



ELSEVIER

Available online at www.sciencedirect.com

SCIENCE @ DIRECT®

International Journal of Industrial Ergonomics 35 (2005) 495–507

International Journal of

**Industrial
Ergonomics**

www.elsevier.com/locate/ergon

Optimal cylindrical handle diameter for grip force tasks

Yong-Ku Kong*, Brian D. Lowe

*Robert A. Taft Laboratories, National Institute for Occupational Safety and Health, 4676 Columbia Parkway,
MS C-24, Cincinnati, OH 45226, USA*

Received 19 February 2004; received in revised form 10 August 2004; accepted 17 November 2004
Available online 8 January 2005

Abstract

This study tested maximum grip force on cylindrical aluminum handles to evaluate the relationships between handle diameter (25–50 mm diameter handles), perceived comfort, finger and phalange force distribution, and electromyographic efficiency of finger flexor and extensor muscle activity. A force glove system containing 16 thin profile force sensors was developed to measure finger and phalangeal forces on the cylindrical handles. Participants ($n = 24$) rated the mid-sized handles (30, 35 and 40 mm) as the most comfortable for maximum grip force exertions. Using a polynomial regression the handle diameter that maximized subjective comfort was calculated as a function of the user's hand length. This optimal handle diameter was 19.7% of the user's hand length. Total finger force capability was inversely related with handle diameter. Electromyographic amplitude of the primary flexor and extensor was unaffected by handle diameter, so the efficiency of the muscle electrical activity followed the same relationship with handle diameter as total finger force. Individual finger and phalange force distributions were examined to evaluate their relationship with perceived comfort. A non-uniform finger/phalange force distribution, in which finger force was proportional to finger muscle capabilities, exhibited a stronger correlation with subjective ratings of comfort than a uniform finger/phalange force distribution.

Relevance to industry

Results obtained in this study will provide guidelines to hand-tool designers and manufacturers for maximizing handle comfort based on the user's hand size.

© 2004 Elsevier B.V. All rights reserved.

Keywords: Handle evaluation; Tool design; Finger force; Subjective comfort rating

1. Introduction

Among the various tool handle design characteristics, handle diameter has been studied extensively because it is an important factor to

*Corresponding author. Tel.: +1 513 533 8312;
fax: +1 513 533 8596.

E-mail address: ykong@cdc.gov (Y.-K. Kong).

maximize grip strength, minimize stress on the digit flexor tendons, first metacarpal ulnar collateral and carpometacarpal ligaments (Meagher, 1987), and it can also influence force exertion in manual work (Khalil, 1973; Grant et al., 1992; Blackwell et al., 1999).

Thus, many investigators have tried to obtain the optimal handle diameters of a cylindrical handle shape with subjective comfort rating (Hall and Bennett, 1956: 44–51 mm; Yakou et al., 1997: 30–40 and 27–36 mm for male and female, respectively) and finger force measurement using by force gauge or sensors (Amis, 1987: 31 mm; Chen, 1991: 28 mm). Relatively few studies have considered both finger force and muscle activity using force sensors and electromyography to define the optimal cylindrical handle diameters (Ayoub and Lo Presti, 1971; Grant et al., 1992; Blackwell et al., 1999). Recently, some researchers have focused on the relationship between handle diameter and user's hand size (Grant et al., 1992; Oh and Radwin, 1993; Johnson, 1993; Yakou et al., 1997; Blackwell et al., 1999).

For measuring forces exerted by all fingers, Amis (1987) and Radhakrishnan and Nagaravindra (1993) designed a cylindrical handle instrumented with individual cantilever beams and strain gauges. Lee and Rim (1991) used a pressure-sensitive film, consisting of two paper-like sheets (*Fuji Film, Fuji Photo Film USA, Inc.*) and Gurram et al. (1995) applied EMED sensors (*NOVEL, Beichstrabe, Munich, Germany*) to record and the grip pressure distribution by wrapping these sensors around cylindrical, flat, and curved handle surfaces, respectively. However, all of these systems have limitations in terms of evaluating forces on handles of non-cylindrical shape and in precise positioning of individual sensors underneath the individual fingers and phalanges. To overcome this shortcoming, Radwin and Oh (1992) and Bishu et al. (1993) directly attached FSRs (force sensing resistors; *Interlink Electronics, USA*) on the palmar sides of the fingers to measure finger forces during sub-maximal static pinch and static holding tasks. Some researchers have developed a force measurement glove system by overlaying FSRs on a flexible glove to measure finger force for evaluating garden tools, hand tools and

meat hook handles (Fellows and Freivalds, 1991; Yun, 1993; Kong and Freivalds, 2003).

In the present study, a force glove measurement system was developed by overlaying flexible sensors on a thin glove which can be selected based on the user's hand size. This force glove can be used to measure finger forces on non-cylindrically shaped handles as it allows precise positioning of each sensor to measure forces exerted by all the fingers and phalanges (including head of metacarpal) engaged in a gripping task.

The objectives of this study were to: (1) evaluate the effects of handle diameter and user's hand size on subjective rating of comfort, efficiency of flexor and extensor electromyographic (EMG) activities, and grip/finger force capability; (2) apply a normalized handle size (NHS) measure to derive recommended handle diameters based on users' hand anthropometry; and (3) evaluate the relationship between the force distributions of individual finger and phalange segments and subjective ratings of comfort in a maximum grip force task.

2. Methods

2.1. Subjects

Twenty-four subjects between the ages of 20 and 43 yrs (mean = 26.6 ± 4.24) were recruited through advertisements within the University of Cincinnati community. Each participant was paid at a rate of \$12.00 per hour for participation. Participants were all healthy volunteers and free of known musculoskeletal injuries. At the beginning of the experiment, informed consent was obtained and anthropometric measurements of hand length, defined by the distance from the crease of the wrist to the tip of the middle finger with the hand held straight and stiff, were made. Based on hand length each participant was assigned into one of the following three hand size groups for each gender (Table 1, source: Pheasant, 1986).

2.2. Experimental design

To evaluate the effects of gender, handle diameter and user's hand size on the subjective

Table 1
Group of hand size for each gender

Hand size	Percentile	Female (mm)	Male (mm)
Small	5–30	160.0–169.8	175.0–186.0
Medium	30–70	169.8–180.3	186.0–196.3
Large	70–95	180.3–190.0	196.3–205.0

comfort rating, muscle efficiency and grip finger/phalange forces, a crossed-nested mixed effects design was employed. Six cylindrical handle diameters (25, 30, 35, 40, 45, and 50 mm) were evaluated. There were three levels of hand size groups (small, medium, and large hand sizes) for each gender. Four subjects were assigned to each combination of gender and hand size. Hand size was nested within gender, and subject was nested under the combination of gender and hand size. The subject was considered as a random effects variable and all others were considered as fixed effects variables. This was a balanced design and all handles were assigned in a random order for each participant.

2.3. Instrumentation and apparatus

2.3.1. Force glove system

To evaluate total grip force and individual finger/phalange force, a force glove system was developed by overlaying flexible and thin (0.127 mm) conductive polymer pressure sensors (FlexiForce Sensor, A101-25; Tekscan Inc.) over the pulpy region of each phalange and each metacarpal head to analyze phalangeal forces of the distal, middle, proximal, and metacarpal segments. The sensors were 1.4 cm wide and 23 cm in length, from the end of the connector to the tip of the sensor. The active sensing area is a 0.95 cm diameter circle at the end of the sensor. The output signals from the sensors were sent to a custom-made amplification circuit, designed to provide an output of 0–5 V to the A/D board (DAS 1802HC, Keithley Instruments). Each sensor was placed on the middle of each phalange on a soft and thin (0.15 mm) synthetic leather golf glove and taped with a medical adhesive tape (Fig. 1). The effects of the thickness of glove on the

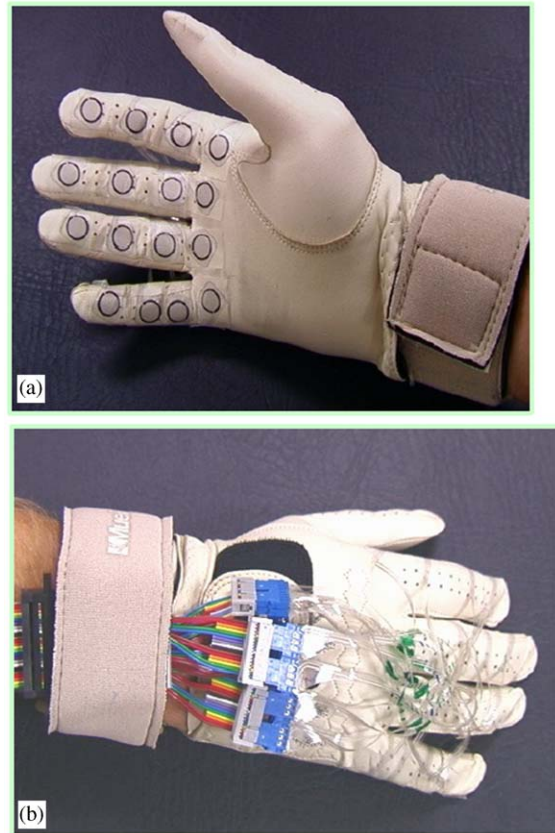


Fig. 1. Finger force measurement system. (a) Volar side, and (b) dorsal side.

magnitude and distribution of the phalange forces were assumed to be negligible. To avoid the effect of the glove size on the force exertion, six sizes of gloves (small, medium, and large sizes for each gender) were used. Each subject chose one of the force gloves according to his/her hand size.

Each FlexiForce sensor was centered over a metal plate of 25 mm diameter mounted over a miniature button-style load cell (force range: 0–22.6 kg) between the metal plate and the thumb of the researcher. The researcher gradually pressed against the sandwiched sensor with the thumb increasing from zero to approximately 22.6 kg and unloading back to zero over about a six-second period. The raw voltage output data from the Flexiforce sensor and the force registered on the load cell were collected at a frequency of 900 Hz

Table 2
Summary of calibration functions for all sensors

Sensor	Fitted linear function	R^2	Sensor	Fitted linear function	R^2
1	Voltage = .0516*Force-.0057	.990	9	Voltage = .0378*Force + .0338	.994
2	Voltage = .0652*Force + .0448	.986	10	Voltage = .0536*Force + .0201	.992
3	Voltage = .0457*Force + .0070	.994	11	Voltage = .0460*Force-.0106	.993
4	Voltage = .0495*Force + .0111	.993	12	Voltage = .0493*Force + .0074	.995
5	Voltage = .0433*Force + .0176	.992	13	Voltage = .0554*Force + .0046	.995
6	Voltage = .0561*Force + .0218	.991	14	Voltage = .0440*Force-.0006	.995
7	Voltage = .0551*Force + .0317	.992	15	Voltage = .0418*Force-.0020	.992
8	Voltage = .0525*Force + .0075	.994	16	Voltage = .0512*Force + .0174	.994

for eight seconds. Voltage output from the Flexiforce sensors was linearly regressed against force to establish the relationship between the sensor output and applied force. Table 2 shows high linearity between voltage output and applied force for typical 16 sensors ($0.986 < R^2 < 0.995$). Each Flexiforce sensor was calibrated individually and a set of 16 sensors was calibrated separately for each subject.

2.3.2. Electromyographic measurement system

The electromyographic (EMG) activity of flexor digitorum superficialis (FDS) and extensor digitorum (ED) were acquired at a sampling frequency of 1000 Hz. The raw signals were digitally filtered using a 6th order Butterworth filter with a 10–350 Hz pass band, and then expressed as the signal RMS (50 ms).

Surface electrodes were positioned over the bellies of the primary digit flexor, FDS, and the primary extensor, ED, parallel to the longitudinal axis of these muscle fibers as recommended by Zipp (1982).

2.4. Experimental procedures

Participants were provided with a brief description of the purposes and procedures of the experiment. All participants were asked to perform a maximum isometric grip exertion for five seconds with two repetitions for each combination, and were provided with two minutes of resting time between repetitions.

2.4.1. Dependent variables

During the maximum grip exertions, the individual finger forces and two EMG muscle activities (FDS and ED) were measured by the force glove system and EMG measurement system, respectively. At the end of each task, participants were asked to rate overall comfort on a 7-point scale, which was modified based on Yakou et al. (1997).

1. *Total finger force*: This was obtained by summing the 16 individual sensors (Eq. (1)), attached on the palmar side of the hand:

$$F_{\text{total}} = \sum_{j=1}^4 \sum_{i=1}^4 [F_{ij}], \quad (1)$$

where F_{total} is the total grip finger force (N), and F_{ij} is the each segment force ($i = 1$, index; 2, middle; 3, ring; 4, little; and $j = 1$, distal; 2, middle; 3, proximal; 4, metacarpal).

2. *Muscle efficiency*: Surface EMG from the flexor and extensor (FDS and ED) were recorded for each handle during the maximum gripping task. The total finger force and muscles' EMG activities were normalized relative to the maximum value measured among all handles, and the muscle efficiency was defined by the ratio of the normalized total finger force to the normalized muscle activity (Eq. (2)):

$$\text{Muscle efficiency} = \frac{\text{Normalized total grip finger force}}{\text{Normalized muscle activity}}. \quad (2)$$

3. *Subjective comfort rating:* All participants were asked to provide subjective ratings of overall finger and hand comfort associated with each handle. Ratings were obtained using a comfort scale with the following numerical values used as indices of the degree of comfort (very comfortable, 7; moderately comfortable, 6; somewhat comfortable, 5; neutral, 4; somewhat uncomfortable, 3; moderately uncomfortable, 2; and very uncomfortable, 1).

3. Results

3.1. Subjective comfort rating

Statistical analysis showed that handle diameter is a significant factor on the subjective rating of comfort ($p < .0001$). Fig. 2 shows the results of the evaluation of subjective comfort ratings in the maximum gripping task. Tukey’s multiple comparison shows that participants rated mid-sized handles (30, 35, and 40 mm) as significantly more comfortable than the other sizes. The 50 mm handle was rated as the least comfortable handle. The highest comfort ratings were obtained for the 35 mm handle for females and the 40 mm handle for males, although the difference between males and females was not statistically

significant. The natural anthropometric differences between genders explain the smaller preferred handle diameter for females compared to males.

3.2. Subjective comfort rating vs. normalized handle size (NHS)

Normalized handle size was applied to determine the optimum handle diameter for maximizing comfort based on the user’s hand size in this isometric maximum gripping task. The ratio of handle circumference to user’s hand length was considered as a ‘Normalized Handle Size (NHS)’ which was defined by the following equation (Kong, 2001, Eq. (3)):

$$NHS_{ij} = \frac{HC_j}{HL_i} * 100, \tag{3}$$

where i is the subject, j the handle, NHS_{ij} the normalized handle size of subject i for handle j , HC_j the circumference (mm) of handle j , HL_i the hand length (mm) of subject i .

The following regression model (Eq. (4)) and Fig. 3, representing the relationship between subjective comfort rating and NHS, was used to derive the NHS that maximizes subjective rating of handle comfort.

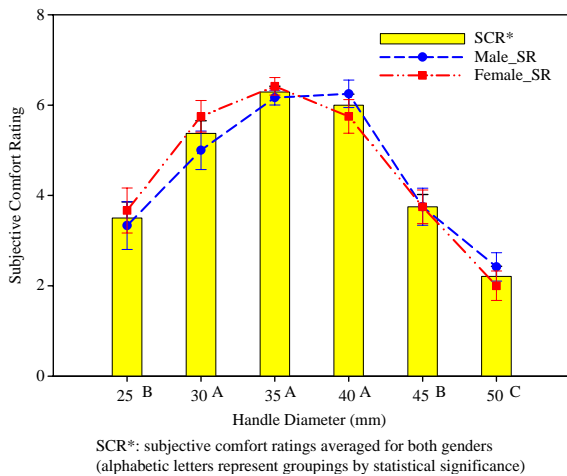


Fig. 2. Subjective comfort ratings for handle diameter.

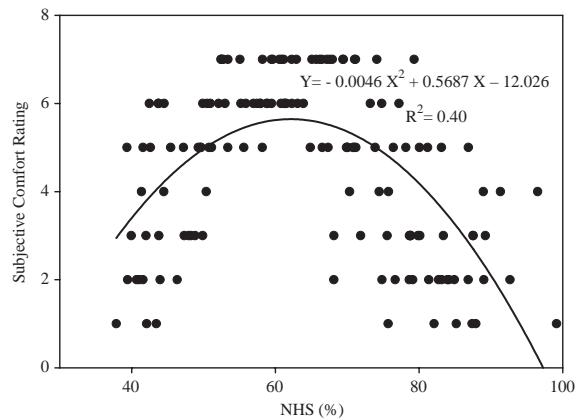


Fig. 3. The relationship between subjective comfort rating and NHS.

Subjective comfort rating

$$= -0.0046 * (NHS)^2 + 0.5687 * (NHS) - 12.026. \quad (4)$$

An NHS between 50.9% and 72.7% corresponded to comfort ratings of 5 (somewhat comfortable) or better. The optimal NHS at 61.8% was obtained based on the first derivative of the Eq. (4), $[NHS\% = 0.5687 / (2 * 0.0046)]$. The optimal NHS can be used to derive recommended handle diameters according to the user's hand length [i.e., handle diameter = user's hand length * NHS/ π], as shown in Table 3.

3.3. Total and individual finger/phalange forces

The individual finger force was defined as the sum of the four phalangeal segment forces for that finger, and the total finger force was defined by the sum of all four finger forces, from index to little fingers. A significant gender effect was found with respect to the total finger force. On average, females (323.96 N) exhibited about 57.6% as much total finger force capability as that of males (562.3 N).

The results also showed that there was a significant negative correlation between the total finger force and handle diameter, i.e., the total finger forces decreased as the cylindrical handle diameter increased (Fig. 4). The trends of finger forces in both genders are similar. The decrease between 25 and 30 mm handles was the least (11.6%), whereas the decrease between 40 and 45 mm handles was the largest (23.5%).

The individual finger and phalange forces were clearly related to handle diameters (Fig. 4). Fig. 4a indicates that the middle finger produces the maximum force with the 30 mm diameter handle and the other fingers produced their maximum force with the 25 mm diameter handle. This probably reflects the effects of differences in finger lengths. Fig. 4b shows the average individual phalange forces for various handle diameters. It indicates that the distal phalange produced the largest force, followed by the middle, proximal, and metacarpal phalanges. Overall metacarpal phalange force was the least, except in the small handle diameters where the force of the metacarpal phalange was higher than that of the proximal phalange, though the difference was not statistically significant.

Table 4 summarizes individual and total finger force in addition to the contribution of individual finger/phalange forces to the total finger force as a function of handle diameter. The average contribution of the middle finger to the total grip finger force was highest (34.8%), followed by ring (26.5%), index (24.9%), and little (13.8%) finger in that order. There were statistically significant differences in forces between ring and middle fingers, whereas there were no significant differences between index and ring fingers. The contribution of the little finger was the lowest. An average of 41.6% of total grip finger force was exerted by the distal phalanges, 23.7% by the middle phalanges, 19.0% and 15.7% by the proximal and metacarpal phalanges, respectively.

The mean percentage contributions of the index and ring fingers were generally constant (at approximately 25% and 27%, respectively) across

Table 3
Recommended handle diameters for maximizing subjective comfort

Hand size	Female		Male	
	Hand length (mm)	Handle diameter (mm)	Hand length (mm)	Handle diameter (mm)
Small ^a	160.0–169.8	31.5–33.4	175.0–186.0	34.4–36.6
Medium ^a	169.8–180.3	33.4–35.5	186.0–196.3	36.6–38.6
Large ^a	180.3–190.0	35.5–37.4	196.3–205.0	38.6–40.3

^aSmall: 5–30 percentile; medium: 30–75 percentile; large: 75–95 percentile for each gender.

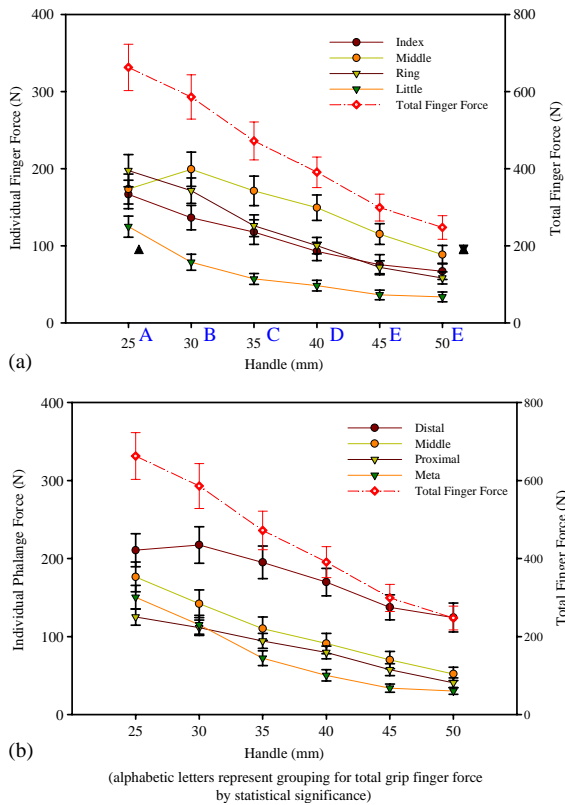


Fig. 4. Total and individual finger/phalange forces for handle diameters. (a) Total and individual finger forces, and (b) total and individual phalange forces.

the range of cylindrical handle diameters, with a slightly increasing pattern for the index finger and a slightly decreasing pattern for the ring finger. The smaller handles show higher contributions from the ring finger than from the index finger, whereas the order of contributions is reversed for the larger handles. The contribution of the little finger was generally constant across handle diameters, except for the 25 mm handle which showed a relatively higher contribution. The contribution of the middle finger increased as the handle diameter increased up to 40 mm. The increase of the middle finger contribution was notably larger (by 8%) between the 25 and 30 mm diameter handles. The smallest handle, 25 mm, was associated with the most evenly distributed phalange forces. The analysis of phalange force indicated that the distal phalange always exerted and

Table 4
The total/individual finger and phalange forces and contributions

Handle (mm)	Total finger force (N)	Mean forces of individual fingers and percentage contributions				Mean forces of individual phalanges and percentage contributions			
		Index	Middle	Ring	Little	Distal	Middle	Proximal	Meta
25	662.8	166.6 N (25.14%)	173.7 N (26.20%)	197.5 N (29.80%)	125.0 N (18.85%)	210.7 N (31.79%)	176.5 N (26.63%)	125.0 N (18.87%)	150.5 N (22.71%)
30	586.0	136.4 N (23.28%)	199.3 N (34.01%)	171.5 N (29.27%)	78.8 N (13.44%)	217.4 N (37.10%)	142.1 N (24.25%)	111.4 N (19.00%)	115.1 N (19.65%)
35	472.1	117.8 N (24.96%)	171.3 N (36.27%)	126.0 N (26.69%)	57.1 N (12.09%)	195.1 N (41.32%)	110.2 N (23.34%)	94.5 N (20.01%)	72.4 N (15.33%)
40	390.9	92.7 N (23.72%)	149.5 N (38.24%)	100.3 N (25.65%)	48.4 N (12.39%)	169.9 N (43.46%)	91.2 N (23.32%)	79.6 N (20.36%)	50.3 N (12.87%)
45	299.3	75.5 N (25.22%)	115.3 N (38.51%)	72.2 N (24.12%)	36.4 N (12.15%)	137.5 N (45.95%)	70.1 N (23.42%)	57.7 N (19.28%)	34.0 N (11.35%)
50	247.7	67.0 N (27.05%)	88.5 N (35.72%)	58.4 N (23.56%)	33.9 N (13.67%)	124.4 N (50.22%)	52.2 N (21.08%)	40.9 N (16.51%)	30.2 N (12.20%)
Mean	443.1	109.4 N (24.9%)	149.6 N (34.8%)	121.0 N (26.5%)	63.2 N (13.8%)	175.8 N (41.6%)	107.0 N (23.7%)	84.8 N (19.0%)	41.9 N (15.7%)

maintained greater force than the other phalanges for all handle diameters tested. The contributions of forces exerted by phalanges varied with handle diameter. The average force contribution of the distal phalange increased from 32% to 50%, whereas the average force contributions of the other phalanges exhibited a constant or slightly decreasing pattern as the handle diameter increased. The smallest handle, 25 mm, exhibited the most evenly distributed phalange forces. Similar trends in individual finger forces and distal phalange forces were reported by Lee and Rim (1991), although there were no data for the forces of metacarpal phalanges in their study.

3.4. Efficiencies of flexor and extensor muscles

The efficiencies of the flexor (FDS) and extensor (ED) muscle activities were analyzed to obtain the optimal handle diameter in the gripping task. The total finger force and muscle EMG activities were normalized for each handle diameter and each subject, respectively. Normalization was relative to the maximum value obtained across handles. Efficiency of the electrical activity was defined by the ratio of the normalized total finger force to the normalized muscle EMG activity (Eq. (2), Section 2.4). Statistical analyses showed that handle diameter had a significant effect on the efficiencies of both muscles. Muscle efficiencies associated with smaller diameter handles were higher than those of larger diameter handles i.e., participants exhibited greater total finger force with the same amount of EMG activity with the small diameter handles than with the large diameter handles. This effect can be attributed to a reduction in total finger force capability as handle diameter increased. The normalized flexor and extensor EMG activity was relatively unaffected by handle diameter, whereas the normalized total finger force showed a decreasing trend as the handle diameter increased (see Fig. 5).

4. Discussion

The evaluation of subjective handle comfort ratings indicated that participants preferred mid-

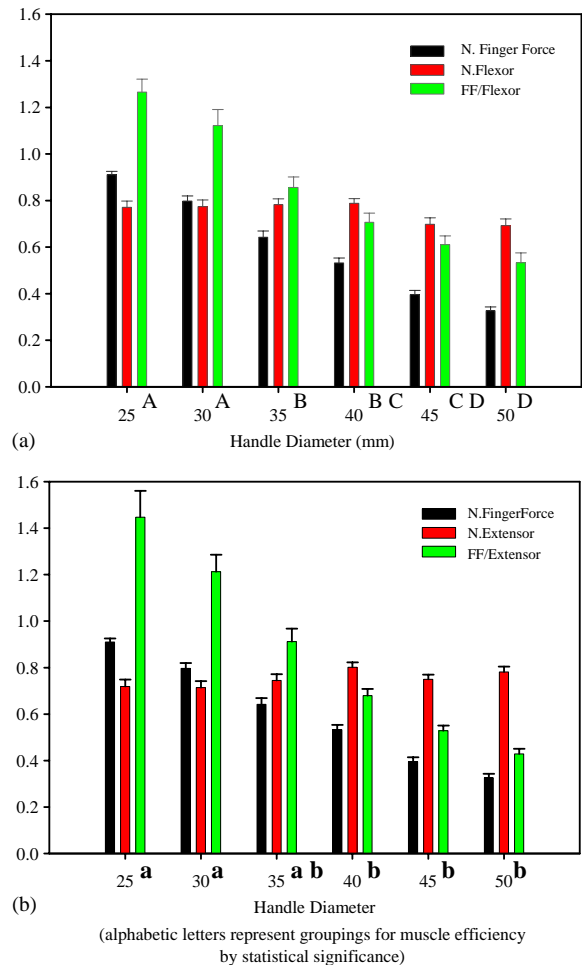


Fig. 5. Normalized finger force/muscle activity and muscle efficiency. (a) Flexor (flexor digitorum superficialis), and (b) extensor (extensor digitorum).

sized handles over the smallest or largest handles which were associated with highest or lowest total finger forces, respectively. In this investigation subjective ratings did not appear to be heavily influenced by impressions of total gripping finger force. This finding was contrary to that of Magill and Konz (1986) who reported that subjective ratings of handle comfort were dominated by impressions of task performance (i.e., torque output) in the evaluation of handle size in a torque task.

All participants were categorized based on the NHS to predict the most comfortable handle

diameter according to their hand sizes. A 61.8% NHS was calculated as the optimal ratio, and was applied to make the recommendations for handle diameters in Table 3. One of the advantages of the NHS calculation is that handle diameters can be assigned to users who have different hand lengths rather than assigning only one size of handle diameter to everyone. Although customization of handle diameter to users' hand size has been suggested by other researchers (Grant et al., 1992; Yakou et al., 1997; Blackwell et al., 1999), these recommendations have typically been made in terms of broad ranges. The NHS findings in the present study may provide a guideline for determining the handle diameter best suited for an individual user's hand size in a gripping task and can be applied in the design of hand tools.

The total finger force, which was defined as the sum of all phalangeal segments showed a significant inverse relationship with handle diameter as the fingers were more extended to grasp larger handles. The forces imposed by the middle finger and distal phalanges were always significantly higher than those imposed by the other fingers and phalanges, respectively. In addition, the contributions of the middle finger and distal phalange to the total finger force were increased as the handle diameter increased. Similar findings were reported by Amis (1987), Lee and Rim (1991), and Radhakrishnan and Nagaravindra (1993) in evaluations of the effect of cylindrical handle diameter in a maximum gripping task. The average maximum finger force capability for females (323.9 N) was 58% of that for males (562.3 N), which is within the ranges reported in previous studies: 51% by Hunter et al. (1978), 66% by McMullin and Hallbeck (1992), and 69% by Hall (1997).

As mentioned in Section 3.3, the smallest handle showed the most uniform phalange force distribution. The smaller handles created a biomechanical configuration that was described by Replogle (1983) in which the fingers more completely encircle the handle and the phalanges can generate forces that effectively counter act one another. As the handle diameter increased, the percentage of the cylindrical handle surface covered by the fingers decreased, thereby reducing the effective-

ness of the phalanges in creating counter acting forces. This was particularly evident in the case of the metacarpal phalanges. In the present study, the analyses of force and contribution for individual phalanges (Table 4) showed that the forces and contributions of metacarpal phalanges at the smaller handles (83.3 N, 22.7% and 64.0 N, 19.7% for 25 and 30 mm handles, respectively) decreased dramatically with the larger handles (18.9 N, 11.4% and 16.8 N, 12.2%).

Finger forces showed a decreasing trend as the fingers were extended to grasp larger handles. When handle diameter increases, the fingers become less flexed. The index finger, the ring finger and the little finger (which are all shorter than the middle finger) may lose some of their mechanical leverage advantages and may thus lose the ability to exert more force (Chen, 1991). In addition, the little finger may be extended to produce a longer relative muscle length with minimal cross-bridge attachments, whereas the middle finger might be at a more optimal muscle length for maximal cross-bridge attachments (Blackwell et al., 1999). Thus, handles should be designed that vary in size between hand and finger sizes to maximize force capability for each finger. According to this study, the middle finger provided maximum force capability with the 30 mm diameter handle, whereas the other fingers produced a maximum force with the 25 mm diameter handle. This indicates that handle shape should be considered in addition to handle diameter in handle design.

To further explore the relationship between subjective comfort and individual phalangeal segment contribution to total finger force, an optimization algorithm was applied (described in Appendix A). The theoretical basis of this algorithm was that to maximize handle comfort, as a function of cylindrical diameter, each finger contributes to the total finger force production in proportion to its muscle force capability. An et al. (1985) assumed that the force production capabilities of extrinsic finger flexor muscles were distributed in proportion to their physiological cross-sectional area (PCSA). The algorithm assumes that handle comfort is inversely related to the sum of the absolute differences between

measured and ideal phalangeal force distributions (*SADFD*). The ideal phalangeal force distribution for the purpose of the optimization was based on two alternatives. The first alternative for the ideal phalangeal force distribution was a non-uniform distribution in which finger force capability was based on the PCSA data of extrinsic muscles of the finger flexors and the average phalange force contributions for each finger. These data were obtained from Freund and Takala (2001) and results of the present study and are shown in Table A.3. The second alternative was a uniform distribution across all 16 phalangeal segments (four phalanges for each finger, Table A.1) in which each phalangeal segment contributed equally to the total finger force production (Table A.2).

The sum of the absolute differences between the measured and ideal phalangeal force distributions under the non-uniform ideal distribution alternative (*SADFD w/non-uniform*) exhibited an inverse relationship with the subjective comfort ratings. Fig. 6 indicates that the 30, 35, and 40 mm handles were associated with the smallest differences between the measured phalangeal force distribution and the ideal phalangeal force distribution. Fig. 6 also illustrates that the difference between the measured and ideal phalangeal force distribu-

tion (*SADFD w/uniform*) was inversely related to total finger force under the uniform distribution alternative. Thus, the assumption that the ideal phalangeal force distribution is uniform yields a poor relationship between the degree of departure from the ideal force distribution and ratings of comfort. The relationships seen in Fig. 6 suggest that users generally preferred handles which have non-uniform phalangeal contributions to total finger force, where the contributions are proportional to muscle capabilities (i.e., with stronger segments contributing more to the total finger force than weaker ones).

Amis (1987) reported total finger force capability as the sum of finger forces measured individually in four successive trials in which each finger exerted maximum finger force in isolation on a cylindrical handle. Radhakrishnan and Nagaravindra (1993) noted weaknesses in the assumption that maximum total finger force capability is equivalent to the sum of maximum individual finger forces. Radhakrishnan and Nagaravindra (1993) overcame the measurement limitations of Amis (1987) by using 12 cantilever beams to obtain individual forces exerted by the proximal, middle, and distal phalangeal segments of each finger simultaneously. However, there are still shortcomings of this measurement system for quantifying finger and phalangeal forces for a variety of handle shapes and for precise adjustment of the sensor positions based on the user's hand/finger sizes. In the present study, a force sensor glove system was developed to simultaneously measure all fingers and phalanges (including metacarpal phalanges). The force glove was designed to allow for easy positioning of sensors based on the user's hand and finger sizes by simply reattaching the sensors on the glove. This glove system can be used to quantify finger forces on hand tools of any shape and for users of any size.

While the glove-based measurement approach adopted in the present study overcomes many of the limitations described above it is not without limitations itself. The glove-attached sensors measure phalangeal segment forces that, when summed, are not equivalent to the total hand force because the handle and hand make contact in other palmar regions where there are no sensors.

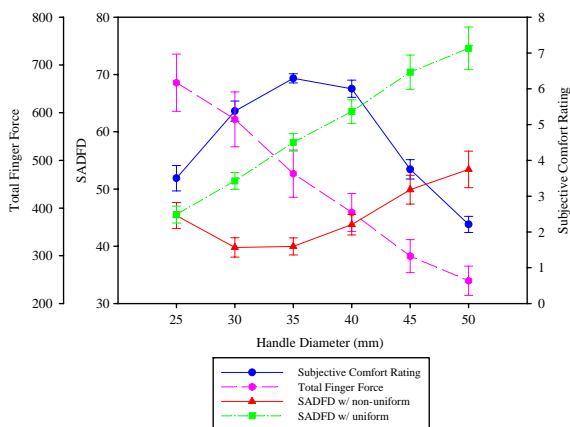


Fig. 6. The relationships among subjective comfort rating, total finger force, and the sum of the absolute differences between measured and ideal force distributions (*SADFD*) with the uniform and non-uniform ideal force distribution alternatives. (See Appendix A for explanation of *SADFD* calculation.)

Further, the synthetic leather glove material does alter the frictional conditions between the hand and handle material which, in turn, may alter the grip distribution and magnitude on the tool handle. In our view, the ability to evaluate the finger/grip force distribution on any tool handle, of any shape, size, or material with repeatable placement of the force sensors with respect to the subject’s hand justifies the acceptance of the limitations imposed by the glove-based system.

Acknowledgements

We would like to express thanks to Dr. Ed Krieg for analyzing data, and Mr. JungYoup Han and Dr. KyuSang Kim for helping this study.

Appendix

1. individual segment forces and calculate total force for each handle

$$SF_{ijk}, \text{ and } TF_k = \sum_{j=1}^4 \sum_{i=1}^4 SF_{ijk},$$

where SF_{ijk} represent each finger force i and each phalange j ($i, j = 1, 2, 3,$ and 4 for index, middle, ring, and little finger; distal, middle, proximal, and metacarpal, respectively), for each handle k , and TF_k the total finger forces of handle k .

2. Calculate each segment force distribution to total force for each handle

$$SFD_{ijk} = (SF_{ijk}/TF_k) * 100.$$

3. Calculate absolute difference in force distributions between individual segment force distribution and Ideal Force Distribution for each handle

$$ADFD_{ijk} = |SFD_{ijk} - IFD_{ij}|.$$

Ideal force distributions (IFD_{ij}) 1 (see Table A1):

Ideal force distributions (IFD_{ij}) 2 (see Tables A2 and A3):

4. Calculate sum of absolute difference of force distribution for each handle

$$SADFD_k = \sum_{j=1}^4 \sum_{i=1}^4 ADFD_{ijk}.$$

Table A1
IFD 1—Uniform distributions (100%/16 segments = 6.25%)

	Distal (%)	Middle (%)	Proximal (%)	Metacarpal (%)	Total (%)
Index	6.25	6.25	6.25	6.25	25
Middle	6.25	6.25	6.25	6.25	25
Ring	6.25	6.25	6.25	6.25	25
Little	6.25	6.25	6.25	6.25	25

Table A2
Finger and phalange force distributions based on Freund (2002) and current study (2003)

PCSA	FDP	FDS	ED	Sum	%	Phalange	Distal	Middle	Proximal	Metacarpal
Index	4.1	3.6	1.1	8.8	28.2	Index	38.74	17.14	20.10	24.02
Middle	4.1	4.2	1.7	10.0	32.1	Middle	42.39	24.36	20.82	12.43
Ring	3.7	2.4	1.2	7.3	23.4	Ring	41.79	25.15	19.27	13.78
Little	2.5	2.1	0.5	5.1	16.3	Little	40.52	24.75	13.77	20.96

Table A3

IFD 2—Non-uniform distributions (proportional to muscle capability)

	Distal	Middle	Proximal	Metacarpal	Total
Index	10.92	4.83	5.67	6.77	28.2
Middle	13.61	7.82	6.68	3.99	32.1
Ring	9.78	5.89	4.51	3.22	23.4
Little	6.60	4.03	2.24	3.42	16.3

5. the *Minimum SADFD* for all handles

$$\begin{aligned} \text{Min. SADFD}_k &= \text{Min} \left\{ \sum_{j=1}^4 \sum_{i=1}^4 |SFD_{ijk} - IFD_{ij}| \right\} \\ &= \text{Min} \left\{ \sum_{j=1}^4 \sum_{i=1}^4 |(SF_{ijk}/TF_k) * 100 \right. \\ &\quad \left. - IFD_{ij}| \right\}. \end{aligned}$$

References

- An, K.N., Chao, E.Y., Cooney, W.P., Linscheid, R.L., 1985. Forces in the normal and abnormal hand. *Journal of Orthopaedic Research* 3, 202–211.
- Amis, A.A., 1987. Variation of finger forces in maximal isometric grasp tests on a range of cylindrical diameters. *Journal of Biomedical Engineering* 9, 313–320.
- Ayoub, M.M., Lo Presti, P., 1971. The diameter of an optimum size cylindrical handle by use of electromyography. *Ergonomics* 4, 503–518.
- Bishu, R.R., Wang, W., Chin, A., 1993. Force distribution at the container hand/handle interface using force-sensing resistors. *International Journal of Industrial Ergonomics* 11, 225–231.
- Blackwell, J.R., Kornatz, K.W., Heath, E.M., 1999. Effect of grip span on maximal grip force and fatigue of flexor digitorum superficialis. *Applied Ergonomics* 30, 401–405.
- Chen, Y., 1991. An evaluation of hand pressure distribution for a power grasp and forearm flexor muscle contribution for a power grasp on cylindrical handles. Ph.D. Dissertation, University of Nebraska, Lincoln, Nebraska.
- Fellows, G.L., Freivalds, 1991. Ergonomics evaluation of a foam rubber grip for tool handles. *Applied Ergonomics* 22 (4), 225–230.
- Freund, J., Takala, E.P., 2001. A dynamic model of the forearm including fatigue. *Journal of Biomechanics* 34, 597–605.
- Grant, K.A., Habes, D.J., Steward, L.L., 1992. An analysis of handle designs for reducing manual effort: the influence of grip diameter. *International Journal of Industrial Ergonomics* 10, 199–206.
- Gurram, R., Rakheja, S., Gouw, G.J., 1995. A study of hand grip pressure distribution and EMG of finger flexor muscles under dynamic loads. *Ergonomics* 38 (4), 684–699.
- Hall, Ch., 1997. External pressure at the hand during object handling and work with tools. *International Journal of Industrial Ergonomics* 20, 191–206.
- Hall, N.B., Bennett, E.M., 1956. Empirical assessment of handrail diameters. *Journal of Applied Psychology* 40, 381–382.
- Hunter, J.M., Schneider, L.H., Mackin, E.J., Bell, J.A. (Eds.), 1978. *Rehabilitation of the Hand*. C.V. Mosby Company, St. Louis, MO.
- Johnson, S.L., 1993. Ergonomic hand tool design. *Hand Clinics* 9, 299–311.
- Khalil, T.M., 1973. An electromyographic methodology for the evaluation of industrial design. *Human Factors* 15 (3), 257–264.
- Kong, Y.K., 2001. Optimal design of handle shape through biomechanical modeling of hand tendon forces, Ph.D. Dissertation, The Pennsylvania State University.
- Kong, Y.K., Freivalds, A., 2003. Evaluation of meat-hook handle shapes. *International Journal of Industrial Ergonomics* 32, 13–23.
- Lee, J.W., Rim, K., 1991. Measurement of finger joint angles and maximum finger forces during cylinder grip activity. *Journal of Biomedical Engineering* 13, 152–162.
- Magill, R., Konz, S., 1986. An evaluation of seven industrial screwdrivers. In: Karwowski, W. (Ed.), *Trends in Ergonomics/Human Factors III*. Elsevier Science Publishers, North Holland, pp. 597–604.
- McMullin, D.L., Hallbeck, M.S., 1992. Comparison of power grasp and three-jaw chuck pinch static strength and endurance between industrial workers and college students: a pilot study, Proceedings of the Human Factors Society 36th Annual Meeting. Human Factors Society, Santa Monica, CA, pp. 770–774.
- Meagher, S.W., 1987. Tool design for prevention of hand and wrist injuries. *Journal of Hand Surgery* 12 (A), 855–857.
- Oh, S., Radwin, R.G., 1993. Pistol grip power tool handle and trigger size effects on grip exertions and operator preference. *Human Factors* 35 (3), 551–569.
- Pheasant, S.T., 1986. *Bodyspace: Anthropometry, Ergonomics and Design*. Taylor & Francis, Philadelphia, PA.

- Radhakrishnan, S., Nagaravindra, M.C., 1993. Analysis of hand forces in health and disease during maximum isometric grasping of cylinders. *Medicine and Biological Engineering and Computing* 31, 372–376.
- Radwin, R.G., Oh, S., 1992. External finger forces in submaximal five-finger static pinch prehension. *Ergonomics* 35 (3), 275–288.
- Replege, J.O., 1983. Hand torque strength with cylindrical handles. *Proceedings of the Human Factors Society 27th Annual Meeting*, pp. 412–416.
- Yakou, T., Yamamoto, K., Koyama, M., Hyodo, K., 1997. Sensory evaluation of grip using cylindrical objects. *JSME International Journal, Series C* 40 (4), 730–735.
- Yun, M.H., 1993. A hand posture measurement system for evaluating manual tool tasks. *Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting*, pp. 754–758.
- Zipp, P., 1982. Recommendations for the standardization of lead positions in surface electromyography. *European Journal of Applied Physiology* 50, 41–54.