# Investigation of Grip Force, Normal Force, Contact Area, Hand Size, and Handle Size for Cylindrical Handles

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**Objective:** To investigate relationships among grip forces, normal forces, contact area for cylindrical handles, handle diameter, hand size, and volar hand area. **Background:** Data describing those relationships are needed to predict thrust forces and torque capability. **Method:** Additional analyses were performed retrospectively on data collected in two previous studies in which participants performed maximum grip exertions on cylinders (diameter 38–83 mm) while grip force, normal force, and contact area were recorded. The length, width, and volar area of the hand were measured. **Results:** Average total normal force on cylinders was 2.3 times greater than grip force measured using a split cylinder ($R^2$ = 65%), regardless of the handle diameter examined. The ratio of handle diameter to hand length explained 62%, 57%, and 71% of the variances in grip force, normal force, and contact area, respectively. Estimated hand area (hand length × width) had a linear relationship with measured hand area (using photographs; $R^2$ = 91%), although it was 8% less than the measured area. **Conclusion:** This work describes the relationship between normal force and grip force independent of handle size (for handle diameters from 38 to 83 mm). Normal force and contact area can be explained by the interaction between handle size and hand size. Hand area can be estimated by hand length times width. **Application:** The quantitative relationships described in this paper can be used in the design of objects and hand tools to determine optimal handle sizes for maximizing grip force, total normal force, or contact area.

## INTRODUCTION

Most grip strength measurements use a dynamometer in which the fingers press one handle against another one that is supported in the palm (Bao & Silverstein, 2005; Greig & Wells, 2004; Peebles & Norris, 2003). The handles are separated by a mechanical or electrical force transducer that measures the resulting grip strength. The Jamar® is a widely used example (Blackwell, Kornatz, & Heath, 1999; Hanten et al., 1999; Härkönen, Piirtomaa, & Alaranta, 1993; Mathiowetz et al., 1985). Grip strength is also measured using a cylinder split along its long axis (i.e., a split cylinder; Ayoub & Lo Presti, 1971; Dong et al., 2004; Edgren, Radwin, & Irwin, 2004; Grant & Habes, 1993; Grant, Habes, & Steward, 1992; Irwin & Radwin, 2008; Marcotte, Aldien, Boileau, Rakheja, & Boutin, 2005). This cylindrical dynamometer closely approximates many of the handles used in activities of work, daily living, and leisure (Dong, Wu, Welcome, & McDowell, 2008), whereas the Jamar®-type grip dynamometer would be appropriate for estimating grip strength for tasks such as gripping wire cutters.

Grip is applied to produce normal surface forces that compress the grip object in the hand. This action occurs when two people shake hands and when a health care provider squeezes a patient's forearm using his or her hand to stop bleeding. In many cases, grip is applied to produce torque that prevents objects from rotating in the hand – for example, twisting the handle of a screwdriver or turning a door knob. Grip force is also applied to produce thrust forces that prevent objects from sliding out of the hand – for instance, pulling on a railing or swinging a baseball bat.

Thrust force can be computed by integrating shear force acting in the longitudinal direction of the handle (Seo, Armstrong, Chaffin, & Ashton-Miller, 2008a; Smaby, Johanson, Baker, Kenney, Murray, & Hentz, 2004). Torque can be computed

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by integrating the product of the shear force and the moment arm about the axis of rotation (Seo, Armstrong, Ashton-Miller, & Chaffin, 2007; Seo, Armstrong, Chaffin, & Ashton-Miller, 2008b). The maximum shear force is related to the product of the normal force and the static coefficient of friction at a given point of contact between the hand and the grip object. Thus, normal force is more relevant for estimation of torque or thrust force than is grip force measured using a Jamar®-type grip dynamometer or split cylinder.

Normal forces have been measured on limited parts of the hand using pressure sensors (Fellows & Freivalds, 1991; Gurram, Gouw, & Rakheja, 1993; Gurram, Rakheja, & Gouw, 1995; Hall, 1997; Kong, Freivalds, & Kim, 2004; Kong & Lowe, 2005a, 2005b; Kong, Lowe, Lee, & Krieg, 2007; Lee & Rim, 1991; Pylatiuk, Kargov, Schulz, & Doderlein, 2006) or force transducers (Amis, 1987; Radhakrishnan & Nagaravindra, 1993). The total normal force on the hand during power grasp was measured only recently by Welcome, Rakheja, Dong, Wu, and Schopper (2004) and Aldien, Welcome, Rakheja, Dong, and Boileau (2005) during submaximal push and grip exertions.

Data for total normal force during maximum grip are scarce. Contact area during power grasp has been measured using paper wrapped around handles touched by a greased or inked hand (Pheasant & O'Neill, 1975; Yakou, Yamamoto, Koyama, & Hyodo, 1997) or using pressure sensors (Welcome et al., 2004). However, the correlation between contact area and hand size has not been investigated, although contact area may largely be influenced by the hand size. Toward this end, data that describe the relationship among normal force, grip force, contact area, and hand size are needed for various handle sizes.

The aim of this work was to investigate the relationship between grip forces and normal forces applied to cylindrical handles and hand size (Aim 1) and the relationship between grip contact area, handle diameter, and measured and estimated hand areas (Aim 2).

## METHODS

### Procedures

To achieve the stated aims, we performed additional analyses on data that had been collected in two previous studies (Seo, Armstrong, & Ashton-Miller, 2006; Seo et al., 2007). For both studies, participants performed maximum grip exertions with the right hand for 5 s while in a seated posture, with the elbow flexed at about 90° and the forearm semipronated. Cylindrical handles or a Jamar® grip dynamometer was presented vertically in front of the participants and grasped in a power grip posture.

In the first study (Seo et al., 2006), grip strength was measured using a Jamar® grip dynamometer and split cylinders for four grip spans and diameters and for two split cylinder force gauge orientations (see Table 1 for details). Total normal force and contact area during maximum grip exertions were also measured for cylindrical handles that were covered with a pressure-sensitive pad (see

**TABLE 1:** Test Conditions for Studies 1 and 2

| | Study 1 (Seo et al., 2006) | Study 2 (Seo et al., 2007) |
|---|---|---|
| Jamar® grip span (mm) | 35, 49, 63, 77 (circumference = 100, 130, 160, 180) | 49 |
| Split cylinder diameter (mm) | 38, 51, 64, 76 (circumference = 120, 160, 199, 239) | 45, 58, 83 |
| Split cylinder force gauge | Parallel and perpendicular to the forearm | Parallel to the forearm |
| Hand size/area measurement | Hand length and width | Hand length and width, photo hand area |
| Dependent variables | Grip strength measured using a Jamar® grip dynamometer and split cylinders<br>Contact area and total normal force measured using pressure sensors | |

*Note.* Study 1 data from Seo et al., 2006; Study 2 data from Seo et al., 2007.

Apparatus section for details). In the second study (Seo et al., 2007), Jamar® grip strength, split cylinder grip strength, normal force, and contact area during maximum grip exertions were measured again with the participant in the same posture for three different cylinder diameters during maximum grip exertions (see Table 1 for details).

In addition, we recruited the participants in the second study again to measure their hand areas using photographs. The dorsum of the hand was flat against a tabletop, which had a sheet of white paper with a rectangular frame (20 × 25 cm) drawn in the middle. The frame was large enough to include the entire hand in it. The four fingers were parallel with one another other and the thumb was abducted away from the hand while the palmar side of the hand was photographed against the white background using a digital camera positioned approximately 70 cm above the center of the hand.

Later, the photos were opened in Adobe® Photoshop®. Any forearm portion (proximal to the first wrist crease) that appeared in the rectangular frame was deleted. Then the photos were converted from color to black-and-white photos using Adobe® Photoshop®. The percentage of black (hand) within the rectangular frame was automatically calculated in Adobe® Photoshop®. The hand area was determined by multiplying the area of the rectangular frame times the percentage of black. This "photo hand area" was compared to "estimated hand area" – hand length times width.

For the two previous studies (Seo et al., 2006, 2007), participants' hand length and width were measured as described in Garrett (1971). Hand length was measured from the middle fingertip to the first wrist crease of a flat hand. Hand width was measured from the second to the fifth metacarpal (Garrett, 1971). Each handle diameter or grip size condition was tested twice and presented to participants in a random order. Two-minute breaks were given between consecutive trials.

## Apparatus

Grip strength was measured using a Jamar® dynamometer or using a split cylinder, in which the two halves of the cylinder are connected by a force gauge (Ayoub & Lo Presti, 1971; Dong et al., 2004; Edgren et al., 2004; Grant & Habes, 1993; Grant et al., 1992; Irwin & Radwin, 2008; Marcotte et al., 2005). The split cylinder was covered with an approximately 305- × 107-mm pressure-sensitive pad (FSCAN DB, Tekscan Pressure Measurement System; Tekscan Inc., Boston, MA; measurement error within 6%) by applying tapes around the pad rim. The pressure pad covered all areas of the cylinder that were touched by the hand. One pad had a total of 954 pressure sensors. Normal pressure was recorded on each 5.08- × 5.08-mm sensor. Each pressure-sensitive pad was calibrated by applying a known weight to the pad on a flat surface.

Total normal force was calculated by summing normal forces (normal pressure × sensor size) on all sensors around the cylinder surface (Aldien et al., 2005; Seo et al., 2007; Welcome et al., 2004). The contact area between the hand and handle was estimated by multiplying the sensor size times the number of pressure sensors that registered pressure (threshold = 5 kPa; Seo et al., 2007; Welcome et al., 2004). Because of difficulties with wrapping the pressure-sensitive pad around a small cylinder, the pressure sensors were used only for handle diameters ≥51 mm.

Except for Jamar® dynamometer grip strengths, all data were recorded in a personal computer at 5 Hz using LabView (National Instruments, Inc., Austin, TX). Data were averaged over 2 s during maximum grip exertions. Statistical analyses were performed using MINITAB®.

## Participants

The first study (Seo et al., 2006) collected data for 6 participants (3 men and 3 women, 23–36 years of age, mean age 27.5 years). The second study (Seo et al., 2007) collected data for 12 participants (6 women and 6 men, 21–35 years of age, mean age 26.7 years). Three participants (1 man and 2 women) were common between the two studies. All participants were free of any upper extremity disorders and gave written informed consent prior to testing. When the two-study participants were combined, the mean hand length was 19.1 ± 1.4 cm for men and 17.1 ± 0.8 cm for women. The mean hand width was 8.3 ± 0.3 cm for men and 7.5 ± 0.5 cm for women. The hand lengths ranged from the 1st to 99th percentiles for men and from the 1st to 67th percentiles for women, based on the U.S. Air Force population data from Garrett (1971).

# RESULTS

## Grip Force and Normal Force

Seo et al. (2006; Study 1) previously reported grip strengths measured using a Jamar® dynamometer and split cylinders and normal forces on cylinders during maximum grip exertions. The force data from Seo et al. (2006) are summarized in Figure 1a. Seo et al. (2007; Study 2) previously reported split cylinder grip strengths and total normal forces. In the present work, additional analyses were performed for the data collected in the two studies. Findings are summarized as follows.

Handle diameter and Jamar® grip strength could explain 61% of the variance in grip strength measured using the split cylinder (see Figure 1b). Average total normal force on cylindrical handles was 2.3 times greater than split cylinder grip strength (Figure 1c; $p < .01$). A linear relationship between normal force and split cylinder grip strength was found in Figure 1c ($R^2 = 65\%$). This relationship did not significantly change for different handle diameters ($p > .05$).

Both split cylinder grip strength and normal force decreased with increasing ratio of handle diameter to hand length (D/L) and hand size (either hand length [L] or width [W]), as shown in Figure 1d ($p < .05$). Gender did not have a significant effect on split cylinder grip strength or normal force when D/L and hand size were controlled ($p > .05$),

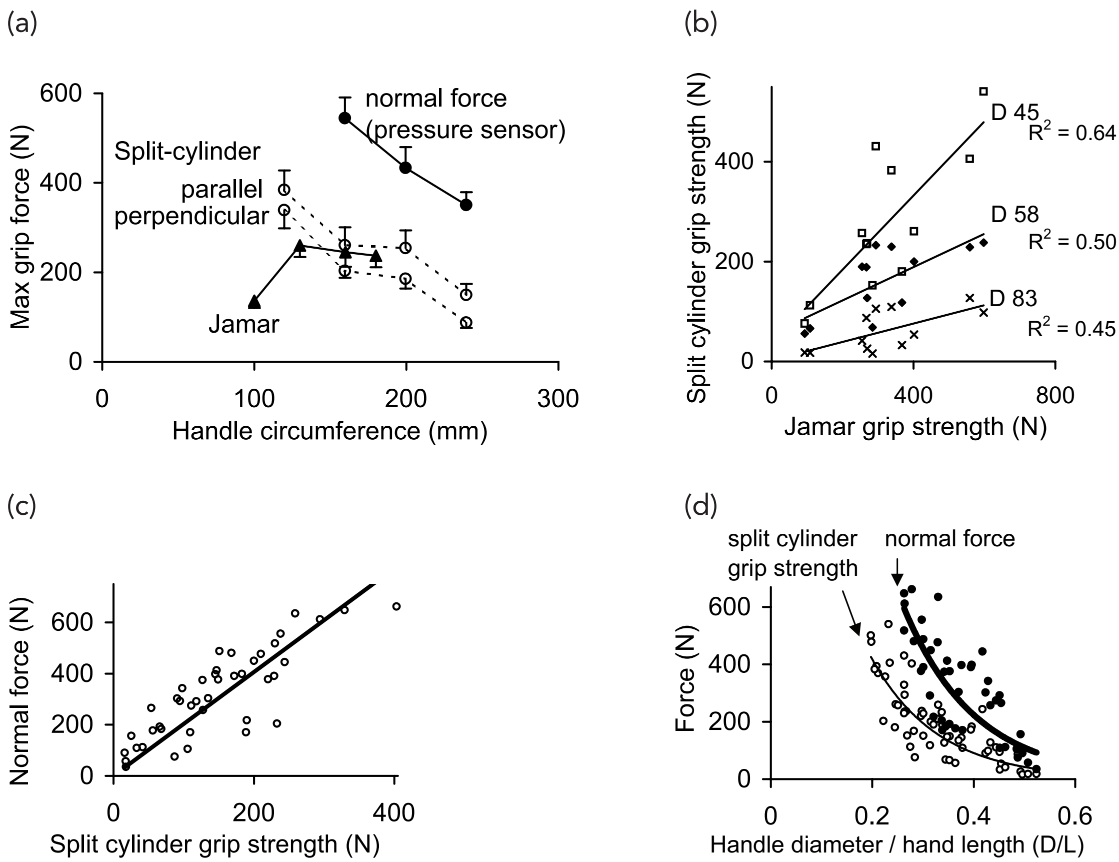


*Figure 1.* (a) Mean ± *SE* Jamar® grip strength (▲), split cylinder grip strength with its force gauge parallel to the forearm and perpendicular to the forearm (●), and total normal force measured using pressure sensors (○) for different handle circumferences. (Panel a from "Grip Forces Measured with Different Methods" by N. J. Seo, T. J. Armstrong, and J. A. Ashton-Miller, 2006, in *Proceedings of the 16th World Congress of the International Ergonomics Association,* New York: Elsevier Science. Copyright 2006 by Elsevier. Adapted with permission.) (b) Split cylinder grip strength as a function of Jamar grip strength for handle diameters (D) of 45, 58, and 83 mm (Study 2; data from Seo et al., 2007); split cylinder force gauge parallel to the forearm; Jamar setting = 2). (c) Normal force as a function of split cylinder grip strength (Studies 1 and 2 pooled; data from Seo et al., 2006, 2007); split cylinder force gauge parallel to the forearm only. (d) Split cylinder grip strength and normal force as a function of the ratio of handle diameter to hand length (D/L; Studies 1 and 2; data from Seo et al., 2006, 2007); split cylinder force gauge parallel to the forearm only. D = handle diameter, L = hand length, W = hand width, D/L = ratio of handle diameter to hand length.

although average grip strength and normal force were 46% greater for men than for women. Average hand length was 12% greater for men than for women. The D/L alone could explain 62% and 57% of the variance in split cylinder grip strength and normal force, respectively.

### Contact Area and Hand Area Estimation

Seo et al. (2006; Study 1) previously reported contact area for four handle diameters. Contact areas measured for three different handle diameters in Study 2 were not reported in Seo et al. (2007). In the present work, the contact area data collected in the two studies were combined. Analyses performed in the present work show that the mean contact area was the greatest for the handle diameters of 51 and 58 mm (Figure 2a). The contact area increased with increasing estimated hand area (Figure 2b). The D/L alone could explain 71% of the variance in contact area (Figure 2c). When D/L was controlled, hand length or width did not significantly affect contact area ($p > .05$).

The estimated hand area (hand length times width) was, on average, 8% less than the hand area measured using photographs ($p < .01$). A significant linear relationship was found between the photo hand area and estimated hand area, as shown in Figure 3.

## DISCUSSION

### Aim 1: Split Cylinder Grip Strength Versus Normal Force

Average total normal force was 2.3 times greater than average split cylinder grip strength (Figure 1c). The total normal force is an arithmetic sum of all normal forces around the handle surface, whereas split cylinder grip force measures force in the direction of the force gauge. Split cylinder grip force represents force applied on one half of the cylinder while the same amount of force is applied on the other half of the cylinder in the opposite direction. Thus, split cylinder grip force will be equivalent to one half of the sum of cosines of all normal forces on the handle surface to the force gauge axis, if shear force is not considered.

A linear relationship was found between normal force and split cylinder grip strength (Figure 1c, $R^2 = 65\%$). This relationship did not significantly change for different handle diameters (Figure 1c). This relationship between grip force and normal force presented in Figure 1c may be used to

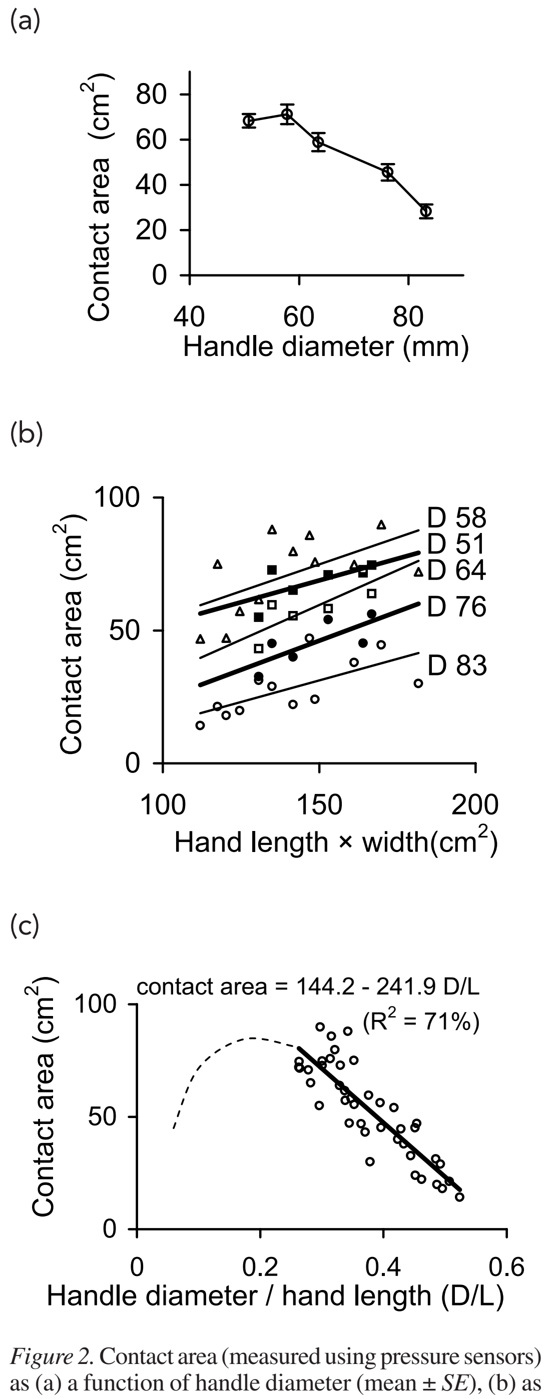


*Figure 2.* Contact area (measured using pressure sensors) as (a) a function of handle diameter (mean ± *SE*), (b) as a function of hand area estimated by multiplying hand length and width for each handle diameter, and (c) as a function of the ratio of handle diameter to hand length. Study 1 and Study 2 pooled (Seo et al., 2006, 2007). (Panel a from "Grip Forces Measured with Different Methods" by N. J. Seo, T. J. Armstrong, and J. A. Ashton-Miller, 2006, in *Proceedings of the 16th World Congress of the International Ergonomics Association,* New York: Elsevier Science. Copyright 2006 by Elsevier. Adapted with permission.)

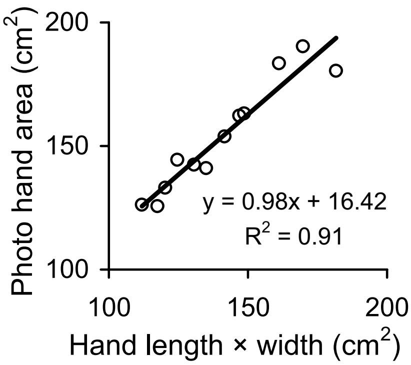


*Figure 3.* The relationship between hand area measured using photographs and hand area estimated by multiplying hand length and width (Study 2).

estimate normal force when only a split cylinder is available to measure maximum grip force for handle diameters from 38 to 83 mm. It is not to be confused with the relationships shown in Welcome et al. (2004), in which different slopes for different handle diameters were reported. In Welcome et al. (2004), the relationship between grip and normal forces was examined while participants increased their grip force from 0 to 75 N (submaximal). In the present studies, the relationship between the maximum grip force and normal forces during maximum grip exertions was examined for different handle diameters and participants.

Different measures of grip force or normal force may be preferred depending on the types of tasks being analyzed. Normal force may be the most relevant for tasks involving torque or thrust force generation. Split cylinder grip strength may be preferred for tasks in which workers squeeze a cylindrical handle. For tasks involving squeezing parallel bars, such as gripping wire cutters, Jamar® type dynamometers may be used for estimating grip strength.

A major drawback of a split cylinder is that grip force measurement changes with orientations of the split cylinder force gauge about its long axis (Figure 1a; Dong et al., 2008; Edgren et al., 2004; Seo & Armstrong, 2006). Thus, when a split cylinder is used to measure strength capability to use a pivot-action tool, the split cylinder should be oriented the same way as for that tool. For measuring the maximum grip force for a given handle size, a split cylinder may be oriented in the axis that results in the greatest grip force (Dong et al., 2008). In addition, when the equations presented in Figures 1b to 1d are used, it is important to ensure that the split cylinder grip strength is measured using the same force gauge orientation as in the present studies (force gauge oriented parallel to the forearm).

Compared with grip force measurement, normal force measurement has the following advantages. First, normal force measurement is not affected by device or hand orientation. Second, normal force is proportional to friction force as described by Coulomb (1785). Thus, normal force data can be used to predict friction force that is applied during object manipulation, such as lifting (Westling & Johansson, 1984), twisting (Nagashima & Konz, 1986; Pheasant & O'Neill, 1975; Seo et al., 2007, 2008b), and pushing (Seo et al., 2008a; Smaby et al., 2004).

Also, normal force (contact force) affects the transmission of vibration from grip objects to the hand (Dong, McDowell, & Welcome, 2005; Dong et al., 2004; Gurram et al., 1995; Marcotte et al., 2005). Hand-transmitted vibration is a factor in chronic tissue injuries (Gemne & Taylor, 1983). In addition, by using the pressure pad, one can find the principal axis of grip force with one grip exertion, whereas multiple grip exertions in various orientations are needed for a split cylinder (Dong et al., 2008).

A disadvantage of normal force is that measurement of normal force during grip does not include direct measurement of shear force, although shear force is present during grip (Amis, 1987). In the future, it may be possible to develop models for predicting shear force patterns from normal force patterns for given tasks, as the shear force is equal to the normal force times the coefficient of friction.

## Aim 1: Grip Strength and Hand Size

Split cylinder grip strength and total normal force increased with increasing hand size (either hand length or width), even when the interaction between handle diameter and hand length (D/L) was controlled (Figure 1d). Split cylinder grip strength and total normal force were not significantly affected by gender when D/L and hand size were controlled. The contact area did not change significantly with hand size (either length or width) when D/L was controlled (Figure 2c). Thus, the positive correlations between grip strength and hand size and between normal force and hand size are probably not the result of a greater contact area. It may be because people with bigger hands tend to have greater muscular strength (Aghazadeh, Waikar, Lee, Backhouse, & Davis, 1989; Crawford, Wabine, & Nayak, 2002; Yakou et al., 1997).

### Aim 2: Contact Area Versus Handle Diameter

Consistent with Pheasant and O'Neill (1975), contact area was the greatest when the handle diameter was 51 or 58 mm, and it decreased as the handle diameter increased from 58 to 83 mm (Figure 2a). The ratio of handle diameter to hand length (D/L) could explain 71% of the variance in contact area (Figure 2c). It shows that contact area is primarily determined by the interaction between handle diameter and hand size (Figures 2b and 2c).

Two explanations may exist for decreasing contact area with increasing handle diameters (for handle diameters greater than 58 mm). First, reduced grip/normal force with increasing handle diameter (Figures 1a and 1b; Edgren et al., 2004; Grant et al., 1992) may have resulted in less skin deformation on the palmar side of the hand and thus reduced contact area (Bobjer, Johansson, & Piguet, 1993; Bullinger, Kern, & Solf, 1979; Welcome et al., 2004). Second, during gripping, forces are concentrated on the fingertips (Amis, 1987; Gurram et al., 1993, 1995; Kong & Lowe, 2005a, 2005b; Kong et al., 2004, 2007; Lee & Rim, 1991; Pylatiuk et al., 2006; Radhakrishnan & Nagaravindra, 1993; Seo et al., 2007), which can cause the middle and proximal phalanges to lift off as the distal interphalangeal joint rotates, reducing the total contact area as depicted in Figure 4c.

As the handle diameter decreases from 50 to 10 mm, the contact area has been reported to decrease (Pheasant & O'Neill, 1975; Welcome et al., 2004; Yakou et al., 1997). Decrease in contact area for small handle diameters may be attributable to reduced available handle surface area (Pheasant & O'Neill, 1975; Rohles, Moldrup, & Laviana, 1983; Yakou et al., 1997). It may also be because finger flexion creates folds in the skin and results in reduced contact with the handle, as illustrated in Figure 4a (see Figure 5 for summary).

Greater contact area can reduce average pressure for a given normal force on the hand because

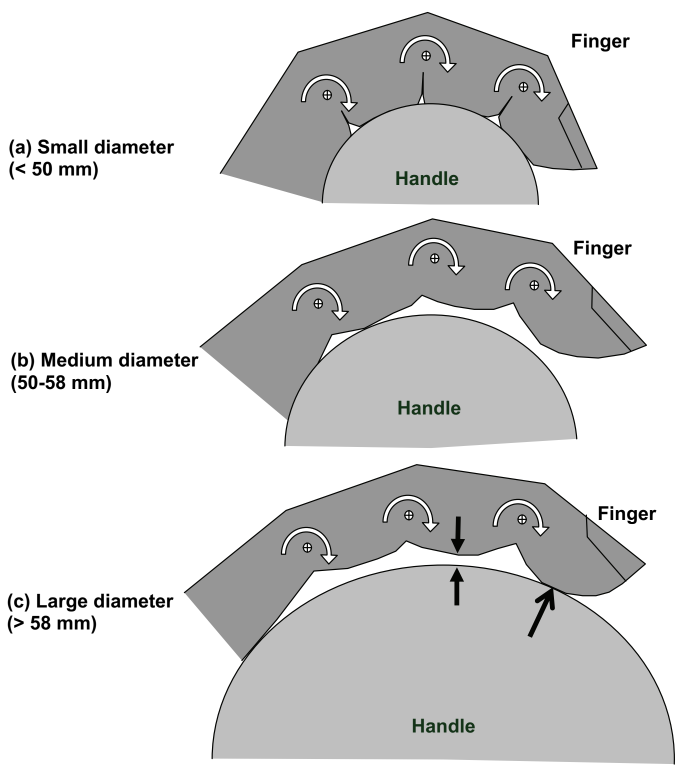


*Figure 4.* Hand-handle fit for (a) small, (b) medium, and (c) large handle diameters. For a small handle diameter, finger flexion results in skin folding and reduced contact with a handle (a). For a large handle diameter, the handle surface may not fit into the curvature of the finger because gripping flexes the fingertip (c).

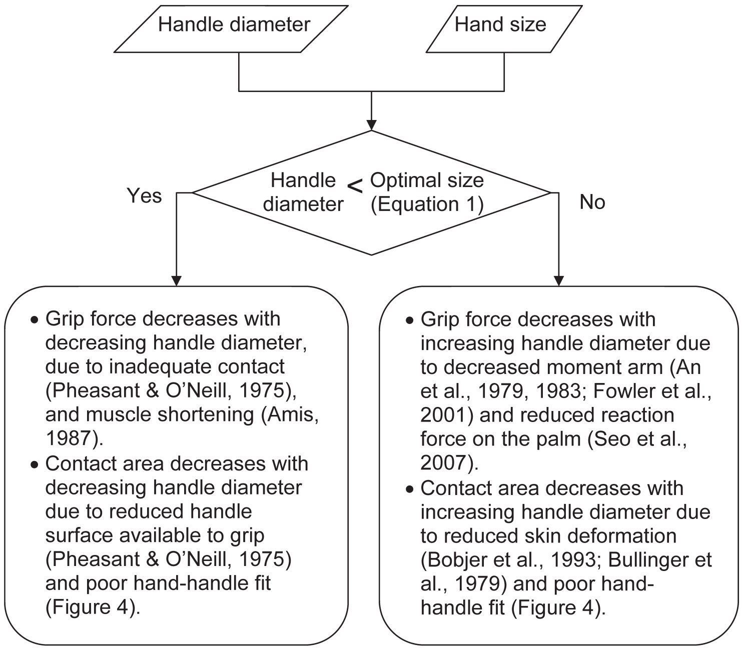


*Figure 5.* Description of the effect of handle diameter and hand size on grip force and contact area, based on previous studies (Amis, 1987; An et al., 1979; Bobjer et al., 1993; Bullinger et al., 1979; Pheasant & O'Neill, 1975; Seo et al., 2007).

average pressure is the ratio of normal force magnitude to contact area. Thus greater contact area may reduce the chances for discomfort or pain from high pressure or pinch (Fransson-Hall & Kilbom, 1993). In addition, greater contact area between skin and an object was shown to be associated with a higher friction coefficient (Bullinger et al., 1979; Comaish & Bottoms, 1971; Seo, 2008; Seo, Armstrong, & Drinkaus, in press). Thus, greater contact area may be preferred when friction force is applied, such as in lifting (Westling & Johansson, 1984), twisting (Nagashima & Konz, 1986; Pheasant & O'Neill, 1975; Seo et al., 2007), and pushing (Seo et al., 2008a; Smaby et al., 2004).

Contact area increased significantly with increasing hand area that was estimated by multiplying hand width and length, as intuitively expected (Figure 2b). Contact area measured during maximum grip was 50% to 20% of the estimated hand area for handle diameters from 51 and 58 mm to 83 mm. This may be because the area of the fingers that actually contacts objects is less than the width of the fingers. The bones of the hand provide stiff frameworks that are surrounded by highly deformable soft tissues. As the hand presses against a hard surface, the contact area increases. The area of contact will depend on the contact force and the size and shape of the underlying bone (Wu & Dong, 2005).

The mechanics of this deformation are quite complex because of the anisotropicity of the soft tissues and the irregular shape of the bones. In addition, the radial side of the thenar eminence is not in contact with objects during grip. Contact area measured during grip may have greater functional implications in object manipulation and discomfort level, as discussed previously, than does estimated hand area.

## Aim 2: Measured Hand Area Versus Estimated Hand Area

The hand area estimated by multiplying hand length times width was 8% less than that measured using photographs. This is probably because hand width was measured from the second to the fifth metacarpal (not including the thumb), which estimates the hand area without the thumb. A linear relationship, described in Figure 3 ($R^2 = 91\%$), may be used to predict the photo hand area.

It is also possible that the hand area was slightly overestimated using photographs because the hand was closer to the camera than the rectangular frame in the background by the thickness of the hand, thereby increasing the angle of view. Using the distance between the palm and the camera lens (70 cm) and assuming 1.5 cm for the hand thickness, it can be calculated that hand area could be overestimated by 4%. In future work, overestimation can be minimized by constructing a frame that is on the same plane as the palm, thus making the distance between the frame and the camera the same as that between the palm and the camera.

## Grip/Normal Force Versus Handle Diameter

Several explanations have been suggested for varying maximum grip/normal force with handle diameter. For handle diameters smaller than the "optimal diameter" (the diameter that results in the greatest grip force or normal force), Pheasant and O'Neill (1975) speculated that normal force is limited by inadequate contact (too little handle surface area available for the hand to work with). Grip/normal force may decrease for small handle diameters because of finger flexor muscle shortening (Amis, 1987), although the change in extrinsic finger flexor muscle force is estimated to be only about 9% (Kamper, Fischer, & Cruz, 2006). When the handle diameter increases from the optimal diameter, fingers open more and moment arms for finger flexor muscles decrease (An, Chao, Cooney, & Linscheid, 1979; An, Ueba, Chao, Cooney, & Linscheid, 1983; Fowler, Nicol, Condon, & Hadley, 2001), which can result in reduced grip and normal forces.

In addition, for large handles, the fingertips and thumb tip are placed in opposition, and thus the major active forces from the fingertips and thumb tip work against each other. This results in little reaction force on the palm, thus reducing total grip/normal force on the hand (Seo et al., 2007; see Figure 5 for summary).

As for the condition of optimal diameter, Seo et al. (2007) suggested that maximum grip/normal force can be achieved when the fingertips and thumb tip work together against the palm, thus resulting in great reaction force on the palm. From Pheasant and O'Neill's (1975) data, it can be seen that normal force was highest when the thumb tip was aligned with the four fingertips. Yakou et al. (1997) speculated that the optimum grasping diameter is when the object is in contact with all fingertips and a full area of palm.

Therefore, the greatest grip/normal force is obtained when the centers of the middle fingertip and the thumb tip are aligned parallel to the long axis of a cylindrical handle (Figure 6a). Thus, the optimal handle diameter can be predicted by the following equation. The middle fingertip length and thumb tip length were estimated to be 0.108 and 0.158 times the hand length, respectively (Buchholz, Armstrong, & Goldstein, 1992).

$$\begin{aligned}\text{Optimal handle diameter} &= (\text{optimal handle circumference})/\pi \\ &= \{\text{inside grip breadth} \times \pi - (\text{middle fingertip length} + \text{thumb tip length})/2\}/\pi \\ &= \text{inside grip breadth} - 0.133 \times \text{hand length}/\pi\end{aligned} \quad (1)$$

Using the mean inside grip breadth (diameter of a circle that can be made by touching the thumb tip with the middle fingertip; Figure 6b) of 49 mm and the mean hand length of 197 mm reported in Garrett (1971) for the U.S. Air Force population,

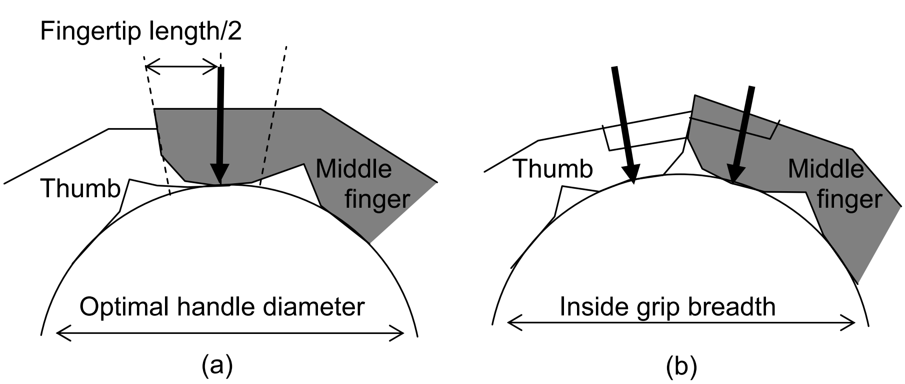


*Figure 6.* Illustrations of (a) optimal handle diameter and (b) inside grip breadth. Thick arrows denote finger force vectors.

the mean optimal handle diameter can be calculated to be 40 mm. It is almost the same as the optimal handle diameter of 38 mm reported by Ayoub and Lo Presti (1971), Edgren et al. (2004), and Yakou et al. (1997), considering that the increment in handle diameters tested in their studies was 5 to 13 mm. It also agrees with the data collected in the two previous studies (Seo et al., 2006, 2007).

### Limitations

The two studies (Seo et al., 2006, 2007) examined handle diameters ranging from 38 to 83 mm only. Decreasing grip strength and normal force for handle diameters smaller than 38 mm could not be demonstrated in these studies, although that is expected from previous studies (Ayoub & Lo Presti, 1971; Edgren et al., 2004). Contact area was examined only for handle diameters from 51 to 83 mm in these studies, although it can be expected that the contact area will decrease as the handle diameter decreases from 51 mm, based on previous studies (Pheasant & O'Neill, 1975; Welcome et al., 2004; Yakou et al., 1997). Future studies should include smaller handle diameters for investigation.

The findings in the present studies are limited to cylindrical handles. Examination of normal force, grip force, and contact area is needed for job analyses concerning different object shapes. The effect of hand posture on hand force distributions and contact areas also needs to be investigated.

## CONCLUSIONS

- Average normal force on cylindrical handles increased proportionally as a factor of 2.3 times grip force measured using a split cylinder for handle diameters from 51 to 83 mm ($R^2 = 65\%$).
- The interaction between handle diameter and hand length (D/L) explained 62% of the variance in grip force (for handle diameters from 38 to 83 mm) and 57% and 71% of the variances in total normal force and contact area, respectively (for handle diameters from 38 to 83 mm).
- Estimated hand area (hand length × width) and measured hand area (using photographs) had a significant linear relationship ($R^2 = 91\%$).
- The quantitative relationships and regression models provided in this paper can be used in the design of objects and hand tools to determine optimal handle sizes for maximizing total normal force or contact area. Total normal force and contact area information can be used as a basis for friction-related studies and applications.

## REFERENCES


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