Multiaxis Grip Characteristics for Varying Handle Diameters and Effort

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Objective: A multiaxis dynamometer was used to quantify grip force vector angles and longitudinal centers of pressure (COPs) while varying handle size and effort used.

Background: Authors of many studies have examined maximum grip strength using scalar instruments; a few have measured two-axis forces limited to one or more finger contact. This novel dynamometer uses two instrumented beams that are grasped by the distal fingers and proximal palm to compute two orthogonal components of force and the longitudinal COP through which the force acts.

Method: Sixteen healthy, right-handed participants grasped the multiaxis dynamometer with plastic handles ranging in diameter from 3.81 to 7.62 cm. They were required to scale their effort to 25%, 50%, 75%, and 100% of maximum.

Results: Grip force vector angles were affected by both handle diameter and effort level, with angles increasing an average of 8.1° from the least to greatest effort. Longitudinal COP, averaged among the two beams, shifted 1.75 cm radially as handle diameter increased from 3.81 cm to 7.62 cm. Average COP along the beam in contact with the distal finger segments shifted 0.75 cm ulnarly as effort level increased from 25% to 100% of maximum.

Conclusion: Grip force characteristics changed with handle diameter and effort level. Overall grip force magnitude comprised both force components measured.

Application: Understanding grip characteristics should be important for handle and grip design and for evaluating hand function.

Keywords: biomechanics, ergonomic design, occupational safety and health, hand dynamometer, grip strength

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INTRODUCTION

Researchers, physicians, therapists, and engineers have long sought to understand the function of hands. Functional hands are imperative for participation in numerous occupational and recreational tasks as well as activities of daily living. Many of the stresses experienced by the hand and upper extremity during grasping might be minimized by incorporating better data on hand function into the design of tools, instruments, equipment, and devices. To aid in understanding hands, researchers have tested grip strength and grip strength characteristics for people of various ages, genders, and geographical locations (e.g., Desrosiers, Bravo, Hébert, & Dutil, 1995; Dong, Wu, Welcome, & McDowell, 2008; Enders & Seo, 2011; Jansen et al., 2008; Mathiowetz et al., 1985; Seo & Armstrong, 2008; Wimer, Dong, Welcome, Warren, & McDowell, 2009). In many of these grip studies, subjects performed maximum voluntary contractions (MVCs), and force was measured along one axis often using the Jamar (J. A. Preston Corporation, Jackson, MI, USA) hand dynamometer. Grip MVC data have aided in handle design (Kim, Yun, & Lee, 1996; Kong & Lowe, 2005; Lee, Kong, Lowe, & Song, 2009), in finding links between grip strength and upper-extremity function (Hyatt, Whitelaw, Bhat, Scott, & Maxwell, 1990; Ranganathan, Siemionow, Sahgal, & Yue, 2001), in illness complication (Windsor & Hill, 1988; Griffith, Whyman, Bassey, Hopkinson, & Makin, 1989), and even in mortality (Gale, Martyn, Cooper, & Sayer, 2007).

To fully understand how the hand produces force, one needs to consider multiple components of force. Measurement of multiple components of force provides greater insight into the neural control of grasp, twisting, and dynamic manipulation especially in the absence of electromyographic data. Presumably, grasp force coordination is driven by the desire not only to stably grasp an object but also to satisfy other neuromuscular constraints (e.g., minimization of muscle stress). As such, measurement of multiple grasp force components could provide a better diagnostic tool for assessing grasp dysfunction than traditional single-axis force measurements. For these reasons, it is advantageous to consider multiple grasp force components when possible.

Therefore, researchers have sought other means to quantify the forces involved in gripping. Some have developed instrumented devices capable of quantifying more relevant grip-related force variables (Amis, 1987; Edgren, Radwin, & Irwin, 2004; Fowler & Nicol, 1999; Jensen, Radwin, & Webster, 1991; McGorry, 2001). Other researchers have used pressure mats or instrumented gloves to quantify grip forces (Hall, 1997; Kong & Freivalds, 2003; Kong & Lowe, 2005; Radwin, Oh, Jensen, & Webster, 1992; Seo & Armstrong, 2008), but instrumented gloves and mats have been typically incapable of measuring shear forces and were limited to localized forces. Regardless of measurement method, independent studies on grip strength in which hand aperture varied report that the amount of grip force people can exert changes as handle diameter changes (e.g., Edgren et al., 2004; Fitzhugh, 1973; Oh & Radwin, 1993; Seo & Armstrong, 2008; Seo, Armstrong, Ashton-Miller, & Chaffin, 2007). Additionally, studies have demonstrated that force direction changes as diameters vary (Edgren et al., 2004; Irwin, Towles, & Radwin, 2013). This finding means the ratio of normal to shear force changes based on hand geometry and is potentially very important to proper hand-handle interface design. Related to this finding, Enders and Seo (2011) found that subjects modulated normal and shear force components when performing maximal gripping tasks in response to changes in surface friction.

The contributions of individual fingers during gripping and pinching are unclear. Some studies indicate finger contributions are similar regardless of effort level and handle size (Amis, 1987; Talsiania & Kozin, 1998) and object weight (Reilmann, Gordon, & Henningsen, 2001), whereas others report varying contributions (Irwin et al., 2013; Radwin et al., 1992).

Understanding the forces exerted by each individual finger is important for handle design, as geometry could conceivably be tapered to improve the efficiency and minimize the stress of each finger (Lee et al., 2009).

The objective of the current study was to examine grip force direction and finger contribution for varying handle diameters and power grip intensity. This goal was accomplished using a multiaxis dynamometer, which quantifies two orthogonal components of force in a reference frame located at the center of the hand and quantifies the longitudinal center of pressure (COP), which determined the location of the origin of the force reference frame.

METHOD

Device

The multiaxis dynamometer described by Irwin et al. (2013) was used in the current experiment. It consisted of two instrumented beams for the fingers and a static reference beam for the thumb. The static reference beam served two functions. First, it was a stationary reference point from which the instrumented beam deflections, and therefore the forces applied, can be measured. Second, it eliminated artefact forces produced by the thumb. An adjustable flange was connected to the thumb beam and its cap when gripping smaller diameter handles to ensure the thumb did not come into contact with the instrumented beams.

This dynamometer has been tested for reliability and validity in different populations (Irwin & Sesto, 2010). An overhead view of the dynamometer, showing the proximal and distal beam vectors as well as the convention for defining resultant vector angle, is shown in Figure 1. We report the measured force components in a reference frame located along the center axis of the handle (Figure 1) to standardize force measurements for different size handles.

Similar to the approach used by Radwin, Masters, and Lupton (1991); Edgren et al. (2004); and Wimer et al. (2009), this device utilizes strain gauges mounted in a manner that ensures that the force measurements do not depend on the point of application on the beam by measuring shear stress inside pockets milled at the base of the beam using four strain gauges mounted at 45° angles to the neutral axis (Figure 2). Equation 1 describes the

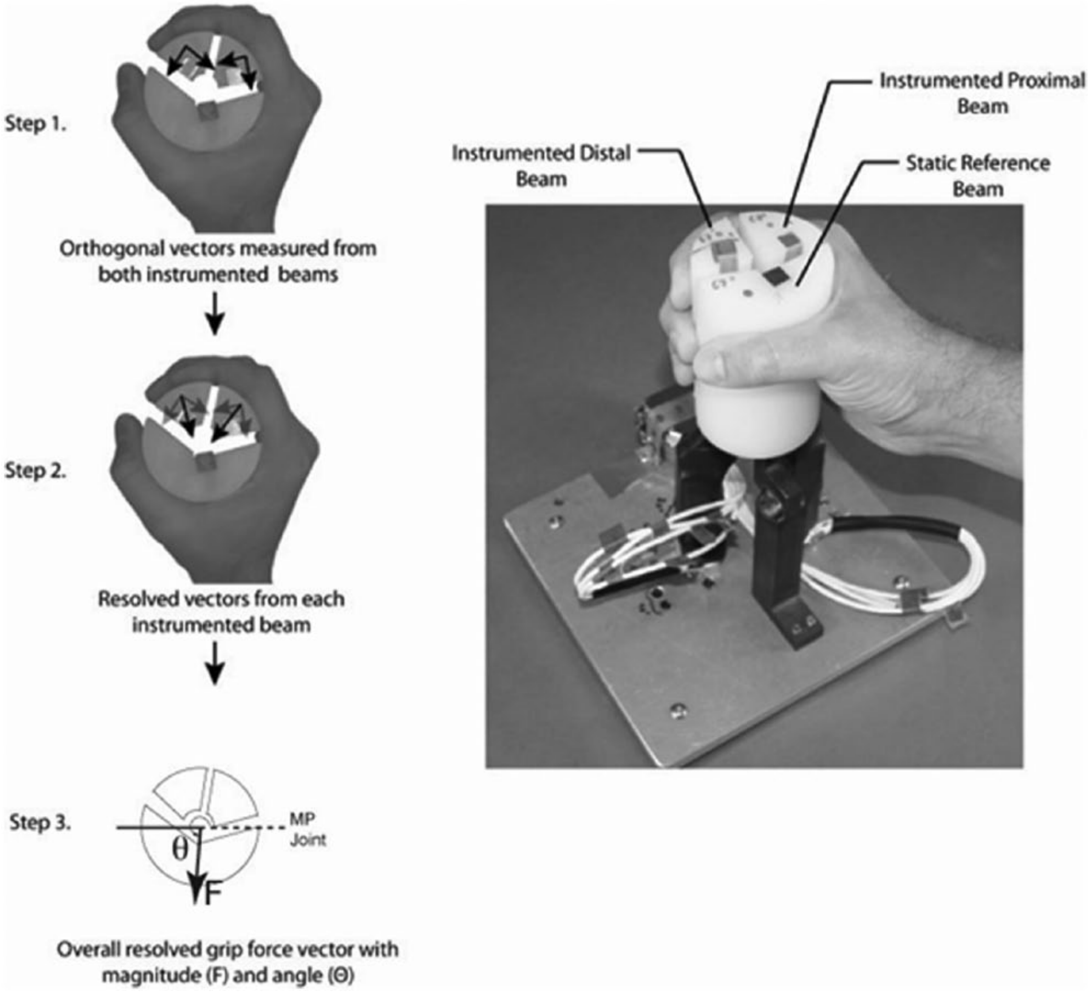

Figure 1. Multiaxis dynamometer with 6.35-cm cover. Components of grip force were measured by proximal and distal instrumented beams (Step 1). Grip force was calculated after a vector transformation to express the resultant force (Step 3) in a reference frame with the origin located along the center axis of the handle in between the instrumented (fingers) and reference (thumb) beams. The longitudinal center of pressure determined the location of the origin of the reference frame along the central axis of the handle. The direction of the force was referenced relative to a horizontal axis extending from the origin away from the metacarpophalangeal (MP) joint. The MP joint was at the level of the dotted line. The index finger metacarpal joint for each subject was positioned at the level of the gap between the proximal instrumented and reference beams. Note that this reference frame differs from Edgren, Radwin, & Irwin (2004).

relationship used to estimate force applied to each beam.

$$F \propto \sigma = \frac{mc}{I}, \qquad (1)$$

where F = force against beam, σ = shear stress in the beam, m = moment from applied load, c = distance from neutral axis, and I = moment of inertia of the beam.

An additional set of bending strain gauges allows calculation of the longitudinal (ulnar-radial direction relative to the hand) COP of grip using the classic bending moment (M) measured by the gauges and force (F) obtained from the pocket

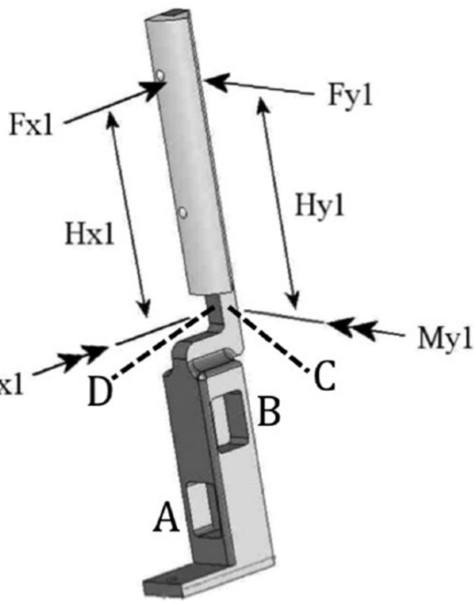

Figure 2. Measurement capabilities of one instrumented beam. At the base of the beam, strain rosettes—each consisting of four strain gauges arranged in a Wheatstone bridge configuration on opposing surfaces—were used to quantify two components of force (fx, fy) applied to an instrumented beam. Pockets were milled at the base of the beam (A, B) to allow placement of strain gauges nearly along the long axis of the beam so that the applied force could be measured independent of the point of application. In the middle area of the beam, two strain gauges were placed on opposing surfaces at C and D to quantify moment components produced by the applied force components. Computed moment and force values were used to calculate Hx, Hy, which were in turn averaged to calculate the center of pressure of force application for a given beam. Note that Hx = Mx/Fy and Hy = My/Fx. As such, the vertical center of pressure was referenced to the location C or D, the location of the base of the cap affixed to each instrumented beam (white, Figure 1), before data collection.

gauges on each instrumented beam (Figure 2). The COP for each instrumented beam was calculated using the relationship in Equation 2 and was referenced to the base of affixed cap (white, Figure 1).

$$\text{COP} = 0.5\left(\frac{M_x}{F_x} + \frac{M_y}{F_y}\right) \tag{2}$$

As Equation 2 indicates, the reported COP for each beam is the mean of the COP values calculated from force and moment components. The COP determined the location of the origin of the reference axis for the forces along the center axis of the handle (Figure 1). It is worth noting that the calculation of longitudinal COP is uncommon for uni- and multiaxial force. The advantage of this calculation is that it facilitates measurement of force when multiple fingers are in contact with the dynamometer.

Whereas the Edgren et al. (2004) dynamometer had a single instrumented beam with a unidirectional sensor that requires 90° rotation and two exertions in order to measure force vectors, the multiaxis dynamometer has two orthogonal instrumented sensors in each beam and a noninstrumented beam that serves as a static reference (Figure 1). Consequently, only a single exertion is required. The thumb is isolated on the reference beam while the long fingers interact with the instrumented beams. Unlike the Edgren et al.'s dynamometer, the multiaxis dynamometer quantifies two independent force vectors, one located distally on the fingers and one proximally. The vectors from each beam are transformed to express the resultant grip force vector in a reference frame whose origin is at the center of the handle (Figure 1). This origin was chosen to provide a measurement that could be standardized across handles of different diameters. Moments (force couples) that might have resulted from transforming the forces were not accounted for.

Participants

Sixteen individuals (8 male and 8 female), ranging in age from 22 to 49 years old, participated. Average hand length was 18.5 cm (*SD* =1.6 cm) and average hand breadth was 8.1 cm (*SD* = 0.7 cm). The subjects were all right hand dominant and required to be injury free in the right arm.

Participants were interviewed and pertinent demographic data were collected. They were paid on an hourly basis and the experimental protocol was reviewed and approved by the University of Wisconsin Human Subjects Committee.

Experimental Design

The experiment contained two independent variables (four handle diameters and four effort levels). Right-hand grip force measurements were taken using four cylindrical handles of varying diameter (3.81 cm, 5.08 cm, 6.35 cm, and 7.62 cm). Effort level varied from 25% to 50% to 75% to 100% of maximum voluntary contraction (MVC). The dependent variables included the force magnitudes from each instrumented beam (N); the angles of the resulting force vectors, which are defined in Figure 1; and longitudinal COP heights for the resultant force vectors (Equation 2).

Procedures

Prior to testing, participants were interviewed and demographic and anthropometric data were collected via questionnaire. These data included height, weight, hand length and breadth, and information on previous upper-extremity injuries. Participants were excluded if they had a prior hand injury. After the anthropometric and demographic data were collected, participants sat in an adjustable-height chair and were instructed to grasp the multiaxis dynamometer in the posture recommended by the American Society of Hand Therapists (Mathiowetz et al., 1985) for grip testing with the forearm rotated in a neutral position and the elbow held at the side and flexed 90°.

The metacarpophalangeal (MCP) joint of each participant's index finger was aligned to a reference point on the handle for consistency between trials (Figure 1). This reference point also ensured accurate calculation of longitudinal COP.

Participants first performed MVC grasps to establish a baseline strength measurement from which the subsequent grip force targets were calculated. The submaximal grip efforts required participants to match their force magnitude to force targets represented visually on a computer screen. These targets were depicted as a horizontal bar. The real-time combined grip force vector magnitude was displayed as a longitudinal column that originated at the bottom of the computer screen and grew in height proportional to the increase of grip force magnitude. Subjects were allowed practice trials to learn the grip force target acquisition task.

The subjects were presented with randomized target grip forces at each level of percentage MVC for each handle size. The handle size order was randomized, as was percentage MVC within each handle size. However, all the percentage MVC trials were completed within each handle size before the next handle size was tested. Handle size was varied by applying different size caps to the instrumented and reference beams (white covers, Figure 1).

Participants were instructed to maintain the grip force at each target level for 5 s. Verbal instructions of when to begin and end each trial were provided. Three grip exertions were replicated for each combination of handle diameter and effort level with a 1-min rest provided between exertions. The first and last second of the 5-s exertion was eliminated from the analysis to ensure the force had stabilized. The average forces, angles, and longitudinal COPs for the intervening seconds were calculated. The results of the three replications were averaged.

Repeated-measures ANOVA was used to determine significant effects for effort level and handle diameter on grip force, angle, and longitudinal COP. The significance level was set at .05.

RESULTS

Average MVC levels for the different handles are shown in Figure 3 stratified by gender. Maximum grip force magnitude decreased with handle diameter, $F(3, 13) = 29.76$, $p < .01$. The overall grip force vector angles are listed by handle diameter and effort level in Table 1. Overall grip force vector angles were affected by both handle diameter, $F(3, 11) = 47.78$, $p < .01$, and effort level, $F(3, 11) = 14.06$, $p < .01$, with angles increasing as effort level increased and decreasing as handle diameter increased. The interaction effect of Handle × Effort Level was not significant ($p > .05$).

A breakdown of the scalar magnitudes of the forces measured for each beam is shown in Figure 4, indicating that a larger proportion of the

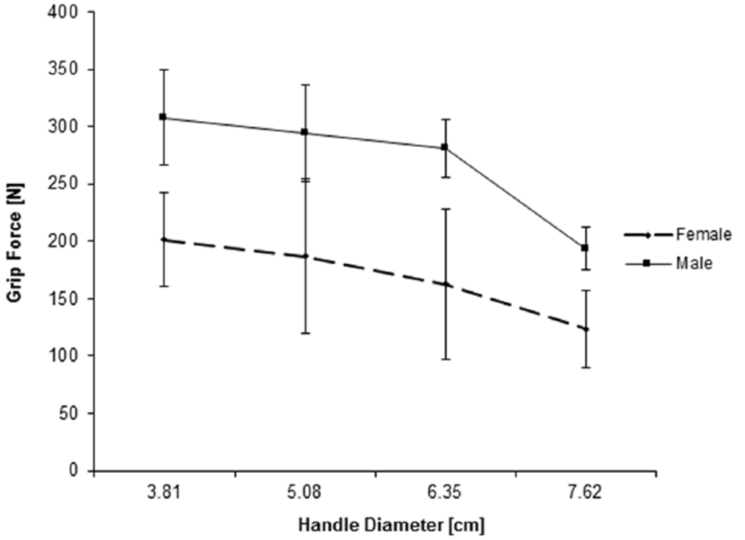

Figure 3. Maximal grip force vector magnitudes. Grip force magnitude decreases with handle diameter for both males and females.

TABLE 1: Grip Force Vector Angles (in degrees)

	Percentage Maximum Voluntary Contraction							
	25%		50%		75%		100%	
Handle	*M*	(*SD*)	*M*	(*SD*)	*M*	(*SD*)	*M*	(*SD*)
3.81 cm	122.6	(13.5)	127.7	(14.3)	129.2	(12.8)	129.4	(7.3)
5.08 cm	100.4	(5.7)	101.9	(8.4)	106.4	(7.0)	110.8	(6.3)
6.35 cm	93.7	(11.8)	95.6	(10.8)	98	(8.3)	99.5	(5.3)
7.62 cm	76.2	(11.3)	80.7	(11.2)	84.1	(9.8)	85.6	(7.5)

force contribution was from the distal portions of the fingers as effort level increased. As the distal portions of the fingers produce proportionately more force, it has the effect of rotating the overall grip force clockwise with respect to reference axis (Figure 1).

Data from the torque gauges were used to calculate the longitudinal COP for both beams (Irwin et al., in press). Results averaged by effort level and by handle size are provided in Table 2 and Figures 5 and 6. Both proximal, $F(3, 12) = 16.22$, $p < .01$, and distal, $F(3, 12) = 38.35$, $p < .01$, longitudinal COPs of the proximal and distal instrumented beams increased with handle diameter, and the distal beam longitudinal COP decreased with effort level, $F(3, 12) = 23.90$, $p < .01$. The interaction between handle and effort level for both the proximal and distal beams was not statistically significant ($p > .05$).

DISCUSSION

Previous research has demonstrated that maximal grip force is highly dependent on handle geometry (Blackwell, Kornatz, & Heath, 1999; Edgren et al., 2004; Irwin & Radwin, 2009; Kong & Lowe, 2005; Lee et al., 2009; Oh & Radwin, 1993; Seo et al., 2007; Seo & Armstrong, 2008). These measurements of maximal grip forces have been used to design handles and other hand-device interfaces. Similar to other studies, the current results concur that maximum grip force is highly dependent on

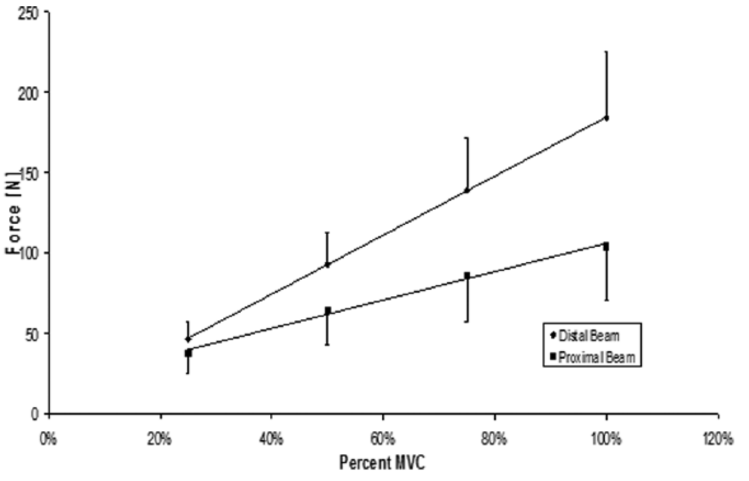

Figure 4. Scalar magnitude of the grip force vectors measured by each individual beam. The distal bean measured a larger portion of grip force applied by the fingers than the proximal beam. MVC = maximum voluntary contraction.

TABLE 2: Vertical Centers of Pressure for Varying Handle Diameters and Effort Levels (in centimeters)

	Vertical Center of Pressure Height by Percentage MVC							
	25%		50%		75%		100%	
Beam	*M*	(*SD*)	*M*	(*SD*)	*M*	(*SD*)	*M*	(*SD*)
Proximal	6.90	(0.67)	6.99	(0.57)	7.00	(0.78)	7.04	(1.11)
Distal	6.76	(0.92)	6.50	(0.94)	6.24	(0.93)	5.98	(0.86)
	Vertical Center of Pressure Heights by Handle Diameter							
	3.81 cm		5.08 cm		6.35 cm		7.62 cm	
Beam	*M*	(*SD*)	*M*	(*SD*)	*M*	(*SD*)	*M*	(*SD*)
Proximal	5.97	(0.26)	6.77	(0.06)	7.68	(0.16)	7.50	(0.34)
Distal	5.37	(0.26)	5.89	(0.38)	6.88	(0.42)	7.35	(0.32)

Note. Center of pressure was measured relative to base of the cap affixed to the instrumented beams (Figure 1). MVC = maximum voluntary contraction.

handle diameter, with participants producing the greatest grip force for the 3.81-cm and 5.08-cm handles (Figure 3; Table 1).

Whereas others have shown that grip force magnitude compared against handle diameter was shaped like an inverted *U* (Edgren et al., 2004; Fitzhugh, 1973; McDowell, Wimer, Welcome, Warren, & Dong, 2012; Oh & Radwin, 1993; Seo & Armstrong, 2008), we conclude that demonstration of the inverted *U*, the ascending region alone or the descending region alone, partly depends on the range over which muscle fibers of the involved muscles operated, as muscle fiber length helps to determine the force-generation capacity of muscle (McMahon, 1984). Perhaps in the current study, the variation in grip force with handle diameter could be represented only by the descending region of the inverted *U* given muscle anatomical

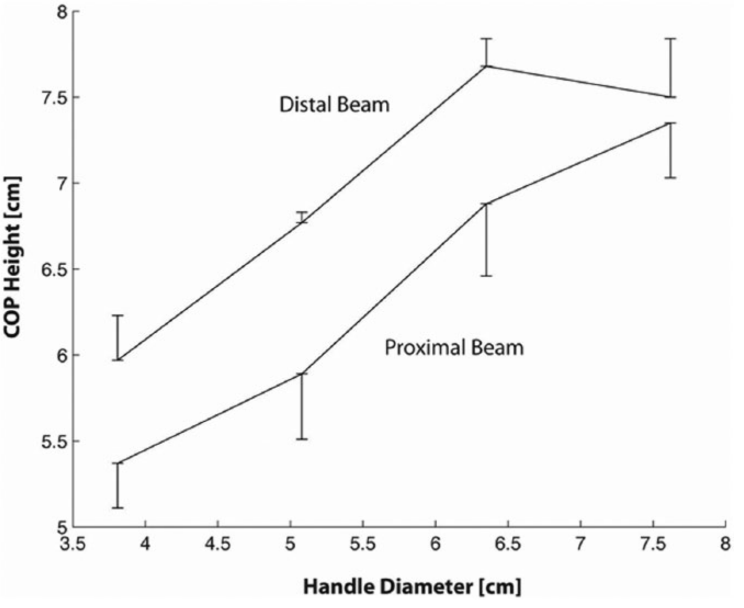

Figure 5. Vertical centers of pressure (COPs) versus handle diameter. Vertical centers of pressure generally increased with handle diameter for both instrumented beams.

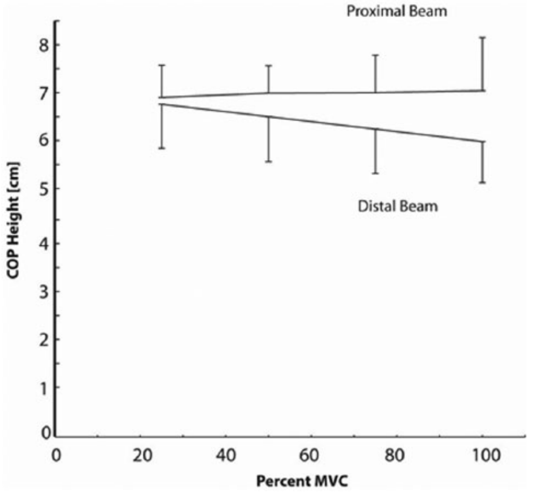

Figure 6. Vertical centers of pressure (COPs) versus percentage maximum voluntary contraction (MVC). Vertical center of pressure for the distal beam decreased with effort.

constraints, subject hand dimensions, and the exertion levels involved.

Few researchers (Amis, 1987; Edgren et al., 2004; Enders & Seo, 2011) have investigated multiple grip force components during a gripping task. Amis (1987) observed that although shear forces were smaller than normal forces, they were considerable particularly for handle diameters less than 5 cm. They concluded that shear forces may still significantly affect moments acting about the joints, particularly when considering the lever arms of fingertip forces acting about the MCP joints. Wu, Dong, McDowell, and Welcome (2009) found that MCP joint moment increases with handle diameter during a maximum-gripping task. In light of Amis (1987), perhaps an increase in shear force during grip might partially account for the increase in joint moment with handle diameter. Although the reported variation in the vector angles of grip forces with handle diameter in this study could represent changes in the balance between normal and shear forces (Table 1), our data do not permit commenting on the exact nature of that balance (i.e., insufficient to resolve) given that we report force components expressed to a reference frame at the center of the handle.

When comparing grip force vector angles for different-sized handles, we posit that much of the shift in vector angle is likely due to differences in hand size relative to the handles. A future study in which we express forces against a reference frame on the handle surface could reveal shear forces that are considerable in magnitude relative to normal force, as Amis (1987) found for a single finger. Wu et al. (2009) found that MCP joint moment increases with handle diameter during a maximum-grip-force generation task. The effect of hand size on the variation in grip force angle with handle diameter agrees with the results of previous studies (Edgren et al., 2004; Seo & Armstrong, 2008) in which two-dimensional grip force was measured in men and women with various-sized hands.

What cannot be explained by simple hand geometry alone is the change in vector angle for different effort levels for similar handle sizes. The average angles in the current study increased a total of 6.8°, 10.3°, 5.8°, and 9.4° from the 25% effort to the MVC effort level for handles 3.81 cm, 5.08 cm, 6.35 cm, and 7.62 cm, respectively (Table 1). These angular changes, however, were not statistically different from handle to handle. Notably, hand size had no effect as the average angle increase was fairly consistent regardless of hand size. As we stated earlier, the interaction effect of handle diameter and effort level was not significant ($p > .05$). This finding means that the quantity of the variation in grip force angle with effort (e.g., slope) for any handle diameter did not differ. Enders and Seo (2011) showed that an increase in the amount of friction between skin and the object being grasped increases the ratio of shear to normal force produced during maximum force generation. In the future, it would be worthwhile to determine if an increase in friction between the fingers and handle in this study would lead to an effect of handle diameter on the grip force angle-effort relationship. It is conceivable that a larger handle would provide greater opportunity for modulating shear-force/normal-force balance and thus effect the force readings expressed relative to the center of the handle.

Figure 4 demonstrates that the scalar force contributions from the distal phalanges increase at a greater rate than the force magnitudes from the proximal phalanges as effort level increases. If the fingertips were producing a relatively greater amount of force as effort level increases, this force would necessitate the flexor digitorum profundus (FDP) contributing more to the grip. The FDP tendon is the only flexor tendon that creates flexion at the distal finger joints. More research is therefore needed to determine if muscle co-contraction of the FDP and flexor digitorum superficialis is altered by effort level. The interaction effect of handle by effort level was not significant ($p > .05$).

Grip longitudinal COP increased as handle diameter increased (Table 2; Figures 5 and 6). The longitudinal COP moved up toward the thumb for both the proximal and distal beams. Although this finding is similar to what was observed in the previous MVC study (Irwin et al., in press), there is a relative difference of individual beam COP variation with handle diameter. This finding could be explained by differences in the hand sizes of the groups tested. It could also be explained by the difference in grip exertions applied in each study. In Irwin et al. (in press), subjects produced only maximal exertions while gripping each handle. In the current study, subjects produced a range of grip exertions. The COPs for each of those were averaged and plotted in Figure 6. At any rate, the overall displacement of the longitudinal COP for each beam could be explained by reduced force contribution from the little finger. Perhaps, as the handle diameter increased, the little finger gradually extended to postures whereby it was increasingly difficult to exert force against the handle. As a result, the COP moved up and away from the little finger toward the index and middle fingers.

Examining the longitudinal COP reveals that as effort level increased, the distal beam longitudinal COP height decreased. This decrease in longitudinal COP was slightly more than 0.75 cm. These data suggest that for submaximal efforts, the index and middle fingers produce a larger proportion of the distal force, and as effort level increases, the ring and little fingers are more heavily recruited. It is presently unclear why the proximal forces do not appear to follow the same trend. Although the variation in longitudinal COP could reflect endpoint force production changes as described earlier, it could have also been due to variations in vertical placement of the fingers by subjects, as we controlled general vertical hand location but not specific finger locations.

Future studies will combine muscle electromyography with grip force measurements to begin to understand neuromuscular control of grip force and COP modulation. Dynamometer capabilities will be extended to measure three-dimensional grip force for dynamic manipulation applications.

The multiaxis hand grip dynamometer used in this study has the capacity to measure loading on the hand that other dynamometers are incapable of measuring by virtue of the presence of additional strain gauges (Figure 1). These data include multiaxis force components and longitudinal COPs resulting from whole-hand contact of the dynamometer. An important question to ask is whether it is ever useful to measure additional components of force. Measurement of multiaxis forces is important during twisting tasks and manipulation tasks (i.e., "dynamic grasping"). One novel application of the dynamometer is to quantify whole-hand force production in persons with neurologic or musculoskeletal injury. In either case, such an individual may have difficulty exerting the usual set normal forces circumferentially for static equilibrium. Rather, it is plausible that one could measure shear force components that represent an injury-induced inefficient grasping pattern or such components that may explain unstable grasping situations.

Also, when measurement of grip force components is coupled with knowledge of COP location relative to the hand, this information may be useful to designers and engineers for developing improved hand interfaces (e.g., handle diameter as a design variable) that, for example, could optimally locate the COP away from vulnerable musculoskeletal anatomy (e.g., superficial nerves and blood vessels that could be subject to prolonged compression; small boney surface where stress concentrations could be large).

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KEY POINTS

- Multiaxis power grip strength magnitude was dependent on handle diameter.
- Handle diameter and effort level influenced the two orthogonal forces measured.
- Handle diameter influenced both proximal and distal longitudinal centers of pressure.
- Effort level influenced distal center of pressure.

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