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The Effects of Handle Shape and Size on Exerted Forces

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This research empirically evaluated the effects of handle shape and size on the hand's ability to resist or exert force in six directions. Thirty-six handles of four sizes and nine shapes were tested for maximum force exertion by male and female subjects. The results show that subjects were able to generate higher forces with different sizes and shapes of handles, depending upon the direction of force exertion. This suggests that handles that are associated with high forces on particular directional tests are probably suited for tasks that incorporate that particular type of force or movement; they may not be appropriate for other tasks that do not incorporate such movement.

INTRODUCTION

In spite of increasing mechanization and automation, hand tools are still important in many industries. In the meat-packing industry, the knife is still the basic tool. Similarly, in assembly-type industries, basic tools such as screwdrivers, wrenches, and pliers are still used extensively, and many have been equipped with powered drivers. All of these tools, even though they may be powered, still remain hand tools and therefore have a handle of some type.

Many hand tools, such as screwdrivers, have traditional handles. These have developed over many years and appear to be satisfactory. There have been some attempts at trying new or unconventional designs. Snap On® has tried square and triangular (in cross-section) handles for screwdrivers and nut drivers. These handles seem to have met with some success; however, there has been limited research to evaluate handle shapes for particular applications. This research evaluated empirically the effects of handle shape and size on the hand's capability to resist or exert force in six different orientations.

BACKGROUND

Many textbooks and reference books discuss handle design (Chaffin and Andersson, 1984; Greenberg and Chaffin, 1979; Konz, 1983; Van Cott and Kinkade, 1972; Woodson, 1981); however, they have seldom addressed the problem of size and configuration as it relates to minimizing fatigue or maximizing tool capability. Although considerable work has been done on grip strength, there is limited information about handle size, handle shape, and force capability. There are, how-

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ever, several research studies that have briefly examined some aspects of handle design.

Pheasant and O'Neill (1975) examined various screwdriver handle designs available in Great Britain and compared them with smooth and rough cylinders. There was no difference in torque capability for the handle shapes used. They did find that twist capability increased as handle diameter increased from 1 to 3 cm with a leveling-off tendency at diameters of 3 to 5 cm and a drop in capability from 5 to 7 cm. The 5-cm-diameter cylindrical handles resulted in the highest torque capability.

Ayoub and Lo Presti (1971) conducted a study to find the optimum size of cylindrical handles for rotational tasks by use of electromyography. For cylindrical handles of approximately 2.54 to 6.35 cm in diameter, electromyography indicated no difference in effort. Dramatic increases were found outside this range. Additionally, they conducted a fatigue study and found the 6.35-cm diameter was inferior, dropping the optimal range to between 2.54 and 5.08 cm. This compares very closely with the Pheasant and O'Neill results.

Drury (1980), in two experiments, examined handles for materials handling. He first found that subjects using a 2.0-cm-diameter cylindrical handle were willing to hold the same load for a longer time than when they used handles of greater or lesser diameters. In the second experiment, the optimum was between 3.1 and 3.8 cm in diameter based upon subjective ratings. Drury concluded that handles should be 11.5 cm long and between 2.5 and 3.8 cm in diameter.

Saran (1973) investigated *T* handles for pronation and supination tasks. He investigated the angle of the *T* and the size of the grip surface. Angles for the *T* varied between 90 deg and 60 deg, and the diameter of cylindrical handles varied between 1.91 cm and 3.175 cm. Subjective ranking showed the 60-deg angle to be better than the other angles tested and 2.54 cm to be the optimum handle diameter.

Armstrong, Foulke, Goldstein, and Joseph (1981) analyzed the problems of trauma disorders of the upper extremities in a poultry-processing plant. They found that workers used knives in such a way as to demonstrate excessive wrist flexion and ulnar deviation while exerting force. Armstrong et al. recommended using larger handles on the knives, banana-shaped knife handles, and even pistol-like grips for some operations. Straps to prevent the hand from slipping off of the handle were also recommended.

Riley and Cochran (1980) conducted a study of improved knife-handle design. Upon examining the cross-sectional perimeter of knives being used by a meat-packing company, they determined that the handles were too small. They also determined that the length fit only the lower 25th percentile of American males. Numerous handles with increased cross-sectional perimeter and increased length were given to meat-packing personnel to use for a day. Workers were questioned extensively after they used each design. The working meat packers preferred a particular handle that was longer and had a larger cross-sectional perimeter.

Objective

The overall objective of this research was to evaluate empirically the effects of handle shape and size on the hand's ability to exert or resist force.

METHOD

All testing for this project was conducted under slippery film conditions. That is, a slippery film (STP®, which is an engine oil additive) was applied to a handle prior to its being grasped by the subject for a trial. This was intended to eliminate the effect of the surface finish of the handles and to more accurately assess the inherent characteristics of each handle. To ensure that the coefficient of friction was constant from trial to trial, subjects wore a disposable plastic glove that was covered with the slippery liquid. This also prevented the liquid from being absorbed by the hand and made for an easy cleanup.

Handles Tested

The handles used in this experiment were machined from solid Plexiglas to the shapes and sizes desired. All handles were then sanded with progressively finer-grit sandpaper until all had a fine, uniform, smooth finish.

Nine cross-sectional handle shapes were tested. These shapes, along with the letter symbols used to designate them, are represented in Figure 1. The shapes were selected because, in the experimenters' judgment, they represented those that are most likely to be accepted by meat packers and/or are capable of being mass produced. Each handle had straight, parallel sides and the same cross-sectional shape and size throughout its length.

The circular handles were included, not because we thought that a meat-packing knife handle should be cylindrical, but because in most of the research done on handles in the past, cylindrical handles have been used and because many hand tools do have handles that are approximately cylindrical.

In addition to the variable of handle shape, handle size was also evaluated. Four sizes of each shape were tested. The size was based on the perimeter of the cross-section of the handle, as this is directly related to grasping surface. The sizes of the handles tested were 7, 9, 11, and 13 cm in perimeter, which on the circular handle translates to diameters of 2.22, 2.86, 3.50 and 4.14 cm, respectively. All handles were 22.5 cm long.

Cross Section Description	Height/Width Ratio	Symbol	Cross-Section
Circular	1:1.00	C	
Circular with flat side	1:1.25	D	
Circular with two flat sides	1:1.25	O	
Triangular		T	
Square	1:1.00	S	
Rectangular	1:1.25	W	
Rectangular	1:1.50	X	
Rectangular	1:1.75	Y	
Rectangular	1:2.00	Z	

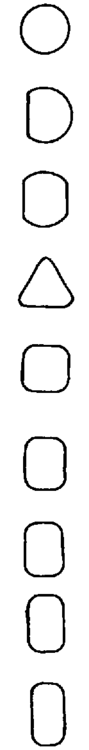

Figure 1. *Handle shapes tested.*

Testing

Six tests were conducted on each of the 36 handles. These tests evaluated the following characteristics:

(1) *Thrust push*—the maximum amount of push force that can be exerted parallel to the long axis of the handle
(2) *Thrust pull*—the maximum amount of pull force that can be exerted parallel to the long axis of the handle
(3) *Orthogonal push*—the maximum amount of push force resisting radial deviation that can be exerted orthogonal to (or perpendicular to) the long axis of the handle when the handle is fixed at one end
(4) *Orthogonal pull*—the maximum amount of pull force resisting ulnar deviation that can be exerted orthogonal to (or perpendicular to) the long axis of the handle when the handle is fixed at one end
(5) *Wrist extension*—the maximum amount of rotational force that can be exerted by an extension movement of the wrist

(6) *Wrist flexion*—the maximum amount of rotational force that can be exerted by a flexion movement of the wrist.

The thrust push test measured the maximum push on a horizontal handle, as shown in Figure 2. The action of pushing (trying to move the handle forward to a position in front of the body) is similar to the activity of sticking or jabbing a knife point-first. The force-measuring device was a cable tensiometer (Pacific Scientific Co. Model T5), which was attached to the rear of the handle so that it resisted the forward movement. This tensiometer recorded the peak force exerted.

The second test, the thrust pull test, is very similar to the thrust push test except that the force is applied in the opposite direction to a horizontal handle in an attempt to move it backward (see Figure 3). Once again, the cable tensiometer resists actual movement and measures the force.

The orthogonal push test measured the maximum push on a vertically held handle, as is shown in Figure 4. The orthogonal pull test, as is shown in Figure 5, measured the maximum pull on a vertically held handle. In both the orthogonal push and pull tests, the force exerted is opposed by a cable attached

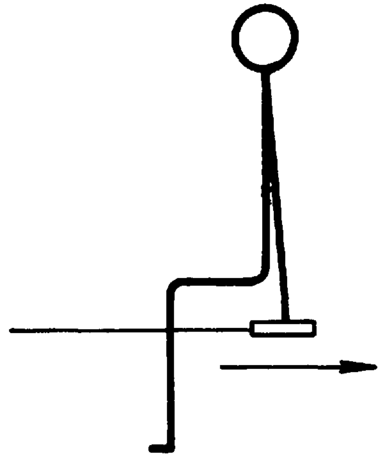

Figure 3. *Thrust pull task. The arrow indicates the direction of force exerted by the subject.*

to the top end of the handle that extends above the thumb side of the hand. The distance from the top of the hand to the point of attachment of the cable for both tests was 8 cm. In these tests, the subject was required to maintain the wrist in a neutral position. In the orthogonal push test, the subject resists force attempting to cause radial deviation and thereby exerts force which, in an uncon-

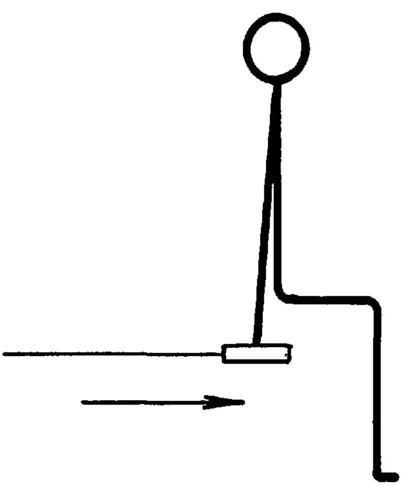

Figure 2. *Thrust push task. The arrow indicates the direction of force exerted by the subject.*

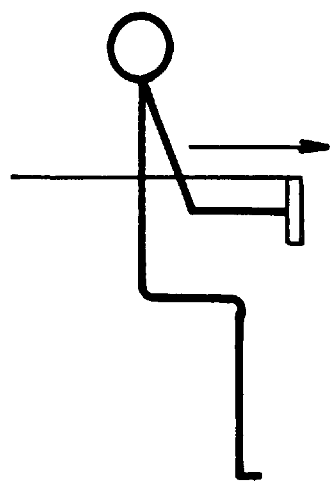

Figure 4. *Orthogonal push task. The arrow indicates the direction of force exerted by the subject.*

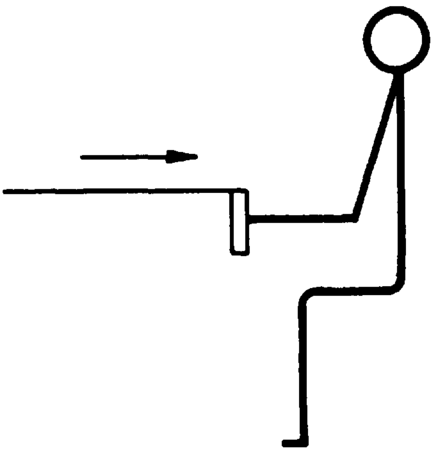

Figure 5. *Orthogonal pull task. The arrow indicates the direction of force exerted by the subject.*

strained situation, would result in ulnar deviation. Just the opposite is true of the orthogonal pull test.

The wrist extension test measured the torque that a subject could develop around the long axis of each handle in attempting to extend the wrist joint. This is shown in Figure 6. The wrist flexion test measured the maximum torque while attempting to flex the wrist, as is shown in Figure 7. The forces in these tests were measured using a Snap On® torque wrench, Model TQSS2FU, with a scale from 0 to 384 ounces and accurate within 1% at full scale. This torque wrench recorded the peak torque exerted.

In the thrust tests and the orthogonal tests, the subject was seated in a dental chair with back support and a footrest. Subjects were required to keep their opposite hand in their lap. The chair height was adjusted so that the force being exerted was in line with the measuring device. In the extension and flexion tests, the subject was standing, with feet spread about shoulder width apart. The height of the measuring device was adjusted so that each subject stood erect and the elbow was straight during testing.

Experimental Design

The experimental design for each maximum force test was a three-factor factorial type with a blocking on subjects. The factors were handle shape with nine levels, handle size with four levels, and gender with two levels. Handle shape, handle size, and gender were considered fixed factors, and subjects

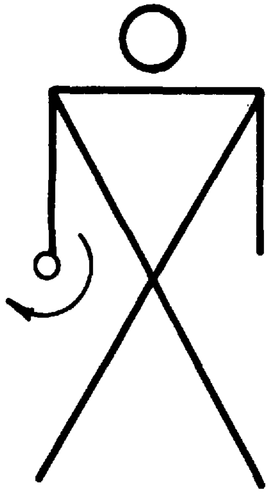

Figure 6. *Wrist extension task. The arrow indicates the direction of force exerted by the subject.*

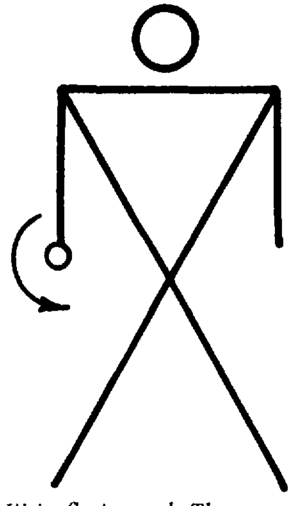

Figure 7. *Wrist flexion task. The arrow indicates the direction of force exerted by the subject.*

and replications random factors. Subjects were nested in gender. Three replicates of data were collected. The sequence of testing the handles was randomized for each subject, and all subjects used their dominant hand. In all tests, the peak force was recorded and used in the analyses. Because the slippery film method was used, the actual forces measured were valid only under degraded conditions. The evaluation of the handles was therefore made on a relative basis.

Subjects

Subjects for this research were selected from a wide variety of sources. Ten male and ten female subjects were used for all tests. An effort was made to recruit subjects with meat-cutting experience; about half of the subjects were currently employed or former meat cutters. The remainder were machinists, homemakers, technicians, laborers, secretaries, teachers, and students. All had a recent history of manual labor.

The average age of the subjects was about 27 years. Males averaged about 26 years and females about 28 years, with ranges from 18 to 44 and 21 to 42, respectively. Anthropometric measures of the hand and forearm were taken. However, the statistical relationships between the anthropometric measurements and hand force capabilities did not result in acceptable predictive models. (For more information, see Cochran, 1983.)

RESULTS

The analysis of variance for all six of the tasks data in Table 1 shows which terms were found to be significant for each task. Figure 8 contains the results of Tukey pairwise comparison tests (Neter, Wasserman, and Kutner, 1985) on the factor of handle shape (H). For each task, if the handle shape factor did not have a statistically significant interaction ($\alpha = 0.05$) with the gender factor (G), only the Tukey test for all subjects data is included. On the other hand, if this interaction term was found to be significant, then Tukey tests results for male and female subjects are reported separately, as are the results for all subjects. Figure 9 contains the results of Tukey pairwise comparison tests on the factor of handle size (B). As was done

TABLE 1

Analyses of Variance for the Six Tests

			Tests					
			Thrust		*Orthogonal*		*Wrist*	*Wrist*
Source	*Error Term*	*D.F.*	*Push*	*Pull*	*Push*	*Pull*	*Extension*	*Flexion*
G	P(G)	1	X	X	X	X	X	X
H	P(G)	8	X	X	X	X	X	X
B	PH(G)	3	X	X	X	X	X	X
P	PB(G)	18	X	X	X	X	X	X
GH	R(GPHS)	8					X	X
GB	PH(G)	3	X	X			X	X
HB	PB(G)	24	X	X		X	X	X
PH(G)	PHB(G)	144	X	X	X	X	X	X
PB(G)	R(GPHB)	54	X	X	X	X	X	X
GHB	R(GPHB)	24					X	X
PHB(G)	PHB(G)	432	X	X	X	X	X	X
R(GPHB)	R(GPHB)	1440						

G–Gender, H–Handle Shape, B–Handle Size, P–Person, R–Replication X–Indicates a statistically significant term ($\alpha = 0.05$) for the factor(s) on that test.

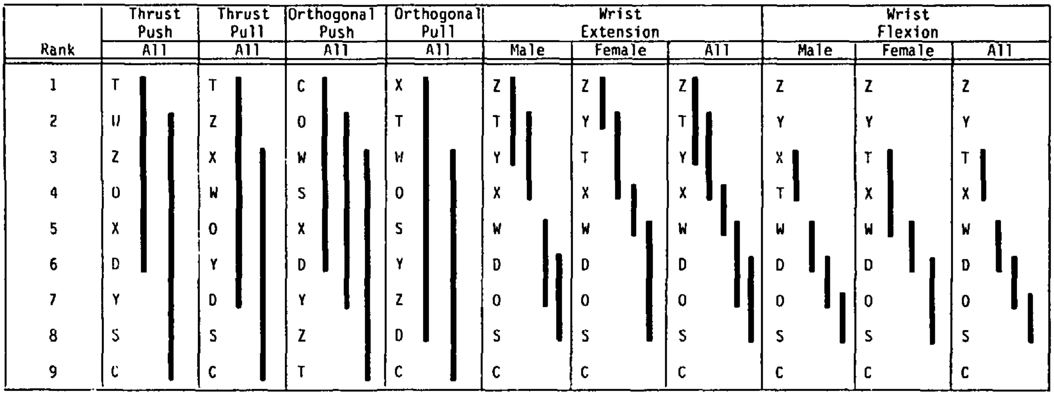

Figure 8. *Results of the Tukey tests on handle shape for all six tests. Refer to Table 1 for definitions of the handle shapes.*

with the factor handle shape, if the interaction of handle size with gender was significant, Tukey test results for male, female, and all subjects are reported. Otherwise, only results for all subjects are reported.

It should be noted that in five of the six tasks the handle shape interacted significantly with handle size. These interactions were examined graphically and judged to be either unimportant or unintelligible, and are therefore not explored here. The concept of statistically significant but unimportant interaction terms is discussed in Neter et al., 1985.

Because of the slippery film method used, all forces measured were not directly transferable as design parameters. The analyses used indicate relative differences among the forces. For the actual forces measured, see Cochran, 1983.

Thrust push. The analysis of variance for the thrust push data in Table 1 shows a significant effect for all terms in the model except the Gender × Handle Shape and the Gender × Handle Shape × Handle Size interactions. The handle-shape factor was further analyzed using a Tukey's test, as is shown in Figure 8. The mean force exerted on the triangular (T) handles was significantly greater than on the circular (C), square (S), and rectangular (Y) 1:1.75 ratio handles. There was no significant difference among any of the remaining handle shapes.

The factor of handle size was significant, as was the interaction of gender and handle size. Because this interaction was significant, the means of males for each handle size were examined separately from those of females using the Tukey test. In examining the significant differences between the handle size

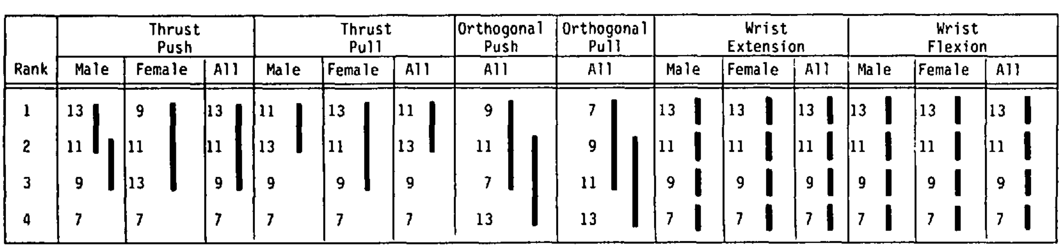

Figure 9. *Results of the Tukey tests on handle size for all six tests.*

means for males (Figure 9), the force exerted using the 7-cm handles was significantly less than for the 9-, 11-, and 13-cm handles. The force was significantly less for the 9-cm handles than for the 13-cm handles. There was no difference between the 9- and 11-cm handles or between the 11- and 13-cm handles. For the factor of handle size, the forces exerted on the 7-cm handles by females were significantly less than for the 13-, 11-, and 9-cm handles—which did not differ among themselves. With data from all subjects, the forces exerted with 13-, 11-, and 9-cm handles did not differ significantly from each other; however, they did differ from those on the 7-cm handles.

Thrust pull. In analyzing the data for the thrust pull task, Table 1, it was found that all terms except the Gender × Handle Size and the Gender × Handle Shape × Handle Size interactions were significant. These results are identical to those found for the thrust push task. In conducting a Tukey test on the means of the forces exerted on the handle shapes, the triangular (T) and rectangular (Z) 1:2-ratio handles were significantly greater than those exerted on the circular (C) and square (S) handles (Figure 8).

Because the Gender × Handle Size interaction was significant, the means for each handle size were analyzed separately for males and females. In analyzing the differences between the means for the four sizes for males on the thrust pull task, the Tukey test showed that the 7-cm handles had significantly less force exerted on them than did the other sizes (Figure 9). The force on the 9-cm handles was significantly less than that on the 11- and 13-cm handles, which did not differ significantly from each other. In evaluating the differences in force due to handle size by female subjects, the 7-cm handles were significantly lower than the others (which were statistically the same). With data for males and females combined, the force exerted with 11- and 13-cm handles did not differ significantly. However, they did differ from those of the 7- and 9-cm handles, which differed from each other.

Orthogonal push. In analyzing the data for the orthogonal push task (Table 1) we found that the following interaction terms were not significant: Gender × Handle Shape, Gender × Handle Size, Handle Shape × Handle Size, and Gender × Handle Shape × Handle Size. All other terms were significant.

In examining the handle shape factor using the Tukey test, Figure 8, the cylindrical handles (C) were associated with significantly higher forces than the forces associated with the rectangular handles (Y and Z) (1:1.75 and 1:2.0 ratios, respectively) and the triangular (T) handles. Additionally, the circular handles with two flat sides (O) were significantly better than the rectangular (Z) (1:2.0 ratio) and the triangular (T) handles. The handle-size factor, Figure 9, indicated a significant difference only between the 9-cm and 13-cm handles.

Orthogonal pull. The analysis of variance for the orthogonal pull task, Table 1, shows a significant effect for all terms in the model except the interactions of gender and handle shape; gender and handle size; and gender, handle shape, and handle size. The handle-shape factor was examined using the Tukey test, and the rectangular (X) (1:1.5 ratio) and triangular (T) handles were associated with significantly higher forces than those associated with the cylindrical (C) handles. The factor of handle size (Figure 9) was examined using the Tukey test, and only the 7- and 13-cm handles were found to differ significantly.

Wrist extension. The analysis of variance results for wrist extension in Table 1 indicate that all terms in the model were significant. Figure 8 shows the results of Tukey tests for handle shape on data for males, for females, and for the two combined. For ranks 4 through 9, the handles for both genders are the same, with cylindrical (C) being the worst. The top rank for both genders is for the rectangular (Z) (1:2.0 ratio) handles. The handle shapes that rank second and third for the male subjects and for all subjects combined are the triangular (T) handles and the rectangular (Y) (1:1.75 ratio) handles, respectively. This ranking of T and Y handles is reversed for the female subjects.

Tukey test results for handle size on wrist extension are in Figure 9. The results show that as handle size increases (in the range tested), the amount of force that can be exerted increases.

Wrist flexion. For wrist flexion, the analysis of variance results in Table 1 show that all terms in the model are significant. Figure 8 depicts the results of the Tukey tests for handle shape on male subjects' data, female subjects' data, and all data. For ranks 5 through 9, the handles for both genders are the same, with cylindrical (C) being the worst. The top two ranks were also the same for both genders with the rectangular handles (Z and Y) (1:2.0 and 1:1.75 ratios, respectively) ranking first and second, respectively. The rectangular (X) (1:1.5 ratio) and triangular (T) handles occupied ranks 3 and 4 for the male subjects and the reverse for the female subjects.

Figure 9 shows Tukey test results for handle size on wrist flexion. The results indicate that as handle size increases (in the range tested), the amount of force that can be exerted increases.

DISCUSSION

Thrust Tests

For the thrust tests, the handle shape and the handle size affect the force that can be exerted. Also, these factors interact so that handle shape and size cannot always be selected independently of one another.

In examining handle shape force means, one fact is apparent—circular (C) handles are significantly inferior to one or more of the other shapes, and the least force was generated using them. In contrast, for most of the analyses conducted, the triangular (T) handles were significantly better than the circular (C) handles. Also, square (S) handles tend to have low forces when they are used, and the 1:2.0 (Z) handles tend to have high forces when they are used. Falling between the two handle shapes associated with low forces and the two associated with high forces are the various rectangular and modified circular handles.

It should be noted that the extremes of force are associated with the extremes in handle shapes. The low-force handles, the circular (C) and square (S), are the most uniform, and the high-force handles are the extreme rectangular 1:2.0 (Z) and the unorthodox triangular (T) handles.

In examining handle size it is apparent that, to a point, thrust forces tend to increase with an increase in size. Quite often in the analyses of both thrust tests, the 7- and 9-cm handles differed from each other and both differed from the 11- and 13-cm handles (which were not significantly different from each other). For the range tested, the peak thrust forces were exerted on handles in the 11- to 13-cm range.

An indication that the female subjects' thrust force may be highest at handle circumferences a little smaller than those of male subjects is shown in Figure 9. In this figure there is no significant difference between the 9-, 11-, and 13-cm handles for female subjects.

In summary, the use of triangular (T) handles and rectangular 1:2.00 (Z) handles will result in maximizing the thrust forces. Circular (C) and square (S) handles should be avoided when large thrust forces are to be exerted. For women, handles 9 cm or larger in perimeter (between 9 and 11 cm) are best for thrust forces. For men, handles in the 11- and 13-cm range appear to maximize the thrust forces that are possible. Where interactions between shape and size were significant, the data also indicated generally that the triangular (T) and rectangular 1:2.0-ratio (Z) handles, in the 11- to 13-cm range for males and 9- to 11-cm range for females, were associated with higher thrust forces.

Orthogonal Force Tests

In the conduct of the orthogonal force tests, the subjects exerted a horizontal force on a vertical handle held stationary at the top (see Figures 4 and 5). Although the wrist was maintained in the neutral position, applying force on the push task caused a moment about the wrist that attempted to force the wrist into radial deviation. The pull task tended to force just the opposite—ulnar deviation. In opposing radial deviation during the push task, the fingers (primarily the smaller fingers) exert a force to prevent the handle from rotating about the crotch between the thumb and forefinger. This crotch with its fleshy padding acts as a fulcrum in a simple Class 1 lever system. In opposing ulnar deviation in the pull task, the handle rests against the hypothenar eminence (fleshy pad on the medial side of the palm) and the fingers (primarily the index and middle fingers) apply a force. In this case, the hypothenar eminence acts as a fulcrum in a simple Class 3 lever system. These differences in classes of levers, in fulcrums, and in fingers exerting force make it apparent that different handles may be preferred for the push task as opposed to the pull task. Upon examination of the data and analyses, this has been found to be true.

For the orthogonal push task, the circular (C) handles had the highest forces exerted on them. The circular with two flat sides (O) was next, and was close in forces to the C handles. Forces exerted on triangular and rectangular ratio 1:2.0 (Z) handles were generally the smallest. The difference between the Z handles and the C handles was significant in every analysis.

In examining the progression of average forces for each handle shape in Figure 8, it becomes apparent that the major determinant of push force is the proportion of the perimeter of the handle that is on a narrow side of the handle. For example, if the rectangular handles with ratios 1:1.25 (W) and 1:2.0 (Z) are compared, the percentage of the perimeter on a narrow side is approximately 22% for W and 17% for Z handles. This means that the W handle has 33% more of its perimeter resting on the fulcrum between the thumb and forefinger. It does not seem surprising, then, that for both genders individually and for all subjects' data combined, the force exerted with W handles for the orthogonal push was greater (although not significantly, $\alpha = 0.05$) than for Z handles.

The triangular handles performed poorly on the push task because no matter how they are oriented, there is always a small bearing surface pointed at the fulcrum between the thumb and forefinger, thereby creating a pressure point. A pressure point caused by

TABLE 2

Handle Shapes with Relative Moment Arms—Relative Maximum Distance from the Handle Center to a Point on the Handle Surface

Handle Shape	*Relative Moment Arm*
C	1.000
O	1.029
D	1.042
S	1.079
W	1.090
X	1.115
T	1.145
Y	1.145
Z	1.176

exerting a force on a handle can cause pain and would limit the force exerted.

On the orthogonal pull task, the handle shape played a significant role in the force exerted. The circular handles were associated with low forces, whereas the rectangular ratio 1:1.50 (X) and triangular handles were associated with high forces. The X and C handles were significantly different from each other.

The triangular (T) handle was near the top of the orthogonal pull test and was the bottom handle on the orthogonal push test. It may have done well on the pull test because of the positioning of the triangular handle in the hand. When performing an orthogonal pull task, a flat side of the triangular handle is placed against the hypothenar eminence of the palm, and the fingers naturally wrap around and form to the opposite apex. This produces a good surface contact of a large area of the palm with a flat side of the handle and a comfortable surface around which the fingers wrap and exert force.

In examining the results of the analyses of the effects of handle size on the forces exerted in the orthogonal push and pull, it becomes apparent that the largest handles (13 cm) were always associated with the lowest forces. On the other hand, the two smaller handles, (7 and 9 cm) were associated with the high forces.

On the orthogonal pull task the interaction of shape and size was significant. This indicates that, for orthogonal pull, handle shape and handle size cannot be selected independently.

Of note is the fact that the orthogonal push forces were significantly greater than the orthogonal pull forces. This is primarily due to the advantage of a Class 1 lever system over a Class 3 system. Another contribution may have been the greater inherent stability of the handle when pushing than when pulling. When pulling, the slippery handle resting on the hypothenar eminence of the palm, which acted as the fulcrum, would tend to slip off. This was not the case for the stable crotch fulcrum of the push task.

Torque Tests

The results of all analyses of the torque tests are in almost complete agreement. Shape of the handle was significant in all cases. When the mean torque values are arranged in ascending order, the sequence is almost identical for all groups for wrist extension and flexion. The triangular handle is the only one to change relative positions.

If the maximum distance from the center of the handle cross-section to the farthest point on the handle perimeter is examined, it gives a strong indication of the cause of the consistent sequence. These distances are closely related to the maximum moment arm available when using these handles to exert torque. Table 2 gives the maximum moment arm for each handle shape relative to the maximum moment arm of the circular handle. With the exception of the square (S) handle, this hierarchy corresponds to that found experimentally. The T and Y handles have the same relative moment arm, which explains why T and Y handles vie for second place in the experimentally derived hierarchies. The only handle shape that really differs in position between the relative moment arm hierarchy and the experimentally derived hierarchies is the square handle. The reason for this is unknown.

The variable of handle size was significant in all analyses of torque data. The effect of handle size on torque is proportional to the size. This means that more torque can be exerted using the larger handles of this study. There is a limit to this relationship, as other researchers have found (Ayoub and Lo Presti, 1971; Pheasant and O'Neill, 1975); however, the handle sizes used in the present research were not large enough to reach that limit.

This was by design, as handles larger than those tested were not considered practical as knife handles.

In the analyses conducted on torque, the interaction of handle shape and handle size was significant. This indicates that, in the selection of handles for the application of torque, shape and size cannot be selected independently.

Results on the torque tests were therefore extremely consistent and were related to the relative moment arm of the handle shapes. In the range of sizes tested, more torque could be exerted using the larger handles. Due to the significance of the interaction of handle shape and size, care should be taken when selecting a particular combination of handle shape and size.

CONCLUSIONS

For tasks that involve a high percentage of thrust push- or pull-type activities, the results indicate selecting handles with a triangular shape. In situations where triangular handles are not feasible, the use of rectangular handles is recommended with no clear choice among the ratios. In thrust-type tasks, handles with square and circular cross-sections are to be avoided.

For tasks involving mostly thrust push activities, handles of about 11 cm circumference will be best for mixed-gender populations. When the population is all male, the size may be increased to 13 cm, and for females decreased to 9 cm. On the other hand, for thrust pull activities, handles with an 11-cm circumference will be best for both genders.

For tasks that have a predominance of both orthogonal push and pull activities together, rectangular handles with a width-to-height ratio of about 1 to 1.25 appear to be the best compromise. If the task involves much more orthogonal push than pull, then circular handles and circular handles with two flat sides are preferred and triangular handles discouraged. For tasks with considerable orthogonal pull and little push, circular handles should be avoided. Rectangular handles of about 1 to 1.5 width-to-height ratio and triangular handles are preferred.

For tasks that have a preponderance of either orthogonal push or pull, sizes 13 cm or greater are inferior. Sizes around 9 cm appear to be the best.

For tasks with a high percentage of wrist extension and/or flexion, rectangular handles with large (up to 1:2.0) width-to-height ratios should be used. Triangular handles are also good for these actions. Circular and square handles appear to be unsuited to this type of forceful task. Also, larger (up to 13 cm) handles are superior to smaller ones.

For any task involving more than one of the six forceful exertions tested, the handle selection is a trade-off. The predominant component should determine the size and shape unless there is some overriding factor. One such factor might be where the predominant activity involves one type of force at low levels and a less-used activity involves very high forces. In this case, a decision has to be made, based on the actual situation, whether to accommodate the more-often-used but low-force activity or the less-often-used, high-force activity.

For a tool that is used with all of the activities, such as a standard meat-packing knife, rectangular handles with width-to-height ratios from 1:1.25 to 1:1.50 appear to be a good compromise. Although these handles were not the best for any test, they were never among the worst and were consistently above the average.

In summary, this research has evaluated 36 handles of nine shapes and four sizes on six different tests. The results show that different shapes and sizes are preferred depending upon the test, and, in many cases, the gender of the user. This indicates that for any particular application, the handle size and shape should be selected carefully with the predominant forces to be exerted and the user population kept in mind.

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REFERENCES

Armstrong, T. J., Foulke, J. A., Goldstein, S., and Joseph, B. (1981). *Analysis of cumulative trauma disorders and work methods* (Tech. Report for NIOSH). Ann Arbor, MI: University of Michigan, Center for Ergonomics.

Ayoub, M. M., and Lo Presti, P. (1971). The determination of an optimum size cylindrical handle by use of electromyography. *Ergonomics, 14,* 509-518.

Chaffin, D. B., and Andersson, G. B. J. (1984). *Occupational biomechanics.* New York: Wiley.

Cochran, D. J. (1983). *An investigation of safe handle design* (Final Report for NIOSH, NTIS-64-83/ISS15). Lincoln, NE: University of Nebraska.

Drury, C. G. (1980). Handles for manual material handling. *Applied Ergonomics, 11,* 35-42.

Greenberg, L., and Chaffin, D. B. (1979). *Workers and their tools: A guide to the ergonomic design of hand tools and small presses.* Midland, MI: Pendell.

Konz, S. (1983). *Work design: Industrial ergonomics* (2nd ed.). Columbus, OH: Grid.

Neter, J., Wasserman, W., and Kutner, M. H. (1985). *Applied linear statistical models* (2nd ed.). Homewood, IL: Irwin.

Pheasant, S., and O'Neill, D. (1975). Performance in gripping and turning—A study in hand/handle effectiveness. *Applied Ergonomics, 6,* 205-208.

Riley, M. W., and Cochran, D. J. (1980). Handles for sharp tools. In *Proceedings of the Symposium on Occupational Safety Research and Education* (pp. 67-74). Morgantown, WV: NIOSH.

Saran, C. (1973). Biomechanical evaluation of T-handles for a pronation supination task. *Journal of Occupational Medicine, 15,* 712-716.

Van Cott, H. P., and Kinkade, R. G. (1972). *Human engineering guide to equipment design* (revised ed.). Washington, DC: American Institutes for Research.

Woodson, W. E. (1981). *Human factors design handbook.* New York: McGraw-Hill.