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Evaluation of handle design characteristics in a maximum screwdriving torque task†

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The purpose of this study was to evaluate the effects of screwdriver handle shape, surface material and workpiece orientation on torque performance, finger force distribution and muscle activity in a maximum screwdriving torque task. Twelve male subjects performed maximum screw-tightening exertions using screwdriver handles with three longitudinal shapes (circular, hexagonal and triangular), four lateral shapes (cylindrical, double frustum, cone and reversed double frustum) and two surfaces (rubber and plastic). The average finger force contributions to the total hand force were 28.1%, 39.3%, 26.5% and 6.2%, in order from index to little fingers; the average phalangeal segment force contributions were 47.3%, 14.0%, 20.5% and 18.1% for distal, middle, proximal and metacarpal phalanges, respectively. The plastic surface handles were associated with 15% less torque output (4.86 Nm) than the rubber coated handles (5.73 Nm). In general, the vertical workpiece orientation was associated with higher torque output (5.9 Nm) than the horizontal orientation (4.69 Nm). Analysis of handle shapes indicates that screwdrivers designed with a circular or hexagonal cross-sectional shape result in greater torque outputs (5.49 Nm, 5.57 Nm), with less total finger force (95 N, 105 N). In terms of lateral shape, reversed double frustum handles were associated with less torque output (5.23 Nm) than the double frustum (5.44 Nm) and cone (5.37 Nm) handles. Screwdriver handles designed with combinations of circular or hexagonal cross-sectional shapes with double frustum and cone lateral shapes were optimal in this study.

Keywords: Screwdriver handle design; Handle shape; Handle surface; Maximum torque exertion

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†The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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1. Introduction

In many industrial work situations, torque exertion and rotational forces are required in maintenance and repair activities to fasten devices. As such, the use of non-powered hand tools (such as screwdrivers and wrenches) is quite widespread (Mital *et al.* 1994). US Bureau of Labor Statistics (2001) data showed that injuries to the hand, finger, wrist and shoulder are the most prevalent upper extremity injuries associated with non-powered hand tools. 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).

Handle diameter is one of the essential criteria in tool design that maximizes performance and reduces stress on the forearm muscles and finger tendons. The general agreement among studies to date is that torque output is proportional to the handle diameter. Previous studies examining ranges of handle sizes (Pheasant and O'Neill 1975, Pheasant and Scriven 1983, Shih and Wang 1996, Kong and Lowe 2005b) have noted a positive non-linear relationship between handle diameter and torque output. Pheasant and O'Neill (1975) reported that a 50 mm knurled cylindrical handle was efficient in terms of strength of maximum torque exertion. Shih and Wang (1996) and Kong and Lowe (2005b) also showed that the increase of maximum torque output as a function of handle diameter levels off when a handle's diameter exceeds 50 mm. Kong and Lowe (2005b) reported the greatest maximum torque output with 45–50 mm diameter handles. They also found that handles with 37–44 mm diameters maximized perceived comfort for females and that 41–48 mm diameter handles did the same for males.

Relatively few studies have investigated the effects of quality or condition of a handle's surface on the task performance and operators' subjective preferences for screwdriver handles. Pheasant and O'Neill (1975) found that knurled cylindrical handles were associated with higher torque output levels than those of smooth steel handles. Magill and Konz (1986) compared seven commercially available screwdrivers of similar design and size with different handle materials (four plastic, two wooden and one rubber-coated), based on the maximum torque output, time for driving a screw and subjective preference. They reported that the rubber handles were generally the most preferred, followed by plastic and wooden handles; the rubber and plastic handles were also associated with greater torque output and manipulative capability than the wooden handles.

The handle shape should be designed to maximize subjective comfort, task performance and area of contact between the palm and the handle to provide better pressure distribution and reduce the unit pressure on the hand when working with hand tools. Mital and Channaveeraiah (1988) reported that triangular handles exhibited maximum torque output, followed by square and circular handles when the screwdriver was positioned at eye height in a sitting posture. There was no significant difference between square and circular handle shapes. Shih and Wang (1996) also reported that triangular handles were associated with higher screwdriver torque output, followed by square-, hexagonal- and circular-shaped handles when tested at standing shoulder height. Cochran and Riley (1986) reported that rectangular and triangular handles were associated with the highest torque output and circular and square handles were associated with the least torque output when assessed at elbow height in a standing posture.

Previous studies have investigated only the effects of longitudinal cross-sectional shape on screwdriver torque performance. The effects of combinations of longitudinal and lateral cross-sectional shape on task performance, subjective discomfort and muscle activity have not been reported.

In this study, screwdrivers with combinations of longitudinal cross-sectional handle shape (circular, hexagonal, triangular), lateral cross-sectional handle shape (cylindrical, double frustum, cone and reversed double frustum) and handle surface material (rubber and plastic), when used with horizontal and vertical workpiece orientations, were evaluated in a maximum screwdriver torque task. The objectives of this study were: (1) to evaluate the effects of screwdriver handle shape, screwdriver handle surface and orientation of workpiece on torque output, total finger force and muscle electromyographic (EMG) activity; (2) to define the handle design characteristics achieving high task performance in a maximum screwdriver torque task.

2. Method

2.1. *Subjects*

A total of 12 right-handed male subjects were recruited from a university population; detailed characteristics of these subjects are listed in table 1. All subjects were screened by questionnaire for any hand injuries or surgical history of the dominant hand. Subjects were provided with a description of the study procedures and provided informed consent to participate.

2.2. *Apparatus*

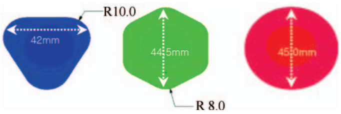
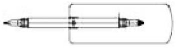
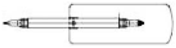
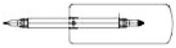
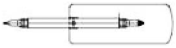
2.2.1. Handles. Twenty-four screwdriver handles, each with a length of 130 mm, were constructed with factorial combinations of longitudinal cross-sectional shape (circular, hexagonal, triangular), lateral cross-sectional shape (cylindrical, double frustum, cone, reverse double frustum) and surface material (plastic, rubber-coated). The nominal diameter of all the handles in cross section was 45.0 mm, but the maximum dimension in cross section depended on the handle cross-sectional shape. Based on the studies cited previously, this dimension optimizes both performance (torque output) and perceived (dis)comfort for the largest percentage of users. Table 2 shows the detailed dimensions of the handles.

Table 1. Characteristics of subjects ($n = 12$).

	Mean (SD)	
	Horizontal condition	Vertical condition
Age (years)	28.2 (9.8)	23.1 (4.6)
Height (cm)	178.1 (8.0)	182.6 (5.9)
Weight (kg)	76.9 (11.1)	86.1 (18.6)
Hand length* (mm)	191.5 (11.9)	197.3 (5.5)
Hand thickness† (mm)	28.3 (3.0)	30.0 (3.0)
Hand breadth‡ (mm)	85.3 (8.3)	86.9 (5.4)
Palm length§ (mm)	109.1 (5.0)	111.5 (2.7)

*Distance from the crease of the wrist to the tip of the middle finger with the hand held straight and stiff.
†Distance between the back and palm surfaces of the hand at the knuckle (metacarpal-phalangeal joint) of the index finger.
‡Maximum breadth across the palm of the hand (at the distal ends of the metacarpal bones).
§Distance between the root of the palm (the crease of the wrist) and the root of the middle finger.

Table 2. Dimensions of screwdriver handles (mm) (the nominal cross-sectional diameter is 45.0 mm).

			Longitudinal (cross-sectional) shape		
					
			Triangular	Hexagonal	Circular
Lateral shape		Cylindrical	42.0^w^ 42.0^n^	44.5^w^ 44.5^n^	45.0^w^ 45.0^n^
		Reversed double frustum	42.0^w^ 33.5^n^	44.5^w^ 35.5^n^	45.0^w^ 36.0^n^
		Double frustum (DF)	42.0^w^ 33.5^n^	44.5^w^ 35.5^n^	45.0^w^ 36.0^n^
		Cone	42.0^w^ 33.5^n^	44.5^w^ 35.5^n^	45.0^w^ 36.0^n^

^{w} = widest cross-section dimension; ^{n} = narrowest cross-section dimension, i.e. for the DF shape, 45 mm is the diameter at the centre of the DF handle, whereas 36 mm is the diameter at the end of the DF handle; R = radius of curvature.

The experimental handles were made of acrylonitrile-butadiene-styrene (ABS), a material known for its durability and impact resistance. The ABS material was milled inside and outside using 3-D data generated by computer. The rubber-coated handles were milled and coated with a neoprene rubber material. All handles were crafted to fit over a cylindrical shaft, which accepted a no. 2 Phillips screwdriver bit.

2.2.2. Measurement system. A computerized data acquisition system was developed to collect biomechanical data from sensors for torque (one channel), individual finger phalangeal forces (16 channels) and muscle EMG activity (two channels) associated with maximum screwdriver torque. The system consisted of a Keithley Metrabyte DAS 1802HC 12-bit A/D board (Keithly Instruments, Cleveland, Ott) and custom software written in Labview (National Instruments, Austin, Texas) to control all of the data acquisition and digital signal processing.

The experimental apparatus is shown in figure 1. For measuring maximum screwdriver torque, a replaceable 5/16-inch (7.94 mm) Philips head screw was fixed to the end of a shaft coupling, which was fixed to the torque sensor (*TQ202,* 0–30 Nm). The connector and torque sensor were mounted on a narrow piece of wood dimensioned to fit in a holding slot of a wooden board. The torque sensor was calibrated by applying known weights (1–5 kg) on an armature at a fixed distance from the measurement axis. The torque sensor exhibited extremely high linearity between output voltage and applied weight ($R^2 > 0.99$).

Individual finger segment (phalangeal) forces were measured with an instrumented glove, as described in Kong and Lowe (2005a). The force glove system contained 16 thin (0.127 mm) flexible conductive polymer pressure sensors with a 9.53 mm diameter sensing area (FlexiForce sensors, A101; Tekscan, Inc., Boston, MA, USA) on the pulpy regions of the phalanges and palm area, enabling analysis of finger force as well as of force distributions for finger and palm. Data from the sensors were input to a custom voltage division circuit box, designed to provide a ±5 V output to the A/D board. Calibration of the Flexiforce sensors followed the same procedures. The voltage outputs

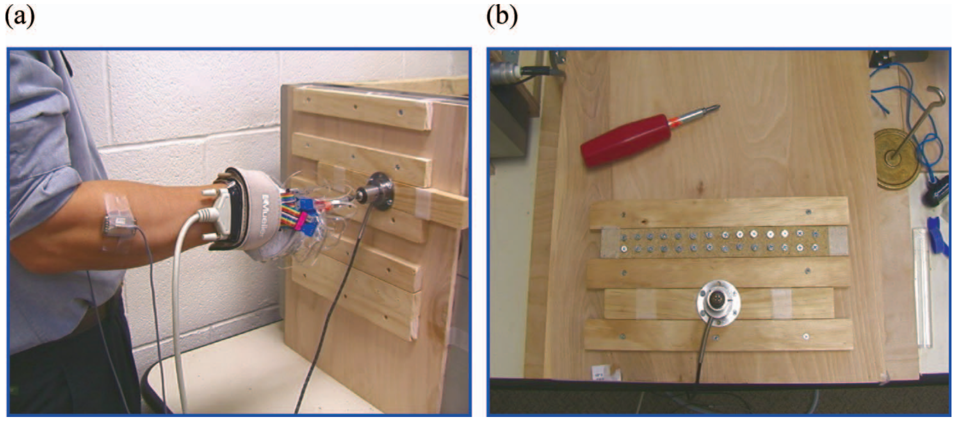


Figure 1. Workplace for maximum torque task. (a) vertical workpiece orientation taken from a side view; (b) horizontal workpiece orientation taken from a top view.

from the sensors were calibrated directly to applied force on a miniature button-style load cell. Each sensor was centred over a metal plate of 25 mm diameter mounted over the button-style load cell. The researcher gradually increased force against the sensor, using the thumb, from zero to 200 N and decreased this pressing force back to zero. The relationship between the voltage output from the force sensor and the applied force (measured by the load cell) resulted in a highly linear relationship ($0.985 < R^2 < 0.995$).

Questions have been raised about the effect of shear forces on the performance of these thin profile resistive force sensors. Information provided by the sensor manufacturer cautions that there may be a shorter sensor life as a result of shear force application. The fact that it may lead to earlier failure of the sensor is one main concern with the shear force application, but failure is visually obvious from a separation in the sensor layers and a sudden loss of electrical conductivity through the sensor. Prior to such failure, the authors have seen no overt indications that measurements of normal force are compromised by the application of shear force. When a sensor fails, it is usually an instantaneous event that is visually obvious and the sensor can be quickly replaced. The sensors do appear to exhibit a gradual loss in sensitivity over time (under any loading conditions), which can be compensated for by frequent recalibration and setting a criterion for a minimum sensor measurement sensitivity in the calibration.

Bipolar surface electrodes were positioned over the bellies of the flexor digitorum superficialis (FDS) and extensor digitorum (ED) muscles, parallel to the longitudinal axis of the muscle fibres. One electrode for the FDS muscle was located by asking the subject to flex the fourth finger against external resistance, while visually observing and palpating the forearm over the contracting muscle (Blackwell *et al.* 1999). The other electrode was positioned over the ED muscle in the orientation recommended by Zipp (1982). The raw EMG signal was acquired at a sampling frequency of 1000 Hz, digitally filtered using a 6th order Butterworth filter with a 10–350 Hz pass band and expressed as the root mean square (RMS) or the signal (50 ms time constant). To minimize differences between subjects and electrodes, task EMG was normalized with regard to maximum EMG, based on the traditional formula (equation 1):

$$\text{Normalized EMG} = \frac{(\text{Task EMG} - \text{resting EMG})}{(\text{Max. EMG} - \text{resting EMG})} \tag{1}$$

2.3. *Experimental procedure*

Maximum EMG was established by averaging maximum RMS EMG amplitude for three isometric hand grip trials at a grip span of 50, 55 or 60 mm on a hand grip dynamometer. The span setting that yielded the highest RMS amplitude was used as maximum EMG and the three maximum voluntary contraction (MVC) trials for that span were averaged. These MVC hand grip exertions were conducted at the beginning of the session. A rest period of 2 min was provided between trials.

There are generally three types of screwdriver grasp, depending on the degree of strength or precision of the task (as described by Matheson *et al.* 1991). High-precision tasks with small-blade screwdrivers require a grip using the fingertips. High-force/low-precision tasks with large-sized screwdrivers involve a grip using the palm and the fingers in a power grip configuration with the thumb placed over the fingers in a locking position to provide maximum gripping force (i.e. 'thumb down'). Medium-sized screwdrivers involve a grip with the handle in the palm of the hand with the index finger and thumb used to guide the blade (i.e. 'thumb up'). The latter 'thumb up' grip was used in this study.

Subjects were presented with the experimental handles and assigned task orientations in a randomized order. Each subject tested all 24 screwdriver handles, presented in a randomized order. The maximum torque exertion was repeated two times for each handle, with 2 min of rest time between trials. Thus, a total of 48 torque outputs were recorded for each subject. Six of the 12 subjects tested maximum torque exertion from the vertical orientation; the other six subjects exerted their maximum torque from the horizontal orientation (see figure 1). All subjects had several trials to familiarize themselves with the equipment, handles and procedure before trial measurements were made.

In each trial, using their dominant hand, the subject was asked to apply maximum torque to the screw assembly on the torque sensor, which was mounted in either the horizontal or the vertical orientation, with one of the handles. The height of the 'workpiece' was adjusted so that, while standing, each subject could maintain a straight elbow in the horizontal workpiece orientation or approximately 90° elbow flexion in the vertical workpiece orientation. Subjects were instructed to maintain consistency in their technique when performing all maximum screwdriver torque exertions.

Subjects were asked to wait to begin until they heard an audible 'beep' signal. At the sound of the beep, they were to increase the exertion of torque to their maximum level in a clockwise 'tightening' direction and hold their maximum torque output until a second beep sounded 4 s later. The individual time series for torque, muscle activity and finger force were averaged over the latter 3 s of the 4-s window between audible beeps.

2.4. *Data analysis*

Mixed models (Proc Mixed, SAS® Version 9.1; SAS Institute Inc., Cary, NC, USA) were used to analyse the dependent variables in the maximum voluntary torque task. All main effects and two-way interactions were included in the models. The dependent variables were maximum torque performance, total/individual finger force and muscle EMG activity. Handle surface, lateral cross-sectional shape and longitudinal cross-sectional shape were fixed within-subjects variables. In the analysis of the dependent variable individual finger force, finger (index, middle, ring, little) and phalange (distal, middle, proximal, metacarpal) were included as within-subjects variables. Finger had four levels, in which the four sensors on each finger segment/metacarpal were summed for a measure of finger specific force; phalange had four levels, in which the four sensors at each similar segment of each finger were summed. Work station orientation was a fixed, between-subjects variable. Subject was a random variable nested within work station orientation.

Total finger force was calculated by summing over all 16 individual force sensors. The percentage contribution of each phalange segment and each finger to the total finger force required torque task was also analysed.

3. Results

3.1. *Torque output*

The effects of handle surface ($p = 0.0146$), longitudinal shape ($p = 0.0306$) and lateral shape ($p = 0.0026$) on maximum voluntary torque output were found to be statistically significant (figure 2). As expected, rubber surface handles were associated with higher torque output than plastic handles. On average, torque output with plastic handles (4.86 Nm) was approximately 84.8% of the torque output of rubber handles (5.73 Nm).

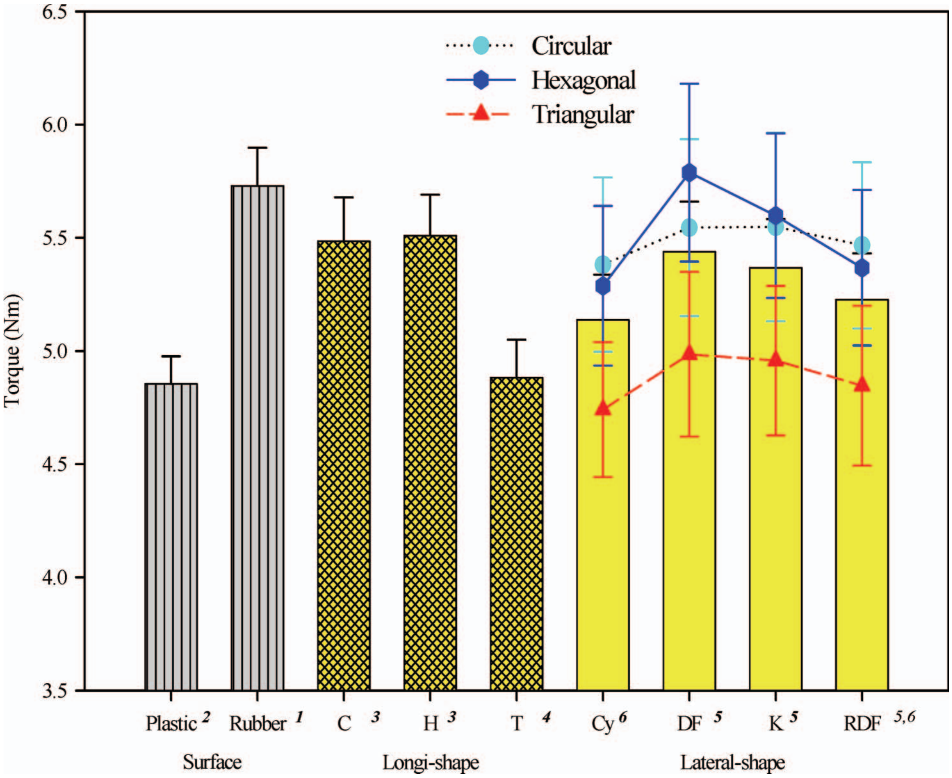


Figure 2. Maximum torque exertions for surface, longitudinal (longi)-shape and lateral-shape. *1, 2, . . . 6* represent groupings by statistical significance. The *5, 6* grouping does not differ significantly from group *5* or group *6*. C = circular; H = hexagonal; T = triangular; Cy = cylindrical; DF = double frustum; K = Cone; RDF = reversed double frustum handles.

Hexagonal (5.57 Nm) and circular (5.49 Nm) handles were associated with statistically greater torque output than triangular (4.88 Nm) handles ($p < 0.05$). In terms of lateral shape, double frustum (5.44 Nm) and cone (5.37 Nm) handles exhibited statistically greater torque output than reversed double frustum (5.23 Nm) and cylindrical handles (5.14 Nm; $p < 0.05$). A multiple comparison test showed that triangular handles showed the least torque output of the longitudinal shapes and the cylindrical handles showed the least torque output of the lateral shapes. With regard to the interaction between longitudinal and lateral shapes, hexagonal and circular (longitudinal shape) handles, especially when combined with double frustum and cone (lateral shape) handles, exhibited higher torque output than any other handles. In general, subjects were able to produce greater screwdriver torque output in the vertical orientation (5.9 Nm) than in the horizontal orientation (4.69 Nm).

3.2. *Total and individual finger/phalange force*

3.2.1. Total finger force. The measure of total finger force was defined as the sum of all 16 segment forces, measured on the three phalangeal segments and metacarpal heads of the index, middle, ring and little fingers. For total finger force, a significant longitudinal shape effect and significant interaction effects of orientation * longitudinal shape and surface * longitudinal shape were found (all $p < 0.05$). The longitudinal * lateral shape interaction was associated with a p-value of 0.064.

As shown in figure 3, total finger force was greatest when subjects used the triangular (112.8 N) and hexagonal (105.0 N) handles. There was also a significant difference between hexagonal and circular handles in the horizontal orientation ($p < 0.001$). There were no significant differences between the longitudinal-shaped handles in the vertical

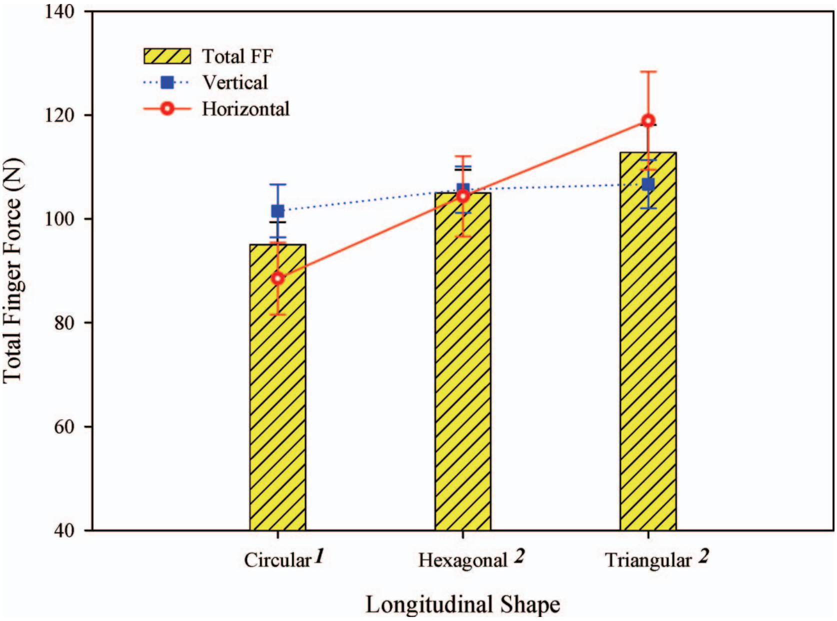


Figure 3. Main and interaction effects on the total finger force (FF). *1* and *2* represent groupings by statistical significance.

orientation. Circular (95.0 N) handles were associated with significantly less total finger force ($p < 0.05$) overall. However, triangular and hexagonal handles in both orientations were associated with greater total finger force than circular handles when exerting maximum torque. Total finger forces were similar in both horizontal (103.9 N) and vertical (104.6 N) orientations.

Figure 4 shows the interaction effect between surface and longitudinal shape for the handles. Circular handles exhibited less total finger force than any other handles, regardless of surface material. Plastic circular handles were associated with statistically less total finger force than plastic hexagonal handles and plastic or rubber triangular handles (both surfaces, $p < 0.05$). Rubber-coated circular and hexagonal handles both exhibited statistically less total finger force than rubber-coated triangular handles ($p < 0.005$).

3.2.2. Individual finger/phalange forces. Significant main effects were observed for longitudinal shape ($p = 0.0035$), as well as finger, phalangeal segment and the interaction between finger and phalangeal segment (all $p < 0.01$). The main effect of lateral shape was associated with a p-value of 0.051. The main effects of longitudinal shape and lateral shape on the individual finger force showed a similar pattern to the results of total finger force (that is, hexagonal and triangular handles showed higher total finger forces than circular handles, whereas cylindrical lateral-shape handles had lower finger forces compared with other handles).

Figure 5 shows the average contribution of individual phalangeal segment forces to the total finger force in the maximum screwdriver torque task. In the analyses of individual

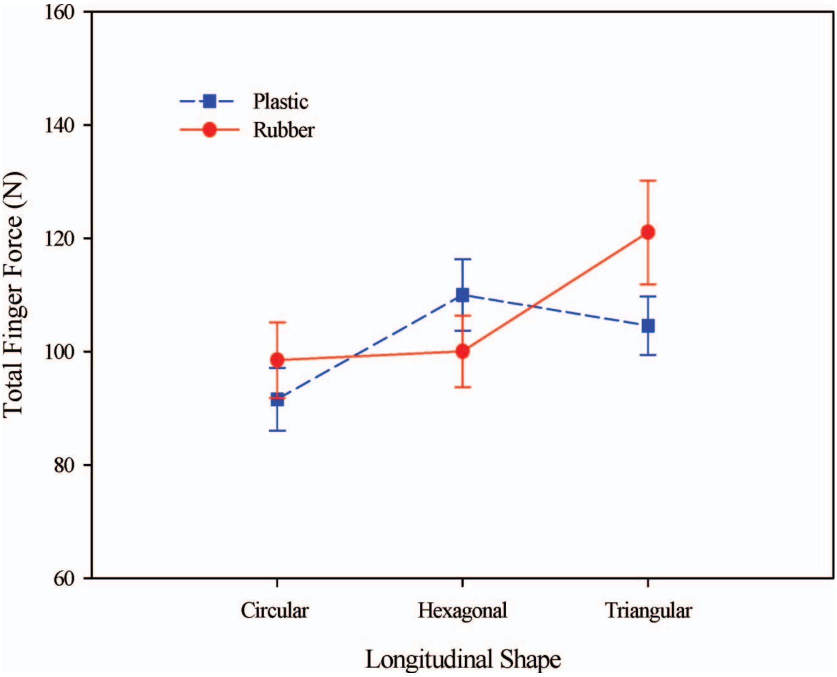


Figure 4. Interaction effects (surface * longitudinal-shape) on the total finger force. C = circular; H = hexagonal; T = triangular; Cy = cylindrical; DF = double frustum; K = cone; RDF = reversed double frustum handles.

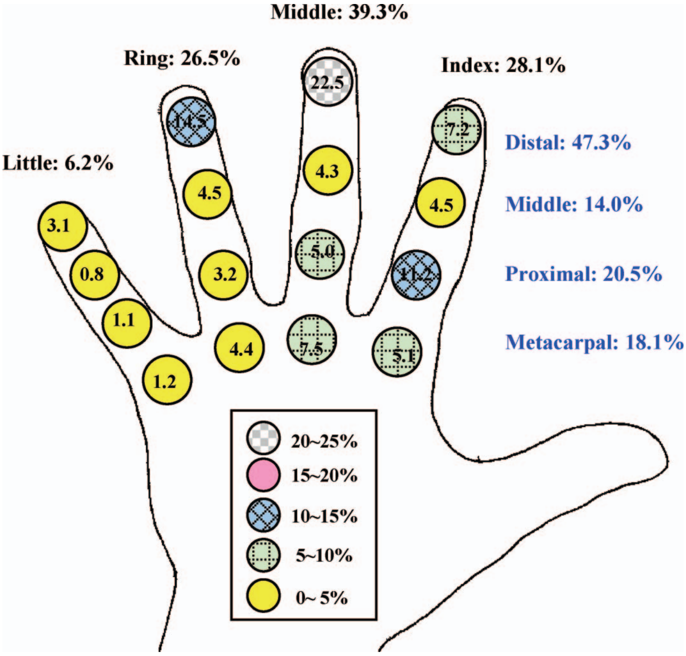


Figure 5. Mean individual segment force distributions for all handles.

finger force, the middle finger had the highest finger force and contribution to total finger force (40.9 N, 39.3%), followed by the index finger (29.2 N, 28.1%) and ring finger (27.7 N, 26.5%). There were no significant differences between index and ring fingers, although the index finger's force and percentage contribution to the total finger force were slightly larger than those of the ring finger. The little finger exhibited significantly less finger force (6.5 N) and percentage contribution to the total finger force (6.2%) than any other finger ($p < 0.05$). In the analyses of individual phalangeal segment force, the forces exerted by the distal phalanges were significantly higher ($p < 0.01$) than those exerted by the other phalanges; the distal phalange exerted the largest force (49.2 N, 47.3%), followed by the proximal (21.4 N, 20.5%), metacarpal (18.9 N, 18.1%) and middle (14.7 N, 14.0%) phalanges.

In the analysis of individual segment force distributions (see figure 5), the distal phalanges of the middle, ring and index fingers and the proximal and metacarpal phalanges of the index and middle fingers were higher contact areas when using the 'thumb up-holding type' in the maximum screwdriver torque task. There were slightly different patterns for each handle type (see details in table 3).

3.3. *Muscle activity (flexor and extensor)*

The statistical analysis showed that workpiece orientation ($p = 0.03$) had significant effects on the normalized EMG activity of the FDS muscle, whereas orientation ($p = 0.02$) and surface ($p = 0.002$) were significant factors for the normalized EMG activity of the ED muscle. The effect of the lateral handle shape on the normalized EMG activity was associated with a p-value of 0.06. The normalized EMG activities of FDS and ED as a

Table 3. Individual finger and phalange forces and contributions as a function of handle shape.

		Index finger					Middle finger					Ring finger					Little finger					
		D	M	P	ME	Total	D	M	P	ME	Total	D	M	P	ME	Total	D	M	P	ME	Total	Total (N)
C	N	7.9	**3.9**	11.2	4.3	**27.3**	22.1	**3.7**	**3.6**	7.6	**37.0**	14.0	4.5	**2.1**	**3.4**	**24.1**	3.6	0.9	**1.1**	**1.1**	**6.7**	**95.0**
	%^{1}	29.0	14.2	41.0	15.9	100	59.8	9.9	9.6	20.7	100	58.0	18.7	8.9	14.3	100	54.2	13.0	16.5	16.3	100	
	%^{2}	8.3	**4.1**	11.8	**4.6**	28.8	**23.3**	**3.9**	**3.7**	**8.0**	**38.9**	14.7	4.7	2.3	**3.6**	25.3	**3.8**	0.9	**1.2**	1.1	**7.0**	
H	N	7.1	**4.0**	12.5	5.6	**29.3**	23.4	**4.4**	**5.6**	9.3	**42.7**	14.8	4.9	**3.9**	**3.5**	**27.2**	3.0	0.7	**1.0**	**1.1**	**5.8**	**105.0**
	%^{1}	24.4	13.8	42.7	19.1	100	54.8	10.3	13.1	21.8	100	54.6	18.2	14.5	12.7	100	51.7	12.5	17.0	18.7	100	
	%^{2}	6.8	**3.8**	11.9	**5.3**	27.9	**22.3**	**4.2**	**5.3**	**8.9**	**40.7**	14.1	4.7	3.7	**3.3**	25.9	**2.9**	0.7	**0.9**	1.0	**5.5**	
T	N	7.4	**6.2**	11.4	6.0	**31.0**	24.6	**5.5**	**6.6**	6.4	**43.1**	16.5	4.6	**3.8**	**6.9**	**31.8**	3.1	0.8	**1.4**	**1.6**	**6.9**	**112.8**
	%^{1}	23.8	20.0	36.7	19.4	100	57.1	12.9	15.4	14.7	100	52.0	14.3	12.0	21.6	100	45.1	11.2	21.0	22.6	100	
	%^{2}	6.6	**5.5**	10.1	**5.3**	27.5	**21.8**	**4.9**	**5.9**	**5.6**	**38.2**	14.7	4.0	3.4	**6.1**	28.2	**2.7**	0.7	**1.3**	1.4	**6.1**	
Cy	N	7.3	4.5	**10.7**	5.3	**27.9**	24.0	3.8	4.0	**6.6**	**38.3**	13.6	3.3	3.5	3.5	**23.8**	2.7	0.7	**0.9**	1.0	**5.3**	**95.3**
	%^{1}	26.3	16.2	38.4	19.2	100	62.6	9.9	10.3	17.2	100	57.1	13.7	14.5	14.7	100	51.3	12.9	16.5	19.3	100	
	%^{2}	7.7	4.7	**11.2**	5.6	**29.2**	25.2	4.0	4.1	**6.9**	**40.2**	14.3	3.4	**3.6**	3.7	25.0	2.8	0.7	0.9	1.1	5.5	
DF	N	8.8	5.4	**7.9**	4.9	**27.0**	23.0	5.0	5.4	**11.5**	**44.9**	15.4	5.6	3.4	4.3	**28.8**	3.6	0.8	**1.3**	1.3	**7.0**	**107.6**
	%^{1}	32.5	20.1	29.3	18.2	100	51.2	11.2	12.0	25.6	100	53.5	19.5	12.0	15.0	100	51.1	11.4	18.2	19.3	100	
	%^{2}	8.1	5.0	**7.3**	4.6	**25.1**	21.4	4.7	5.0	**10.7**	**41.7**	14.3	5.2	**3.2**	4.0	26.8	3.3	0.7	1.2	1.2	6.5	
K	N	7.7	4.4	**11.3**	5.5	**28.9**	22.6	4.8	6.0	**7.0**	**40.4**	16.2	5.0	4.0	4.9	**30.0**	3.2	0.8	**1.5**	1.3	**6.9**	**106.2**
	%^{1}	26.8	15.2	39.1	18.9	100	56.0	11.8	14.8	17.3	100	54.0	16.6	13.3	16.2	100	47.0	11.9	21.9	19.3	100	
	%^{2}	7.3	4.1	**10.6**	5.1	**27.2**	21.3	4.5	5.6	**6.6**	**38.0**	15.3	4.7	**3.8**	4.6	28.3	3.1	0.8	1.4	1.3	6.5	
RDF	N	6.1	4.5	**16.9**	5.7	**33.2**	23.8	4.5	5.7	**6.0**	**40.0**	15.4	4.8	2.3	5.7	**28.2**	3.5	0.9	**1.1**	1.3	**6.7**	**108.1**
	%^{1}	18.5	13.6	50.9	17.1	100	59.5	11.3	14.3	15.0	100	54.7	17.0	8.2	20.1	100	51.8	12.9	16.0	19.3	100	
	%^{2}	5.7	4.2	**15.6**	5.2	**30.7**	22.0	4.2	5.3	**5.6**	**37.0**	14.3	4.4	**2.1**	5.2	26.1	3.2	0.8	1.0	1.2	6.2	

N = segment force in Newtons; %^{1} = segment contribution within each finger; %^{2} = segment contribution for total finger force].

Values shown in bold denote statistical significance for handle shape factor.

Handle shapes (longitudinal): C = circular; T = triangular; h = Hexagonal; handle shapes (lateral): Cy = cylindrical; DF = double frustum; RDF = reversed double frustum; K = cone.

Phalangeal segments: D = distal; M = middle; P = proximal; ME = metacarpal phalange.

function of the workpiece orientation are shown in figure 6. The FDS muscle was more active in the vertical workplace orientation than in the horizontal orientation, whereas the ED muscle exhibited the opposite effect. Results of this study also indicate that the normalized EMG activity of the extensor was lower with rubber-coated handles than with plastic handles. The activity of the flexor was generally larger with the reversed double frustum (RDF) handles compared to that with any other lateral handle shape.

4. Discussion

In the analysis of handle surface material, rubber-coated handles were associated with greater torque output than plastic handles. Normalized extensor EMG activity was also less with the use of rubber-coated handles than with plastic handles. In a previous study, Magill and Konz (1986) reported a similar finding; in an evaluation of seven industrial screwdrivers, rubber handles had similar or better preferences and torque outputs than plastic or wooden handles. Based on these findings, rubber-coated handles may provide more friction, permitting users to perform with maximum torque exertion. Anecdotal evidence suggests that the increased friction does not yield greater levels of discomfort.

Hexagonal and circular handles were associated with higher torque outputs than triangular handles, while the measured total finger force was the largest when triangular handles were used. The results of the present study indicate that circular and hexagonal handles, which had only slightly larger effective moment arms, were associated with higher torque capability than triangular handles (moment arm ratios 1.075:1.05:1.0 for circular:hexagonal:triangular). Thus, there is a positive relationship between the effective

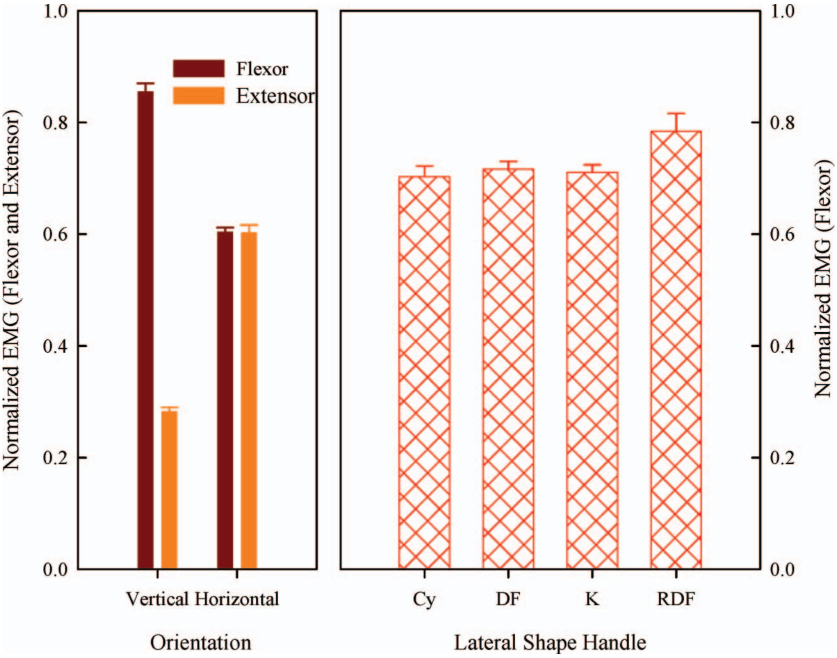


Figure 6. Main effects on the flexor and extensor normalized electromyography (EMG). Cy = cylindrical; DF = double frustum; K = cone; RDF = reversed double frustum handles.

moment arm afforded by the shape and torque output (Pheasant and O'Neill 1975, Pheasant and Scriven 1983, Shih and Wang 1996, Kong and Lowe 2005b). This indicates that designing screwdrivers with circular or hexagonal longitudinal-shaped handles will improve torque output capability with less finger force.

The relationships between handle longitudinal shape and torque output observed in the present study differ somewhat from those of previous studies. Cochran and Riley (1986), for example, indicated that rectangular and triangular handles produced more torque than square and circular handles. Similarly, Shih and Wang (1996) reported that screwdrivers with triangular handles produced more torque than those with square, hexagonal or circular handles. Most of these differences (between the two studies' findings) can be attributed to differences in the effective moment arms among the tested handle shapes. Cochran and Riley's ratios among the moment arms of the handles were 1.18:1.15:1.08:1.0 for rectangular, triangular, square and circular, respectively. Shih and Wang, on the other hand, tested handles with moment arm ratios of 1.16:1.41:1.0:1.0 (triangular:rectangular:hexagonal:circular, respectively). Differences in handle orientation between the present study and the previous studies of Cochran and Riley (1986), Mital and Channaveeraiah (1988) and Shih and Wang (1996) might also have resulted in the differences among the relationships between torque output and moment arm ratios in the evaluation of handle shapes. In these previous studies, the maximum screwdriver torques were measured at standing elbow height (Cochran and Riley 1986), at eye level with a straight elbow in the sitting posture (Mital and Channaveeraiah 1988) and at shoulder height with a straight elbow in a standing posture (Shih and Wang 1996).

Thin profile force sensors, attached to the palmar surface of a snug-fitting athletic grip glove, were used to investigate the contribution of individual finger segments to the total finger grip force in the maximum screwdriver torque task. The average contributions of each of the fingers were measured as 28.1%, 39.3%, 26.5% and 6.2% for the index, middle, ring and little fingers, respectively, and 47.3%, 14.0%, 20.5% and 18.1% for the distal, middle, proximal and metacarpal phalangeal segments, respectively. While the contributions of the segments exhibited similar trends with those reported in a previous study investigating the effect of cylindrical handle diameter on maximum torque output (Kong and Lowe 2005b), there were differences between the findings of the two studies in terms of the contributions of distal phalange and the middle and little fingers. In the maximum exertion of torque on cylindrical handles (Kong and Lowe 2005b) the distribution of individual finger forces with maximum torque on cylindrical handles was 28.3%, 36.2%, 25.0% and 10.5% for the index, middle, ring and little fingers, respectively, and 36.8%, 22.7%, 21.3% and 19.2% for the distal, middle, proximal and metacarpal segments, respectively. The differences between the two tasks in terms of finger force distribution can be at least partially explained by the difference in the grasp configuration. In the previous study of torque exertion, subjects grasped the handles with all fingers perpendicular to the long axis of the handles and the thumb placed over the fingers to provide maximum gripping force (i.e. thumb down). In the present study, subjects were asked to use the screwdriver to exert their maximum screwdriving torque and did so as if they were using a screwdriver to tighten a screw. The typical grasp configuration for this exertion was with the screwdriver in the palm of the hand with the index and middle fingers and thumb used for grasping and guiding the tool handle in the 'thumb up' grasp configuration. The wrist was also more ulnarly deviated in the maximum screwdriving torque task than in the previous maximum torque task. Thus, differences in the nature of the grasp of the handles affected the contributions of individual finger segments to the total grip force on the handles.

5. Conclusion

This study investigated the effects of screwdriver handle shape, surface material and workpiece orientation on torque performance, total finger force and muscle activity in a maximum screwdriving torque exertion task that was representative of the near maximal final tightening torque statically imparted on a screw.

In terms of torque performance, longitudinal-shaped (short axis) hexagonal and circular handles were associated with greater torque output than triangular handles. Lateral-shaped (long-axis) double frustum and cone handles were associated with greater torque output than reversed double frustum and cylindrical handles. With regard to the interaction between longitudinal and lateral shape, torque capability was maximized when hexagonal and circular longitudinal shapes were combined with double frustum and cone lateral shapes. Total finger force was lower with the circular handles than with triangular and hexagonal handles, for both plastic and rubber-coated handles. This indicates that screwdrivers with longitudinally-shaped circular handles might maximize torque performance capability while minimizing finger force. Triangular-shaped handles revealed no advantages in this study; however, this study did not examine conditions where grease or other contaminants may be present, which could reduce the coefficient of friction at the tool-handle coupling.

The analysis of muscle activity indicated that the primary finger flexor (FDS) was more active in the vertical workpiece orientation than in the horizontal orientation, whereas the extensor muscle group (ED) exhibited the opposite effect. The activity of the extensor was lower with rubber-coated handles than with the plastic-coated handle and the activity of the flexor was larger with the RDF handle relative to the other handles.

The results of this study define handle design characteristics that achieve greater task performance and that minimize finger force and muscle activity in a maximum screwdriver torque task under typical conditions in which a fastener is firmly tightened under high levels of static torque. Additional work should be conducted to examine screw insertion under dynamic, submaximal conditions, in which time-based measures of work performance can also be considered.

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