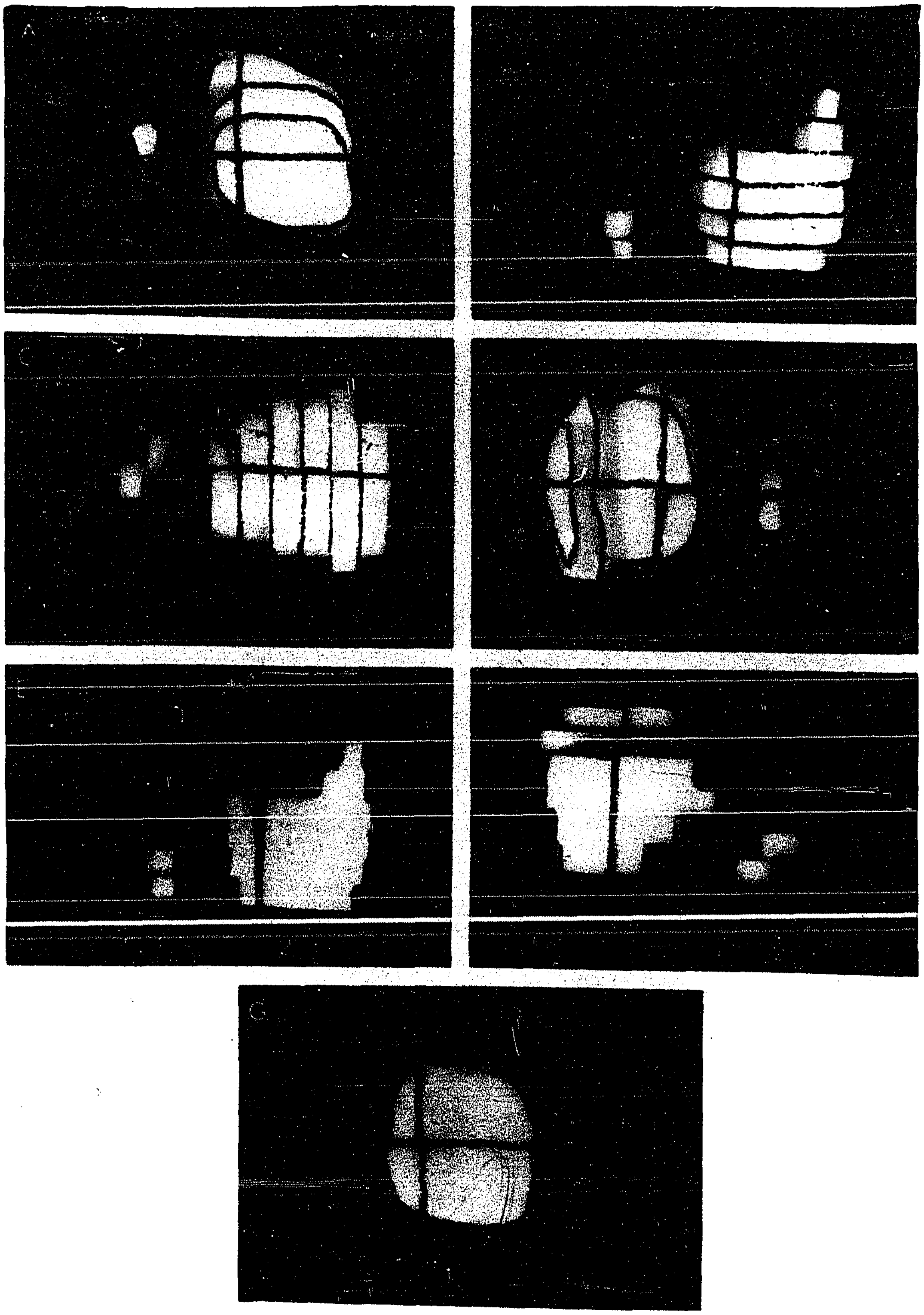

Plate VII. Balsa wood models of the normal and prosthetic work spaces for the below elbow amputee with the percentage difference closest to the mean. A. Front view of the prosthetic work space. B. Front view of the normal work space. C. Side view of the prosthetic work space. D. Side view of the normal work space. E. Top view of the prosthetic work space. F. Top view of the normal work space.

PLATE VII

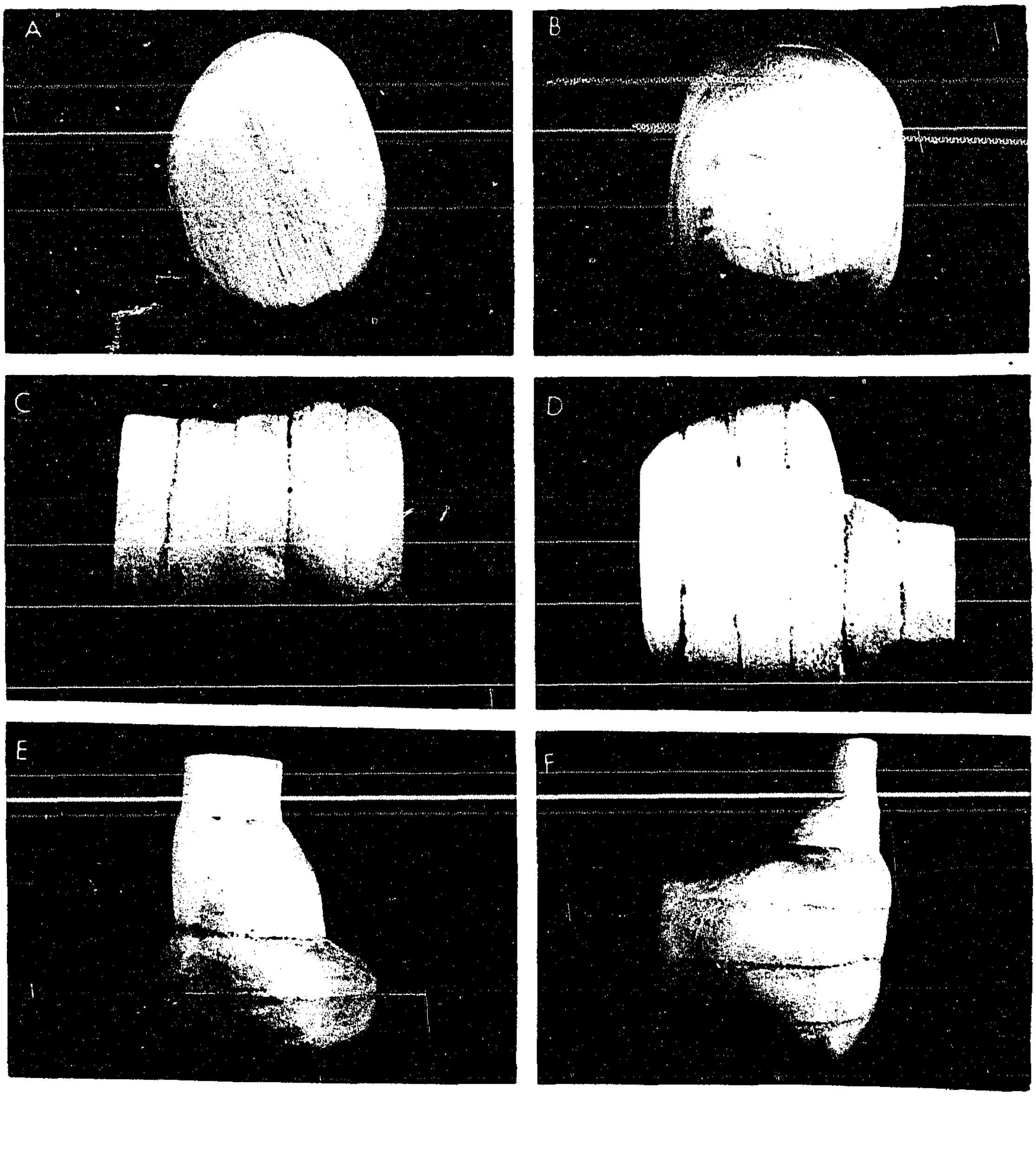

Plate VIII. Balsa wood models of the normal and prosthetic work spaces for the above elbow amputee with the percentage difference closest to the mean. A. Front view of the normal work space. B. Front view of the prosthetic work space. C. Side view of the normal work space. D. Side view of the prosthetic work space. E. Top view of the normal work space. F. Top view of the prosthetic work space.

PLATE VIII