Grip Force Vectors for Varying Handle Diameters and Hand Sizes

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Grip force was measured along two orthogonal axes and vector summed. Sixty-one participants recruited from a manufacturing facility (29 men and 32 women) grasped instrumented cylinders (2.54, 3.81, 5.08, 6.35, and 7.62 cm diameter) using a maximal voluntary power grip. Two orthogonal force measurements relative to the third metacarpal were resolved into a magnitude and corresponding angle. On average, magnitude increased 34.8 N as handle diameter increased from 2.54 cm to 3.81 cm, and then monotonically declined 103.8 N as the handle diameter increased to 7.62 cm. The average direction monotonically decreased from 59.2° to 37.7° as handle diameter decreased from the largest to the smallest. When the diameter was smallest, the greatest force component, F_x (168.6 N), was in the direction where the fingertips opposed the palm. Conversely, when the diameter was largest, the smallest component, F_x (77.7 N), was in the same direction. These values are averaged for the left and right hand. The angle for the largest diameter increased with increasing hand size. These relationships should be useful for the design of handles that require gripping in specific directions, such as for hand tools and controls. Actual or potential applications of this research include the design of handles that require gripping in specific directions, such as for hand tools and controls, that reduce effort, and that prevent fatigue and overexertion.

INTRODUCTION

Designers often depend on published grip strength data obtained using an apparatus that varies handle size by controlling only a single dimension (e.g., span). One such instrument is the Jamar dynamometer, which measures force in a single axis and has a geometry that is not truly representative of cross sections often encountered for handles and tools. Handles used in the workplace with power hand tools, stick controllers, and other equipment often involve a cylindrical shaped handle. Furthermore, although numerous studies of grip strength have been conducted, grip force has typically been measured as a scalar quantity with the underlying assumption that grip force is exerted in a single direction or distributed equally throughout the handle (Pheasant & O'Neill, 1975). The purpose of this study was therefore to investigate hand exertion properties while grasping cylindrical handles of various sizes when considering grip force as a vector, having properties of both magnitude and direction.

Conventional methods for measuring grip strength consider force applied in a single direction. This, however, does not provide a true indication of forces applied when grasping a cylindrical handle, as it considers only a component of the force being generated and acting upon the handle surface. Although many earlier studies regarding grip strength have been published (Armstrong & Oldham, 1999; Crosby, Wehbe, & Mawr, 1994; Hanten et al., 1999; Harkonen, Piirtomaa, & Alaranta, 1993; Josty, Tyler, Shewell, & Roberts, 1997; Mathiowetz et al., 1985; Swanson, Goran-Hagert, & Swanson, 1990), most previous work has viewed grip force as either a scalar or unidirectional quantity.

Published strength data are limited in handle geometry variations. Swanson et al. (1990) and Josty et al. (1997) studied the third handle

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breadth position of a Jamar dynamometer (6.03 cm). Hanten et al. (1999) and Mathiowetz et al. (1985) used the second handle breadth position (4.76 cm). Petersen, Petrick, Connor, and Conklin (1989) reported either the second or third position, depending on the comfort of the participant. Conversely, Crosby et al. (1994) and Harkonen et al. (1993) measured grip strength using all five positions of the Jamar dynamometer. The former concluded that grip strength must be measured for a variety of handle sizes; only 61% of the Crosby et al. participants had their maximum grip strength at the second breadth of the Jamar dynamometer (4.76 cm). The shape of Jamar dynamometers and similar instruments do not resemble cylindrical handles, and therefore grip strength measurements may not be representative of strength when gripping these handles.

Pheasant and O'Neil (1975) considered grip strength as the sum of the components of the compressive forces uniformly distributed about the handle. The contribution of different parts of the finger (Amis, 1987; Buchholz & Armstrong, 1992) or different fingers (Chadwick & Nicol, 2001; Kinoshita, Murase, & Bandou, 1996; Radwin & Oh, 1992) has not supported this assumption. Amis measured the normal and tangential shear forces of the fingers on cylindrical handles of different diameters and found that forces at the phalanges vary.

This study considered grip force as a vector, having both magnitude and direction, when participants grasped cylindrical handles of varying diameters. Grip strength for different-sized handles was measured to determine how forces are directed in the handle during a maximum voluntary exertion. Force was measured along two perpendicular axes, and then the vector was resolved to find the maximum grip force generated.

MATERIALS AND METHODS

Participants

The 61 participants, who were recruited from a manufacturing facility in the Midwest region of the United States, included a mixture of 26 office and 35 production personnel. All were healthy volunteers who gave informed consent to participate. Their ages ranged from 20 to 59 years. There were 29 men and 32 women. Hand length, measured from the wrist crease to the distal end of the longest finger, ranged from 15.2 to 21.6 cm, with a mean of 18.33 cm (SD = 1.27 cm) for the right hand. Four women and 4 men self-reported they were left-handed, and the remainder reported they were right-handed or preferred to use their right hand when using hand tools. The participants were also asked to self-report body weight, stature, job functions, tools used in their job, and any previous injuries. The participants were queried to ensure that they did not have any existing medical conditions that could interfere with their grip. Hand length and breadth were measured using an anthropometry caliper. These data were compared with previously published data of U.S. Army personnel. The protocol was reviewed and approved by the University of Wisconsin Human Subjects Committee.

Apparatus

A cylindrical strain gauge dynamometer was designed and constructed to measure force in a single axis of sensitivity and to measure all forces applied along the handle length, independent of point of contact. The dynamometer design is described in detail in Radwin, Masters, and Lupton (1991). The strain gauge signals were amplified and digitized using a 12-bit analog-digital converter. The data acquisition sample rate was 50 samples/s. The dynamometer was cylindrical and so allowed the researchers to measure the force generated by the participant in different directions by simply rotating the handle 90° and obtaining another set of force measurements, thereby providing force vectors to determine the true total force being generated (see Figure 1).

Different-sized diameter cylindrical handle caps were attached to the dynamometer. The handles included cylinders of 2.54, 3.81, 5.08, 6.35, and 7.62 cm diameter (see Figure 2). The caps were made of aluminum and were interchangeable.

Experimental Design

The experiment contained two independent variables: handle diameter (five levels) and the hand being measured (left or right). Other factors analyzed included participant gender, age, and hand length. Forces were measured in two

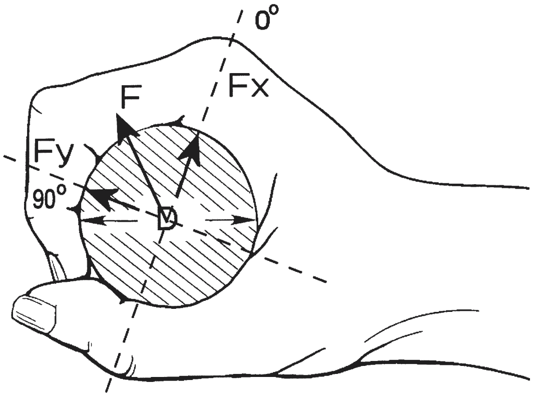

Figure 1. Grip force vectors. The *x* axis was aligned with the metacarpophalangeal joint, and the *y* axis was perpendicular.

orthogonal directions referenced to the third metacarpal. The dependent variables included force magnitude (in newtons) and the angle of the resulting force vector.

Procedures

At the start of the experiment, participants were interviewed and demographic data were collected. Grip strength testing was conducted in accordance with the American Society of Hand Therapists recommended procedures (Mathiowetz et al., 1985). The participant was seated comfortably in a chair. The shoulder was adducted and neutrally rotated and the elbow was flexed at 90°, with the forearm and wrist in neutral position (Figure 3).

Participants were instructed to grip the dynamometer handle using maximum force for 5 s. The participant was asked to start and stop an exertion when instructed by the experimenter. After a 5-min rest break, the handle was rotated 90° to measure force in the orthogonal direction. The two force measurements were classified as the finger force and palmar force, corresponding to the forces acting in orthogonal directions relative to the fingers and palmar sides of the hand. The first and last second of each 5-s exertion were eliminated, and the average force of the remaining 3 s was calculated, along with the peak force and the standard deviation.

The forces measured for each condition (handle diameter and hand) were expressed as a force vector magnitude and angle. When the dynamometer handle axis of sensitivity aligned with the metacarpophalangeal joint, the force F_x was measured in the *x* axis (Figure 1). The force in the orthogonal direction, F_y, was measured in the *y* axis (Figure 1). The magnitude was calculated as the square root of the sum of the square forces in each orthogonal direction, such that

$$|F| = \sqrt{F_x^2 + F_y^2}.$$

The angle was a measure of the direction of the vector-summated grip forces acting against the handle and was calculated as

$$\tan^{-1}\frac{F_y}{F_x}$$

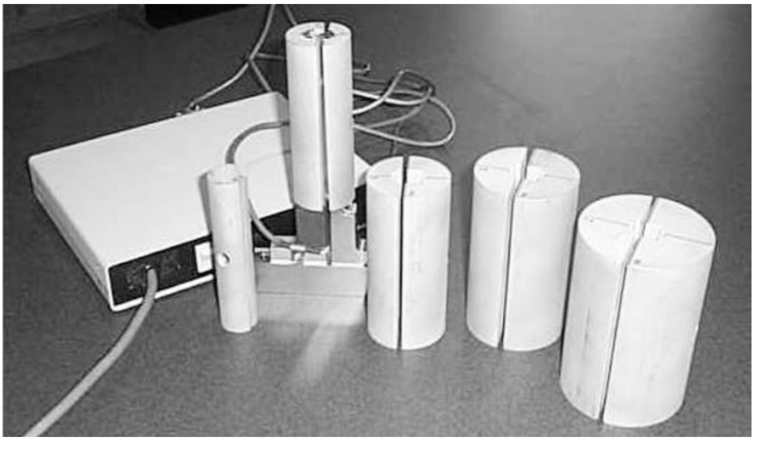

Figure 2. Dynamometer handle “caps” of varying sizes. Different caps were attached to the dynamometer in order to change the diameter of the cylindrical handle.

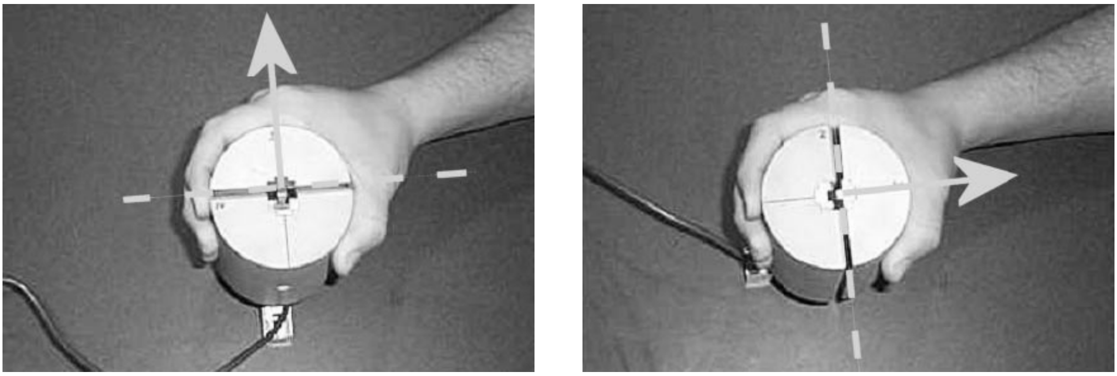

Figure 3. Procedure used for grasping the dynamometer. The handle was rotated 90° between trials in order to measure force in two orthogonal directions.

Data were collected over the course of 5 workdays, with a different size handle tested on each day. During a single session, each hand was tested twice so that both axes could be measured during the same session. Data were collected at the beginning of the shift to reduce any affects of fatigue. The order in which each experimental condition and direction was presented was randomized. All data were collected at the worksite, including both office and factory employees. The data were analyzed using analysis of variance (ANOVA) with age as a covariate.

RESULTS

Average force magnitude was 198.1 N (*SD* = 68.7 N), 232.8 N (*SD* = 82.8 N), 204.4 N (*SD* = 79.3 N), 170.3 N (*SD* = 72.9 N) and 129.1 N (*SD* = 60.0 N) for handle diameters of 2.54, 3.81, 5.08, 6.35, and 7.62 cm, respectively, $F(4, 579) = 120.6$, $p < .01$. A summary of the grip force outcome is broken down by gender and handle diameter in Table 1.

Grip force is plotted against handle diameter for both the dominant and nondominant hands in Figure 4. The difference between the hands that generated the force (dominant vs. nondominant) was statistically significant, $F(1, 579) = 8.7$, $p < .01$. Gender was also statistically significant, $F(1, 579) = 1107.6$, $p < .01$.

The handle diameter at which most participants generated maximum force was 3.81 cm for both women and men. This included 69% of the women (166.9 N) and 79% of the men (305.6 N). The interaction between gender

TABLE 1: Average Grip Strength for Both Hands Stratified by Age and Gender (*N*)

	Handle Diameter									
	2.54 cm		3.81 cm		5.08 cm		6.35 cm		7.62 cm	
Age (years)	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
Women										
24–30 (*n* = 7)	168.9	48.5	192.1	37.9	172.5	39.6	139.0	34.3	102.1	21.3
31–44 (*n* = 8)	169.3	35.4	192.8	47.6	155.5	41.7	121.9	37.9	98.6	24.3
45–49 (*n* = 8)	130.4	46.9	142.4	41.7	115.6	41.4	97.1	30.0	62.7	21.2
50–57 (*n* = 8)	135.7	35.9	148.9	27.0	131.8	32.0	99.4	27.4	77.5	22.9
Men										
20–29 (*n* = 7)	274.7	40.6	331.9	31.5	283.7	34.0	254.3	30.0	177.3	36.0
30–35 (*n* = 7)	248.4	53.7	309.4	41.5	283.5	54.3	249.1	38.0	197.9	48.2
36–46 (*n* = 8)	238.7	35.7	299.7	41.5	275.0	29.9	230.5	27.9	179.6	34.6
47–60 (*n* = 7)	243.1	50.7	282.3	40.2	253.7	40.5	203.9	51.2	161.1	47.7

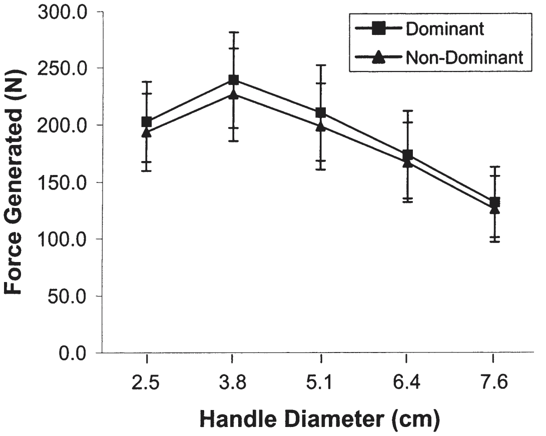

Figure 4. Average grip force magnitude versus handle diameter for the dominant and nondominant hands. Error bars represent ±1 *SD.*

and diameter was also statistically significant, $F(4, 579) = 6.8$, $p < .01$. A plot of grip force magnitude against handle diameter for men and women is shown in Figure 5. Age was a significant covariate for force, $F(1, 579) = 86.2$, $p < .01$.

A plot of the grip force vector angle versus handle diameter is shown in Figure 6. The force angle at maximum strength was 52.7° for women and 51.5° for men. Diameter was the only significant variable for the force angle, $F(4, 579) = 175.5$, $p < .01$. The two force vector components, F_x and F_y, are graphed in Figure 7.

Participants were divided into three groups consisting of the upper, middle, and lower 33rd percentiles based on hand length (small, medium, and large). A plot of the grip force vector angle for the largest handle diameter (7.6 cm) is shown in Figure 8. The force angle increased (from 33.7° to 40.0°) as hand size increased from small to large. This increase in angle was most evident in the larger-sized handles. The three hand size groups were small (15.4–17.69 cm), medium (17.7–18.79 cm), and large (18.8–21.3 cm). Although the force vector angle between the two genders was similar, the force magnitude generated was predictably different. Age was not a statistically significant covariate for angle, $F(1, 579) = 0.002$, $p > .05$.

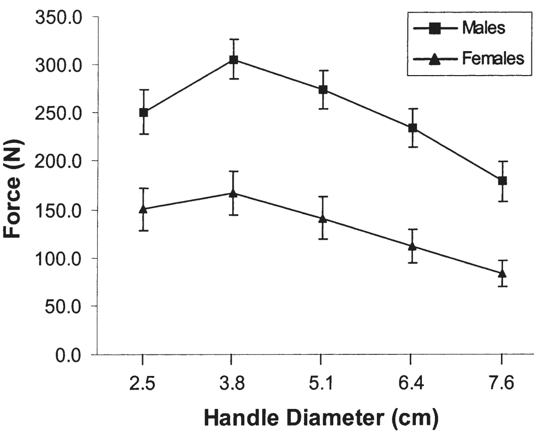

Figure 5. Plot of average grip force magnitude versus handle diameter, by gender. Error bars represent ±1 *SD.*

DISCUSSION

The results showed that 3.81 cm was the optimal size handle for achieving maximum strength for most of the participants (73%). Crosby et al. (1994) found that 60% of their participants achieved maximum grasp strength at the second position of the Jamar dynamometer (4.76 cm). Interestingly, only 11% of our participants had their greatest strength at 5.08 cm, which is closer in diameter to the second position of the Jamar dynamometer.

A direct comparison with previous studies is not possible, given the nature of the equipment used for collecting data. The Jamar dynamometer has handle span settings of 3.49, 4.76, 6.03, 7.30, and 8.57 cm, whereas the cylindrical dynamometer used in this study was 2.54, 3.81, 5.08, 6.35, and 7.62 cm in diameter. In general, the forces measured in this study were considerably less than in previous studies, even taking into account the difference in handle sizes and shapes. This may be attributable in part to the way data were collected: Strength was averaged over 3 s in this study, whereas typical use of a Jamar dynamometer usually considers the peak strength only. The shape of the cylindrical handle was also an important factor.

The differences between the Jamar dynamometer studies and the current study may be attributed in part to the different shapes of the handles. A Jamar dynamometer more closely approximates a two-handled tool (pliers, etc.), whereas the dynamometer used in this study approximates a cylindrical tool, for which leverage is not possible. The data reported in this

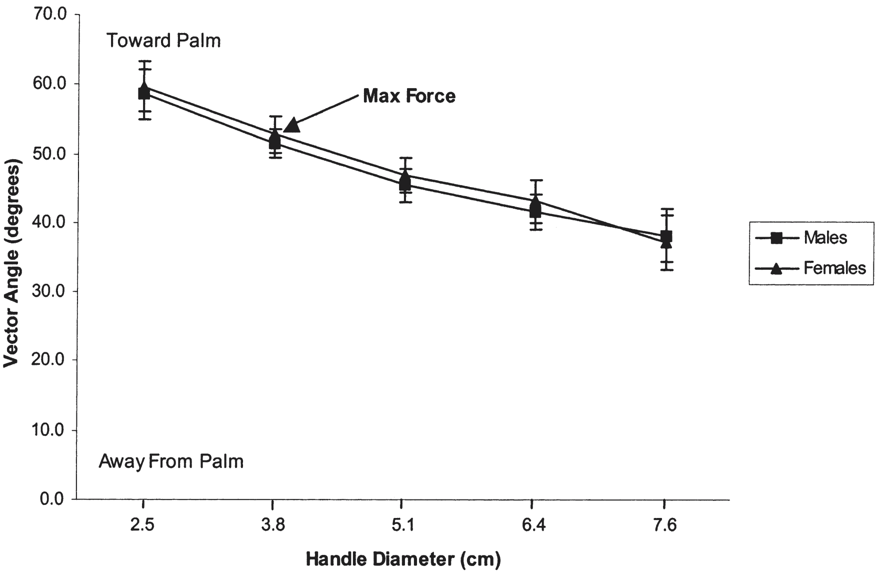

Figure 6. Plot of total grip force vector angle versus handle diameter. Error bars represent ±1 *SD*.

study are also not actual readings of strength – rather, they are vector quantities derived from two readings in perpendicular directions, in an attempt to approximate forces in all directions. Consideration of grip force as a vector quantity enabled us to better understand how force was directed into the handle.

Because two orthogonal trials were performed and the final outcome was the vector sum of the two, some error may have been introduced if the two trials were not identical. The resultant grip force vector may underestimate total grip force, given that the dynamometer does not measure shear forces between the hand and the handle. It is anticipated that these errors, however, are small. A new, instrumented dynamometer is planned for future investigations for measuring shear and cross-sectional force components simultaneously.

A difference in age stratification between men and women was observed because of the makeup of the study group (Table 1). Therefore

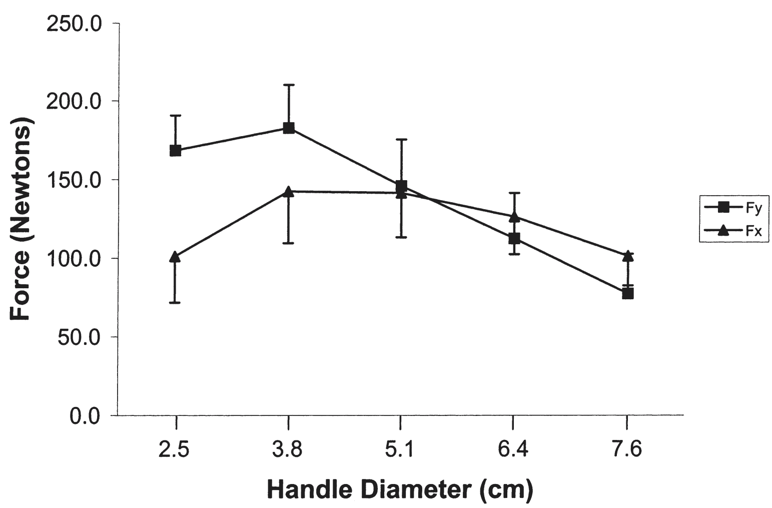

Figure 7. Plot of the two orthogonal force vector components versus handle diameter. Error bars represent ±1 *SD*.

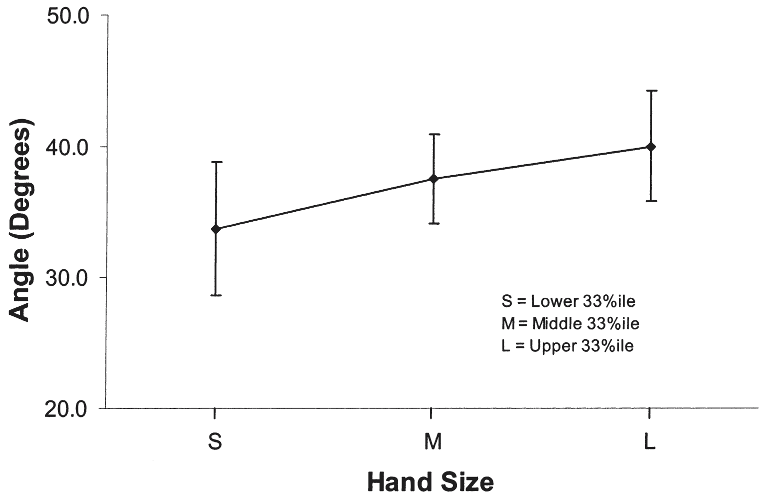

Figure 8. Plot of average vector angle versus hand size. Error bars represent ±1 *SD*.

the observed gender effect may be confounded with age. Age was a significant factor for force magnitude but not for angle. Harkonen et al. (1993) found that both men and women had their highest strength (averaged across all age groups) at Position 3 (6.03 cm) on the Jamar dynamometer (men = 510.6 N, women = 305.2 N). Mathiowetz et al. (1985) reported data for Position 2 (4.76 cm) on the Jamar dynamometer (men = 463.1 N, women = 276.7 N on the dominant hand). Conversely, the current study found that both men and women had the greatest strength (averaged across all participants) for a handle diameter of 3.81 cm (men = 305.6 N, women = 166.9 N). Crosby et al. (1994) found that men achieved a maximum grip strength (regardless of handle size) of 609.4 N and women achieved a strength of 360.3 N. The current study resulted in maximum grip strength for the dominant side of 313.7 N for men and 171.7 N for women, but certain individuals yielded forces much higher than the averages.

An, Chao, Cooney, and Linscheid (1985) found that effective function of the hand requires both stability and strength. Therefore to simply choose a handle size at which a majority of persons will reach maximal strength is not necessarily correct for an application that also requires stability.

The concept of the "power" and "precision" grips, terms that were coined by Landsmeer (1962), depends on the portion of the hand contributing to the grasp. In a precision grip, the pulp surfaces of the thumb and fingers are placed opposite each other – the fingers are flexed and abducted at the metacarpophalangeal joints. In a power grip, the combined fingers form one "jaw" of the clamp with the palm as the other jaw. It can be inferred that the major difference between the two grips is whether the pulp surfaces of the fingers are opposite the thumb (precision) or opposite the palm (power). Napier (1956) indicated that although in almost any activity either "power" or "precision" is the predominant characteristic, the two concepts are not mutually exclusive. There are activities in the hand in which the two grips are combined together to provide both force and stability to the object being held. The force vector angle may provide an indication of the predominant grip. In the current study, larger angles are directed toward the palm whereas smaller angles are directed away from the palm. Therefore a greater angle may correspond to a grip that is more predominantly a power grip than a pinch grip (see Figure 8).

Forceful pinching involves greater stresses on the tendons of the forearm than does power gripping. Chao, Opgrande, and Axmear (1976) and Cooney and Chao (1977) investigated hand biomechanics in relation to different hand positions (grasping versus pinching). Armstrong (1976) showed that tension in the long finger tendons is greater when the handle size is large and when hand size is small. It is therefore advantageous for handles to be designed so that handle size minimizes tendon stress. A conflicting criterion, however, occurs because the handle size that maximizes strength does not necessarily maximize angle. In addition, it is often recommended that handle size be maximized in order to minimize contact stress. The maximum handle diameter in which the power grip predominates, however, is not completely obvious. The methodology explored in the current paper may provide a way to optimize grip.

The data resulting from this research should benefit designers by enabling them to design tools with optimally sized handles for operators of varying hand sizes. When the handle design should prevent the handle from rotating in the hand, then it would be desirable to design for the maximum grip force. When the handle is to be pulled, it is desirable to design it so that most of the force is directed toward the palm. Force vector angles may also be useful for aligning handle-mounted controls in order to minimize hand exertions. Force vectors may also assist in the design of handles that direct forces in such a manner that balances the trade-off between providing the user the necessary grip force and controlling the handle for precision grip.

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