THE INFLUENCE OF FOREARM AND WRIST ORIENTATION ON STATIC GRIP STRENGTH AS A DESIGN CRITERION FOR HAND TOOLS

Robert Terrell
Tennessee Eastman Company

Jerry L. Purswell
School of Industrial Engineering
University of Oklahoma

ABSTRACT

The amount of force required to use a hand tool and its relationship to the user's capacity to exert this force is a critical design criterion of hand tools, often affecting the immediate safety of the tool user and the propensity of the tool to cause injury to the user with long-term use. Because the wrist is often placed in deviated positions, the available data on grip strength with an undeviated wrist configuration may not be applicable to the design of many hand tools. This study demonstrates the decreases in grip strength due to wrist deviations and forearm rotation. The position of maximal static grip strength is the neutral wrist with a supinated forearm. Decrements from the neutral position for wrist flexion, hyperextension, radial flexion and ulnar flexion are 30%, 22%, 18% and 15%, respectively. The pronated forearm allows only 87% of the strength of the supinated forearm, and the differences between the supinated and the midposition forearm are not significant.

INTRODUCTION

During the design and evaluation of various hand tools, there are many task and human factors variables to be considered in order to produce a tool which is capable of performing its task and which will not cause undue or excessive strain on the operator. Many tools perform well for infrequent or occasional use, but when the operation and use of the tool is continuous throughout the working day, many additional problems with the tool design are encountered.

Drillis (1963) itemizes some of the basic requirements for efficient hand tool design, which are:

1. the tool must perform its function effectively,
2. the tool's initial and maintenance costs should be low,
3. the tool must be properly proportioned to the appropriate body dimensions of the operator,
4. the tool should not cause premature or excessive fatigue,
5. the tool must be adapted to the senses of the operators, and,
6. the tool must be adjusted to the strength and work capacity of the operator.

In order to properly design a tool for the strength of an operator, there must exist the proper type of strength data. Specifically, the data on grip strength are needed in the design of many hand powered tools such as pliers and crimpers, but they are also needed in many other tools and situations. A significant grip force is required to actuate the mechanical staple drivers so often found in industry. A knowledge of grip strength is also required in the design of many control mechanisms that are released from the locked position by grip force. Many types of pneumatic tools require significant grip force to control the operation of the tool.

Proper design of the length and configuration of the moment arms of various hand tools and of hand caliper brakes is dependent upon a knowledge of maximal grip strength data. For instance, in braking a bicycle with hand caliper brakes, the forces required to stop the bicycle may be excessive for a given hand/wrist/forearm configuration, especially for a weak female or small child.

Grip strength has been frequently measured, but it is often difficult to use this data in equipment design because it is not easy to determine from the data the conditions under which grip strength was obtained. Therefore, much of the published data taken with a undeviated wrist and unspecified forearm position is not suitable for the design of hand tools because of the necessity of a deviated wrist during various operations.

BACKGROUND

Napier (1956) defines all movements of the hand as prehensile (grasping) or non-prehensile (manipulation by pushing or lifting). Further he states that a prehensile movement is either a power grip or a precision grip, although the two concepts are not mutually exclusive. In a grip in which the power concept is dominant, the object is grasped by partially flexed fingers and the palm with counter pressure applied by the thumb lying more or less in the plane of the palm. In a precision grip the object is pinched between the fingers and opposing thumb.

According to Napier's definitions, the grip used in many hand tools and other grasping tasks is a special case of the power grip, the coal hammer grip, in which the thumb is fully abducted. With this grip, Napier maintains that the greater the force required of the grip, the more the thumb is required to act as a reinforcing and buttressing mechanism and the less it is able to contribute to precision (the normal role of the abducted thumb).

Bechtol (1954) in discussing the function of the hand theorizes that the limiting factor in the force of the grip is the power of the thumb and the thenar eminence to oppose the more powerful force of the four fingers. Therefore, he maintains that the most important muscles in the grip are those of the thenar eminence. Unfortunately, there is no experimental evidence to support his contention.

The variation of strength of a limb through its range of movement is well documented for most limbs (McCormick, 1970; Campney and Wehr, 1965). Williams and Stutzman (1959) published strength values for the following movements through the range of the particular joint:

1. elbow flexion and extension
2. knee flexion and extension
3. shoulder flexion and extension
4. shoulder horizontal abduction
5. hip flexion and abduction

Information on the strength of the grip for various combinations of hand/wrist/forearm movements is much less available. Erb and Rabinowitsch (1932) report that larger maximum grip strength values were obtained with the elbow extended than with the elbow flexed at a right angle. Taylor and Schwartz (1955) report that the forearm/hand angle in the relaxed position with the hand and arm hanging at the side is 145° (35° hyperextension) and that this is the position of maximum prehensile force although they offered no experimental data to validate this contention. Other investigators have made qualitative statements on the optimal position of the wrist when gripping a tool. Kraft and Detels (1972) state that there was no difference in grip strength between 30 degree extension, 15 degree extension and neutral positions of the wrist, but there was a significant decrement in grip strength with 15 degrees of wrist flexion. They also cite the work of other authors to find the optimal position or the "position of function", but this work is based on clinical experience, rather than controlled experimentation. The following table shows their results.

POSITION OF FUNCTION AS
SUGGESTED BY VARIOUS AUTHORS*

Author and Year of Publication	Position of Function
Kanavel, 1933	Hyperextension
Liebolt, 1938	25 to 30 degree extension
Watson-Jones, 1943	15 to 35 degree extension
Steindler, 1955	12 degree extension
Shands and Raney, 1967	15 to 25 degree extension
Boyes, 1969	Dorsiflexion
Bunnell (Boyes), 1970	20 degree extension

*(From Kraft and Detels, 1972)

Anderson (1965) reports the only preliminary study on the effect of wrist position with grip strength. Anderson's results show that the neutral wrist is the position of greatest strength. The ulnarly flexed wrist, radially flexed wrist, hyperextended wrist, the flexed and ulnarly flexed wrist, the flexed wrist and the hyperextended and radially flexed wrist positions all resulted in decreasing performance on the grip strength task. Anderson did not document the amount of wrist deviation for each position nor did he attempt to control the amount of wrist deviation while testing his subjects. Anderson used an unsupported Cable Tensiometer to obtain peak readings of grip strength performance.

Hazelton et al. (1975) report some interesting results on the influence of wrist position on finger flexor strengths. They show that finger flexor strength is the greatest with the wrist ulnarly flexed, and strength of the other wrist positions in descending order were the neutral position, radial flexion, hyperextension, and finally flexion. Although they do not theorize about the reasons for this order, they do recognize many of the factors that influence the force patterns exhibited in the fingers.

Taylor and Schwartz (1955) cite a University of California report in which a precision grip of a one-half inch block between the thumb and opposing index and middle fingers was tested with varying degrees of flexion and hyperextension. It was shown that there was a significant decrease in the maximal prehensile forces on the block in either extreme position of flexion or hyperextension.

Fitzhugh (1973a) reports that in a recent University of Michigan Human Performance Laboratory Study the static grip strength with the hand radially flexed 30° is approximately 88% of the maximum value attained in the neutral position, but this result is from an informal survey as pilot work for a later study, thus the methodology may not have been completely rigorous.

The only study on the interaction of forearm rotation and grip strength is just a minor portion of a larger study. Fitzhugh (1973b), using a Preston Dynamometer, tested grip strength in a pronated or supinated position and found that there was no decrement in grip strength due to forearm position.

Thus, there are some preliminary studies and results showing the interaction of grip strength and hand/wrist/forearm configuration, but there is a definite need of knowledge of grip strength throughout the range of wrist deviation and forearm rotation as applied to the design of hand tools, or other tasks such as bicycle braking.

METHODOLOGY

A specially designed hand dynamometer utilizing the handles of a T-5 Cable Tensiometer was used to measure grip strength performance. A proof ring with its associated strain gages were used to give a rapidly reactive and continuous measure of grip strength. The upper extremity configuration (shoulder abduction 10°, shoulder flexion 10°, elbow flexion 80°) was controlled and maintained by a subject restraint system. The hand/wrist/forearm configuration was controlled by an orientation mechanism. For each measurement of grip strength, the hand dynamometer was oriented such that it required the subject to assume the desired hand/wrist/forearm configuration.

The grip span for the dynamometer was 5.25 cm. for both males and females, based on the work of Cotten and Bonnell (1969) and Cotten and Johnson (1970). This grip span was felt to be the most appropriate because the handles of the dynamometer used in this study were from a T-5 Cable Tensiometer similar to those used in the above studies in which the 5.25 cm. setting was found to be optimal for college-age subjects.

A buzzer was used to control the duration of the grip strength measurement. The subjects were instructed to begin gripping the device when the buzzer began and to continue for the four second duration of the buzzer. The subjects were not given instantaneous feedback of performance, but rather, in accordance with Caldwell et al. (1974), they were given post-test qualitative feedback on their performance.

The procedure that Caldwell et al. suggested for determining the average grip strength was followed with some modifications. Caldwell suggests that the mean value for the first three seconds of the sustained four second exertion be used as the performance of the subject and that one second before and after the sustained contraction be ignored. In this study the subjects were required to grip the dynamometer as strongly as possible for the duration of the four second buzzer. Since it normally took one second to reach their maximal performance, the mean of the three remaining seconds was used as the performance of the subject. This process agrees in essence with Caldwell's recommendations, although the maximal excursion limit of $\pm$ 10% suggested by Caldwell was not used because of procedural difficulties.

The independent variables in this study were wrist position and forearm orientation. There were three levels of forearm rotation; pronation, mid-position, and supination, and five levels of wrist deviation; neutral, flexion ($45^{\circ} \pm 5^{\circ}$), hyperextension ($50^{\circ} \pm 5^{\circ}$), radial flexion ($20^{\circ} \pm 5^{\circ}$) and ulnar flexion ($20^{\circ} \pm 5^{\circ}$).

RESULTS

The data from this experiment was analyzed in two formats; one, as data in units of force and two, as an index in which the supinated forearm/neutral wrist grip strength of each individual served as his/her indexing position. This index significantly (α = .05) reduced the variation of the observation, even though the two formats followed the same trends. Figures 1-4 demonstrate these trends.

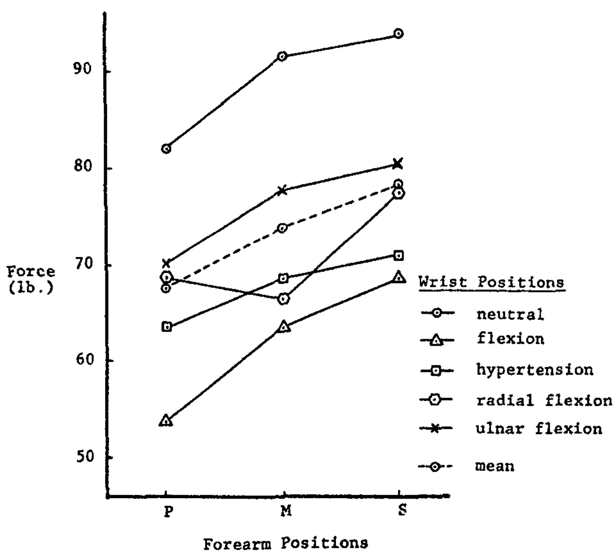

Figure 1. Grip strength (force) versus forearm position.

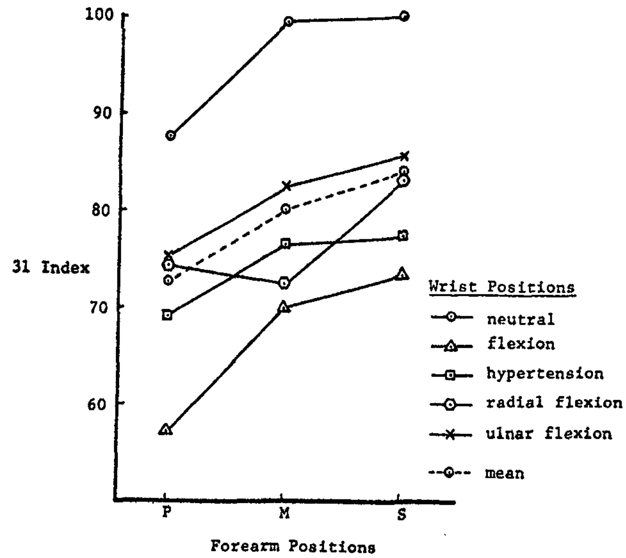

Figure 2. Grip strength (index) versus forearm position.

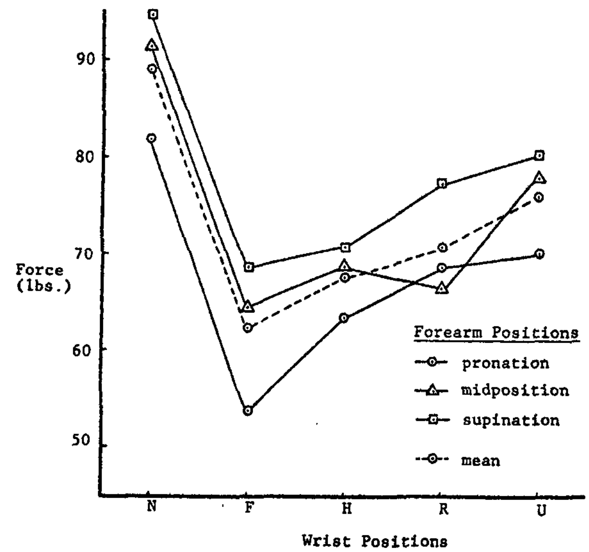

Figure 3. Grip strength (force) versus wrist position.

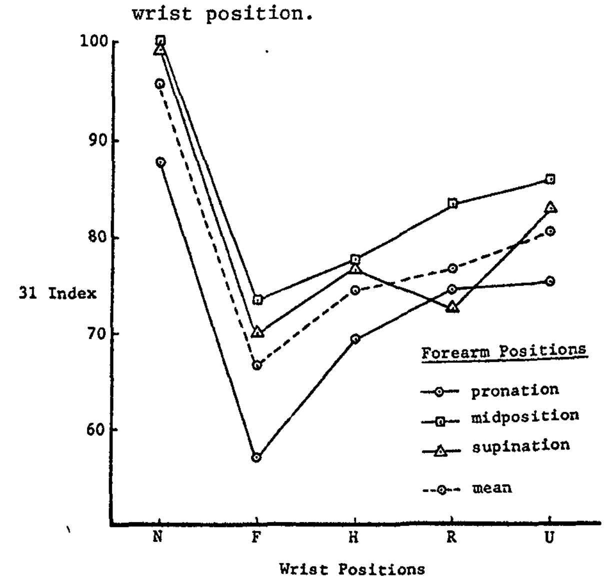

Figure 4. Grip strength (index) versus wrist position.

In both analyses the effects of forearm position and wrist deviation were highly significant ($\alpha = .01$) while the interaction of forearm position and wrist deviation was not significant ($\alpha = .25$). The significant differences due to forearm position may be largely attributed to the decrement in performance with the forearm in the pronated position based on the results of Tukey's HSD test (Kirk, 1968) on forearm position.

The results of Tukey's HSD test on the wrist positions show that performance with a neutral wrist is significantly different ($\alpha = .05$) from performances with all the other wrist positions. The performances with the other wrist positions are not significantly different from one another except for the pair wise comparison of the flexed wrist and the ulnarly flexed wrist.

Based on tests of simple main effects (Kirk, 1968), the effects of wrist position are highly significant ($\alpha = .01$) at all levels for forearm position, but the effect of forearm position at different levels of wrist position is variable.

DISCUSSION

The results of the effects of forearm position generally follow the trend predicted by a kinesiological analysis of the muscles involved in the power grip. Based on muscle palpation, in pronating the forearm from the fully supinated position to the fully pronated position, the flexor digitorum superficialis is continually reduced in length. Based on the length-tension relationship of single muscle fibers (Gordon, et al., 1966) and of entire muscles in situ (Pertezon, 1971), one would expect the reduction in grip strength which was demonstrated. Perhaps the initial shortening from the supinated to the midposition was not enough to show a significant decrease in performance, but the shortening was enough to produce the significant decrease in performance with the pronated forearm.

The reversal of the strength performance of the midposition and the pronated forearm with radial flexion is not readily understood. Since there is no significant interaction, perhaps this reversal may be attributed to random variation.

The results of the effects of wrist position on grip strength at a given forearm position cannot be as readily explained with a kinesiological analysis as for forearm position alone. The muscle length and strength relationship is required, but the position of the dynamometer handles within the hand is also important. The reduction in muscle length is the most important factor in the decrease in grip strength in the flexed wrist position versus the neutral wrist position because the hypothenar and thenar eminences oppose the flexing finger equally in the two positions. In comparing the neutral and the hyperextended wrist position, the muscle length is not reduced below that of the neutral wrist, but the hypothenar eminence and much of the thenar eminence cannot provide the buttressing force in the hyperextended wrist position that they can provide in the neutral wrist position.

The comparison of the neutral, the flexed and the hyperextended wrist positions reveal the relative effects of the muscle length-tension relationship and the efficiency of the grasp on the dynamometer handles. Based on the performance in the two deviated positions, the effect of reduced muscle length is much greater than the effect of a poor grip on the handles of the dynamometer. This may be related to the amount of flexion of the wrist versus the degree to which the thenar and hypothenar eminence are unable to oppose the finger. It is critical that no matter how hyperextended the wrist may be, the thumb is still able to oppose the flexing finger; but with extreme flexion of the wrist the finger cannot effectively exert any force even though the hand can properly grasp the dynamometer handles.

The statistical comparison of the ulnarly and the radially flexed wrist was not significant and this is expected since there are minimal if any changes in muscle length, but there is a difference in the way the handles are grasped. The hypothenar eminence does not make as good contact on the handles in the radially flexed hand as it does in the ulnarly flexed hand. Evidently this difference is not critical enough to cause a decrease in performance.

If a comparison is made of performance at any particular wrist and forearm combination, to that of the position of maximum grip strength, the supinated forearm/neutral wrist, the data in Table 1 is obtained.

TABLE 1

GRIP STRENGTH FOR VARIOUS POSITIONS AS A PERCENTAGE OF THE MAXIMUM STRENGTH

Forearm Position	Wrist Position				
	Neutral	Flexion	Hyper-Extension	Radial Flexion	Ulnar Flexion
Pronation	88	57	69	74	75
Mid Position	99	70	77	72	83
Supination	100	73	77	83	86

The trend of Anderson's (1965) study generally follows the trend of the data from this study, although they differ absolutely as shown in Table 2.

TABLE 2

GRIP STRENGTH AS FUNCTION OF WRIST POSITION (% OF NEUTRAL)

Investigator	Wrist Position				
	Neutral	Flexion	Hyper-Extension	Radial Flexion	Ulnar Flexion
Terrell	100%	70%	78%	82%	85%
Anderson	100%	83%	94%	94%	96%

It may be theorized that the absolute differences may be attributed to different degrees of wrist deviation although the contention is unsupported. The differences may also be a function of the experimental methodology and the performance criteria (3 second average strength vs. peak strength).

This data also shows a greater decrease in grip strength performance with the wrist radially flexed than does Fitzhugh (1973a). Overall there was an 18.4% decrease in performance as opposed to Fitzhugh's 12% decrease in performance. Again, methodological differences may account for the discrepancy.

CONCLUSIONS

It can be stated that grip strength is affected by wrist and forearm position, but that there is no significant interaction between the two factors. The forearm position is significant in that with a pronated forearm one can exert only 87% of force that can be exerted with the supinated forearm. There is a small difference in the force exerted with a mid-position versus a supinated forearm, but it is not statistically significant.

In each of the forearm positions, the flexed wrist is able to exert 70% of the strength of the neutral position. In comparing the remaining wrist positions to the neutral, one finds that the hyper-extended wrist limits the grip strength to 78% of the neutral, the radially flexed wrist to 82% of the neutral, and the ulnarly flexed wrist to 85% of the neutral wrist position. If the comparison is made of any particular wrist and forearm combination to that of the maximum grip strength of the supinated forearm/neutral, the results are slightly different.

It is, therefore, easy to see that knowledge of the forces that can be developed in grasping are highly influenced by the position of the wrist and forearm. Therefore, in the design of a tool that requires significant grasping forces, it is necessary to consider the orientation of the wrist and forearm because of this relationship between hand/wrist/fore-arm configuration and grip strength.

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