AN ANTHROPOMETRIC STUDY OF THE SHAPE OF THE NORMAL WORK AREA IN THE HORIZONTAL PLANE

by

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INTRODUCTION

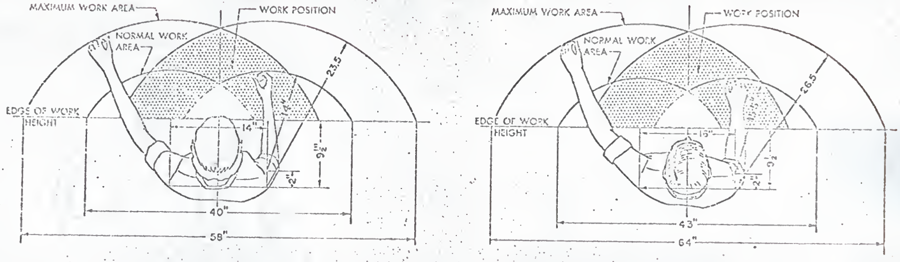
Motion study had its beginning when Gilbreth (8) observed the methods by which work was performed in brick laying. These first observations gradually developed into a set of "Rules for motion economy and efficiency," formulated mainly on the basis of experience but not verified by controlled experiments.

Barnes (2) revised the rules of motion economy and formulated his own principles of motion economy by collecting the fragments of early works and conducting studies of his own. While discussing one of these principles about the work place, he says that there is a very definite and limited area which the worker can use with a normal expenditure of effort. There is a normal working area for the right hand and for the left hand, working separately, and for both hands working together. He further states that the normal working area for the right hand is determined by an arc drawn with a sweep of the right hand across the table. The forearm only is extended, and the upper arm hangs at the side of the body in a natural position until it tends to swing away as the hand moves toward the outer part of the work place. The normal working area for the left hand is determined in a similar manner. The normal arcs drawn with the right and left hands will cross each other at a point in front of the worker. The overlapping area constitutes a zone in which two-handed work may be done most conveniently. He had a dimensionless sketch of normal and maximum working areas from Maynard (9).

In Barnes' third edition (3), he gave the sketch dimensions based on Asa's thesis (1). Asa measured 30 male students of the State University of Iowa. In Barnes' fourth edition (4), he cited a study made by

Farley (7) at General Motors. Farley gave one area for men and one for women which, he said, were based on "average" operators. The average forearm length for men was given as 15.5 inches and for women as 14 inches. The average shoulder to shoulder distance for men was 16 inches and for women was 14 inches. Figure 1 is reproduced from Farley.

According to Squires (14), the normal work area represented by two intersecting semicircles is incorrect. He proposed a prolate epicycloid curve and described a parametric equation based upon an anthropometric study. In particular, Squires pointed out that, in forearm movements, the elbow does not stay at a fixed point as indicated by other investigators, but rather moves out and away from the body as the forearm moves outwards. The combined movement of the forearm and elbow in describing an area covered conveniently by the fingertips is the formation of an area that is somewhat different from that proposed by other authors. In particular, it is somewhat flattened, and the right and left corners are chopped off as shown in Figure 2. The line C_1C_n represents the path along which the elbow moves as the forearm-hand (vector) describes an arc; the assumption that this arc is circular constitutes a fair approximation to the actual curve described by the elbow as it swings from C_1C_n. The point 0, the origin for the coordinate system of Figure 2, is the perpendicular projection of the shoulder pivot upon the horizontal work surface. As the pivot (elbow) moves from the initial position C_1 to the terminal position C_n, the radius vector (forearm-hand) turns through the entire range in such a manner that C_n and P_n are reached simultaneously. Only the normal working area for the right hand is shown in Figure 2 since that for the left hand is symmetrical. The angle between the forearm and the tangent



FOR WOMEN FOR MEN

Figure 1. Farley's Proposed Work Area.

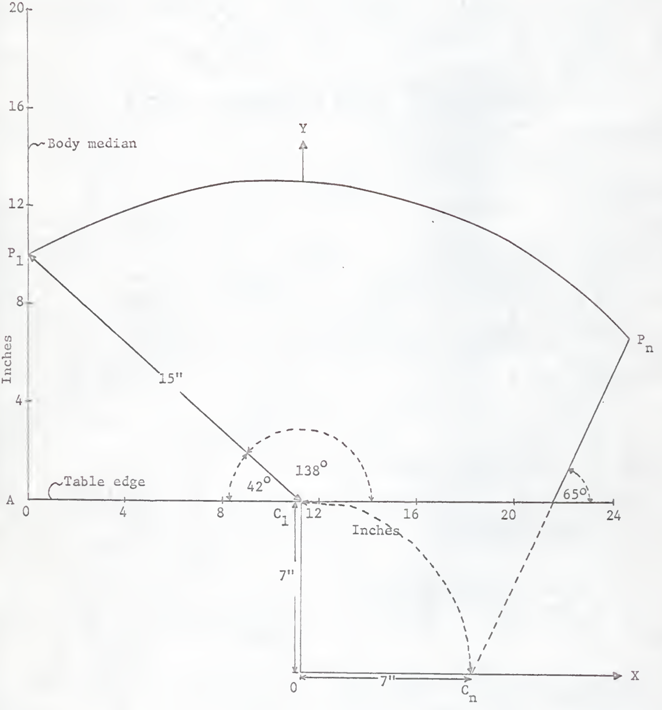


Figure 2. Squires' Proposed Shape for the Normal Work Area.

to the arc C_1C_n was assumed to gradually decline from 42^{o} to 25^{o}. He referred to the Brackett's data (15) and found (a) the distance from the elbow to the center of the fist equal to 13.33 inches (b) the distance from the elbow to the fingertips equal to 17.75 inches. The average of these two was 15.54 inches. He adopted 15 inches as the length of the forearm-hand, because the thumb, with the first and second fingers, is necessary for manipulative purposes. Squires gave the dimension AC_1 the value of 11.12 inches and OC_1 the value of 7 inches.

The parametric equations of the prolate epicycloid of Figure 2 were:

$$x = 7 \text{ Cos } \theta + 15 \text{ Cos } (65 + (73/90)\theta) \qquad \text{........(1)}$$

$$y = 7 \text{ Sin } \theta + 15 \text{ Sin } (65 + (73/90)\theta) \qquad \text{........(2)}$$

Here θ is the angle given at any instant by the radius which sweeps out the arc C_1C_n. The x, y pairs of cartesian values for this locus may be computed for as many points as desired. The coefficients of angle θ in the above equation, i.e. 7 and 15, are the distances OC_1 and C_1P_1 respectively.

Perczel (12), in Hungary, basically agreed with Squires in designing the body positions for tramway drivers. He noted that Hungarians were smaller than Americans.

Doxie and Ullam (6), while designing controlled ambient systems, suggested a 'butterfly' pattern of work place in the horizontal plane rather than the full arcing pattern of Barnes.

PROBLEM

The shape of the normal work area is very important for human engineers and designers of assembly work stations, instrument panel layouts in submarines, tanks and aircraft, radar consoles and certain small gun turrets.

There is no study, except that of Squires and of Farley, which determined the normal work area from the anthropometric measurements of the population. Squires, however, did not provide all the details of his study. For example, the technique of measurement, the number of subjects used, the sex of the subjects, and the characteristics of the subjects were not revealed. It was therefore decided to make an anthropometric study to determine the shape of the normal work area for the middle 90% of the population (male and female) of this country. Specifically the following hypotheses were tested: (Figure 2)

I. Distance OC_1 is greater for men than women.

II. Forearm length (C_1P_1) is greater for men than women.

III. Distance OC_1 is significantly correlated with height for men and women.

IV. Forearm length (C_1P_1) is significantly correlated with height for men and women.

METHOD

The following anthropometric measurements were taken:

1. Height
2. Forearm length (C_1P_1)
3. Upperarm length (C_1M)

4. Distance between the elbow pivot and the orthogonal projection of the shoulder pivot upon the horizontal work surface (OC_1)

Subjects:

The National Health Survey (1960-62) of United States (16) showed that the middle 90% of male heights vary from 63.6 to 72.8 inches within the age range of 18-79 years. Similarly, the middle 90% of female heights vary from 59.0 to 67.1 inches in the same age group. The above heights of the male population (63.6 to 72.8 inches) were divided into four quartiles of 63.6 to 66.2, 66.3 to 68.2, 68.3 to 70.2, and 70.3 to 72.8 (11). Similarly heights of females (59.0 to 67.1 inches) were also divided into four quartiles of 59.0 to 61.2, 61.3 to 63.0, 63.1 to 64.8, and 64.9 to 67.1.

The subjects were 40 male and 40 female American students at Kansas State University. The subjects were selected so that 10 men had heights between 63.6 and 66.2, 10 were between 66.3 and 68.2, etc.

Experimental Procedure:

This experiment was performed in the Kansas State Union. Each subject was assigned a number ranging from 1 to 40 and only his or her number, and not the name, was recorded on the form.

First of all, information regarding sex, age and assigned number was recorded. Form A. Next, the following measurements were made.

1. Body Height:

   (i) Definition: This is the vertical distance from the plywood base to the top of the head (10).

FORM 'A'

1. SUBJECT NUMBER: DATE:

2. AGE:

3. SEX: MALE / FEMALE

4. HEIGHT:

5. SHOULDER-ELBOW LENGTH (C_1M):

6. FOREARM-HAND LENGTH (C_1P_1):

7. ANGLE β(C_1M MAKES WITH HORIZONTAL PLANE):

8. $C_1M \cos \beta$ (OC_1):

RECORDER

NOTE: ALL MEASUREMENTS IN INCHES AND DEGREES

(ii) Instrument used: Anthropometer. A 7 foot rod, calibrated in inches and mounted on a 2 x 4 foot plywood base, served as an anthropometer.

(iii) Position of subject: Subject stood errect without shoes on the plywood base, eyes directed forward, with his back towards the anthropometer. While positioning his body, he moved backward slowly until some part of his body touched the upright scale of the anthropometer. The feet of the subject were as close together as possible. The arm rested by the side, with palms on thighs and weight evenly distributed.

(iv) Position of experimenter: The experimenter stood to the left of the subject.

2. <u>Upperarm Length</u>:

(i) Definition: This is the distance from the top of the acromion process (the uppermost point on the lateral edge of the shoulder) to the bottom of the elbow (5).

(ii) Instrument used: Slide Caliper. A standard 2 foot long slide caliper was used.

(iii) Position of subject: The subject sat erect on the chair, upper-arm vertical and making a right angle with the forearm.

(iv) Position of experimenter: The experimenter stood at the right of the subject.

3. <u>Forearm Length</u>:

(i) Definition: This is the distance from tip of the elbow to the tip of the thumb, first finger and second finger when the tips of these three fingers are touching.

(ii) Instrument used: Adjustable table. The top of this table could be adjusted at any desired height. This table top was operated hydraulically. A piece of cardboard was fixed on the top of the table. Point C_1 of Figure 2 was marked on the edge of the cardboard. C_1P_1 was drawn similar to Figure 2 at an angle of 138^o on the cardboard. Squires stated that, for normal working, with a 180^o arc, the hand will be comfortable up to only 138^o in one side and 65^o on the other side as shown in Figure 2. The line C_1P_1 was graduated in inches up to 20 inches. Plate I.

(iii) Position of subject: The subject sat erect on the chair. His elbow joint touched the point C_1 on the edge of the table and the forearm was on the graduated line C_1P_1.

(iv) Position of experimenter: The experimenter stood on the left side of the subject.

(v) Technique: First, the subject was asked to sit on the biomechanics chair. The height of the chair was adjusted in such a way that the upper and lower leg made a right angle with each other. The height of the table was adjusted to 1 inch above the elbow height of the subject. The subject was required to put his elbow joint on the C_1 point and forearm on C_1P_1 line. The subject held a 1/2 inch diameter and 3/4 inch long marker with tips of his thumb, first and second finger. The center of the marker had a point which was allowed to touch the C_1P_1 graduated line. The distance between the tip of the elbow to the tip of the marker on the C_1P_1 graduated scale was recorded. Plate I.

Plate I

Measurement of Forearm Length.

4. Distance OC_1:

(i) Definition: This is the distance between the elbow pivot and the orthogonal projection of the shoulder pivot upon the horizontal work surface.

$$OC_1 = C_1M \cos \beta$$

where C_1M = Length of the upperarm

β = Angle that C_1M makes with the horizontal plane.

Since C_1M was recorded earlier, β was measured for calculating OC_1.

(ii) Instrument used: Special angle protractor. This instrument was designed by the author to measure the angle β. Plate II.

(iii) Position of subject: The position of the subject was the same as in the forearm measurement. In addition to that, care was taken to see that the line joining the two shoulder pivots was parallel to the floor. The plane passing through the two shoulder pivots was perpendicular to the plane of the upperarm. This position was obtained by moving the chair forward or backward.

(iv) Position of experimenter: The experimenter stood first at the right and then behind the subject.

(v) Technique: The special angle protractor was brought near the subject's elbow. The tip of the acromion process and the bottom of the elbow joint was joined by moving the upper part of the protractor. The required angle was read directly from the angle protractor.

Plate II

Measurement of Angle β.


FOAM

RESULTS

The data obtained are shown in Table 1. The distance OC_1 varied from 4.4 to 7.8 inches for males and from 3.6 to 7.4 inches for females. The average value of OC_1 was 6.0 inches for men and 5.71 for women. A Mann Whitney U Test (13) showed that there is no significant ($\alpha = .11$) difference in OC_1's for male and female subjects. Table 2.

The forearm length (C_1P_1) varied from 14.9 to 18.0 inches for males and from 14.0 to 16.3 inches for females. The average value of C_1P_1 was 16.23 inches for men and 14.82 for women. A Mann Whitney U Test showed that there is a significant difference in C_1P_1 for male and female subjects ($\alpha < .01$). Table 3.

The Spearman Rank Correlation Coefficient (13) between OC_1 and height was .32 for men and .18 for women. The .32 is significant ($\alpha < .05$) but the .18 is not. Table 4 and 5.

The Spearman Rank Correlation Coefficient between forearm length and height was .80 for men and .78 for women. Both the .80 and the .78 are significant ($\alpha < .01$). Table 6 and 7.

Thus, the results failed to prove hypothesis I, that distance OC_1 is greater for men than for women. However hypothesis II, that forearm length is greater for men than for women was accepted. Hypothesis III, that OC_1 is significantly correlated with the height was accepted for men while it was rejected for women. Hypothesis IV, that forearm length is significantly correlated with the height was proved for both men and women.

From the data of this experiment, normal work areas were drawn for

Table 1

Age, Height, C_1P_1 and OC_1 Distances for Male and Female Subjects

Male					Female				
Subject No.	Age	Height	C_1P_1	OC_1	Subject No.	Age	Height	C_1P_1	OC_1
22	17	72.8	18.0	6.6	25	18	67.0	15.8	5.3
7	20	71.6	17.8	5.3	10	21	67.0	16.3	5.5
5	19	71.3	17.3	6.3	13	20	66.5	15.4	5.8
32	19	71.3	17.0	5.5	23	18	66.3	15.5	5.2
10	22	71.0	16.8	5.6	7	19	66.0	15.1	4.6
17	21	71.0	16.5	7.1	4	18	66.0	15.1	3.6
39	19	71.0	16.5	7.1	2	18	65.1	14.9	6.4
38	21	70.9	16.3	6.6	8	20	65.0	15.0	5.7
35	20	70.6	16.4	5.1	12	20	65.0	15.5	6.5
21	26	70.4	16.9	7.8	19	18	64.9	15.3	7.0
4	21	70.1	16.6	7.3	15	20	64.8	14.8	5.9
36	19	70.0	16.5	7.7	3	21	64.6	15.0	6.4
33	18	69.9	16.3	6.2	26	18	64.5	15.5	6.8
16	19	69.8	16.8	6.5	28	19	64.3	14.9	7.4
12	21	69.5	16.1	6.3	17	19	64.3	14.5	4.6
18	18	69.4	16.5	7.5	30	18	64.1	16.3	7.0
14	20	69.3	16.0	4.8	18	18	64.0	14.8	6.6
29	20	69.3	16.4	5.3	6	18	64.0	15.0	6.6
2	18	68.6	16.3	5.9	20	18	63.4	15.0	6.2
25	19	68.3	16.1	7.0	5	20	63.3	15.3	7.3
1	18	68.1	16.6	6.2	1	19	63.0	14.3	4.7
8	23	68.1	16.6	4.9	16	19	63.0	14.8	4.2
28	19	68.0	16.5	5.2	24	18	62.9	14.4	6.5
9	27	68.0	16.3	4.8	21	18	62.8	14.6	6.3
6	19	67.6	16.0	4.8	9	18	62.5	14.0	5.7
27	18	67.0	15.9	6.3	37	17	63.3	14.4	5.6
11	26	67.0	15.4	5.2	22	18	62.0	14.3	5.6
3	19	66.4	16.1	6.0	40	19	61.5	14.5	4.5
20	20	66.4	17.3	5.4	36	18	61.4	14.6	5.7
19	27	66.3	15.6	5.7	33	18	61.3	14.1	4.8
13	20	66.0	15.6	5.9	35	19	61.1	14.5	6.2
15	21	66.0	15.4	5.9	14	24	61.1	15.1	5.0
30	19	65.9	16.0	6.0	31	18	61.1	14.4	4.8
24	18	65.8	15.4	5.2	11	20	61.0	14.0	4.4
34	20	65.5	15.9	5.0	39	21	60.6	14.4	5.8
23	18	65.1	15.6	6.5	34	19	60.1	14.4	5.4
26	18	64.8	14.9	5.9	27	20	59.8	14.0	6.1
40	21	64.8	15.4	7.1	32	17	59.5	14.8	4.8
31	21	63.9	14.9	4.4	38	20	59.5	14.0	5.7
37	19	63.6	15.0	6.0	29	18	59.0	14.3	6.1
Average	20	68.3	16.2	6.0		19	63.3	14.8	5.7
Estimated 5th %ile		63.6	14.9	4.4			59.0	14.0	3.6
Estimated 95th %ile		72.8	18.0	7.8			67.0	16.3	7.4

Table 2

Mann Whitney U Test Between OC_1's of Male and Female Subjects

Male		Female	
OC_1	Combined Rank	OC_1	Combined Rank
7.8	80.0	7.4	77.0
7.7	79.0	7.3	75.5
7.5	78.0	7.0	70.0
7.3	75.5	7.0	70.0
7.1	73.0	6.8	68.0
7.1	73.0	6.6	65.5
7.1	73.0	6.6	65.5
7.0	70.0	6.5	61.5
6.6	65.5	6.5	61.5
6.6	65.5	6.4	58.5
6.5	61.5	6.4	58.5
6.5	61.5	6.3	55.5
6.3	55.5	6.2	51.0
6.3	55.5	6.2	51.0
6.3	55.5	6.1	47.5
6.2	51.0	6.1	47.5
6.2	51.0	5.9	42.0
6.2	51.0	5.8	38.5
6.0	45.5	5.8	38.5
6.0	45.5	5.7	35.0
5.9	42.0	5.7	35.0
5.9	42.0	5.7	35.0
5.9	42.0	5.7	35.0
5.9	42.0	5.6	31.0
5.7	35.0	5.6	31.0
5.6	31.0	5.5	28.5
5.5	28.5	5.4	26.5
5.4	26.5	5.3	24.0
5.3	24.0	5.2	20.5
5.3	24.0	5.0	16.5
5.2	20.5	4.8	11.5
5.2	20.5	4.8	11.5
5.2	20.5	4.8	11.5
5.1	18.0	4.7	8.0
5.0	16.5	4.6	6.5
4.9	15.0	4.6	6.5
4.8	11.5	4.5	5.0
4.8	11.5	4.4	3.5
4.8	11.5	4.2	2.0
4.4	3.5	3.6	1.0
R_2=1752.0		R_1=1488.0	

$$U = n_1 n_2 + n_1 (n_1 + 1)/2 - R_1$$

$$= 40x40 + 40x41/2 - 1488$$

$$= 930$$

$$Z = \frac{U - n_1 n_2 /2}{\sqrt{n_1 n_2 (n_1 + n_2 + 1)/12}}$$

$$= \frac{930 - 800}{\sqrt{40x40 (40 + 40 + 1)/12}}$$

$$= 1.25$$

Reference to table A (Siegel, 1956) $\alpha = 0.1056$

Since $\alpha > 0.05$, it is concluded that there is no significant difference in OC_1's for male and female at 5% confidence level.

Table 3

Mann Whitney U Test Between C_1P_1's of Male and Female Subjects

Male		Female	
C_1P_1	Combined Rank	C_1P_1	Combined Rank
18.0	80.0	16.3	59.5
17.8	79.0	16.3	59.0
17.3	77.5	15.8	48.0
17.3	77.5	15.5	43.0
17.0	76.0	15.5	43.0
16.9	75.0	15.5	43.0
16.8	73.5	15.4	39.0
16.8	73.5	15.3	35.5
16.6	71.0	15.3	35.5
16.6	71.0	15.1	33.0
16.6	71.0	15.1	33.0
16.5	67.0	15.1	33.0
16.5	67.0	15.0	29.0
16.5	67.0	15.0	29.0
16.5	67.0	15.0	29.0
16.5	67.0	15.0	29.0
16.4	63.5	14.9	24.5
16.4	63.5	14.9	24.5
16.3	59.5	14.8	20.5
16.3	59.5	14.8	20.5
16.3	59.5	14.8	20.5
16.3	59.5	14.8	20.5
16.1	55.0	14.6	17.5
16.1	55.0	14.6	17.5
16.1	55.0	14.5	15.0
16.0	52.0	14.5	15.0
16.0	52.0	14.5	15.0
16.0	52.0	14.4	11.0
15.9	49.5	14.4	11.0
15.9	49.5	14.4	11.0
15.6	46.0	14.4	11.0
15.6	46.0	14.4	11.0
15.6	46.0	14.3	7.0
15.4	39.0	14.3	7.0
15.4	39.0	14.3	7.0
15.4	39.0	14.1	5.0
15.4	39.0	14.0	2.5
15.0	29.0	14.0	2.5
14.9	24.5	14.0	2.5
14.9	24.5	14.0	2.5
R_2=2317.0		R_1=923.0	

$$U = n_1 n_2 + n_1(n_1 + 1)/2 - R_1$$
$$= 40\text{x}40 + 40\text{x}41/2 - 923$$
$$= 1497$$

$$Z = \frac{U - n_1 n_2/2}{\sqrt{n_1 n_2 (n_1 + n_2 + 1)/12}}$$
$$= \frac{1497 - 800}{\sqrt{40\text{x}40(40+40+1)/12}}$$
$$= 6.71$$

Reference to table A (Siegel, 1956) $\alpha < 0.00003$

Since $\alpha < 0.01$, it is concluded that C_1P_1 is greater for male than for female at 1% confidence level.

Table 4

Spearman Rank Correlation Test Between OC_1 and Height for Male Subjects

No.	Height	Rank	OC_1	Rank	d_i	d_i^2
22	72.8	40.0	6.6	31.5	8.5	72.25
7	71.6	39.0	5.3	11.5	27.5	756.25
5	71.3	37.5	6.3	27.0	10.5	110.25
32	71.3	37.5	5.5	14.0	23.5	552.25
10	71.0	35.0	5.6	15.0	20.0	400.00
17	71.0	35.0	7.1	35.0	0.0	0.00
39	71.0	35.0	7.1	35.0	0.0	0.00
38	70.9	33.0	6.6	31.5	1.5	2.25
35	70.6	32.0	5.1	7.0	25.0	625.00
21	70.4	31.0	7.8	40.0	9.0	81.00
4	70.1	30.0	7.3	37.0	7.0	49.00
36	70.0	29.0	7.7	39.0	10.0	100.00
33	69.9	28.0	6.2	24.0	4.0	16.00
16	69.8	27.0	6.5	29.5	2.5	6.25
12	69.5	26.0	6.3	27.0	1.0	1.00
18	69.4	25.0	7.5	38.0	13.0	169.00
14	69.3	23.5	4.8	3.0	20.5	420.25
29	69.3	23.5	5.3	11.5	12.0	144.00
2	68.6	22.0	5.9	17.5	4.5	20.25
25	68.3	21.0	7.0	33.0	12.0	144.00
1	68.1	19.5	6.2	24.0	4.5	20.25
8	68.1	19.5	4.9	5.0	14.5	210.25
28	68.0	17.5	5.2	9.0	8.5	72.25
9	68.0	17.5	4.8	3.0	14.5	210.25
6	67.6	16.0	4.8	3.0	13.0	169.00
27	67.0	14.5	6.3	27.0	12.5	156.25
11	67.0	14.5	5.2	9.0	5.5	30.25
3	66.4	12.5	6.0	21.5	9.0	81.00
20	66.4	12.5	5.4	13.0	0.5	0.25
19	66.3	11.0	5.7	16.0	5.0	25.00
13	66.0	9.5	5.9	17.5	8.0	64.00
15	66.0	9.5	5.9	17.5	8.0	64.00
30	65.9	8.0	6.0	21.5	13.5	182.25
24	65.8	7.0	5.2	9.0	2.0	4.00
34	65.5	6.0	5.0	6.0	0.0	0.00
23	65.1	5.0	6.5	29.5	24.5	600.25
26	64.8	3.5	5.9	17.5	14.0	196.00
40	64.8	3.5	7.1	35.0	31.5	992.25
31	63.9	2.0	4.4	1.0	1.0	1.00
37	63.6	1.0	6.2	24.0	23.0	529.00
					$\sum d_i^2 =$	7276.50

$$\sum x^2 = (N^3 - N)/12 - \sum T_x$$ Seigel (13)

$$= \frac{(40)^3 - 40}{12} - 4$$

$$= 5326$$

$$\sum y^2 = (N^3 - N)/12 - \sum T_y$$

$$= \frac{(40)^3 - 40}{12} - 17$$

$$= 5313$$

$$r_s = \frac{\sum x^2 + \sum y^2 - \sum d_i^{\,2}}{2\sqrt{\sum x^2 \sum y^2}}$$

$$= \frac{5326 + 5313 - 7276.5}{2\sqrt{5326 \times 5313}}$$

$$= 0.316$$

Testing hypothesis by Kendall's method for large samples,

$$t = r_s\sqrt{\frac{N-2}{1 - r_s^{\,2}}}$$

$$= 0.316\sqrt{\frac{40-2}{1 - 0.316^2}}$$

$$= 2.053$$

By Table B: $t_{38.\ 0.05} = 1.686$

As $2.053 > 1.686$, it is concluded that there is positive significant correlation between the height and OC_1 for male subjects.

Table 5

Spearman Rank Correlation Test Between OC_1 and Height for Female Subjects

No.	Height	Rank	OC_1	Rank	d_i	d_i^2
25	67.0	39.5	5.3	13.0	26.5	702.25
10	67.0	39.5	5.5	15.0	24.5	600.25
13	66.5	38.0	5.8	22.5	15.5	240.25
23	66.3	37.0	5.2	12.0	25.0	625.00
7	66.0	35.5	4.6	5.5	30.0	900.00
4	66.0	35.5	3.6	1.0	34.5	1190.25
2	65.1	34.0	6.4	30.5	3.5	12.25
8	65.0	32.5	5.7	19.5	13.0	169.00
12	65.0	32.5	6.5	32.5	0.0	0.00
19	64.9	31.0	7.0	37.5	6.5	42.25
15	64.8	30.0	5.9	24.0	6.0	36.00
3	64.6	29.0	6.4	30.5	1.5	2.25
26	64.5	28.0	6.8	36.0	8.0	64.00
28	64.3	26.5	7.4	40.0	13.5	182.25
17	64.3	26.5	4.6	5.5	11.0	121.00
30	64.1	25.0	7.0	37.5	12.5	156.25
18	64.0	23.5	6.6	34.5	11.0	121.00
6	64.0	23.5	6.6	34.5	11.0	121.00
20	63.4	22.0	6.2	27.5	5.5	30.25
5	63.3	21.0	7.3	39.0	18.0	324.00
1	63.0	19.5	4.7	7.0	12.5	156.25
16	63.0	19.5	4.2	2.0	17.5	306.25
24	62.9	18.0	6.5	32.5	14.5	210.25
21	62.8	17.0	6.3	29.0	12.0	144.00
9	62.5	16.0	5.7	19.5	3.5	12.25
37	62.3	15.0	5.6	16.5	1.5	2.25
22	62.0	14.0	5.6	16.5	2.5	6.25
40	61.5	13.0	4.5	4.0	9.0	81.00
36	61.4	12.0	5.7	19.5	7.5	56.25
33	61.3	11.0	4.8	9.0	2.0	4.00
35	61.1	9.0	6.2	27.5	18.5	342.25
14	61.1	9.0	5.0	11.0	2.0	4.00
31	61.1	9.0	4.8	9.0	0.0	0.00
11	61.0	7.0	4.4	3.0	4.0	16.00
39	60.6	6.0	5.8	22.5	16.5	272.25
34	60.1	5.0	5.4	14.0	9.0	81.00
27	59.8	4.0	6.1	25.5	21.5	462.25
32	59.5	2.5	4.8	9.0	6.5	42.25
38	59.5	2.5	5.7	19.5	17.0	289.00
29	59.0	1.0	6.1	25.5	24.5	600.25
					$\sum d_i^2 = 8727.25$	

$$\sum x^2 = (N^3 - N)/12 - \sum T_x$$ Seigel (13)

$$= \frac{(40)^3 - 40}{12} - 5.5$$

$$= 5324.5$$

$$\sum y^2 = (N^3 - N)/12 - \sum T_y$$

$$= \frac{(40)^3 - 40}{12} - 11.5$$

$$= 5318.5$$

$$r_s = \frac{\sum x^2 + \sum y^2 - \sum di^2}{2\sqrt{\sum x^2 \cdot \sum y^2}}$$

$$= \frac{5324.5 + 5318.5 - 8727.25}{2\sqrt{5324.5 \times 5318.5}}$$

$$= 0.18$$

Testing hypothesis by Kendall's method for large samples,

$$t = r_s\sqrt{\frac{N-2}{1 - r_s^2}}$$

$$= 0.18\sqrt{\frac{40-2}{1 - 0.18^2}}$$

$$= 1.128$$

By Table B: $t_{38,\ 0.10} = 1.3044$

As $1.128 < 1.3044$, it is concluded that there is no significant correlation between the height and OC_1 for female subjects.

Table 6

Spearman Rank Correlation Test Between C_1P_1 and Height for Male Subjects

No.	Height	Rank	C_1P_1	Rank	d_i	d_i^2
22	72.8	40.0	18.0	40.0	0.0	0.00
7	71.6	39.0	17.8	39.0	0.0	0.00
5	71.3	37.5	17.3	37.5	0.0	0.00
32	71.3	37.5	17.0	36.0	1.5	2.25
10	71.0	35.0	16.8	33.5	1.5	2.25
17	71.0	35.0	16.5	27.0	8.0	64.00
39	71.0	35.0	16.5	27.0	18.0	324.00
38	70.9	33.0	16.3	20.5	12.5	156.25
35	70.6	32.0	16.4	23.5	8.5	72.25
21	70.4	31.0	16.9	35.0	4.0	16.00
4	70.1	30.0	16.6	31.0	1.0	1.00
36	70.0	29.0	16.5	27.0	2.0	4.00
33	69.9	28.0	16.3	20.5	7.5	56.25
16	69.8	27.0	16.8	33.5	6.5	42.25
12	69.5	26.0	16.1	17.0	9.0	81.00
18	69.4	25.0	16.5	27.0	2.0	4.00
14	69.3	23.5	16.0	14.0	9.5	90.25
29	69.3	23.5	16.4	23.5	0.0	0.00
2	68.6	22.0	16.3	20.5	1.5	2.25
25	68.3	21.0	16.1	17.0	4.0	16.00
1	68.1	19.5	16.6	31.0	11.5	132.25
8	68.1	19.5	16.6	31.0	11.5	132.25
28	68.0	17.5	16.5	27.0	9.5	90.25
9	68.0	17.5	16.3	20.5	3.0	9.00
6	67.6	16.0	16.0	14.0	2.0	4.00
27	67.0	14.5	15.9	11.5	3.0	9.00
11	67.0	14.5	15.4	5.5	9.0	81.00
3	66.4	12.5	16.1	17.0	4.5	20.25
20	66.4	12.5	17.3	37.5	25.0	625.00
19	66.3	11.0	15.6	9.0	2.0	4.00
13	66.0	9.5	15.6	9.0	0.5	0.25
15	66.0	9.5	15.4	5.5	4.0	16.00
30	65.9	8.0	16.0	14.0	6.0	36.00
24	65.8	7.0	15.4	5.5	1.5	2.25
34	65.5	6.0	15.9	11.5	5.5	30.25
23	65.1	5.0	15.6	9.0	4.0	16.00
26	64.8	3.5	14.9	1.5	2.0	4.00
40	64.8	3.5	15.4	5.5	2.0	4.00
31	63.9	2.0	14.9	1.5	0.5	0.25
37	63.6	1.0	15.0	3.0	2.0	4.00

$\sum d_i^2 = 2154.00$

$$\sum x^2 = (N^3 - N)/12 - \sum T_x \tag{13}$$

$$= \frac{(40)^3 - 40}{12} - 4$$

$$= 5326$$

$$\sum y^2 = (N^3 - N)/12 - \sum T_y$$

$$= \frac{(40)^3 - 40}{12} - 26.5$$

$$= 5303.5$$

$$r_s = \frac{\sum x^2 + \sum y^2 - \sum di^2}{2\sqrt{\sum x^2 \cdot \sum y^2}}$$

$$= \frac{5326 + 5323.5 - 2154}{2\sqrt{5326 \text{ x } 5303.5}}$$

$$= 0.797$$

Testing hypothesis by Kendall's method for large samples,

$$t = r_s \sqrt{\frac{N-2}{1 - r_s^2}}$$

$$= 0.797 \sqrt{\frac{40-2}{1 - 0.797^2}}$$

$$= 8.13$$

By Table B: $t_{38,\ 0.01} = 2.43$

As 8.13 > 2.43, it is concluded that there is positive significant correlation between height and forearm length (C_1P_1) for male subjects.

Table 7

Spearman Rank Correlation Test Between C_1P_1 and Height for Female Subjects

No.	Height	Rank	C_1P_1	Rank	d_i	d_i^2
25	67.0	39.5	15.8	38.0	1.5	2.25
10	67.0	39.5	16.3	39.5	0.0	0.00
13	66.5	38.0	15.4	34.0	4.0	16.00
23	66.3	37.0	15.5	36.0	1.0	1.00
7	66.0	35.5	15.1	30.0	5.5	30.25
4	66.0	35.5	15.1	30.0	5.5	30.25
2	65.1	34.0	14.9	23.5	10.5	110.25
8	65.0	32.5	15.0	26.5	6.0	36.00
12	65.0	32.5	15.5	36.0	3.5	12.25
19	64.9	31.0	15.3	32.5	1.5	2.25
15	64.8	30.0	14.8	20.5	9.5	90.25
3	64.6	29.0	15.0	26.5	2.5	6.25
26	64.5	28.0	15.5	36.0	8.0	64.00
28	64.3	26.5	14.9	23.5	3.0	9.00
17	64.3	26.5	14.5	15.0	11.5	132.25
30	64.1	25.0	16.3	39.5	14.5	210.25
18	64.0	23.5	14.8	20.5	3.0	9.00
6	64.0	23.5	15.0	26.5	3.5	12.25
20	63.4	22.0	15.0	26.5	4.5	20.25
5	63.3	21.0	15.3	32.5	11.5	132.25
1	63.0	19.5	14.3	7.0	12.5	156.25
16	63.0	19.5	14.8	20.5	1.0	1.00
24	62.9	18.0	14.4	11.0	7.0	49.00
21	62.8	17.0	14.6	17.5	0.5	0.25
9	62.5	16.0	14.0	2.5	13.5	182.25
37	62.3	15.0	14.4	11.0	4.0	16.00
22	62.0	14.0	14.3	7.0	7.0	49.00
40	61.5	13.0	14.5	15.0	2.0	4.00
36	61.4	12.0	14.6	17.5	5.5	30.25
33	61.3	11.0	14.1	5.0	6.0	36.00
35	61.1	9.0	14.5	15.0	6.0	36.00
14	61.1	9.0	15.1	30.0	21.0	441.00
31	61.1	9.0	14.4	11.0	2.0	4.00
11	61.0	7.0	14.0	2.5	4.5	20.25
39	60.6	6.0	14.4	11.0	5.0	25.00
34	60.1	5.0	14.4	11.0	6.0	36.00
27	59.8	4.0	14.0	2.5	1.5	2.25
32	59.5	2.5	14.8	20.5	18.0	324.00
38	59.5	2.5	14.0	2.5	0.0	0.00
29	59.0	1.0	14.3	7.0	6.0	36.00
					$\sum d_i^2$ =	2374.75

$$\sum x^2 = (N^3 - N)/12 - \sum T_x$$ Seigel (13)

$$= \frac{(40)^3 - 40}{12} - 5.5$$

$$= 5324.5$$

$$\sum y^2 = (N^3 - N)/12 - \sum T_y$$

$$= \frac{(40)^3 - 40}{12} - 31.5$$

$$= 5298.5$$

$$r_s = \frac{\sum x^2 + \sum y^2 - \sum d_i^2}{2\sqrt{\sum x^2 \cdot \sum y^2}}$$

$$= \frac{5324.5 + 5298.5 - 2374.75}{2\sqrt{5324.5 \times 5398.5}}$$

$$= 0.776$$

Testing hypothesis by Kendall's method for large samples,

$$t = r_s\sqrt{\frac{N-2}{1 - r_s^2}}$$

$$= 0.776\sqrt{\frac{40-2}{1 - 0.776^2}}$$

$$= 7.56$$

By Table B: $t_{38,\ 0.01} = 2.43$

As $7.56 > 2.43$, it is concluded that there is positive significant correlation between height and forearm length (C_1P_1) for female subjects.

the 5th, 50th, and 95th percentiles men and women on lines similar to those suggested by Squires. Figure 3 and 4. The minimum values of OC_1 and C_1P_1 correspond to the 5th percentile, the average values correspond to 50th percentile and the maximum values correspond to the 95th percentile of men and women.

The cartesian coordinates were calculated with the help of equation (1) and (2), which are shown in Appendix I. The procedure of calculating the coordinates was different from that of Squires study since in this experiment AC_1 was taken as half of the elbow to elbow distance. The elbow to elbow distance for 5th, 50th, and 95th percentile of men and women was taken from the National Health Survey (1960-62). Table 8 shows the value of coordinates at different increment of θ for all the three percentiles for men and women.

DISCUSSION

The result of this experiment came out as hypothesized, except that the distance OC_1 was not significantly greater for men than for women and there was no positive significant correlation between the OC_1 and height for women. The interesting point is that OC_1 and height was significantly correlated for men. There was significant correlation ($\alpha < .01$) between the height and the upper arm length of women (Table 9). Thus the reason for getting nonsignificant correlation of OC_1 and height for female subjects was due to variation in angle β. Why β varied is unknown.

The results of this experiment are not in agreement with those obtained by Squires. The mean value of OC_1 for men is 6.00 inches and that for women is 5.71 for this experiment, while Squires gave a value

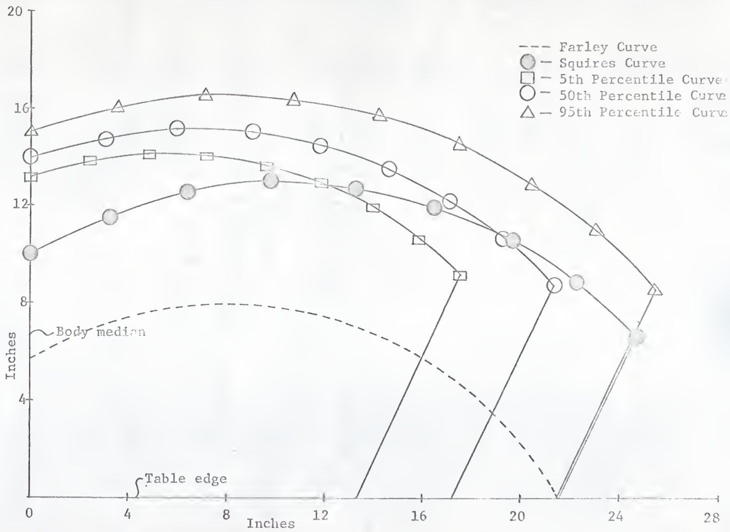


Figure 3. Proposed Normal Work Area for Men.

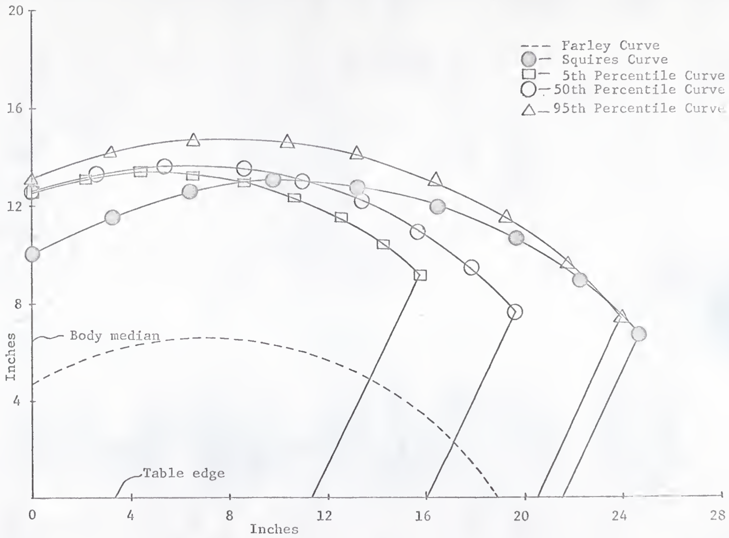


Figure 4. Proposed Normal Work Area for Women.

Table 8

Cartesian Coordinates for Figure 3 and 4

Recommended Curve	θ	x	y
By Squires	0.00	13.34	13.60
	11.25	10.97	15.59
	22.50	8.23	17.58
	33.75	5.20	18.88
	45.00	1.96	19.65
	56.25	- 1.40	19.86
	67.50	- 4.77	19.49
	78.75	- 8.05	18.54
	90.00	-11.15	17.03

Recommended Curve	θ	5th Percentile		50th Percentile		95th Percentile	
		x	y	x	y	x	y
For Males	0.00	10.70	13.50	12.86	14.71	15.40	16.31
	11.25	9.03	14.99	10.91	16.60	13.12	18.67
	22.50	7.14	16.26	8.66	18.22	1o.44	20.69
	33.75	5.05	17.28	6.15	19.52	7.44	22.31
	45.00	2.81	18.01	3.43	20.45	4.18	23.47
	56.25	0.45	18.42	0.56	20.98	0.72	24.12
	67.50	- 1.96	18.51	- 2.39	21.08	- 2.84	24.24
	78.75	- 4.43	18.25	- 5.37	20.74	- 6.43	23.80
	90.00	- 6.85	17.64	- 8.30	19.95	- 9.95	22.81
For Females	0.00	9.51	12.69	11.97	13.43	14.29	14.77
	11.25	8.00	13.97	10.17	15.21	12.11	17.00
	22.50	6.29	15.06	8.09	16.73	9.57	18.90
	33.75	4.41	15.93	5.77	17.96	6.72	20.40
	45.00	2.41	16.55	3.25	18.84	3.62	21.45
	56.25	0.31	16.89	0.58	19.34	0.35	22.01
	67.50	- 1.85	16.95	- 2.17	19.44	- 3.01	22.06
	78.75	- 4.02	16.71	- 4.94	19.13	- 6.37	21.56
	90.00	- 6.15	16.17	- 7.65	18.40	- 9.65	20.53

Table 9

Spearman Rank Correlation Test Between C_1M and Height for Female Subjects

No.	Height	Rank	C_1M	Rank	di	di^2
25	67.0	39.5	14.3	39.5	0.0	0.00
10	67.0	39.5	14.0	35.0	4.5	20.25
13	66.5	38.0	14.3	39.5	1.5	2.25
23	66.3	37.0	14.0	35.0	2.0	4.00
7	66.0	35.5	13.6	28.5	7.0	49.00
4	66.0	35.5	13.8	30.5	5.0	25.00
2	65.1	34.0	13.5	26.0	8.0	64.00
8	65.0	32.5	13.6	28.5	4.0	16.00
12	65.0	32.5	13.9	32.0	0.5	0.25
19	64.9	31.0	14.0	35.0	4.0	16.00
15	64.8	30.0	13.4	21.5	8.5	72.25
3	64.6	29.0	13.4	21.5	7.5	56.25
26	64.5	28.0	14.1	38.0	10.0	100.00
28	64.3	26.5	14.0	35.0	8.5	72.25
17	64.3	26.5	13.5	25.5	1.0	1.00
30	64.1	25.0	14.0	35.0	10.0	100.00
18	64.0	23.5	12.5	2.0	21.5	462.25
6	64.0	23.5	13.1	15.0	8.5	72.25
20	63.4	22.0	13.1	15.0	7.0	49.00
5	66.3	21.0	13.3	18.5	2.5	6.25
1	66.0	19.5	13.8	30.5	11.0	121.00
16	63.0	19.5	13.4	21.5	2.0	4.00
24	62.9	18.0	13.5	25.5	7.5	56.25
21	62.8	17.0	13.1	15.0	2.0	4.00
9	62.5	16.0	12.8	4.5	11.5	132.25
37	62.3	15.0	13.3	18.5	3.5	12.25
22	62.0	14.0	13.4	21.5	7.5	56.25
40	61.5	13.0	13.1	15.0	2.0	4.00
36	61.4	12.0	13.0	11.0	1.0	1.00
33	61.3	11.0	12.9	7.5	3.5	12.25
35	61.1	9.0	13.1	15.0	6.0	36.00
14	61.1	9.0	13.5	25.5	16.5	272.25
31	61.1	9.0	13.0	11.0	2.0	4.00
11	61.0	7.0	12.9	7.5	0.5	0.25
39	60.6	6.0	12.9	7.5	1.5	2.25
34	60.1	5.0	12.8	4.5	0.5	0.25
27	59.8	4.0	12.6	3.0	1.0	1.00
32	59.5	2.5	13.0	11.0	8.5	72.25
38	59.5	2.5	12.9	7.5	5.0	25.00
29	59.0	1.0	12.3	1.0	0.0	0.00
						$\sum d_i^2 = 2004.75$

$$\sum x^2 = (N^3 - N)/12 - \sum T_x$$ Seigel (13)

$$= \frac{(40)^3 - 40}{12} - 5.5$$

$$= 5324.5$$

$$\sum y^2 = (N^3 - N)/12 - \sum T_y$$

$$= \frac{(40)^3 - 40}{12} - 39.5$$

$$= 5290.5$$

$$r_s = \frac{\sum x^2 + \sum y^2 - \sum d_i^{\,2}}{2\sqrt{\sum x^2 \cdot \sum y^2}}$$

$$= \frac{5324.5 + 5290.5 - 2004.75}{2\sqrt{5324.5 \times 5290.5}}$$

$$= 0.81$$

Testing hypothesis by Kendall's method for large samples,

$$t = r_2 \sqrt{\frac{N-2}{1 - r_s^{\,2}}}$$

$$= .81 \sqrt{\frac{40-2}{1 - .81^2}}$$

$$= 8.51$$

By Table B: $t_{38,\ 0.01} = 2.43$.

As $8.51 > 2.43$, it is concluded that there is positive significant correlation between height and upperarm length (C_1M) for female subjects.

of 7.00 inches. The mean values of C_1P_1 are 16.23 and 14.82 inches for men and women respectively for this experiment. Farley gave a value of 15.5 inches for men and 14 inches for women. Squires gave a value of 15.00 inches. He referred to Brackett's table for this distance. This table was made during World War II. It is a well known fact that human body dimensions change over a period of time. For example as quoted by Morgan, Cook, Chapanis and Lund (10), ... "American Soldiers of World War II averaged 0.7 inch taller and 13 pounds heavier than those of World War I."

The mean elbow to elbow distance was taken from the National Health Survey (1960-62) as 16.6 inches for men and 15.3 inches for women. Squires gave a value of 22.3 inches. Farley gave a value of 16 inches for men and 14 inches for women. In comparing the elbow to elbow distance of Squires to the National Health Survey (1960-62) and of Farley it can be concluded that Squires over estimated this distance. This overestimation might be possible with navy personnel serving as subjects. Navy personnel are a relatively healthy group, since all have passed a physical examination before acceptance and those who develop various incapacitating conditions while in the service are normally discharged.

In comparing the normal work area of Squires to the proposed area for male and female (Figure 3 and 4), it is observed that Squires' area has been underestimated in front of the operator and is overestimated at the sides. When the proposed area for male and female is compared with that of Farley, it is observed that in Farley's area the upperarm is perpendicular to the horizontal plane ($\beta = 90^{\circ}$), but in this study the angle β averaged 66° for men and 64° for women.

Further developments could be made on this study with respect to the movement of the elbow from one extreme to another. The trajectory C_1C_n of Figure 2 needs to be confirmed. In addition, the angle which the right upper arm makes in its extreme position with the table edge (Squires' 65^o) needs to be verified. Further scope of research exists in determining the normal work area in a inclined plane and for standing operators.

SUMMARY AND CONCLUSIONS

The shape of the normal working area is very important for human engineers and designers of assembly work stations and control panels and can be used wherever operator movements may be relatively restricted.

An anthropometric study for determining the shape of the normal working area in a horizontal plane for the middle 90% of men and women of this country was made. A stratified sample of forty male and forty female American students of Kansas State University were the subjects. The subjects were measured for their height, forearm length (C_1P_1), upperarm length and the distance between the elbow pivot and the perpendicular projection of the shoulder pivot upon the horizontal work surface (OC_1).

From this study, it was concluded:

1. There was no significant difference between OC_1's for male and female subjects.
2. Forearm length was greater for males than for females.
3. Distance OC_1 was significantly correlated with the height of male subjects but not for females.
4. Forearm length was significantly correlated with the height for both male and female subjects.

In short, it can be concluded that the normal working area is directly proportion to the height of the subject.

The normal working area of this study for 5th, 50th, and 95th percentile of men and women was compared with the area recommended by Squires. It was concluded that Squires underestimated the area in front of the subject and overestimated at the sides.

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APPENDIX I

Method of Calculating Cartesian Coordinates for Figure 3 and 4

Equations (1) and (2) can be restated as follows:

$$x = OC_1 \text{ Cos } \theta + C_1P_1 \text{ Cos } (65 + (\phi/90)\theta)$$

$$y = OC_1 \text{ Sin } \theta + C_1P_1 \text{ Sin } (65 + (\phi/90)\theta)$$

where OC_1 = The distance between the elbow pivot and the orthogonal projection of the shoulder pivot upon the horizontal work surface, inches.

C_1P_1 = Length of forearm, inches.

θ = The angle at any instant by OC_1 which sweeps out arc C_1C_n, degrees.

ϕ = 180 - 65 - Angle AC_1P, degrees. Figure 2.

Angle $AC_1P = \text{Cos}^{-1} AC_1/C_1P$

and AC_1 = 1/2 of elbow to elbow breadth, inches.

Recommended Curve	OC_1	C_1P_1	AC_1	Angle AC_1P	ϕ
By Squires	7.00	15.00	11.15	42.0	73.0
For Males					
5th Percentile	4.40	14.90	6.85	62.7	52.3
50th Percentile	6.00	16.23	8.30	59.3	55.7
95th Percentile	7.8	18.00	9.95	56.5	58.5
For Females					
5th Percentile	3.60	14.00	6.15	63.9	51.1
50th Percentile	5.71	14.82	7.65	58.9	56.1
95th Percentile	7.40	16.30	9.65	53.7	61.3

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by

SATISH CHANDRA GOEL

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ABSTRACT

The shape of the normal working area in a horizontal plane for the middle 90% of men and women of this country was studied. A stratified sample of forty male and forty female American students of Kansas State University was taken. All the students were measured for their height, forearm length, upperarm length, and the distance between the elbow pivot and the perpendicular projection of the shoulder pivot upon the horizontal work surface (OC_1).

Forearm length and height was significantly correlated for males and females. Distance OC_1 and height was significantly correlated for males but was not significantly correlated for females.

The shape of the recommended normal working area for the 5th, 50th, and 95th percentile of men and women is given.