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THE EFFECT OF FOOT-REST POSITION ON THE STRENGTH OF HORIZONTAL PULL BY THE HAND

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ABSTRACT

THE EFFECT OF FOOT-REST POSITION ON THE STRENGTH OF HORIZONTAL PULL BY THE HAND

OBJECT

To determine the effect of foot-rest position on the strength of horizontal pull by the hand at four different elbow angles.

RESULTS AND CONCLUSIONS

At all elbow-angles the strength of hand pull increased as the thigh was elevated above the horizontal or as the leg was straightened. The effect of foot-rest position on output increased as the arm was straightened. The knee-angle exerted a greater effect on the strength of the hand movement than did the thigh-angle.

The results were in agreement with the hypothesis that the strength of hand pull is greatest when the legs are in the position at which they can exert the greatest force against the foot-rest. The force developed by the legs tends to counteract the force exerted by the hand and thus limits the strength of hand pull.

RECOMMENDATIONS

In order to maximize the strength of horizontal pull by the hand, the foot-rest should be in such a position as to produce a thigh-angle of approximately 20° above the horizontal and a knee-angle of approximately 150°. The foot-rest position is important even at comparatively low output levels.

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THE EFFECT OF FOOT-REST POSITION ON THE STRENGTH OF HORIZONTAL PULL BY THE HAND

I. INTRODUCTION

Hooton (6), Åkerblom (1), and others have devoted considerable attention to the task of determining the desirable characteristics of seats for resting persons, or for those engaged in sedentary tasks. Comparatively little attention, however, has been given to the problem of determining the best seating for those engaged in tasks which require the application of large forces to various controls. Proper design of the operator's supporting structure possibly can do as much to improve the mechanical efficiency of the body and to reduce fatigue as can the proper placement of controls. When large forces are applied to a control, and especially when the body is poorly supported, the body must work as a whole to counteract the control force. Many of the muscular forces developed do not contribute directly to the control force, but rather they are required to support the action of the prime movers. The efficiency of the operator may be increased greatly by improving seat design, and thereby reducing the work load on the accessory muscles. Clark says:

> "In certain types of manipulations involving the use of machinery, it may occasionally be found that almost as much muscular energy is being expended in resisting unnecessary movements by static muscular work, as in the dynamic muscular work required for the actual operation of the machine. The reduction of unnecessary static work of this sort can often be achieved by supports of one sort or another, adjusted in position to the body dimensions of the worker." (4, p 8)

In a recent study, the author demonstrated that the degree of stabilization of the shoulder influenced the strength of horizontal push by the hand. It was found that as the height of the back-rest was increased the strength of the movement increased. It is obvious that a body member can exert no more force on a control than can be counteracted by the body, and the force which can be counteracted is dependent upon certain supporting structure characteristics--the height and angle of the back-rest, the position of the foot-rest, etc. Rees and Graham (9) found that the maximum force which could be applied to a foot-pedal was dependent upon the back-rest position. In Hugh-Jones' (7) analysis of the forces of arm and leg extension the importance of the back-rest is obvious, since the limb acts as a mechanical toggle between the control and back-rest.

When pulling horizontally on a handle there is no physical structure against which the operator can directly brace his shoulder to oppose the forces developed by the arm. Unless the operator is wearing a shoulder-harness, the only way he can resist pulling himself out of his seat during heavy exertion is to produce the necessary counter-force by pushing against the foot-rest. Hugh-Jones found that the force exertable against a foot-pedal was greatly influenced by pedal position. In general, he found an increase in output as the angle of the thigh above the horizontal was increased, and as the leg was straightened up to a "limiting angle" of about 160°. Also, Rees and Graham reported that the strength of push was better at the high than at the low pedal position.

The purpose of the present investigation was to determine the effect of foot-rest position on the strength of horizontal pull by the hand. It was hypothesized that the strength of pull by the hand would increase both as the thigh was elevated above the horizontal, and as the leg was straightened. That is, the strength of pull should be greatest at those foot-rest positions found to be most favorable for exerting force on a foot-pedal. As the force applicable to the foot-rest increases, a greater stabilizing force is developed, and an increased hand pull can be developed. The effect of foot-rest position on the strength of hand pull should increase as the arm is straightened, for it has been shown by Hunsicker (8), Hugh-Jones (7), and Caldwell (2) that an increase in elbow angle up to 180° results in an increased strength of pull. Thus, as the subject's output increases, and a greater demand is placed on the legs to stabilize the body, the foot-rest position should have an increasing effect on the force of the hand movement.

II. EXPERIMENTAL

A. Apparatus

The apparatus consists of an isometric dynamometer handle, a display, an adjustable seat and back-rest, and an adjustable foot-rest. The handle and seat have been described in detail in a previous report (3). The handle is mounted on a ball which is secured to a steel bar on which strain gages are mounted. The swivel-mounting insures that the subject will exert pressure on the ball, for if the hand is positioned too high or too low the handle will swivel when force is applied to it. This insures that all subjects will grasp the handle and exert pressure on it in an identical manner. Four strain gages, which are wired as a Wheatstone Bridge, are mounted on the steel bar below the handle. A display which is simply a voltmeter in parallel with the oscillograph has a scale marked in pounds. The handle was calibrated against known forces so that the pen deflections of the oscillograph could be read in pounds of force. During this calibration the readings of the voltmeter were recorded and from these data the display scale was constructed. The display enables the subject to determine how much force he is applying to the handle. It has been found in previous work that this display, which provides the subject with continuous information about his performance, tends to increase and stabilize his output.

The seat has vertical, lateral, and fore and aft adjustments which make it possible to place all subjects, regardless of size, in an identical position with respect to the handle. The back-rest is a 12 inch by 4 inch pad of sponge rubber backed by a metal plate slightly bowed to fit the curvature of the back. The seat is covered with a 1/4 inch pad of felt impregnated with liquid latex. The output of the strain gages mounted on the handle was amplified by a Brush Universal Strain Amplifier and recorded on a two-channel, ink-writing Brush oscillograph. The foot-rests are 6 inch by 12 inch steel plates covered with a sheet of hard, corrugated rubber. The distance between the centers of the plates is 12 inches. The plates are free to pivot on a horizontal shaft so that whatever the position of the legs, the subject can select the most comfortable ankle position for exerting pressure on the foot-rest. The foot-rest distance can be varied from approximately 21 inches to 40 inches from the hip-joint and from 2 inches above the seat to 16 inches below the seat.

B. Subjects

The eleven subjects used in this experiment were obtained primarily on the basis of availability. No attempt was made to select subjects of average or extreme sizes or physiques. The subjects reported no abnormalities or injuries which would seem to interfere with the performance of the assigned task. The weights of the subjects ranged from 143 to 194 pounds with a mean of 168 pounds, and their heights ranged from 66 inches to 74 inches with a mean of 70.2 inches.

C. Procedure

On the first day the experimenter measured the arms and legs of the subjects to determine the settings of the dynamometer handle and foot-rest which would produce the necessary elbow-angles and thigh- and knee-angles. Also, the proper seat position was determined for each subject. This required the determination of the seat height which would put the center of the subject's shoulder joint at the height of the center of the handle, and the fore- and aft-position which would place his shoulder directly under a plumb-bob which marked the zero point of the scale along which the handle is adjusted. The lateral adjustment was not determined because it has been found that the slight differences in the horizontal angle of the handle with respect to the shoulder introduced by differences in shoulder width would have no appreciable effect on the strength of the pull movement. The seat adjustments enable the experimenter to place all subjects in the same position with respect to the handle. The seat position was recorded for each subject and used on all subsequent days of testing.

On the second day the handle was set at the four distances computed to produce the necessary elbow-angles for each subject, and the angles were checked by means of a protractor-type goniometer. On all subsequent days of testing these handle settings were used to eliminate the necessity of repeatedly checking the angles. From the two measurements of the leg -- the femoral length, and the length of the line from the knee-joint to the floor -- the foot-rest positions required to produce the various thigh- and knee-angles were determined. The subject was correctly positioned in the seat, the foot-rest was set at the nine selected positions and the leg angles were checked with the goniometer. Thereafter, the foot-rest could be set at the pre-determined heights and distances from the seat to produce the desired leg-angles for each subject.

Three thigh-angles (0°, 10°, and 20°) were combined factorially with three knee-angles (110°, 130°, and 150°) to produce the nine foot-rest positions. At each of these positions the strength of horizontal hand pull was measured at elbow-angles of 60°, 95°, 130°, and 165°. Thus, there was a total of 36 experimental conditions under which each subject was tested. The sequence of conditions for each subject was determined in a random manner. Each subject received four trials per day for a total of nine days. Two trials were given in the morning and two were given in the afternoon. There was always at least a three hour interval between the morning and afternoon tests. Each trial lasted for seven seconds. The subject was instructed to build up to his peak output in two or three seconds and to keep trying to increase his score to the end of the trial. This was done to eliminate the common tendency to "slam" the handle and thus to produce artifically high outputs. The score for a trial was the peak output recorded during the last five seconds of the trial. A five-minute rest period was given between trials. This rest period duration was more than adequate to allow for the dissipation of any fatigue produced during the brief trial.

Prior to the actual testing the subjects were given practice in pulling on the dynamometer handle. They were told to grasp the handle in such a manner as to keep it from swiveling when large forces were applied to it, and to pull straight back along the line connecting the handle and shoulder-joint. The subjects were cautioned against throwing the shoulder out of position when applying force to the handle. A guide was placed against the shoulder when the subject was correctly positioned in the apparatus and he was instructed to maintain light contact with the guide during the trial. The subjects reported that this requirement did not seem to make the response unnatural. This is supported by the fact that only two trials had to be repeated because of extreme shoulder movement.

III. RESULTS

The results of the study are shown in Table 1, and the analysis of variance of these data is presented in Table 2, page 6. It should be noted in Table 2 that all the sources of variation except for "Thigh-angles x Subjects" was found to be significant at less than the 1% level of confidence. The first- and second-order interactions with "Subjects" should not be surprising since there were large individual differences in absolute strength, and the relative advantages of the various foot-rest positions should be influenced greatly by the forces applied to the handle. This interpretation is supported by the fact that all the second-order interactions proved to be non-significant when the data were transformed in such a manner as to reduce differences in absolute output among the subjects. The F-ratio for the two significant first-order interactions containing "Subjects" were not substantially changed by the transformation, but they remained at comparatively low levels. This remaining significance probably reflects a residual difference in motivation of the subjects.

TABLE 1

MEAN STRENGTH OF THE PULL MOVEMENT IN POUNDS AT THE NINE FOOT-REST POSITIONS FOR THE FOUR ELBOW-ANGLES

	THIGH ANGLE												
	0°				10°				20°				
	Knee Angle				Knee Angle				Knee Angle				
Elbow Angle	110°	130°	150°	Mean	110°	130°	150°	Mean	110°	130°	150°	Mean	Mean
60°	72.6	84.4	84.5	80.5	77.9	84.5	84.3	82.2	80.7	87.5	86.8	85.0	82.6
95°	90.6	102.0	108.7	100.4	94.1	104.1	109.4	102.5	99.5	109.7	112.0	107.1	103.4
130°	92.1	108.0	117.8	106.0	101.7	120.6	119.3	113.9	113.8	123.0	124.2	120.3	113.4
165°	95.7	116.5	135.0	115.8	106.9	129.7	135.8	124.1	120.8	137.6	147.0	135.2	125.0
Mean	87.8	102.8	111.5	100.7	95.2	109.8	112.2	105.7	103.7	114.5	117.5	111.9	106.1

TABLE 2

ANALYSIS OF VARIANCE OF DATA ON STRENGTH OF HAND PULL AT NINE FOOT-REST POSITIONS FOR FOUR ELBOW-ANGLES

	Source of Variation	Sum of Squares	df	Mean Square	F	Error Term
(1)	Thigh-Angles (T)	8,338.56	2	4,169.28	65.91*	7
(2)	Knee-Angles (K)	23,497.53	2	11,748.76	64.68*	9
(3)	Elbow-Angles (E)	96,092.25	3	32,030.75	117.70*	10
(4)	Subjects (S)	80,036.67	10	8,003.67	42.89*	7, 9, 10
(5)	T x K	1,277.12	4	319.28	5.01*	12
(6)	T x E	2,418.92	6	403.15	9.06*	14
(7)	T x S	1,265.17	20	63.26	1.21	12, 14
(8)	K x E	4,805.46	6	800.91	11.75*	13
(9)	K x S	3,632.86	20	181.64	2.74*	12, 13
(10)	E x S	8,164.37	30	272.14	4.83*	13, 14
(11)	T x K x E	553.25	12	46.10	22.82*	15
(12)	T x K x S	2,549.34	40	63.73	31.55*	15
(13)	K x E x S	4,090.86	60	68.18	33.75*	15
(14)	T x E x S	2,671.16	60	44.52	22.04*	15
(15)	T x K x E x S	242.88	120	2.02		
(16)	Total	239,634.40	395			

*Significant at the .01 level of confidence.

The transformation consisted of dividing each subject's scores by his output at the most favorable combination of elbow-angle and foot-rest position. These converted scores may be called "percentage-of-maximum" scores. The subsequent discussion is in terms of the raw scores rather than the transformed scores.

It is shown in Table 2 that the thigh-angle had a significant effect on the output of the subjects. Table 1 and Figure 1 show that the strength of the movement increased as the angle increased. The mean output was 100.7 pounds at the 0° thigh-angle, 105.7 pounds at the 10° angle, and 111.9 pounds at 20°. These differences are small, though highly uniform. An examination of the performance of the individual subjects at the three thigh-angles revealed that in every instance an increased thigh-angle resulted in an increase in output. It should be noted, however, that "Thigh-angles" interacted significantly with both "Knee-angles" and "Elbow-angles." The data in Figure 1 show that at every knee-angle an increase in thigh-angle resulted in an increased output, but the amount of increase was dependent on the knee-angle. At the most favorable knee-angle (150°) the thigh position had less effect on output than it did at the least favorable knee-angle (110°). The difference between the strength of pulls at the 20° and 0° thigh-angles was 15.9 pounds at the 110° knee-angle, but only 6.0 pounds at the 150° knee-angle. Despite this slight effect of thigh-angle on output at the 150° knee-angle, every subject had a greater output

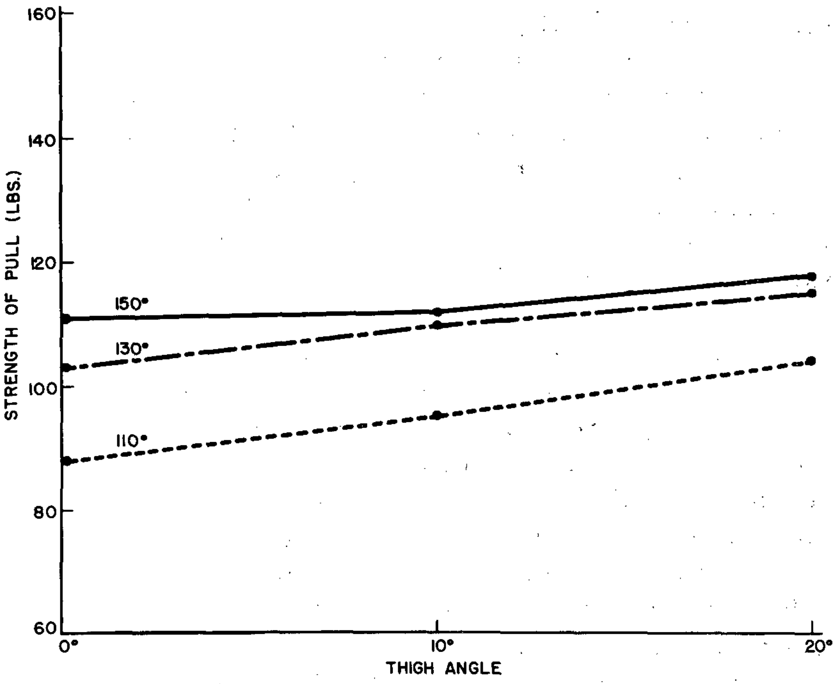

Fig. 1. Strength of hand pull with the thigh at three angles from the horizontal and with the knee at three angles.

at the 20° thigh-angle than at 0°. Thus, within the limits tested in this study, it may be stated that the greater the knee-angle--and the farther the foot-rest from the subject--the less important becomes the thigh position.

The reduced effect of thigh-angle on output at the greatest knee-angle suggests that, in general, even at the 0° thigh-angle the legs can generate almost all the force needed to support the hand action, and that further increase in leg strength introduced by increasing the thigh-angle would have only a slight effect on the hand strength. If this were true then at the best knee-angle (150°) there should be a smaller difference between the measured strengths at the 0° and 20° thigh-angles at the 60° elbow-angle than at the 165° angle. That is to say, the effect of the thigh-angle on output should increase as a greater demand is placed on the legs to generate forces to counteract those developed by the arm. From Table 1 it may be seen that when the knee-angle was 150° and the elbow-angle was 60° there was only a 2.3 pounds difference between outputs at the 0° and 20° thigh-angles. However, at the same knee-angle, but with the elbow-angle at 165°, there was a 12.0 pounds difference in the strength of pulls at the 0° and 20° thigh-angles. A comparison of the differences in outputs at the 0° and 20° thigh-angles revealed that for 9 of 11 subjects the effect of the thigh-angle on output was greater at the 165° elbow-angle than at the 60° angle. A one-tailed statistical sign test showed that this departure from chance was significant at the 5% level of confidence. These findings help to explain the significant F-ratio for the "Thigh-angles" x "Knee-angles" x "Elbow-angles" interaction shown in Table 2.

The interaction between "Thigh-angles" and "Elbow-angles" is shown in Figure 2. Here it may be seen that at all elbow-angles an increase in thigh-angle resulted in an increased output, but that the amount of increase was dependent upon the elbow-angle. The difference between the means at the 20° and 0° thigh-angles was 4.5 pounds at the 60° elbow-angle, 6.7 pounds at 95°, 14.3 pounds at 130°, and 19.4 pounds at 165°. Again, it is evident that the greater the strength of hand pull, the more important becomes the foot-rest position, but even at the handle position at which the movement is weakest the foot-rest position is important. Even at the 60° elbow-angle, 10 of the subjects performed better when the thigh-angle was at 20° than when it was at 0°.

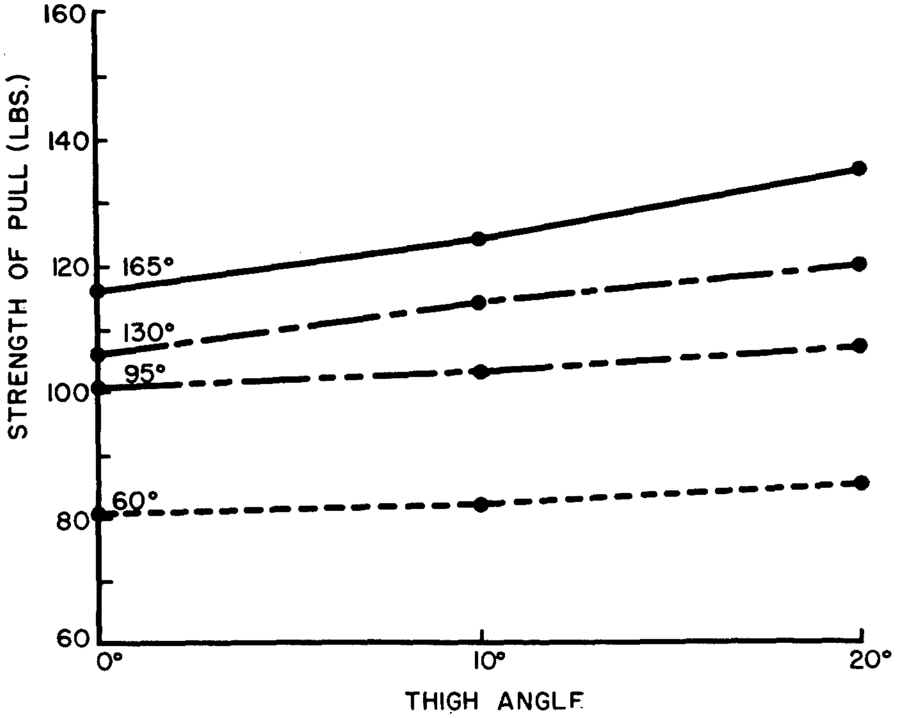

Fig. 2. Strength of hand pull with the thigh at three angles from the horizontal and with the elbow at four angles.

In Table 2 it is shown that the knee-angle had a statistically significant effect on the strength of the hand movement. The mean output was 95.6 pounds at the 110° knee-angle, 109.0 pounds at 130°, and 113.7 pounds at 150°. It should be kept in mind, however, that this effect was found to be dependent upon both the thigh and elbow positions. It may be seen in Figure 3 that the effect of the knee position on output tended to decrease as the thigh-angle increased. The difference between the output at the 110° and 150° knee-angles was 23.7 pounds at the 0° thigh-angle, 17.0 pounds at the 10° thigh-angle, and 8.2 pounds at the 20° thigh-angle. Though the effect of knee-angle on output was quite small in the latter instance, all subjects showed a greater output at 150° knee-angle than at 110°.

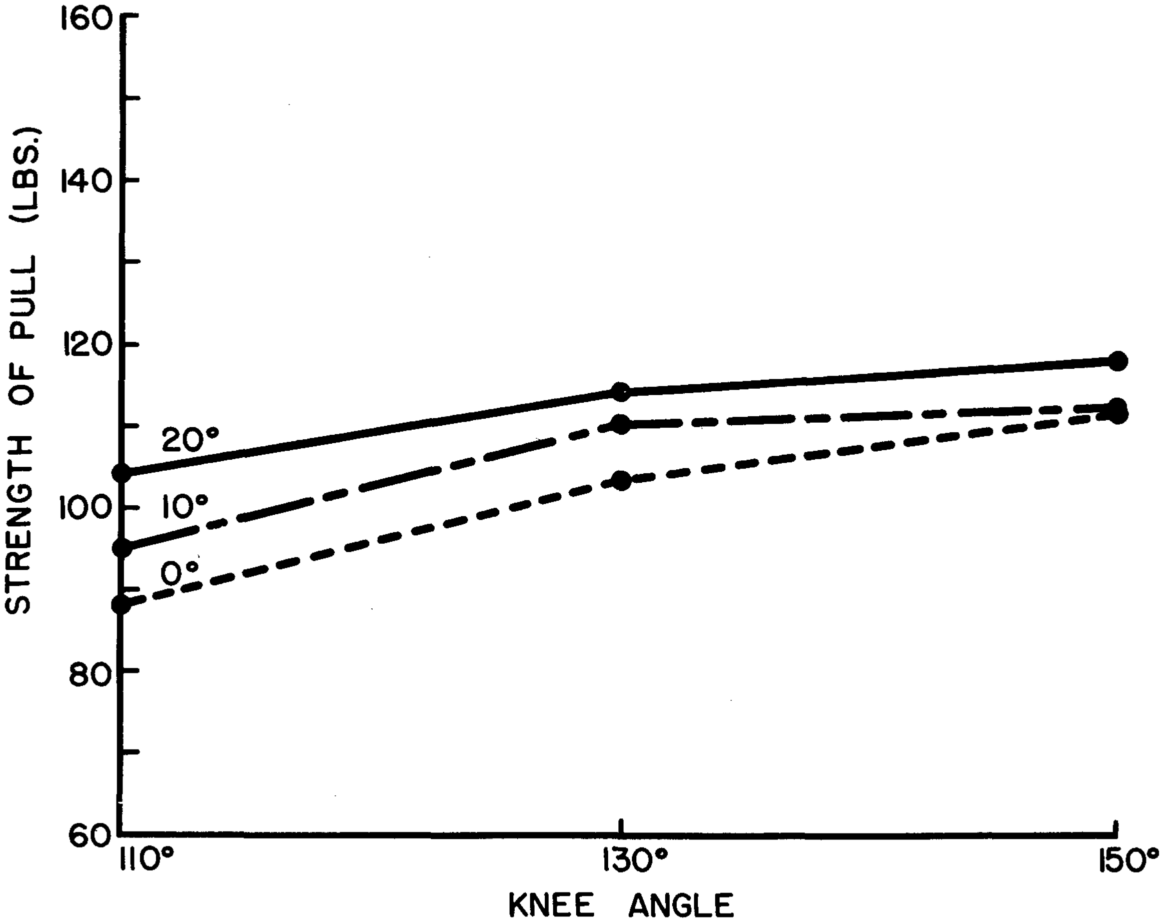

Fig. 3. Strength of hand pull with the knee at three angles and with the thigh at three angles from the horizontal.

As shown in Figure 4, the effect of the knee position on output was quite different at the four elbow-angles. The increase in output as the knee-angle increased from 110° to 150° was 8.1 pounds at 60° elbow-angle, 15.3 pounds at 95°, 17.9 pounds at 130°, and 31.5 pounds at 165°. Thus, it may be stated that the greater the elbow-angle -- and the greater the output of the subject -- the more critical becomes the foot-rest position. At the 60° elbow-angle, 9 of the 11 subjects had a greater output at the 150° knee-angle than at the 110° knee-angle. A one-tailed statistical sign test showed that this r of 2 was significant at the 5% level of confidence. At the other elbow-angles, any increase in knee-angle resulted in an increased strength of pull for all subjects.

The analysis of variance shows that the elbow position had a greater effect on the strength of the response than did any of the other variables. In Table 1 it is shown that the output increased from 82.6 pounds at the 60° elbow-angle to 125.0 pounds at the 165° position. It should be noted, however, that this effect was dependent upon both thigh and knee positions. Since these interactions have already been examined, no further elaboration is necessary.

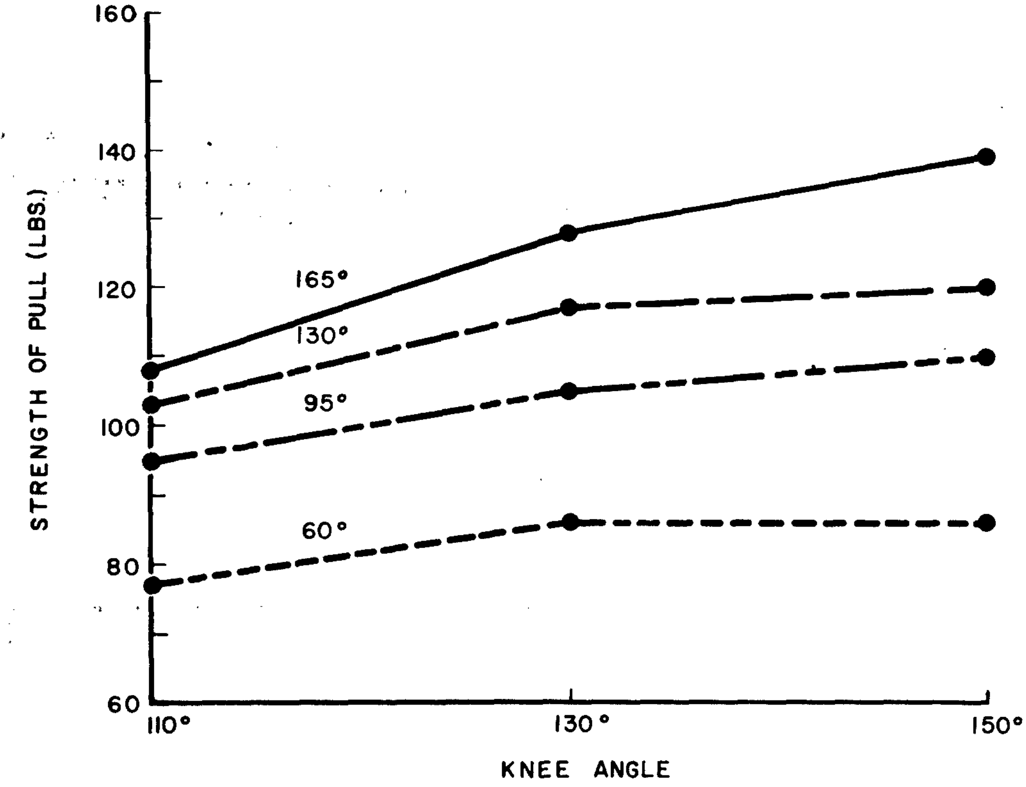

Fig. 4. Strength of hand pull with the knee at three angles and with the elbow at four angles.

IV. DISCUSSION

These results are understandable in terms of the findings of Hugh-Jones (7), who reported an increase in the strength of leg extension with an increase of thigh- or knee-angle. The similarity in these two sets of data lends support to the hypothesis that the strength of this hand movement is dependent upon the stabilizing force developed by the legs. The Hugh-Jones data are shown in Figure 5. The solid curves were drawn from these data and the points connected by the dashed curves were obtained by interpolation or extrapolation. Only the upper two points of the curve for the 20° thigh-angle were obtained by extrapolation. These derived values and their ranks are shown below.

	------- KNEE ANGLE -------		
Thigh Angle	110°	130°	150°
0°	105(9)	178(7)	341(4)
10°	130(8)	249(5)	470(2)
20°	184(6)	384(3)	742(1)

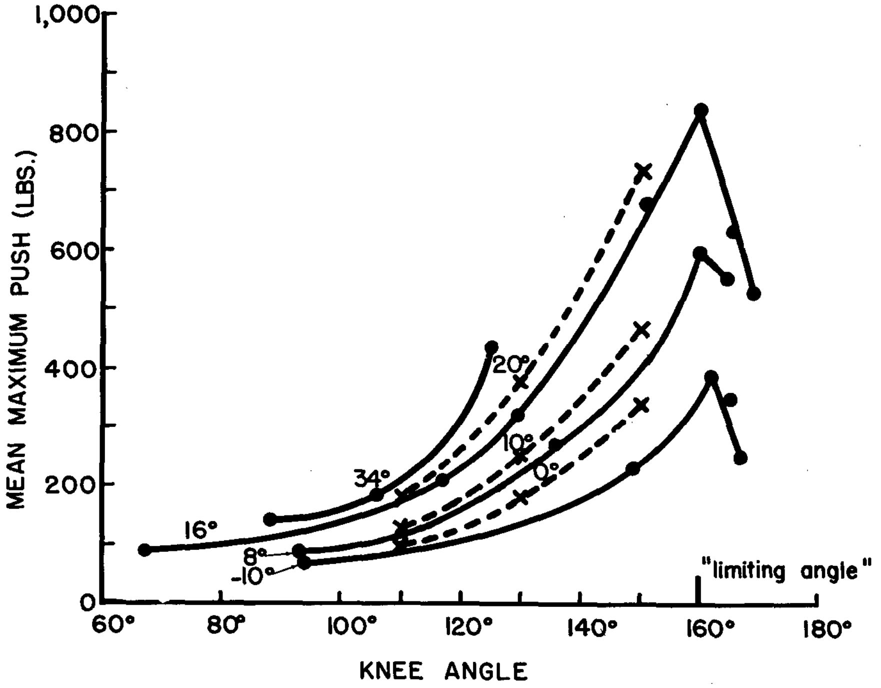

Fig. 5. Mean maximum push on a foot-pedal placed in different positions that allowed different degrees of knee-extension for several different angles of the thigh to the horizontal. Solid curves drawn from data obtained by Hugh-Jones (7).

A comparison of the ranks for the estimated maximum strength of foot push with the ranks for hand pull at the same foot-rest positions yielded rank-difference coefficients as follows: .762 for the 60° elbow-angle, .967 for the 95° elbow-angle, .950 for the 130° elbow-angle, and .997 for the 165° elbow-angle. The first correlation is significant at the 5% level of confidence, and the others are significant at the 1% level. In interpreting these correlations it should be kept in mind that the data were from two different groups of randomly selected subjects, and not from a single group measured twice, as is the usual case. The Hugh-Jones study merely provided the criteria with which the results of the present study were compared. The comparatively low correlation obtained for the 60° elbow-angle data reflects the reduced need for stabilization of the body at the lower levels of output by the hand.

There are two factors to be considered in explaining the effects of foot-rest position on the maximum strength of pull by the hand; the effect of knee-angle on the maximum force developed by the legs, and the effect of foot-rest position on the direction of application of the leg force to the supporting structure. Hugh-Jones has demonstrated that the leg must act as a mechanical toggle between the foot-rest and the back-rest. In his formulation the strength of leg extension equals the power of the quadriceps, which may be taken as a constant, times one-half the tangent of one-half the knee-angle. This formula generates a postively accelerated output curve which reaches an ordinate of infinity at 180° knee-angle. Thus, as the knee-angle increases the legs can generate a greater force to counteract the tendency of pulling oneself out of the seat when pulling on the handle, and the strength of hand pull should increase. When the foot-rest is in a low position and the operator forcibly extends his legs, there is a tendency for the body to rise in the seat and much of the force generated by the legs is lost. As the foot-rest is raised this tendency decreases and a greater proportion of the force developed by the legs can be used to counteract the hand force. Thus, it would seem that the usable power generated by the toggle-action of the leg is reduced by the cosine of the angle between the horizontal and the line connecting the foot and hip. It should be noted that this angle is increased either by straightening the leg, or by raising the thigh. The increase in this angle is approximately the same for a 10° increase in thigh-angle as for a 20° increase in knee-angle. Thus, an increase in knee-angle increases the efficiency of the toggle and reduces the angle of application of the leg force, while an increase in thigh-angle results only in a decrease in the angle of application of force. This may account for the fact that the knee-angle had a greater effect on hand strength than did the thigh-angle.

So far no mention has been made of the effect of foot-rest position on the utilization of body dead weight in generating forces which aid hand pull. At some foot-rest positions--particularly the lower ones in which the subject's weight is transferred to the foot-rest during exertion--this factor must be appreciable, while at other foot-rest positions it must be negligible. If a determination could be made of the distribution of body mass at the two contact points--the seat and foot-rest--the contribution of this factor to the measured output could be evaluated. A general treatment of the effect of body mass on certain control forces has been presented by Gaughran and Dempster (5). With a measurement of the forces exerted on the supporting structure it would be possible to make a complete analysis of the force system involved in exerting pressure on a control.

V. SUMMARY AND CONCLUSIONS

The purpose of this investigation was to determine the effect of foot-rest position on the strength of horizontal pull by the hand. Three thigh-angles (0°, 10°, and 20°) were combined factorially with three knee-angles (110°, 130°, and 150°) to produce nine foot-rest positions. At each position the peak strength of the hand movement was determined at four elbow-angles (60°, 95°, 130°, and 165°). Thus, there was a total of 36 experimental conditions under which each of the eleven subjects was observed.

The results were consistent with the hypothesis that the strength of hand pull is proportional to the stabilizing force developed by the legs in pushing against the foot-rest. This follows from the observation that those conditions which optimize the strength of leg extension are also the ones which optimize the strength of hand pull. The main results of the investigation were as follows:

1. The thigh-angle had a significant effect on the strength of hand pull. This influence was small, but for every subject an increase in thigh-angle resulted in an increase in output.

2. The effect of thigh-angle on output was somewhat different at the three knee-angles. As the knee-angle increased the thigh elevation had a diminishing influence on output.

3. The influence of thigh-angle on the strength of the movement was also dependent on the elbow-angle. The higher elevation of the thigh became increasingly favorable as the arm was straightened and the output level increased.

4. The knee-angle had a greater influence on output than did the thigh-angle. As the leg was straightened there was an increase in the force of the hand movement.

5. The increment in output as the leg was straightened increased as the elbow-angle increased.

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APPENDIX

The raw data expressed in terms of pounds of force were transformed in such a manner as to reduce individual differences in absolute strength. This transformation consisted of dividing each subject's strength of pull at each position by his output at the most favorable combination of leg position and elbow-angle. These data were analyzed by the method of orthogonal polynomials. The results of the analysis of variance are shown in Table 1. The residual is composed of all interactions containing "Subjects" as a term. The complete analysis is not shown since it is rather lengthy. Only the main effects and their interactions plus the significant curve-fittings are shown. The statistically significant sources of variation were selected and their coefficients were derived by the method illustrated by Caldwell (3). From Table 1 it may be seen that the empirical equation must include the mean of the obtained data ($\overline{Y} = 70.8$); a term for the linear component of "Thigh angles"; linear and quadratic terms for "Knee-Angles"; linear, quadratic,

TABLE 1

THE ANALYSIS OF VARIANCE OF THE PERCENTAGE OF MAXIMUM DATA BY METHOD OF ORTHOGONAL POLYNOMIALS SHOWING ONLY THE MAIN EFFECTS AND THEIR INTERACTIONS PLUS THE SIGNIFICANT COMPONENTS OF THE CURVES

Source of Variation	Sum of Squares	df	Mean Square	F
Thigh-Angles (T)	3,618.47	2	1,809.24	57.86*
Linear	3,608.24	1	-----	115.39*
Knee-Angles (K)	10,371.65	2	5,185.52	165.84*
Linear	9,672.74	1	-----	309.33*
Quadratic	698.91	1	-----	22.35*
Elbow-Angles (E)	42,259.63	3	14,086.54	450.48*
Linear	40,954.55	1	-----	1,309.71
Quadratic	961.33	1	-----	30.74*
Cubic	343.75	1	-----	10.99*
Interaction: T x K	542.51	4	135.63	4.34*
Linear x Linear	455.05	1	-----	14.55*
Interaction: T x E	1,052.35	6	175.39	5.61*
Linear x Linear	981.09	1	-----	31.37*
Interaction: K x E	2,049.41	6	341.57	10.92*
Linear x Linear	1,862.59	1	-----	59.56*
Interaction: T x K x E	260.24	12	21.69	-----
Between Subjects	10,000.09	10	1,000.01	31.98*
Residual	11,059.84	350	31.60	
TOTAL	81,214.19	395		
Pooled Error (Residual + T x K x E)	11,320.08	362	31.27	

*Significant at less than 1% level of confidence and cubic terms for "Elbow-angle"; a linear x linear term for the interaction between "Thigh-angles" and "Knee-angles"; a linear x linear term for the interaction between "Thigh-angles" and "Elbow-angles"; and a linear x linear term for the interaction between "Knee-angles" and "Elbow-angles." Thus the equation must take the form:

$$\hat{Y} = \bar{Y} + A\left(\frac{T - \bar{T}}{10}\right) + B\left(\frac{K - \bar{K}}{20}\right) + C\left[\left(\frac{K - \bar{K}}{20}\right)^2 - .67\right] + D\left(\frac{E - \bar{E}}{35}\right)$$

$$+ E\left[\left(\frac{E - \bar{E}}{35}\right)^2 - 1.25\right] + F\left\{\left(\frac{E - \bar{E}}{35}\right) \times \left[\left(\frac{E - \bar{E}}{35}\right)^2 - 1.25\right] - 0.8\left(\frac{E - \bar{E}}{35}\right)\right\}$$

$$+ G\left(\frac{T - \bar{T}}{10} \times \frac{K - \bar{K}}{20}\right) + H\left(\frac{T - \bar{T}}{10} \times \frac{E - \bar{E}}{35}\right) + I\left(\frac{K - \bar{K}}{20} \times \frac{E - \bar{E}}{35}\right)$$

In the above equation $\bar{T}$, $\bar{K}$, and $\bar{E}$ refer to the mean positions of the thigh, knee, and elbow, respectively. In this study $\bar{T}$ equaled 10° $\bar{K}$ equaled 130°, and $\bar{E}$ equaled 112.5°. The demonimators 10, 20, and 35 in the equation indicate the sizes of the steps between adjacent positions of the thigh, knee, and elbow, in the order given.

The equation, with the proper coefficients, may now be written:

$$\hat{Y} = 70.8 + 3.7\left(\frac{T - 10}{10}\right) + 6.1\left(\frac{K - 130}{20}\right) - 2.8\left[\left(\frac{K - 130}{20}\right)^2 - .67\right]$$

$$+ 9.1\left(\frac{E - 112.5}{35}\right) - 1.6\left[\left(\frac{E - 112.5}{35}\right)^2 - 1.25\right] + 1.4\left\{\left(\frac{E - 112.5}{35}\right) \times\right.$$

$$\left.\left[\left(\frac{E - 112.5}{35}\right)^2 - 1.25\right] - 0.8\left(\frac{E - 112.5}{35}\right)\right\} - 1.6\left(\frac{T - 10}{10} \times \frac{K - 130}{20}\right)$$

$$+ 1.7\left(\frac{T - 10}{10} \times \frac{E - 112.5}{35}\right) + 2.4\left(\frac{K - 130}{20} \times \frac{E - 112.5}{35}\right)$$

This equation may be reduced to the following algebraic equivalent:

$$\hat{Y} = .864T + 1.820K + .06E - .007K^2 - .0013E^2 - .008TK$$

$$+ .00485TE + .00342KE - 87.51$$

The cubic term for "Elbow-angles" was dropped in the simplified equation because, though statistically significant, it added little to the predicted output. At the extreme arm positions this term added only ± .4% to the value of $\hat{Y}$.

The simplified equation may be used to "predict" the output of an operator at any combination of thigh-angle, knee-angle, and elbow-angle, within the limits employed in this study. The primary usefulness for the equation should be in determining the relative advantages of various foot-rest positions. Other design considerations may necessitate placing a foot-rest in something other than its most favorable position, and the formula may be used to estimate the loss in output resulting from employing a secondary foot-rest position.

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