THE OPTIMUM SEATED WORK HEIGHT

by 45

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INTRODUCTION

The importance of the design of work stations:

Industrial engineers are concerned with the problem of reduction of fatigue, since fatigue has a strong influence over both the quality and quantity of production. Dreyfuss (1955) points out that the primary concern of an industrial designer is the arrangement of the components in relation to operator convenience and his goals are elimination of unnecessary physical motion, reduction of physical, mental and psychological fatigue and providing convenient controls and levers. Most of the industrial tasks can be made less fatiguing for the worker, if the position of the body and the arm motions are designed to reduce the physiological cost of the job to a minimum. Moore (1942) stresses the above point and says "alternating sitting and standing in office work, supplying seats with adjustable heights for both sitting position and back and foot rests, and providing arm rests that are adjustable for different workers are among the minor changes that add to the comfort of the worker and postpone the onset of the feeling of fatigue".

The importance of anthropometric characteristics of the human in the design of inanimate facilities such as furniture, equipment and work places has been the subject of a number of investigations. The general conclusions from these investigations is that ideally the facilities should be adjusted so as to "fit" the user. Tichauer (1964) emphasizes this idea when he states "Even minor changes in the dimensions of the work place may cause considerable changes in the posture and position of the limbs. This is most noticeable under conditions involving differences between the level of the elbow and the principal plane of work".

Measurement of physiological cost:

Physiological cost refers to the cost to the body caused by physical work. Work energy requirements have been measured by many different and elaborate methods. Most industrial concerns, now, measure this in terms of time only, neglecting or only partially taking into account the physiological cost affected by various factors and conditions of work.

A few other methods have been tried but no one method gives an accurate measurement of human work in which muscular, visual and mental control on the part of the worker is involved. Lucien Brouha (1960) discusses the various methods of measuring the physiological cost. He points out that evaluating the work load by measuring the oxygen consumption is reasonably accurate and has been used extensively, but, in many industrial operations, measuring oxygen consumption alone gives only a partial picture of the total physiological cost. The most serious problem with the oxygen consumption method is the high effort required before the difference between the basal oxygen and the working oxygen consumption can be distinguished.

Though heart rate is a sensitive indicator of physiological cost, it was found by Nicholas and Amrine (1959) that the heart rate is affected by environmental temperature, relative humidity and the amount of clothing worn. Nichols and Amrine measured the energy expenditure by using the heart rate and assumed that a faster heart rate was associated with more effort or energy exerted. Konz and Day (1966) pointed out that the earlier experiments indicated that there was not a linear relationship between the energy and the heart rate. Brouha concludes that the above methods can be applied only to work of sufficient intensity and duration to produce reactions that are measurable by these techniques. He adds "If the work is too short or too light, other methods must be used. Among them the force platform has proved valuable in measuring the effort involved in motion". Some of the measurement problems can be overcome by the use of the force platform.

Purpose of the investigation:

Experiments have been conducted to find the optimum table heights for individuals when they perform tasks in a standing position. Konz (1967) found that the optimum height of the table for an operator performing a task in the standing position was about one inch below the elbow. However a large portion of light assembly is done by a seated worker. For a continuous, repetitive task of this kind, it is desirable to minimize the physiological cost, as over a long period of time this factor will have a strong bearing on fatigue. Hastings (1966), using heart rate and pulmonary ventilation as the measures of physiological cost, found that the optimum height of the table, for a sitting operator, is at the elbow level.

The present investigation will verify whether this conclusion is valid when physiological cost is measured by the force platform.

A second objective is to determine whether the physiological cost for movements in an inward direction and in an outward direction are the same.

LITERATURE REVIEW

The literature review has been divided into five parts. The first part brings out that an appropriate design of work station is an important factor in minimizing the physiological cost of a task. The second and third parts deal with the experiments conducted to determine the optimum height of the work station for the standing condition and then for the sitting condition. The fourth part indicates the need for further investigations to be made to confirm the conclusions on the physiological cost requirement for the inward versus outward movements. The fifth and last part summarizes the different investigations carried out for evaluating the best angle of movement of the right hand in the horizontal plane.

Design of work stations:

Scientific consideration of the design of work stations was started in 1911 by Gilbreth.

Dempster (1955) pointed out that studies based upon dynamic measurements of the body should contribute to comfort, efficiency, convenience and safety in various phases of human life. The applications could contribute to the improved design of work equipment, vehicles, furniture, prothetic devices and many other facilities and items of personal equipment.

Dunnington (1961) and Hudson (1962) studied the effect of work place dimensions on the physiological cost as measured by the force platform. The simulated drilling task contained a variety of motions. They found that adjusting the work place to fit the subject's anthropometric measurements significantly reduced the effort (lb-sec. of area) to perform the task.

Barany (1963) found that the anthropometric measurements of individuals do not affect the ability of individuals to perform specific motor tasks. However the position of an operator in relation to his work was thought to be important. He indicated that, although there are accepted average values for placement of tools, knobs, handles, cranks etc., there is also a great need for an analysis of the specific work place design for specific individuals.

Height of work station - standing condition:

Ellis (1951) studied the effect of work surface height on performance of a block turning task for 48 subjects. The subjects performed the task in the standing condition. Each subject worked for two three - minute trials at each of the six heights. A two minute rest period was given between the trials. The maximum performance was at three inches below the elbow (42 inches for Ellis' subjects); the feeling of strain (determined by the subject's vote) also was a minimum at this height. The following interesting observations were noted. At 19 inches below the elbow (-19 inches) performance was only 4.4 percent lower than at -3 inches; at -4 inches it was 1.7 percent lower; at -8 inches it was 0.7 percent lower; at two inches above the elbow (+ 2 inches) it was 4.4 percent lower; and at +8 inches it was 6.4 percent lower.

Frederick (1959) measured the energy consumption for men of "average heights" when lifting weights of 20 to 65 pounds. Each lift was made over a 20 inch vertical distance with starting heights of 0,20,40 and 60 inches. The least energy was required when lifting from 40 inches to 60 inches.

Drillis (1963) cited the work by Lysinski (1925) and Nebel (1929) at the German Research Institute on the optimum height of a filing bench for a standing operator. The amount of file dust produced for a 10 minute period was used as the criterion. Lysinski found that the maximum output was obtained when the bench was at approximately 60% of the operator's height. Nebel found 1 1/2 inches below the elbow to be the optimum height.

Konz (1967) cited that Knowles (1946) at Cornell made a study on the proper heights of ironing boards. For one criterion, she used the output of a crude force platform; the other criteria were postural shifting, calories required, heart rate and respiratory rate. Each of the standing subjects individually selected a height for the ironing board. This height averaged 6 inches below the elbow (note that an iron is about 5 inches high). When this preferred height was contrasted with the standard height of 31 inches, respiratory rate was the only one of the five criteria that was not significantly better.

Konz and Day (1966) and Day (1965) varied the height and handle orientation of a push - pull task performed on the force platform in the standing condition. The subjects operated the push - pull device at each of the five handle heights (knee,hip,waist,chest and eye). Even though the force required for the task itself did not vary, changing the height of the handle forced each subject to exert a force to maintain his own body position. This force exerted by the subject was minimum when the handle was at chest height.

Height of the work station - sitting condition:

Konz (1967) has cited that Bratton (1959) measured oxygen consumption and calculated the calories required for doing light work while sitting and standing at a 36 inch high counter. She found that there was no significant difference between the energy costs of sitting and standing. But Hans (1968), from his investigation on the arm motions in both sitting and standing conditions, using the criterion of physiological cost on the force platform, concluded that standing requires less physiological cost than sitting.

H.O. Rhode's work at Purdue University in 1952 was cited by McCormick (1957). A seated subject performed an assembly task at five different work surface heights, -6 inches, -2 inches, +2 inches, +6 inches and +10 inches, where 0 inches indicated elbow height. Oxygen consumption at each height was not statistically different.

Burandt and Grandjean (1963) performed an experimental study of the most comfortable seat height on 68 subjects. The subjects sat on a fixed chair and completed, in writing posture, a questionnaire placed on a fixed table top. The distance between the table top and seat was varied by varying the seat heights, the chair being placed on an adjustable floor panel. The subjects were asked to indicate, on the questionnaire, the height adjustment most comfortable to them and the admissible upper and lower limits. The following recommendations were made. For writing purposes, the necessary space range between the seat and the table top is 27 to 30 cm. (10.6 to 11.8 inches). For typing or key punching, this distance should be less than 28 cm. (11 inches). The height of the seats from the floor should be adjustable between 40 and 48 cm. (15.8 to 19.2 inches).

Langdon (1965) studied the measurements of 142 female key punch operators and the dimensions of their chairs and key punch machines. The subjects answered a questionnaire. He measured the heights from the floor of the seat, keyboard and, in some cases the elbow, while the hand was actually depressing a key in the middle of the keyboard bank. High correlations between seat height and keyboard height (0.45 for 141 d.f., significant at the 1 percent level) and between elbow height and keyboard height (0.41 for 45 d.f., significant at the 1 percent level) were found. It was concluded that, when the height of the middle rank keys of a keyboard is about 29 inches above the floor, the seat height to which most of the chairs would probably be set would be 18 inches above the floor.

Chatterjee and Daftuar (1966) conducted an experiment to verify Corbusier's concept, the modulor, that is, whether a constant relationship of ϕ (1:1.617) between the chair and table height yielded the best efficiency. Fifteen professional typists were given a two-minute typing test at each of the eleven heights of the table. The table was initially set at 1.617 times the height of the seat and five successive trials above and five below the initial table height were tested, increasing or decreasing the height by one inch in each case. The performance score (correct words - omitted words - repeated words) was the criterion.

It was found that the constant relationship of ϕ (1:1.617) between the chair and table height yielded the best efficiency. The best height of the table, 24.68 inches above the floor, was 1.18 inch below the elbow, with the seat height of 15.09 inches. They concluded that the results of the study confirmed the validity of Corbusier's concepts.

Hastings (1966) at Texas Technological College determined the optimum height of the work station for an operator in the sitting condition at -4,-2,0,+2,+4 and +6 inches. The simulated assembly task contained a variety of motions. The criteria used were the average change in heart rate, the average change in pulmonary ventilation and alpha wave depression. He found that +2 (two inches above the elbow) was the best height and -4 the worst height using heart rate as the criterion; there was no significant difference between +2, 0 and -2. But with pulmonary ventilation as the criterion, 0, the elbow level, was the best height and -4 was the worst. He did not find any significant difference between 0 and -2 and 0 and +2 and concluded that 0, the elbow level, is the best height and -4 is the worst height of those studied. He further noticed that a strong correlation existed between the length of the upper arm and the average increase in ventilation rate. He concluded that the optimum work stations height in terms of minimum physiological cost is best determined on an individual basis.

Wu (1965) investigated the effect of direction of movement and height of the work station. The seated subject moved a two pound weight with the right hand from a central point to a peripheral point 15 inches away; five different heights of work station and five different angles were considered. The physiological cost as measured by the force platform was used as the criterion. He found that an optimum vertical distance for the best work was at 0.85L, L being the length of the upper arm of the individuals.

Inward versus outward movements:

Wu (1965) concluded that the cost for an inward motion was 1.2 times greater than the cost for the outward motion.

Jeans (1966) studied the physiological cost of simultaneous and symmetrical motions. The subject moved a two pound weight in each hand between the specified points 18 inches apart under three experimental conditions. It was concluded that the outward motions of both hands required more force than the inward motions.

Rode (1968) investigated the effect of weight and direction on the performance of right hand movements. The task consisted of striking the targets with a stylus by making repetitive hand movements between the inner and outer targets. The diameter of the target was kept at 1 inch, while the amplitude, the distance between the centers of the two targets, was kept 16 inches. Four different weight styli were used, 0.12, 1.25, 2.38 and 3.25 pounds. The direction of the movement was varied from 0 to 180 degrees in increments of 30 degrees. The standing subject performed the task with the right hand while the physiological cost of doing the task was measured by the force platform. Rode concluded that the outward motions were significantly more accurate than inward motions and that direction had a significant effect while weight did not affect the accuracy of in and out motions.

Direction of movement of the right hand:

Lincoln and Konz (1966) studied the speed and accuracy of operating a switch and concluded that the movements of the right hand at an angle of 45 degrees were better than the movements made at an angle of 135 degrees.

Konz (1967) performed a series of experiments with different tasks at varying angles. He concluded that, for right-handed movements, movements to the right (that is a forearm pivot about the elbow) are more desirable than movements to the left (i.e. the movements of the entire arm from the shoulder).

Goyal and Kapur (1967), in a class project, studied simple repetitive in and out arm movements from a simulated bin at various angles. They found that the direction of movement does have an effect on accuracy of hand motions; the angle of maximum accuracy was at 45 degrees for right hand movements.

Based upon the above experimental results the following hypotheses were made.

Hypothesis I:

There is an optimal height of the work table for the operator performing the task in the sitting condition.

Hypothesis II:

The physiological cost is greater for an inward motion than an outward motion.

METHOD

Task:

The subjects transferred .62 pound bolts from the inner bin to the outer bin, or vice-versa, both being identical in design. The bins were located 40 cms. (15.8 inches) apart with their longitudinal axes mutually perpendicular and lay on a line making 45 degrees with the adjacent edges of the top of the adjustable work table. In the starting bin, there were 14 bolts arranged in two rows, one on top of the other, with their hexagonal heads facing the subjects. The subjects transferred one bolt at a time from the inner bin to the outer bin during the ten second trial period, keeping pace with the metronome. For the return motion the hand was empty. The same task was repeated under the same set of conditions with the inward motion loaded and the outward empty. Both inward and outward motions were performed by each subject at each height of the work table.

The entire motion pattern for the task is Grasp, Move, Release and Reach. Using the Methods Time Measurement (MTM) Table, which assigns to each motion a predetermined time standard that is determined by the nature of the motion and the condition under which it is made, the time for the entire motion pattern of the task was found to be 43.9 TMUs (time measurement units)(1.58 seconds). This is the sum of the individual time requirements for G4B, M16B, RL1, and R16C. Since there were 14 bolts in the bin and the subject had to pick one of them from among the others, a 'C type' Reach and 'G4B type' Grasp were taken as the appropriate motions. The subjects transferred nine bolts so 14.22 seconds is the total time required.

Because of a calculational error, the metronome was set at 105 beats per minute (a movement speed of 70 cm./second). The subjects transferred the nine bolts in 10 seconds instead of 14.22 so their pace was 142%.

The effects of learning and fatigue were balanced among the five conditions by using ten sequences, each subject following a specific sequence (Table 1). To balance among subjects, the odd numbered subjects performed the outward motion first while the even numbered subjects performed the inward motion first.

Equipment:

(a) Force platform:

The force platform used in this study was designed and constructed by Hearn (1966).

Three two - channel Texas Instrument Oscillographic recorders were used. As one of the carrier amplifiers was under repair, only five of the six channels were used. The forces in three perpendicular axes were recorded graphically on the first three channels. The remaining two channels recorded the torque exerted about the frontal and vertical axes (i.e. cartwheel and twist). Since, in performing this particular task, the torque exerted about the lateral axis (summersault) was expected to

Table 1

Sequence of experiment by subject

Subject	Begin	Sequence
1	O	A B C D E E D C B A
2	I	B C D E A A E D C B
3	O	C D E A B B A E D C
4	I	D E A B C C B A E D
5	O	E A B C D D C B A E
6	I	E D C B A A B C D E
7	O	A E D C B B C D E A
8	I	B A E D C C D E A B
9	O	C B A E D D E A B C
10	I	D C B A E E A B C D

A - Work table height 3 cms. above elbow

B - Work table height at elbow level

C - Work table height 3 cms. below elbow

D - Work table height 6 cms. below elbow

E - Work table height 9 cms. below elbow

O - Start with outward motion first

I - Start with inward motion first

be much lower than that exerted about either the frontal or the vertical axes, it was decided to use only the frontal and vertical torque axes. The force trace originates from an established zero mark and deviates either above or below it. The area above or below the zero mark is directly proportional to the force exerted in the specific plane. The physiological cost is the area under the curve in pound-seconds. The arithmetic sum of the areas for each plane gives the total orthogonal cost exerted. Similarly the arithmetic sum of the torques areas gives the total torque cost.

(b) Adjustable Table: (Plate I)

An adjustable table (Adjustable work station - Western Electric Drawing No. FPF-744144.) was used. The height of the work station and also the inclination to the horizontal of the 25 x 20 inch work surface, whose longer edge faces the subject, can be varied. A point (inner target) near the inner edge of the work surface was chosen and a 45 degree line in the counter clockwise direction (zero degrees is referred to as the three o'clock position) was marked. The outer target point was fixed at 40 cms. (15.8 inches) from the inner target point. The distance between the center of the inner target and the front edge of the table was kept at four inches (Barnes, 1963).

(c) Biomechanics chair:

A biomechanics chair whose seat and back rest can be adjusted to the desired positions was used to seat the subject. The chair was placed on the force platform.

The top surface of the seat was 16 inches above the top surface of the force platform. All the subjects said this seat height was comfortable. To simulate an industrial situation, the arm rests of the

PLATE I

The layout of apparatus with the subject ready to start.

chair were removed.

(d) Bins:

Two identical bins were used. These nine inch long bins have vertical back and sides, a flat base and a sloping front inclined at 45 degrees to the horizontal.

(e) Bolts:

Subjects worked with 14 bolts of equal size and shape. Each 3/4 inch diameter, hexagonal head bolt was 3 inches long and weighed 5/8 pound.

(f) Metronome:

A metronome was used to pace the hand movements of the subjects.

(g) Stop watch:

A decimal - minute stop watch was used to time the 10 second trials and the rest periods.

(h) Planimeter:

A planimeter was used to determine the area of physiological cost from the record paper.

(i) Measuring tape:

A steel tape with half inch increments was used to measure the elbow height of the seated subject and arm length of the subjects and to set the table to the desired heights.

Subjects:

Ten female students, all right handed, from Kansas State University were paid by the hour. Their ages varied from 18 to 24 with an average of 20.8 years; their heights varied from 60 to 67 with an average of 63.3 inches; their arm length varied from 30 to 34 inches with an average of 31.4 inches and their elbow heights ranged from 34.25 to 36.75 with an average of 35.58 inches. (Table 2)

Experimental Procedure:

The experiment was conducted in the Human Engineering Laboratory.

Each subject was brought into the experimental room where the following anthropometric measurements were taken: (1) height (2) weight (3) arm length and (4) elbow height.

The definition of arm length was taken as the "Distance from wall to tip of the longest finger; subject stands erect, with heels, buttocks, and shoulders pressed against a wall, right arm and hand extended forward horizontally and maximally" (Damon, Stoudt and McFarland, 1966). The elbow height was measured in the following way. First the popliteal height, measured as the vertical distance from the floor (here the top surface of the force platform) to the sitting surface, was taken. Then the elbow rest height, the vertical distance from the sitting surface to the bottom of the right elbow; the subject sitting erect, upper arm vertical at side, forearm at right angle to upper arm, was measured. The sum of the popliteal height and the elbow rest height gives the elbow height. After taking the elbow height, the subject's personnel data such as name, age and major course of study were recorded. Then the back rest was adjusted about the vertical axis to the comfort of the subject.

Next, the subject was asked to go through the instruction sheet which was kept on the working table. The instruction read as follows:

> "You are about to perform a simple motor task. The purpose of this experiment is to determine the optimum height of the work table, at which you can perform this task with minimum physiological cost at a given pace set up by the metronome placed in front of you. The task consists of picking up a 5/8 pound bolt from the bin at the starting target with the right hand and placing it in the bin at the other target

Table 2

Personal data for subjects

Subjects	Initials	Major	Age, years	Weight, pounds	Height	Arm length	Elbow rest height	Seated elbow height
					inches			
1	E.M.	English	21	106	60	30	11.25	36.50
2	R.P.	Litt.	21	119	62	32	10.50	35.75
3	P.K.	Fam. Eco.	21	115	63.5	31.5	11.50	36.75
4	P.R.	Lingust.	23	118	63	30	11.00	36.25
5	L.J.	Home Eco.	19	115	64.5	32	9.50	34.75
6	M.S.	History	22	118	62	30	11.00	36.25
7	T.T.	Litt.	19	112	62	30	10.50	35.75
8	I.G.	Fam. Eco.	24	135	64	32.5	9.50	34.75
9	S.K.	E.E.	19	122	65	32	9.00	34.25
10	M.M.	Home Eco.	19	137	67	34	9.50	34.75
	Average		20.8	119.7	63.3	31.4	10.32	35.58

which is separated 40 cms. from the starting target and set at an angle of 45 degrees in the horizontal plane on the adjustable table. You are then to return to the starting target with empty hand following the pace of the metronome and repeat the task for 10 seconds. This task is to be performed at five different heights. You have to perform the same task for both inward and outward motions. Please observe the following guidelines during the experiment:

(1) Pace your motion such that you make a contact when the metronome clicks at either end.

(2) Work uniformly and do not slow down at the end.

(3) You will be given a rest period of two minutes between trials. Please do not concentrate on the next set up during the rest period.

(4) Let your left arm rest freely at your side and please keep your posture the same between the trials. This is important."

Any questions by the subjects were answered immediately during the course of the reading.

In order to make the subject conversant with the task, each subject was given a practice session of 20 trials. Ten trials were for the inward movement and the remaining ten trials were for the outward movement. After completion of the practice trials, the subject was given a rest period of two minutes.

When the subject began the experimental task, the experimenter assumed a position near the subject to verbally indicate to her the sequence and also the beginning and end of each work cycle by the words "yes", "start" and "stop". One other experimenter assumed a position in front of the recorders to adjust the recording pens to a null position after every trial and to mark on the record paper the start and end of each trial while it recorded data on the three force axes and two torque axes.

When the experimenter said "yes" the subject started moving her empty hands, keeping pace with the metronome, making contacts at either bin when the metronome clicked at either end. When the experimenter said

PLATE II

A subject performing the task.

"start" the subject started transferring the bolts keeping pace with the metronome. The experimenter indicated to the other experimenter near the recorders to start marking the beginning of the trial by the words "okay". The first "okay" signal was given after the subject had transferred two bolts. The next "okay" indicated to the other experimenter that the 10 second trial period had ended. After giving the "okay" signal to the other experimenter the "stop" signal was given to the subject. This method takes only the middle 10 seconds of the task and thus can give more accurate data. Each subject performed a total of 10 trials. The cycle time for each trial was 15 seconds, and the rest period after completion of a trial was two minutes. Total duration for completion of the experiment by each subject was 40 minutes.

By calibration with known weights the scale factors, which gives the amount of cost in pound-seconds per square inch of area on the output paper for the force axes and the amount of cost in inch-pound-seconds per square inch of area on the output paper for the torque axes were determined for each axis after each subject finished the experiment.

The experimenter first calculated the area of the curves on the output paper for each trial in each of the five axes and converted the area under the curve into pound-seconds by multiplying by the corresponding constants of the force axes and into inch-pound-seconds by multiplying by the corresponding constants of the torque axes. The pound-seconds for all the force axes, X,Y and Z, were added arithmetically to determine the total orthogonal cost and the inch-pound-seconds for the two torque axes were added arithmetically to determine the total torque cost exerted.

The total number of bolts transferred in each trial by each subject was noted from the output record paper. All the subjects, in most of the trials, transferred nine bolts in the 10 second trial period. The cost exerted in transferring a single bolt in each of the three force axes and in each of the torque axes was calculated for each height and subject by dividing the pound-seconds and inch-pound-seconds for the trial by the number of bolts transferred in that particular trial. Then the total cost exerted by a single subject, at a particular height in transferring a single bolt, was determined by adding up the pound-seconds/bolt/subject in each of the three (lateral, frontal and vertical) force axes. Similarly the total torque cost exerted by a subject at each height, in transferring a single bolt, was determined.

RESULTS

A three-way analysis of variance was used to analyze the data from each of the five axes (three force axes and two torque axes) and the total orthogonal cost and total torque cost (Tables 3 through 9).

The main effect of height was found to be significant ($p < 0.05$) in six out of the seven analyses; the exception was the lateral axis (Table 3). The direction effect was significant ($p < 0.05$) only for the total orthogonal cost (Table 6), but not for the components or the torques. The subject x height interaction was significant in six of the seven analyses; the exception being the vertical torque cost (Table 8). The subject x direction effect was significant in only two of the analyses, the lateral (Table 3) and vertical cost (Table 5) axes. No other interaction was significant. Duncan's New Multiple Range Test was used ($p < 0.05$) to test the significant differences between the means.

Table 3

Analysis of variance for lateral force axis

VARIATION	D/F	MEAN SQUARE	F
Subjects (S)	9	0.2235	-
Heights (H)	4	0.0360	2.57
Direction (D)	1	0.0140	0.67
S x H	36	0.0140	2.19*
S x D	9	0.0207	3.23*
H x D	4	0.0040	0.65
S x H x D	36	0.0064	
Total	99		

*$p < 0.05$

Table 4

Analysis of variance for frontal force axis

VARIATION	D/F	MEAN SQUARE	F
Subjects (S)	9	0.3060	--
Heights (H)	4	0.1430	3.49*
Direction (D)	1	0.0250	2.12
S x H	36	0.0410	6.21*
S x D	9	0.0118	1.80
H x D	4	0.0140	2.12
S x H x D	36	0.0066	
Total	99		

*$p < 0.05$

Table 5

Analysis of variance for vertical force axis

VARIATION	D/F	MEAN SQUARE	F
Subjects (S)	9	0.4310	--
Heights (H)	4	0.6720	14.50*
Direction (D)	1	0.0800	3.24
S x H	36	0.0463	5.94*
S x D	9	0.0247	3.17*
H x D	4	0.0160	2.05
S x H x D	36	0.0078	
Total	99		

*$p < 0.05$

Table 6

Analysis of variance for total force

VARIATION	D/F	MEAN SQUARE	F
Subjects (S)	9	0.7530	-
Heights (H)	4	1.8200	16.50*
Direction (D)	1	0.3040	7.24*
S x H	36	0.1097	3.54*
S x D	9	0.0420	1.35
H x D	4	0.0640	2.06
S x H x D	36	0.0310	
Total	99		

*$p < 0.05$

Table 7

Analysis of variance for frontal torque axis

VARIATION	D/F	MEAN SQUARE	F
Subjects (S)	9	382.03	-
Heights (H)	4	240.82	15.95*
Direction (D)	1	4.44	0.55
S x H	36	15.20	2.24
S x D	9	8.05	1.19
H x D	4	0.77	0.11
S x H x D	36	6.77	
Total	99		

*$p < 0.05$

Table 8

Analysis of variance for vertical torque axis

VARIATION	D/F	MEAN SQUARE	F
Subjects (S)	9	54.600	-
Heights (H)	4	47.560	11.65*
Direction (D)	1	12.59	2.90
S x H	36	4.09	1.09
S x D	9	4.35	1.16
H x D	4	0.0175	0.005
S x H x D	36	3.74	
Total	99		

*$p < 0.05$

Table 9

Analysis of variance for total torque

VARIATION	D/F	MEAN SQUARE	F
Subjects (S)	9	371.05	-
Heights (H)	4	480.41	22.80*
Direction (D)	1	22.18	2.86
S x H	36	21.16	2.58*
S x D	9	7.75	0.95
H x D	4	4.24	0.52
S x H x D	36	8.20	
Total	99		

*$p < 0.05$

Table 10

Result of DNMR test as applied to the lateral, frontal, vertical and total orthogonal costs (lb-sec./bolt/subject) averaged over heights

Heights	-9	+3	-6	0	-3
Costs					
Lateral	2.13	2.06	2.04	1.93	1.93
Frontal	2.82	2.60	2.49	2.49	2.37
Vertical	2.53	2.33	2.12	1.93	1.57
Total	7.48	6.99	6.65	6.35	5.87

Scores underlined by the same line are not significantly ($p < 0.05$) different from each other. Heights are in cms.

The test on the differences for the total orthogonal cost (Table 10) indicates that -3, three cms. below the elbow required minimum physiological cost. However the difference between -3 and 0 was not statistically significant. Both -3 and 0 were significantly better than the other heights. Zero and -6 were not statistically different, -6 and -3 were not significantly different and +3 and -9 were not significantly different.

The test on the total torque cost exerted (sum of the frontal torque and vertical torque) again points out that -3 is the best height (Table 13). The worst heights are +3 and -9.

The direction effect is significant only in the analysis of the total orthogonal cost (Table 6). It is clearly seen from the figures (Fig. 2 through 7) that outward movements require less physiological cost than the inward movements. It is also noticed that in the lateral axis, the cost required for outward motions are 2.3% less than that for inward; in the frontal axis it is 2.4% less; in the vertical axis it is 5.3% less and in the total orthogonal cost exerted it is 3.3% less. The torque cost exerted about the frontal axis for the outward movement is 1% less than for the inward movement; about the vertical axis it is 3.6% less and for the total torque exerted it is 1.8% less.

Nine out of the ten subjects felt that +3 would be the best height for writing purposes but for performing this particular task, they found this height to be inconvenient. Only one subject expressed three cms. above the elbow to be the best height, but from the data, it is found that she expended a lower physiological cost at 0 than at +3. From the above results, it is concluded that -3, three cms. below the elbow, is the best height, the one that requires minimum physiological cost, and -9, nine cms.

below the elbow, and +3, three cms. above the elbow, are the worst heights. The elbow level, 0, is not significantly different from -6. The significant direction effect indicates that the movement for an outward motion requires less physiological cost than that for an inward motion. It is 3.3% less in the total orthogonal cost exerted and 1.8% less in the total torque cost.

DISCUSSION

The results of this investigation, that three cms., approximately 1.15 inches, below the elbow is the best height agrees with the findings of Chatterjee and Daftuar (1966) and the recommendations of Langdon (1963). Chatterjee and Daftuar found that the height of the table set at 1.18 inches below the elbow yielded the best efficiency. Langdon's recommendation, that the best distance between the seat and the middle ranked keys of a keyboard set on a table should be about 11 inches, is also confirmed by the results of this study. Taking into account the fact that the middle rank keys of a keyboard are at a distance of about 2 inches from the top of the table, Langdon's height is 9 inches above the seat. In this study the best height of the table is about 9 inches above the seat.

The result of this investigations can also be considered as an extention of the findings of Hastings (1966). Hastings found, using ventilation as a criterion, that the elbow level, 0 inches, was the best height and there was no significant difference between -2, 0 and +2. Using heart rate as the criterion, +2 was best although there was no significant difference between -2, 0 and +2. Using the criterion of physiological cost as measured by the force platform, which is better suited for measuring the physiological cost requirements for light assembly tasks (Bruha , 1960), the intermediate

Table 11

Results of DNMR test as applied to the torque costs about the frontal axis (inch-lb-sec./bolt/subject) averaged over heights

Heights:	-9	+3	-6	0	-3
Costs:	83.5	82.3	75.8	75.4	66.1

(A single line underlines the costs 83.5, 82.3, 75.8 and 75.4.)

Scores underlined by the same line are not significantly ($p < 0.05$) different from each other. Heights are in cms.

Table 12

Results of DNMR test as applied to the torque costs about the vertical axis (inch-lb.-sec./bolt/subject) averaged over heights

Heights:	+3	-9	0	-6	-3
Costs:	32.6	30.5	28.0	26.4	24.9

Scores underlined by the same line are not significantly ($p < 0.05$) different from each other. Heights are in cms.

Table 13

Results of DNMR test as applied to the total torque costs exerted (inch-lb-sec./bolt/subject) averaged over heights

Heights:	+3	-9	0	-6	-3
Costs:	114.9	114.0	103.5	102.3	91.0

Scores underlined by the same line are not significantly ($p < 0.05$) different from each other. Heights are in cms.

height of three cms. (-1.15 inches) below the elbow is the best height. This can be considered as a finer evaluation of Hastings' conclusion. Konz (1967) concluded that one inch below the elbow is the best height for a standing operator. From these investigations, it can be said that the same can be applied for a sitting operator also.

Hastings found that four inches below the elbow to be the worst height. This investigation also indicates that nine cms., approximately 3.5 inches, below the elbow is the worst height. In this investigation there is no significant difference between +3 and -9. Hastings' other conclusion that, as we go down below the elbow level, the physiological cost requirement increases also conforms with the result of this experiment.

It has been mentioned earlier that nine out of ten subjects felt that three cms. above elbow, (+1.15 inches) that is, the table height at 29 cms. above the seat, would be a convenient height for writing purposes. This agrees with the recommendation of Burandt and Grandjean (1963). They recommended the range 27 to 30 cms. above the seat to be the best height of the table for writing purposes. Their other recommendation, that the seat height for light tasks, such as writing and typing, should be between 40 and 48 cms. from the floor is also agreeable to the subjects of this study. All the subjects said that 16 inches, approximately 41 cms., is a comfortable seat height.

It is clearly seen from the figures (Fig. 1 through 7) that the costs exerted to perform this simple task at various heights are different from each other. The differences are not in performing the task itself but in the way the subject orients her body and arm movements for different heights. So it is evident that positioning the body to each

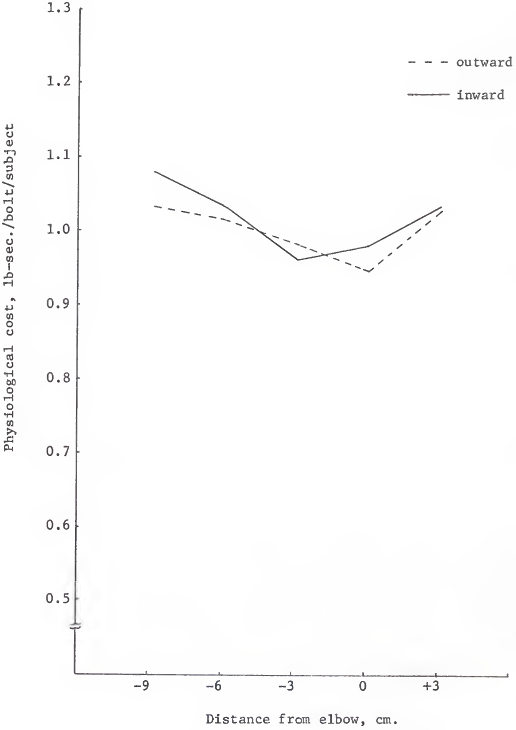

Fig. 1. Height Vs physiological cost (lateral)

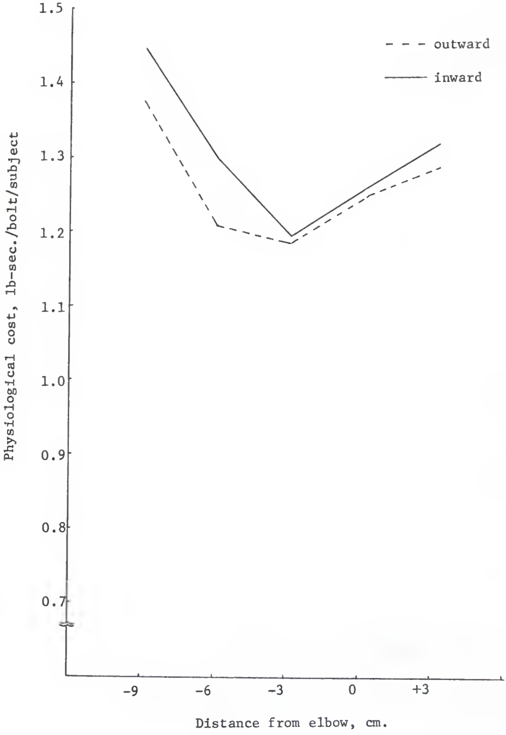

Fig. 2. Height Vs physiological cost (frontal)

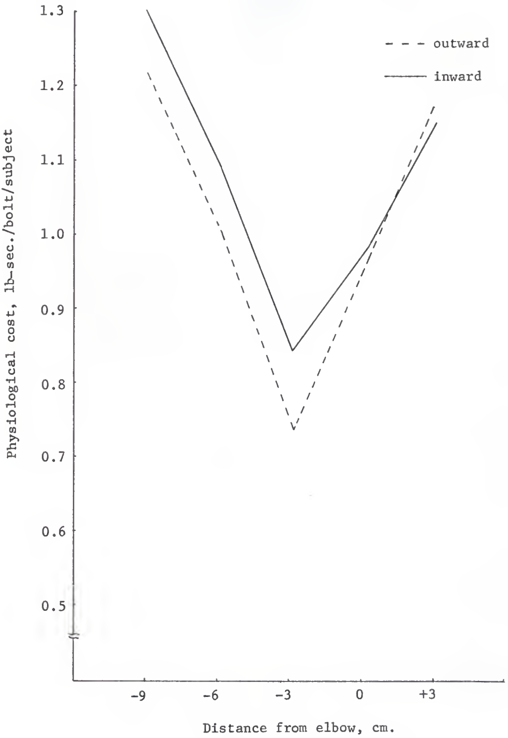

Fig. 3. Height Vs physiological cost (vertical)

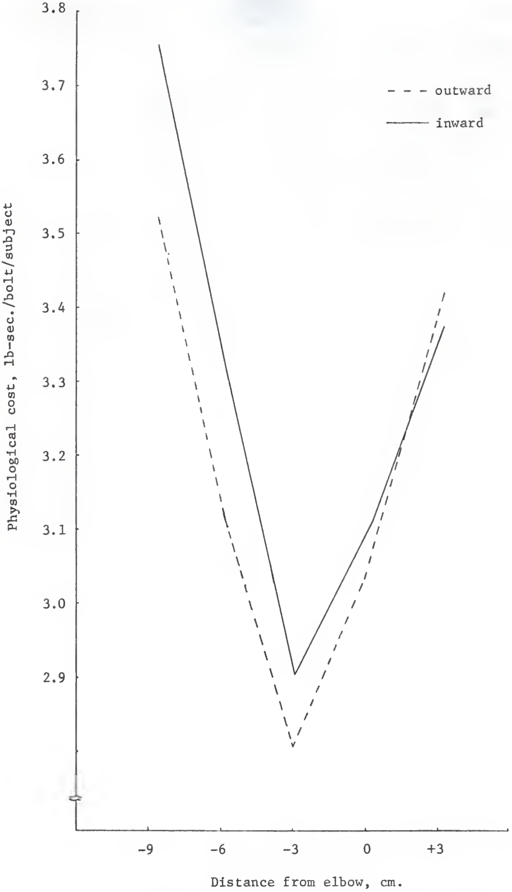

Fig. 4. Height Vs physiological cost (total orthogonal)

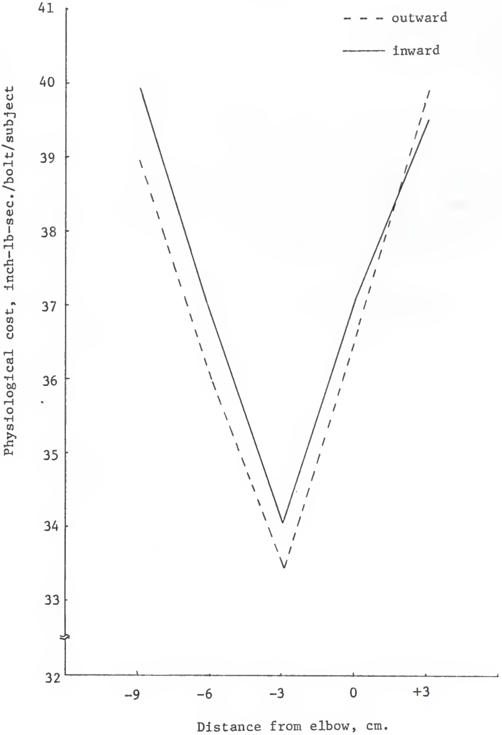

Fig. 5. Height Vs physiological cost (frontal torque)

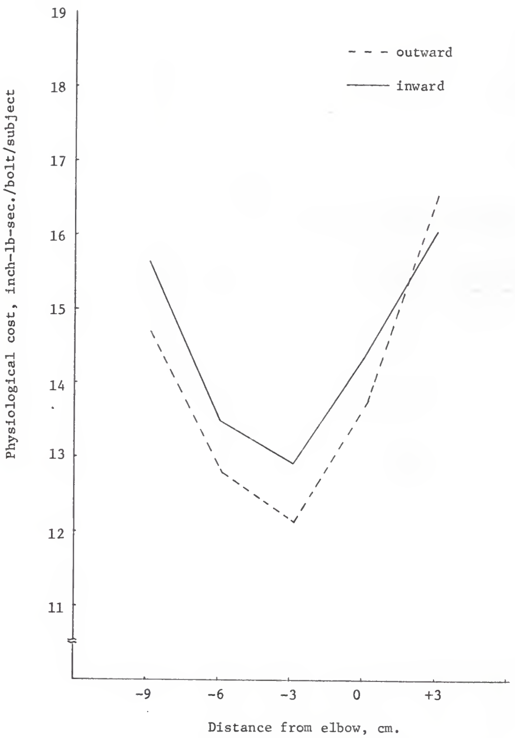

Fig. 6. Height Vs physiological cost (vertical torque)

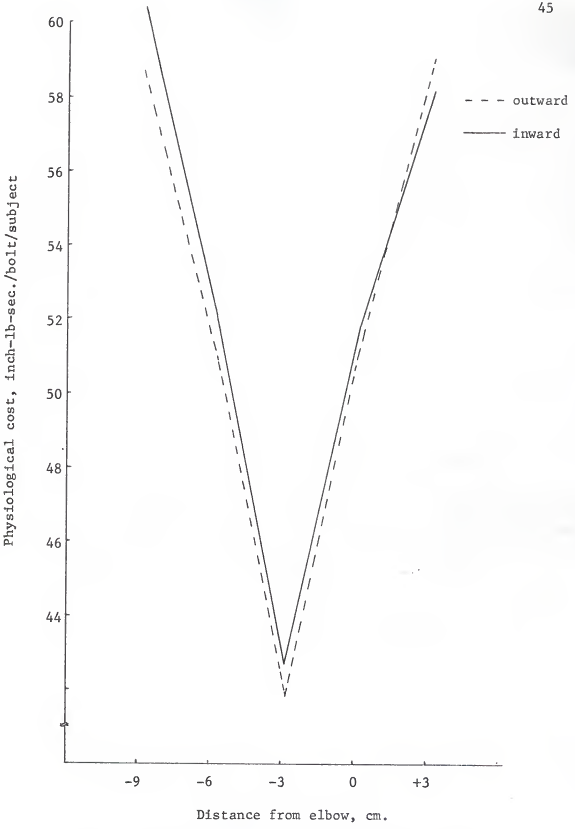

Fig. 7. Height Vs physiological cost (total torque)

of the five heights requires differing muscular complexity.

When performing the task at lower levels, the movement is an entire arm movement whereas at and above the elbow level, it is only the movement of the forearm, that is the forearm pivot about the elbow. The higher physiological cost at three cms. above the elbow can be reasoned as follows. The position of the elbow is slightly higher than the natural position of the elbow and the upper arm is also inclined more towards the horizontal axis to perform the task at this higher level. This is an uncomfortable posture and there is a tension in the upper arm muscles. This may be said to account for the higher energy requirements at three cms. above the elbow level. The above would seem correct, if only the height at the elbow level required the minimum physiological cost. But, when performing the task at the elbow level, the hand movements are in the same plane as the elbow. When performing at three cms. below the elbow, the movement is one 'with gravity' and the movements are not the entire arm movements. The forearm is kept at an angle to the elbow plane, a more comfortable position than keeping it at right angles to the upper arm, and the movements are only the forearm movements. But when the height of the table is lowered below three cms., the arm movements required to perform the task at these lower levels are entire arm movements. Further since the bolts are kept at a much lower height, positioning to grasp the bolt requires some more muscular activities. This partly accounts for the increase in the physiological cost.

The direction is significant only in the analysis of the total orthogonal cost, the sum of the costs for each of the three force axes. It was expected that there would be a significant direction effect in the total torque cost analysis. But strangely, the direction effect was not statistically significant although the figure (Figure 7) clearly shows that outward motion requires less physiological cost than the inward motion. From the figures (Fig. 2 through 7) it can be seen that outward movements require less physiological cost than the inward movements. This result confirms the conclusion of Wu (1965). Dudek and Petruno (1965) explained the difference in energy expenditure as

> "The mechanical advantage of the arm is best when the arm is contracted as at the beginning of an outward motion. The mechanical advantage changes to a 'least' value when the arm is extended as at the beginning of an inward motion. This causes a difference in the amount of energy, the subject must expend to move his arm in to and out from the body. From this it may be concluded that when the arm is considered to be a lever, it will require more energy expenditure to move the arm in toward the body than to away from the body".

One other reason that could be given is that positioning to grasp the bolt at the inner target is easier than that at the outer target and this also accounts for the increase in the cost requirements for the inward motions.

Since the cost required for the inward motion at one particular height, 3 cms. above the elbow, is less than that for the outward motion; an simpler explanation can be given for the difference between inward and outward motions. This argument is based on fact that it is easier to move "with gravity" than "against gravity". When the work surface is above the elbow level it is easier to move an object towards the body and return empty "uphill". But when the work surface is below the elbow level, it is easier to move the object away from the body and return empty "uphill".

The subject x height interaction was significant in all the analyses except the vertical torque. This can be explained as when an individual subject performs the task at different heights, the best height for that particular subject may be some height other than 3 cms. below the elbow. That is, for each individual there is a particular height at which this task can be performed with minimum physiological cost and this height is not the same for all. But, on an average, this height happens to be three cms. below the elbow. Thus, although it can be said that the optimum work station height in terms of minimum physiological cost is best determined on an individual basis, an agreement with the conclusion of Hastings (1966), from a practical basis 3 cm. below the elbow (-1.15 inches) can be used.

The subject x direction interaction was significant only for two of the seven analyses; they being the lateral and vertical axes. This indicates that not all the subjects performed the task alike. For some of them the outward was more costly than the inward, particularly in the lateral and vertical axes. But the overall effect was non-significant. This can probably be explained as follows. Some of the subjects tend to place the bolts in the nearest corner of the bin. This was noticed and the subjects were asked to place them preferrably in an order so that the distance of 40 cms. was always maintained. During the earlier trials the subjects lateral movement might not have been 40 cms. and might have been less for the inward motion than for the outward motion. So there might have been less cost in those particular trials. As for the vertical cost, not all the subjects placed the bolts smoothly as some of them tend to drop them from a distance. This might possibly have increased the area under the curve which results in an extra cost. The subjects were watched and some of the trials were repeated but there might have been some misses.

An interesting side light of this investigation is the confirmation of the constant relationship ϕ (1:1.617) between the chair and the table heights. Chattarjee and Daftuar (1966) verified this relationship. In this investigation the best height of the table is 3 cms., 1.15 inches, below the elbow. That is, the table set at 25.18 inches above the floor when the seat height is 16 inches above the floor, required the minimum physiological cost. The ratio ϕ is 1.58. This value of ϕ is very close to 1.617, the golden mean ratio of Corbusier (1951). Although the value of ϕ from the results of this experiment is not exactly the same as the golden mean ratio, it is reasonably close to the value of the golden mean ratio.

CONCLUSIONS

Moving a load with gravity is helpful, for motions loaded in one direction and empty on the return, so the absolute physiological cost is larger for inward loaded motions than outward loaded motions as long as the work surface is below the elbow. On an average, a work table set at three cms. below the elbow (-1.15 inches) requires the minimum physiological cost for a seated person.

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REFERENCES

Barany, J., 1963. "The nature of individual differences in bodily forces exerted during a motor task as measured by a force platform", Journal of Industrial Engineering, Vol. XIV.

Barnes, R.M., 1963. Motion and Time Study, Fifth Edition, Wiley, New York.

Burandt, U., and Grandjean, E., 1963, "Sitting habits of office employees", Ergonomics.

Chatterjee, A., and Daftuar, C.N., 1966. "Application of Corbusier's human scale to the layout of work space for typing:, Journal of Engineering Psychology, Vol. 5, No. 2.

Corbusier, L., 1951. The Modular, Vol. I., Translated by P.D. Franci & A. Bostock, London: Faber & Faber.

Damon, A., Stoudt, W.H., and McFarland, A.R., The Human Body in Equipment Design, Harvard University Press, Massachusetts, 1966.

Day, R., 1965. "The effects of hand, wrist and body orientation on force requirement to perform a push-pull task", M.S. thesis, Kansas State University.

Dempster, W.T., 1959. "The anthropometry of the manual work space for the seated subject", American Journal of Physical Anthropology, Vol. 17, No. 4.

Dreyfuss, Henry., 1955. Designing for People, Simon and Schuster, New York.

Drillis, R., 1963. "Folk norms and biomechanics", Human Factors, Vol. 5.

Dunnington, T., 1961. "The effect of work place dimensions upon the effort required to perform a simulated light industrial task", M.S. thesis, State University of Iowa.

Dudek, R.A., and Petruno, J.J., 1965. "Investigation of an operator's ventilation rate under static loads", Journal of Industrial Engineering, Vol. 16, No. 6.

Ellis, D., 1951. "Speed of manipulative performance as a function of work-surface height", Journal of Applied Psychology, Vol. 35.

Frederick, W., 1959. "Human energy in manual lifting", Modern Materials Handling, March, 1959.

Fryer, H.C., 1966. "Concepts and Methods of Experimental Statistics", Allyn and Bacon Inc., Boston.

Goyal, M., and Kapur, 1967. "Accuracy of right-handed inward motions as a function of direction and bin height", Human Engineering Class Project, Kansas State University.

Hans, B.S., 1968. "The physiological cost of arm motions in sitting versus standing", M.S. thesis, Kansas State University.

Hastings, R.D., 1966. "An investigation of the effect of work surface height and operator size on physiological cost in an assembly task", M.S. thesis, Texas Technological College.

Hearn, M., 1966. "Design and construction of a force platform with torque measuring capability", M.S. thesis, Kansas State University.

Hudson, W., 1962. "The study of the dynamic characteristics of a reaction free aparatus for measuring physiological cost of dynamic manual work", Journal of Industrial Engineering, Vol. XIII.

Jeans, C., 1966. "A study of physiological cost of symmetrical and simultaneous motions", M.S. thesis, Kansas State University.

Konz, S., 1967. "Design of work stations", Journal of Industrial Engineering, Vol. XVIII, No. 7.

Konz, S., and Day, R., 1966. "Design of controls using force as a criterion", Human Factors, April, 1966.

Langdon, F.J., 1965, "The design of card punches and the seating of operators", Ergonomics, 8 (1).

Lincoln, R., and Konz, S., 1966. "Effect of switch configuration on the operations of a switch matrix ", Journal of Applied Psychology, Vol. 50, No. 5.

Lucien, Brouha., 1960. Physiology in Industry, Pergamon Press, New York.

McCormick, E., 1957. Human Engineering, McGraw-Hill, New York.

McCormick, E., 1964. Human Factors Engineering, McGraw-Hill, New York.

Moore, Herbert., 1952. Psychology for Business and Industry, McGraw-Hill, New York.

Nichols, D., and Amrine, H., 1959. "A physiological appraisal of selected principles of motion economy", Journal of Industrial Engineering, Vol. 10.

Rode, V.P., 1968. "A study of effect of weight and direction on the speed, accuracy and physiological cost of one hand motions in the horizontal plane", M.S. thesis, Kansas State University.

Tichauer, E.R., 1964. "Human capacity, a limiting factor in design", The Institute of Mechanical Engineers Proceedings, Vol. 178, Part 1, No. 37, London.

Wu, L., 1965. "An investigation of the effect of work of varying the distance between shoulder and work table", M.S. thesis, Kansas State University.

THE OPTIMUM SEATED WORK HEIGHT

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ABSTRACT

The optimum height of a work table for simple arm movements while sitting was determined. The criterion used was the physiological cost as measured by the force platform. The task was to pick up, with the right hand, a 5/8 pound bolt from a bin starting from the inner bin and place it in the outer bin. The movement angle was 45 degrees and the distance 40 cms. The return motion was empty. The subjects were asked to transfer the bolts keeping pace with the metronome, set at 105 beats per minute, during one ten second trial. The same task was repeated for the inward motion. The ten female subjects performed at five heights (+3, 0, -3, -6, -9 cm. from the elbow).

There was a significant difference between heights. On an average, a work table set at three cms. below the elbow (-1.15 inches) requires the minimum physiological cost for a seated person. Moving a load with gravity is helpful, for motions loaded in one direction and empty on the return, so the absolute physiological cost is larger for inward loaded motions than outward loaded motions as long as the work surface is below the elbow.