

# Evaluation of handle diameters and orientations in a maximum torque task

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## Abstract

The effects of gender, handle diameter (25–50 mm), and handle orientation (horizontal and vertical) on the perceived comfort, torque, total finger force, and efficiency of flexor and extensor muscle activity were examined in a maximum torque task. A 16-force sensor glove system was applied to measure finger and phalangeal forces, and a surface EMG was recorded to investigate muscle activities in the torque task. Average maximum torque in the horizontal orientation was about 23.4% more than that in the vertical orientation. The maximum torque was the largest with the 45 and 50 mm diameter handles and least with the 25 mm diameter handle. In both orientations, torque increased as the handle diameter increased, whereas total finger force showed a decreasing pattern which can explain the positive and non-linear correlation between torque output and handle diameter. The efficiency of muscle activity in both orientations followed a similar trend with the torque output for the handle diameters (i.e., the efficiency increased when the handle diameter increased). 35–45 mm handles were rated as the most comfortable for maximum torque exertions. According to a polynomial regression, 37–44 mm and 41–48 mm diameter handles (23.3% of the user's hand length) maximized perceived comfort and were thus recommended for females and males, respectively in this study.

## Relevance to industry

This study will provide guidelines for designing better workstations and hand-tools maximizing performance, muscle efficiency, and user's comfort in manual torque tasks.

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**Keywords:** Maximum torque task; Handle diameter; Muscle efficiency; Handle comfort

## 1. Introduction

In the United States, use of hand tools accounts for about 10% of all industrial injuries (Mital and

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Aghazadeh, 1985). Injuries to the hand, finger, wrist, and shoulder are the most prevalent upper extremity injuries associated with non-powered hand tools (Bureau of Labor Statistics, 1995–2001). It is likely that these injuries could be reduced if the hand tools were ergonomically well-designed with emphasis on user comfort and safety (Lewis and Narayan, 1993).

The handle diameter is one of essential criteria in tool designs to maximize performance, reduce stress on the forearm muscles and finger tendons while hand tool use. General agreement of the previous studies (Pheasant and O'Neill, 1975; Pheasant and Scriven, 1983; Shih and Wang, 1996) is that the effect of handle diameter on the torque exertions is proportional to the handle diameter. From the various ranges of handle sizes, they found that there is non-positive linear relationship between handle size and torque exertion. Pheasant and O'Neill (1975) recommended that 50 mm knurled cylindrical handle was efficient in terms of strength of maximum torque exertion. Shih and Wang (1996) showed that the increase of maximum torque exertion becomes flatter while handle diameter gets more than 50 mm handle size. Although Cochran and Riley (1986) and Habes and Grant (1997) confirmed the positive relationship between handle diameter and torque exertions, they could not show the non-linear correlation because the handle sizes used in their studies were not large enough to cover the ranges (i.e., up to 41.4 and 37 mm handle diameters, respectively). Habes and Grant (1997) also investigated the effects of handle diameter, working height and distance, and handle orientation on torque output and efficiency of six muscle groups (where efficiency is the ratio of torque output to muscle activity) in the maximal and sub-maximal torque exertions. They showed that a larger handle diameter (37 mm) was associated with 23% more torque than a smaller handle diameter (29 mm). Handle orientation was a significant factor on torque strength at shoulder height, and the effects of handle diameter and height were significant on the efficiency of muscles.

Relatively few studies have focused on the relationship between handle diameter and user's hand size, and its effects on subjective comfort

rating, although much research has been conducted on handle diameter studies. Also, none of studies have considered the effects of cylindrical handle diameters and handle orientation on the torque output, finger force capability/distribution, muscle activity, and subjective comfort rating in maximum torque exertion tasks. To measure forces exerted by all fingers and phalanges (including heads of metacarpals) while each handle used, a force glove measurement system was developed by overlaying flexible sensors on a thin glove in the present study. This force glove system, especially, was applied to evaluate the relationship between handles and finger force (distribution) in maximum torque exertions.

The objectives of this study were to: (1) evaluate the effects of handle diameter and handle orientation on torque, total finger force, efficiency of flexor and extensor electromyographic (EMG) activity, and subjective comfort rating in a maximum voluntary torque task; (2) define the handle diameters that maximize perceived comfort rating according to the user's hand length. These findings in this study would be fundamental information for designing handles considering handle position, users' hand size, muscle efficiency, performance, comfort rating, and finger force capability in maximum torque tasks.

## 2. Methods

### 2.1. Subjects

Twenty-four participants, 12 males and 12 females, were recruited from college student population for this experiment. The physical characteristics of the subjects were: (1) age:  $26.6 \pm 4.24$  years; (2) body weight:  $66.1 \pm 11.5$  kg; (3) stature:  $170.3 \pm 8.1$  cm; and (4) hand length:  $183.2 \pm 12.8$  mm. All participants were healthy and free of known musculoskeletal disorders. At the beginning of the experiment, each participant was provided with an informed consent form and a brief description of the goals and procedures of the experiment. Hand length, defined by the distance from the crease of the wrist to the tip of the middle finger with the hand held straight, was measured

and assigned to one of three hand size groups (small, middle and large) for each gender as follows (source, [Pheasant 1986](#)): (1) Small hand: up to 30 percentile (less than 186 mm and less than 169.8 mm, for male and female, respectively); (2) Middle hand: 30–70 percentile (186–196.3 mm and 169.8–180.3 mm for male and female, respectively); (3) Large hand: over 70 percentile (over 196.3 mm and over 180.3 mm for male and female, respectively).

## 2.2. Instrumentation and apparatus

### 2.2.1. Force glove system

To measure individual finger and phalange forces in the maximum voluntary torque task, a force glove system with 16 thin (0.127 mm) flexible conductive polymer pressure sensors (FlexiForce Sensor, A101-25; Tekscan Inc.) was used. The sensors are 13.97-mm-diameter circles with an active sensing area of 9.53 mm diameter. The voltage output signals from the sensors were input to a custom voltage circuit box, designed to provide a  $\pm 5$  V output to a 12-bit A/D board (Keithley Instruments 1802 HC). The force glove system allows for easy repositioning of force sensors according to the user's hand size by simply reattaching the flexible sensors on the palm side of the thin leather glove. Those sensors were placed on the middle of phalanges and the heads of metacarpal segments by affixing on a soft and thin glove ([Fig. 1a](#)).

To calibrate these sensors, each FlexiForce sensor was centered over a metal plate of 25 mm diameter mounted over a miniature button-style load cell (22.7 kg capacity) 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 22.7 kg and unloading back to zero over about a 6 s period. The raw voltage output data from the Flexiforce sensor and the force registered on the load cell were collected at a sampling rate of 900 Hz. Voltage outputs from the Flexiforce sensors were linearly regressed against force to establish the relationship between the sensor output and applied force. The sensors exhibited extremely high linearity

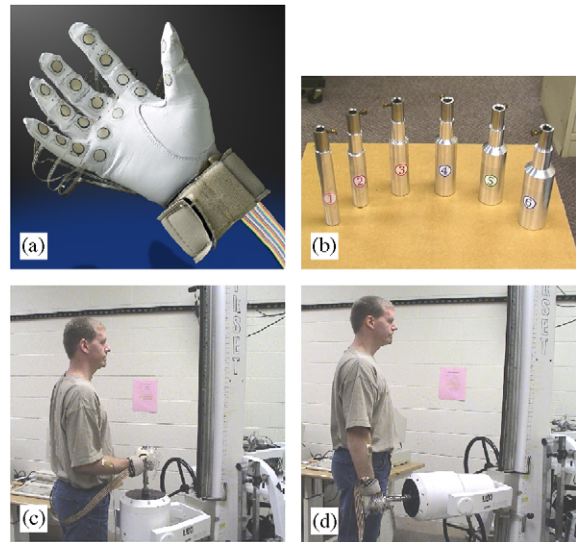


Fig. 1. Torque, finger force, EMG measurement system: (a) force glove system; (b) experimental handles; (c) vertical handle orientation and EMG attachments; (d) horizontal handle orientation.

( $0.986 < R^2 < 0.995$ ) between voltage output and applied force.

### 2.2.2. Electromyographic measurement system

The 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 (Therapeutics Unlimited Inc., Model 544, Iowa City, IA) 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 \(1982\)](#).

### 2.2.3. LIDO WorkSET II

The LIDO WorkSET II (Loredan Biomedical, Inc.) integrates various upper limb functional tests in a single device. With a variety of attachments, it can simulate diverse job tasks and daily activities. Handles were attached to the actuator shaft for the measurement of torque. In this study, the long axis

of the handle/actuator was positioned horizontal or vertical to the floor (Fig. 1c and d). The height of the handle/actuator was also controlled according to the participant's height. Participants used the LIDO WorkSET II work simulator system to perform the maximum voluntary torque exertion in a clockwise direction, which simulates tightening a screw. The analog voltage output from the LIDO Workset II actuator shaft were connected to the Keithley A/D board and were sampled with 16 channels of finger forces and 2 channels of EMG activity, simultaneously.

### 2.3. Experimental procedure

Participants were provided with a brief description of the purposes and procedures of the experiment. Six cylindrical handle diameters (25, 30, 35, 40, 45 and 50 mm, Fig. 1b) with two handle orientations were tested: vertical (axis of the handle perpendicular to the floor) and horizontal (axis of the handle parallel to the floor). The heights of the handle from the floor were adjusted for each participant to keep the elbow angle about 90° in the vertical orientation, and to keep the forearm and upper arm straight for holding the handle in the horizontal orientation. All participants wore the force glove and waited for about 2 s until the first beep sound. As soon as they heard the sound, they exerted the maximum torque and maintained about 3 s until the second beep sound. All dependent variables i.e., torque, finger force and muscle activity (FDS and ED) data were collected and averaged during the 3 s of maximum exertions. At the end of each task, each participant was asked to rate overall comfort for use of handles with a following 7-point scale: [very comfortable—7; moderately comfortable—6; somewhat comfortable—5; neutral—4; somewhat uncomfortable—3; moderately uncomfortable—2; and very uncomfortable—1]. Each participant was provided with 2 min of rest time between tasks.

### 2.4. Experimental design

A mixed effects analysis of variance (ANOVA) was employed to evaluate the effects of handle

diameter, gender, user's hand size and handle orientation on maximum torque performance, total finger force, efficiency of muscle EMG activity, and subjective comfort in the maximum torque task. Hand size was nested within gender and subject was nested under the combination of gender and hand size. There were three levels of hand size groups (small, medium and large hand size) for each gender. In each combination of gender and hand size, four subjects were evenly assigned based on their hand length. Since each subject was involved in only one level of gender and hand size combination, this is the nested design. Subject effect was considered as random and the others were considered as fixed effects. Six cylindrical handle diameters were tested and all handles had a length of 130 mm. Two levels of handle orientation (horizontal and vertical) were evaluated as seen in Fig. 1c and d. This was a balanced design and all handles were assigned in a random order for each participant. A total of 24 treatment combinations (6 handles\*2 orientations\*2 trials) were performed in a random order for each participant.

### 2.5. Dependent variables

- (1) *The torque* was recorded from the LIDO WorkSET II and averaged over a 3-s period of maximum torque exertion.
- (2) *Total finger force* was obtained and averaged during 3 s of maximum torque exertion. It was defined as the summing all 16 individual sensors. *Individual finger force* and *phalange force* were also measured.
- (3) *Muscle activity and efficiency of the flexor and extensor (FDS and ED)* were recorded and averaged for each handle during the maximum torque task. The maximum torque and muscle EMG activity were normalized relative to the maximum value measured among all handles. Then, muscle efficiency was defined by the ratio of the normalized maximum torque output to the normalized EMG activity of each muscle, in Eq. (1). The normalization of each muscle exertion for each handle was performed in the same forearm positions i.e., horizontal or vertical

handle orientation, respectively.

$$\text{Muscle efficiency} = \frac{\text{Normalized torque output}}{\text{Normalized muscle EMG}}, \quad (1)$$

(where normalized muscle EMG = (measured EMG for each trial—resting EMG)/(maximum EMG measured for all trials—resting EMG) for each participant)

- (4) *Subjective comfort rating* was obtained for overall finger and hand comfort associated with handle uses. Comfort ratings were obtained using the following numerical values used as indices of the degree of comfort (from 1 to 7, very comfortable to very uncomfortable).
- (5) *Normalized handle size (NHS)* was applied to determine the optimum handle diameter for maximizing subjective comfort based on the user's hand length in the maximum torque task. The ratio of handle circumference to user's hand length was used to define the NHS, as follows in Eq. (2). Regression modeling was used to evaluate the relationship between subjective comfort rating and NHS. A General Linear Test was applied to derive recommended handle diameters that maximized subjective comfort.

$$\text{NHS}_{ij} = \frac{\text{HC}_j}{\text{HL}_i} 100, \quad (2)$$

(where  $i$  = subject;  $j$  = handle;  $\text{NHS}_{ij}$ : normalized handle size of handle  $j$  for subject  $i$ ;  $\text{HC}_j$ : circumference of handle  $j$ ;  $\text{HL}_i$ : hand length of subject  $i$ ).

### 3. Results

#### 3.1. Maximum voluntary torque

The effects of handle diameter, orientation, and the interactions between handle diameter and orientation were statistically significant on the maximum voluntary torque output (all  $p < 0.0001$ ). Gender and hand size were not statistically significant.

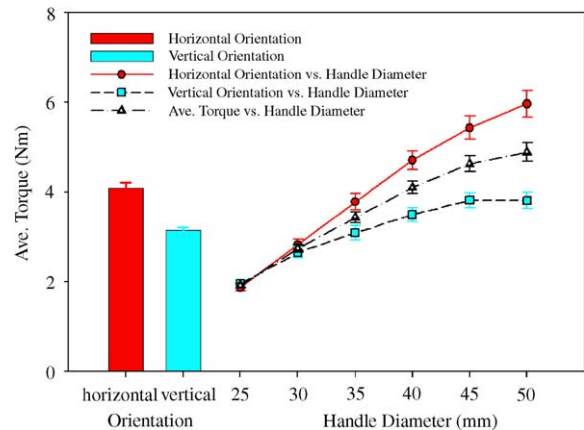


Fig. 2. Torque for handle diameters and handle orientations.

In general, the maximum voluntary torque increased as handle diameter increased in both handle orientations (see Fig. 2). The torque outputs with the 45 and 50 mm handles were the largest followed by the 40, 35, and 30 mm handles. The 25 mm handle showed the smallest torque output. Average maximum voluntary torque in the vertical orientation (3.14 Nm) is about 76.6% of that in the horizontal orientation (4.10 Nm). Although the effect of gender was not statistically significant ( $p = 0.07$ ), on average, females (3.24 Nm) exerted a maximum torque exertion approximately 81.0% of that of males (4.0 Nm).

Fig. 2 also shows the average torque exertions as a function of handle diameter and orientation. Generally, the maximum torque increased as the handle diameter increased in both orientations; however, the maximum torques between the 45 and 50 mm handles in the vertical orientation were not apparently different (i.e., the increase in maximum torque output levels off as handle diameter gets larger in vertical orientation). The differences in torque outputs between vertical and horizontal orientations are greater as handle diameters are increased.

#### 3.2. Individual phalange forces

Significant main effects of handle diameter, finger and phalange (all  $p < 0.001$ ), and interaction effects between orientation and handle diameter,



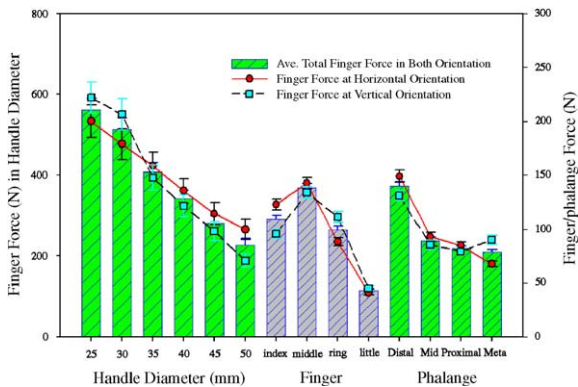


Fig. 3. Finger forces for handle diameters, fingers, and phalanges.

orientation and finger, orientation and phalange, handle diameter and finger, handle diameter and phalange, and finger and phalange (all  $p < 0.001$ ) were found in the maximum torque tasks.

Fig. 3 and Tables 1a and b show that the total finger forces, finger/phalange forces as well as the trends in force contributions to the total finger force are associated with handle diameters. There is a significant negative correlation between the total finger forces and handle diameters, i.e., the total finger forces decreased as the cylindrical handle diameter increased. The decreasing trends of total finger force in both orientations are similar, although there is a dramatic drop of finger force between 30 and 35 mm handle diameters in the vertical handle orientation.

With respect to individual fingers, the average force and percentage contribution to total finger force was highest for the middle finger in both orientations (138.2N, 35.5% of total finger force), followed by those of the index and ring fingers (109.1N, 28.0% and 99.5N, 25.4%, respectively). The little finger exhibited the lowest average finger force as well as percentage contribution to the total finger force (42.8N, 11.0%). Although there is no significant difference between the index and ring finger, the force and contribution of the index finger is higher than that of the ring finger in the horizontal orientation, whereas it is lower in the vertical orientation. In Table 1 and Fig. 4a, the middle finger shows the maximum force at 30-

mm-diameter handle and the other fingers produce their maximum force at 25-mm-diameter handle. In addition, the mean percentage contributions of the middle finger show an increasing pattern across the range of cylindrical handle diameters in both handle orientations. The mean contribution of the ring and little fingers generally decreased as the handle diameters increased in both orientations.

With respect to the phalangeal segments, the distal phalange always produced the largest forces for all handle diameters, followed by the middle, proximal, and metacarpal phalanges in both handle orientations (Fig. 4b). An average of 35.9% (140.0N) of the total finger force was exerted by the distal phalanges, which was significantly higher than the forces exerted by the other phalanges. The other phalanges showed a similar pattern of contribution to the total finger force distributions: 22.9%, 21.0%, and 20.2% for middle, proximal, and metacarpal phalanges, respectively. The mean contribution of force exerted by the distal phalange to the total finger force increased from 31.8% to 41.8% over the range of handle diameters in the horizontal handle orientation and increased from 30.8% to 38.3% in the vertical handle orientation. The mean contributions of forces exerted by the metacarpal phalange decreased from 28.4% to 15.3% through various handle diameters in the vertical handle orientation. The mean contributions of forces exerted by the other phalanges showed a fairly constant pattern across handle diameters. Overall distal phalanges provide the largest force through all fingers followed by middle, proximal, and metacarpal phalange. The middle phalange and proximal phalange show the least force in the index finger and little finger, respectively (Fig. 4c).

### 3.3. Muscle activity and efficiency of flexor and extensor muscles

The ANOVA analysis shows that orientation and the interaction between handle diameter and orientation were significant factors on the activities of flexor and extensor muscles ( $p < 0.001$ ). In the activities of flexor and extensor muscles as a function of handle diameters, overall the flexor

Table 1  
Summary of torque and finger forces

Handle diameter (mm)	Torque (Nm)	Total finger force (N)	Mean forces of individual fingers (N) and percentage contributions (%)				Mean forces of individual phalanges (N) and percentage contributions (%)			
			Index	Middle	Ring	Little	Distal	Middle	Proximal	Meta
<i>(a) In the horizontal orientation</i>										
25	1.87	533.5	149.4 (28.01%)	159.8 (29.96%)	142.4 (26.70%)	81.8 (15.34%)	169.7 (31.80%)	141.8 (26.57%)	117.6 (22.05%)	104.4 (19.58%)
30	2.82	476.8	140.9 (29.54%)	170.2 (35.69%)	113.3 (23.77%)	52.4 (11.00%)	178.1 (37.36%)	111.7 (23.43%)	102.9 (21.58%)	84.0 (17.63%)
35	3.79	422.9	125.0 (29.56%)	165.5 (39.12%)	95.1 (22.48%)	37.4 (8.84%)	166.8 (39.44%)	100.1 (23.66%)	92.7 (21.91%)	63.4 (14.99%)
40	4.71	360.9	117.4 (32.53%)	143.6 (39.79%)	70.3 (19.49%)	29.6 (8.19%)	147.74 (40.93%)	82.0 (22.73%)	75.4 (20.88%)	55.8 (15.46%)
45	5.43	304.1	107.9 (35.48%)	115.4 (37.97%)	57.3 (18.85%)	23.4 (7.70%)	120.9 (39.75%)	62.4 (21.50%)	65.5 (21.55%)	52.3 (17.21%)
50	5.96	264.7	95.2 (35.95%)	100.4 (37.94%)	49.2 (18.60%)	19.9 (7.51%)	110.7 (41.83%)	55.9 (21.12%)	53.5 (20.20%)	44.6 (16.85%)
Mean	4.10	393.8	122.6 (31.9%)	142.5 (36.7%)	87.9 (21.7%)	40.8 (9.8%)	149.0 (38.5%)	92.8 (23.2%)	84.6 (21.4%)	67.4 (16.9%)
<i>(b) In the vertical orientation</i>										
25	1.96	591.6	149.3 (25.23%)	174.6 (29.51%)	183.3 (30.98%)	84.4 (14.27%)	182.3 (30.81%)	130.4 (22.05%)	110.7 (18.71%)	168.2 (28.44%)
30	2.652	550.6	135.9 (24.68%)	191.5 (34.79%)	161.2 (29.28%)	62.0 (11.26%)	178.5 (32.41%)	120.6 (21.91%)	108.8 (19.77%)	142.7 (25.91%)
35	3.09	394.0	105.2 (26.71%)	137.5 (34.90%)	110.2 (27.97%)	41.1 (10.42%)	135.0 (34.25%)	86.5 (21.95%)	80.6 (20.46%)	91.9 (23.33%)
40	3.50	323.9	76.3 (23.55%)	125.7 (38.80%)	90.1 (27.82%)	31.9 (9.84%)	117.8 (36.37%)	69.8 (21.54%)	71.6 (22.09%)	64.8 (20.01%)
45	3.82	261.3	57.4 (21.98%)	104.4 (39.96%)	72.4 (27.70%)	27.1 (10.36%)	99.7 (38.15%)	60.5 (23.17%)	61.0 (23.34%)	40.1 (15.34%)
50	3.81	189.6	49.0 (25.84%)	69.2 (36.50%)	49.2 (25.95%)	22.2 (11.70%)	72.6 (38.29%)	43.5 (22.96%)	42.2 (22.22%)	31.3 (16.53%)
Mean	3.14	385.2	95.5 (24.7%)	133.8 (35.7%)	111.1 (28.3%)	44.8 (11.3%)	131.0 (35.05%)	85.2 (22.26%)	79.1 (21.10%)	89.8 (21.59%)

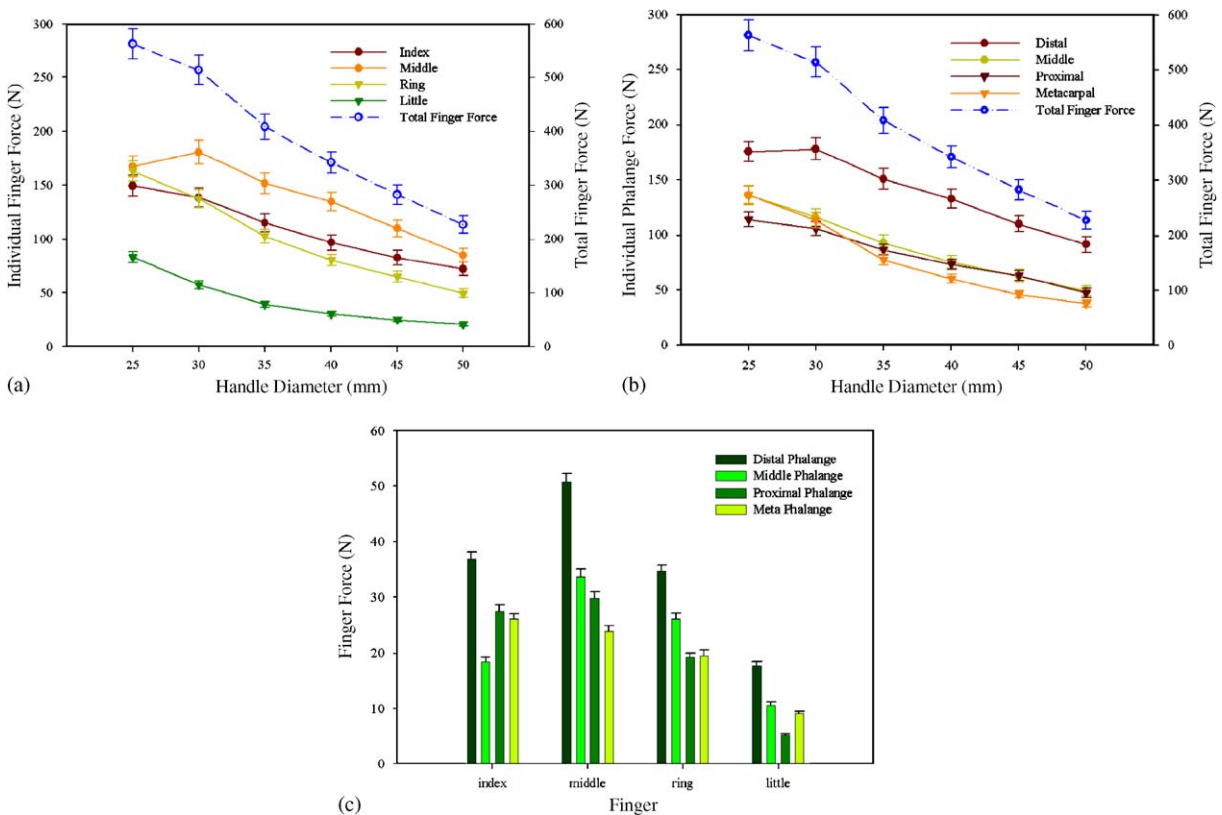


Fig. 4. Interaction effects on finger forces in the maximum torque task (a) finger force vs. handle diameter; (b) phalange forces vs. handle diameter; (c) finger force vs. phalange force.

muscle is more active in the horizontal handle orientation than in the vertical handle orientation, whereas the extensor muscle is more active in the vertical orientation than in the horizontal orientation. Statistical analysis shows that the flexor exertion increased and the extensor exertion decreased as the handle diameter increased in the horizontal torque task, whereas the EMG activities of these two muscles do not appear to be affected by handle diameter in the vertical torque task.

The efficiencies of the flexor (FDS) and extensor (ED) muscle activities were analyzed to obtain the optimal handle diameter based on the ratio of torque output to muscle activity. The torque output and the 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 muscle activity was defined by the ratio of the normalized torque output to the normalized muscle EMG activity (Eq. (1), Section 2.5). Statistical analyses showed that handle diameter and orientation were significant factors for the muscle efficiencies. In general, the condition maximizing the efficiency of both muscle groups simultaneously was larger diameter handles, i.e., participants exhibited greater torque output with the same amount of muscle activities with the large diameter handles than with the small diameter handles (see Fig. 5).

In detail, in the case of smaller diameter handles, the efficiencies of the flexor and extensor muscles were significantly higher in the vertical handle orientation than in the horizontal handle orientation. In the case of large diameter handles,



however, the efficiency of the extensor in the horizontal orientation was higher than in the vertical orientation, whereas the efficiency of the flexor in the vertical orientation was higher than in the horizontal orientation.

### 3.4. Subjective comfort rating and normalized handle size (NHS)

Results of Tukey comparison test for the subjective comfort ratings indicated that participants rated 40, 45 and 35 mm handles as comfortable handles followed by 50 and 30 mm handles. The smallest handle (25 mm) was rated as the least comfortable.

Regression modeling was used to evaluate the relationship between subjective comfort rating and NHS. A General linear test was applied to derive

optimal handle diameters that maximize comfort ratings. Results showed that a quadratic regression model was a better-fitted model than a linear model for the relationship between subjective rating and NHS. Thus, a quadratic regression model (Eq. (3)) was applied in this study.

$$\begin{aligned} \text{Subjective rating} = & -0.0035(\text{NHS})^2 \\ & + 0.5127(\text{NHS}) \\ & - 13.176, (R^2: 35.4\%). \quad (3) \end{aligned}$$

The 73.2% NHS was obtained from the first derivative of the Eq. (3) in terms of maximizing subjective comfort. This NHS ratio was used to derive recommended handle diameters according to the user's hand length, [handle diameter = user's hand length(0.732)/ $\pi$ , i.e., 23.3% of the user's hand length], as shown in Table 2.

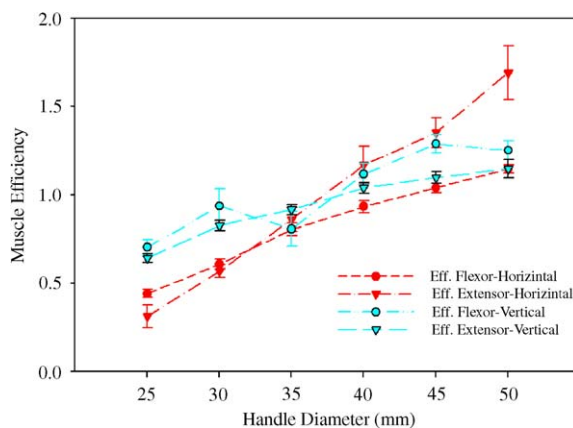


Fig. 5. Muscle efficiencies of the flexor and extensor muscles for handle diameters.

## 4. Discussion

There was a positive relationship between handle diameter and torque output, which showed that the maximum voluntary torque increased as the cylindrical handle diameter increased in both handle orientations. The finding is straightforward and consistent with other studies (Pheasant and O'Neill, 1975; Replege, 1983; Shih and Wang 1996; Habes and Grant 1997). However, the relationship is not simply a linear function (see Fig. 2), because torque is a function of shear force ( $G\mu$ ) and the radius of the handle ( $R$ ). The negative correlation between grip/finger force and handle diameter (Fig. 3) indicated that the total normal grip/finger force decreased from 533.5 to 264.7 N

Table 2  
Handle diameters for maximizing subjective comfort (unit: mm)

Hand size <sup>a</sup>	Female		Male	
	Hand length	Handle diameter	Hand length	Handle diameter
Small	160.0–169.8	37.3–39.6	175.0–186.0	40.8–43.3
Medium	169.8–180.3	39.6–42.0	186.0–196.3	43.3–45.7
Large	180.3–190.0	42.0–44.3	196.3–205.0	45.7–47.8

<sup>a</sup>Small: 5–30%; Medium: 30–75%; Large: 75–95% for each gender.

and from 591.6 to 189.6 N for horizontal and vertical orientations, respectively, as the cylindrical handle diameter increased from 25 to 50 mm. Thus, the maximum voluntary torque exhibits a more complex relationship between grip/finger forces and handle diameters. Therefore, a positive and non-linear increasing trend of the maximum torque according to the handle diameter was obtained in this study.

Individual finger and phalange forces were analyzed based on the handle diameters. On average, the forces produced by the middle finger and distal phalange were always significantly larger than those produced by the other fingers and phalanges. In addition, the contributions of middle finger and distal phalange to the total finger force increased as the handle diameter increased in both handle orientations. These patterns for the magnitudes and percentage contributions of individual finger and phalange forces to the total force in the maximum torque task are similar with the findings in previous studies of the maximum grip force tasks (Amis 1987; Lee and Rim 1991; Radhakrishnan and Nagaravindra 1993; Kong and Lowe 2005).

The average total finger force for females (356.8 N) was 84.6% of that for males (421.7 N) and the average torque capability for males and females was 4.10 and 3.24 Nm, respectively (females had about 81% of that of males). This difference in torque capability between males and females is within the range of past findings of 71.2–85% for screwdriver torque test (Mital 1986; Adams and Peterson 1988; Mital and Channaveeraiyah 1988).

The effects of handle orientation and handle diameter on torque output as well as muscle activities (EMG) and efficiencies of muscle activity were analyzed in this study. With a vertical handle orientation the clockwise torque direction required extension of the wrist which involves the extensor muscles of the forearm, whereas the clockwise torque direction in the horizontal orientation required flexion of the wrist involving more flexor muscle activity. The results showed that torque output and flexor muscle activity in the horizontal orientation were higher than those in the vertical orientation, whereas extensor muscle activity in

the horizontal orientation was lower than in the vertical orientation. The ratio of normalized torque output to normalized muscle activity produced an “efficiency” measure: the larger the ratio, the less muscle activation required to produce greater torque output. Results showed that the efficiency of muscle activity increased when the handle diameter was increased. With the smaller handles (25, 30 and 35 mm) the vertical handle orientation showed higher muscle efficiencies than the horizontal handle orientation. With the larger handles, the efficiencies of the extensor in the horizontal orientation and the flexor in the vertical orientation were higher than those of the extensor in the vertical orientation and the flexor in the horizontal orientation, respectively. Similar findings were reported by Habes and Grant (1997) who found that torque was greater when participants used larger handles, and the efficiency of muscles was larger in the vertical orientation than in the horizontal orientation in evaluating two handle diameters (29 and 37 mm) that were similar to the small handle diameters in this study.

The analysis of subjective comfort ratings in the maximum voluntary torque task showed that the 40, 45 and 35 mm handle diameters were more comfortable handle sizes than the smallest handle (25 mm), which had the lowest torque output and the highest total finger force, and the largest handle (50 mm) which had the highest torque output and the lowest total finger force. Therefore, it is hard to conclude whether the subjective ratings of handle comfort are more closely related to torque output or total finger force.

The relationship between subjective comfort rating and the ratio of the handle circumference to hand length (NHS) was used to establish a relationship between handle size and user's hand length in the isometric maximum torque task. A 73.2% NHS ratio was derived and applied for recommendations of handle diameters in Table 2. The recommended handle diameters were 37–44 and 41–48 mm for females and males, respectively. The 8–9.8% differences in optimal handle diameters were due to the anthropometric difference in hand length between females and males.

A force glove system was used in the present study to quantify hand forces on a cylindrical tool

handle during maximum torque tasks. There are some limitations of the force glove system. First, the measure of total finger force, the summation of the outputs from all 16 sensors on the glove, is not equivalent to the true total hand force in the task, because of incomplete coverage of the force sensors on the palmar regions in contact with the tool handle. There were palmar regions making contact with the handle under which there was no sensor coverage. Estimation of the percent coverage by the force glove system on the palmar surface of one hand showed approximately 8% to 13% coverage based on the total sensing area (4.77 mm dia.\*16 sensors) divided by palmar surface area of the hand ( $0.78 \pm 0.08\%$  of body surface area, BSA, Amirshaybani et al., 2001). Formula of BSA [BSA =  $0.024265 \text{Height}^{0.3964} \text{Weight}^{0.5378}$ , (Haycock et al., 1978)] was applied to calculate BSA for each participant. Thus, the true total hand force in the torque tasks was likely to be underpredicted by the force glove system.

A second limitation of the glove measurement system is the fact that the glove alters the frictional conditions between the hand and tool handle. Thus, when wearing the force glove the ratio of the total hand force to maximum torque output is different than this ratio would be a bare-handed condition (Riley et al., 1985; Mital et al., 1994; Shih and Wang, 1997). The increase in friction on the handle for the glove system means that equivalent hand force results in greater torque output relative to that in the bare-handed condition.

While the force glove system possesses the limitations described above, there are advantages to this system. The force glove system allows for easy repositioning of force sensors based on the user's hand size by simply reattaching the flexible sensors on the palm side of the thin leather glove. By incorporating the force sensors on the hand of the user, the glove can be used to evaluate any type of tool handle, of any shape, size, or material. This offers obvious advantages over the need to instrument a special handle with internal force transducers to sense handle forces transmitted through the tool (McGorry, 2001). Therefore, the force glove system will be applied to evaluate

various shapes of hand tools such as screwdriver, hammer, and saw in near future study.

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