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Evaluation of handle shapes for screwdriving ☆

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Abstract

This study investigated the effects of screwdriver handle shape, surface, and workpiece orientation on subjective discomfort, number of screw-tightening rotations, screw-insertion time, axial screwdriving force, and finger contact forces in a screwdriving task. Handles with three longitudinal cross-sectional shapes (circular, hexagonal, triangular), four lateral shapes (cylindrical, double frustum, reversed double frustum, cone), and two surface materials (plastic, rubber coated) were tested. Individual phalangeal segment force distributions indicated how fingers and phalangeal segments were involved in the creation of total finger force (15.0%, 34.6%, 34.5%, and 15.9% for the index, middle, ring, and little fingers; and 45.7%, 22.4%, 12.9%, and 19.0% for the distal, middle, proximal, and metacarpal phalanges, respectively). From this finding, the index and little fingers appeared to contribute mainly in the guiding and balancing of the screwdriver handles, whereas middle and ring fingers played a more prominent role in gripping and turning. Participants preferred circular and hexagonal longitudinal-shaped and double frustum and cone lateral-shaped handles over the triangular longitudinal-shaped handles, and cylindrical and reversed double frustum lateral-shaped handles. Circular, cylindrical, and double frustum handles exhibited the least total finger force associated with screw insertion. In terms of combinations of longitudinal and lateral shapes, circular with double frustum handles were associated with less discomfort and total finger force.

Keywords: Screwdriver handle; Handle surface; Finger/phalange force; Screwdriving

1. Introduction

It has been reported that over 6% of all compensable work injuries in the US and 10% of all industrial injuries are caused by the use of hand tools (Ayoub et al., 1975; Mital and Sanghavi, 1986; Aghazadeh and Mital, 1987). Although mechanically, electrically, or pneumatically powered hand tools are prevalent in many industrial work situations, non-powered hand tools (such as hammers, screwdrivers, wrenches, knives, etc.) are still routinely used in industry. Industry data indicate that over 56,000 injury and illness cases have been attributed to the use of non-powered hand tools and over 23,000 cases to powered hand tools. The most injured body parts by non-powered and powered hand tools were the upper extremities (66.7% and 47.3%, respectively) followed by the trunk (including back and shoulder) and lower extremities. The fingers are the most frequently injured body part, (i.e., about 26–43% of all body parts and 54–64% of the upper extremity injuries) followed by the hand and wrist for both powered and non-powered hand tool uses (Bureau of Labor Statistics, 1992–2001). Thus, the use of non-powered hand tools can contribute to upper extremity injuries of the hand, finger, wrist, and shoulder. Non-powered hand tools should be ergonomically designed to reduce user discomfort, biomechanical stresses, and risk factors for cumulative trauma disorders of the musculoskeletal system (Freivalds, 1996).

Much research has been conducted to understand the interrelationship between user preference, task performance, and hand-tool design to ensure that hand tools are used more effectively, accurately, comfortably and safely (Örtengren et al., 1991). A few studies have tested

☆*Note*: 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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commercially available non-powered screwdrivers. Mital (1986) tested various types of screwdriver use from 21 body postures on maximum torque exertion capability. The peak torque increased with increasing grip diameter (23–35 mm), but not with increasing handle length. There was no significant association found between body posture and peak torque. Magill and Konz (1986) tested seven screwdrivers to investigate the effects of grip length and grip volume on the maximum torque performance, task completion time for driving a screw, and subjective preference. They reported that maximum torque and handle preference were related to grip length and volume, while task time was inversely related to grip volume and grip length (in both cases, grip volume was a better predictor of torque output and handle preference than grip length). In their study, preference seemed to be more related to maximum torque capability than to manipulative capability, defined by the time to completion of the standardized screwdriving task. Dempsey et al. (2004) investigated two types of screwdrivers to determine the effects of work height, workpiece orientation, gender, and screwdriver type (Phillips or flat head) on productivity and wrist deviation during a screwdriving task. Subjects performed better with the Phillips-head screwdriver and there were strong interactions between workpiece orientation and work height on productivity and measures of wrist deviation.

It is important to note that these above-mentioned studies have only focused on evaluating commercially available screwdrivers in maximum torque or submaximum dynamic screwdriving or tightening tasks. Although there are other studies that have evaluated handles with various handle design characteristics (Pheasant and Scriven, 1983; Cochran and Riley, 1986; Shih and Wang, 1996; Habes and Grant, 1997; Kong et al., in press), these studies investigated the effects of handle size, shape, and surface material on only maximum torque performance. Also, in terms of handle shape, most research has studied only the effects of longitudinal cross-sectional shape (i.e., triangular, rectangular, circular, hexagonal, etc.) on maximum torque output. The effects of lateral (lengthwise) cross-sectional shape have not been investigated.

Only a few studies have examined axial screwdriver contact force (Örtengren et al., 1991) and individual finger forces (Kong et al., in press) associated with screwdriver use. Örtengren et al. (1991) measured axial force applied with a pistol-grip electric screwdriver and a manual screwdriver. Their results suggested that the screw-head design had more influence on axial driving force than the type of screwdriver, with a TORX head resulting in lower axial force than a Phillips head. Kong et al. (in press) evaluated the effect of screwdriver handle shapes on torque output, and finger forces, in a static maximum screwdriver torque exertion. Circular handles were associated with more torque output than triangular or hexagonal lateral-shaped handles, and the long axis shapes that were conical or double frustum were associated with greater torque output.

The purpose of the present study was to evaluate the effects of screwdriver handle shape (including three longitudinal cross-sectional shapes and four lateral shapes), surface material (rubber and plastic), and workpiece orientations (horizontal and vertical) on subjective discomfort, screwdriving performance, axial force, and total/individual finger force in a dynamic screwdriving task. The dynamic screw-insertion task involves submaximal torque exertion, which was not measured in this study. However, the effects of the design parameters on screwdriving performance (number of tightening rotations required, time per screw insertion) were quantified as were the axial force transmitted through the screwdriver and the contributions of individual finger and phalange forces to the total grip force distribution.

2. Method

2.1. Subjects

Twelve males, ranging from 19 to 42 years in age, were recruited from a university population. Detailed characteristics of the participants are listed in Table 1. All participants were screened by questionnaire for any hand injuries, musculoskeletal disorders, or previous surgeries of the dominant hand. None of the participants reported any of these conditions. Participants were provided with a description of the study procedures and provided informed consent to participate.

2.2. Apparatus

2.2.1. Handles

Screwdriver handles were constructed with factorial combinations of three longitudinal cross-sectional shapes (circular, C; triangular, T; hexagonal, H), and four lateral shapes (cylindrical, Cy; double frustum, DF; cone, K; reverse double frustum, RDF) with two surface materials (plastic and rubber coated). Therefore, 24 different screwdriver handles were tested in this study which was a $3 \times 4 \times 2$ factorial design. The nominal outside dimension of the handles in cross section (short axis) was 45 mm. This dimension was chosen based on previous work (Kong and Lowe, 2005) reporting that 45 and 50 mm diameter handles (cylindrical) were associated with the greatest torque

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

Characteristics	Mean	s.d.	Range
Age (years)	23.7	6.2	19–42
Height (cm)	183.0	5.0	172–188.0
Weight (kg)	85.0	15.0	63.5–113.4
Hand length (mm)	196.3	7.0	188.0–200.0
Hand thickness (mm)	29.6	2.8	25.5–34.7
Hand breadth (mm)	86.7	6.6	78.0–99.9
Palm length (mm)	111.2	2.6	107.6–114.7

output and that 37–44 and 41–48 mm diameter handles were associated with the greatest perceived comfort. Handle cross-sectional shapes (short axis) were chosen based on previous work of others (e.g. Cochran and Riley, 1986; Shih and Wang, 1996), however, no studies to our knowledge have evaluated screwdriver long-axis shapes (cylindrical, double frustum, reversed double frustum, and cone).

The handles were made of acrylonitrile butadiene styrene (ABS) for its material characteristics of high-impact resistance. The ABS material was milled inside and outside using 3D data generated by computer. The handles were milled and those to have the rubber surface were coated with a neoprene rubber material. All of the handles fit over the cylindrical shaft, which accepted a screwdriver bit (♯2 Phillips bit). Table 2 shows detailed dimensions of the screwdriver handles. All handles had a long-axis length of 130 mm.

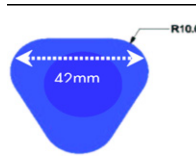
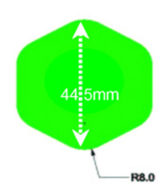
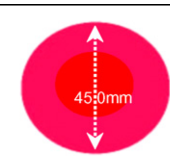
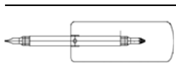
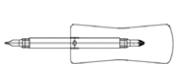
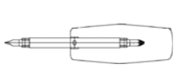
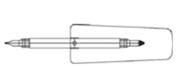
2.2.2. Measurement system

A computer data acquisition system was used to collect the biomechanical data including axial screwdriving force and individual finger/phalangeal forces associated with the screwdriving task. The system consisted of a Keithley Metrabyte DAS 1802HC 12-bit A/D board and custom software written in Labview 6.0 (National Instruments, Austin, TX, USA) to control all of the data acquisition and digital signal processing.

Axial screwdriving force was measured on a force plate (AMTI) mounted on the work surface. For the horizontal orientation, the force platform was placed underneath the wood workpiece and calibrated by applying known weights (0, 44.34, 66.61, 88.78, and 110.95 N). For the vertical orientation, the force platform was placed behind the wood workpiece, which was oriented vertically 90° from the work surface. Calibration was again performed by applying known forces (0, 44.34, 66.61, 88.78, and 110.95 N) using a Chatillon digital force gauge (DFG-50) with a horizontal line of action perpendicular to the plane of the force plate. For the vertically oriented force platform, a custom-made clamping fixture was fabricated to control the various force levels by clamping the force gauge against the force plate. In both cases, the force platform exhibited high linearity between output voltage and applied calibration force ($0.95 < R^2 < 0.99$).

Individual finger/phalangeal forces were measured with a hand-contact force glove system. The force glove system incorporated 16 thin flexible conductive polymer pressure sensors (FlexiForce, A101, Tekscan, Inc) on the pulpy regions of each phalangeal segment and metacarpal head. These sensors are 0.127 mm thick and have a sensing area that is 9.53 mm in diameter. The sensors were connected to a custom voltage division circuit box, designed to provide a ±5 V output to the data acquisition board. Calibration of the Flexiforce sensors followed the same procedures as described by Kong and Lowe (2005). The voltage outputs from the sensors were calibrated directly to applied force measured on a miniature button-style load cell underneath the sensor. Each sensor was centered 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 0 to approximately 150 N and decreased this pressing force back to zero. The calibration exhibited a high linearity ($0.985 < R^2 < 0.995$).

Table 2
Dimensions of screwdriver handles

Lateral shape		Longitudinal (cross-sectional) shape		
		 Triangular (T)	 Hexagonal (H)	 Circular (C)
	Cylindrical (Cy)	42.0^{w} 42.0^{n}	44.5^{w} 44.5^{n}	45.0^{w} 45.0^{n}
	Reversed double frustum (RDF)	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 (K)	42.0^{w} 33.5^{n}	44.5^{w} 35.5^{n}	45.0^{w} 36.0^{n}

Note: ^{w}-widest cross section dimension; ^{n}-narrowest cross section dimension, i.e., for the double frustum (DF) shape, 45 mm is the diameter at the center of the DF handle whereas 36 mm is the diameter at the end of the DF handle.

2.3. Experimental procedure

At the beginning of the experimental session participants were provided with practice driving screws in the configuration to be tested. Using each of the 24 handles, participants were asked to drive a 1.9 cm (0.75 inch) length, small-sized Phillips-head screw into a predrilled wood-piece mounted on a wooden board in either horizontal or vertical orientation. One screw was inserted for each combination of treatment conditions (3 longitudinal shapes $\times 4$ lateral shapes $\times 2$ surface materials). Screw-insertion resistance was assumed to be constant throughout the study because the same wood material stock was used with a predrilled hole of constant diameter and a constant depth of screw insertion. The wooden board was placed flush against the force plate. The height of the wooden board was adjusted so that, while standing, the participant could maintain a straight elbow for the horizontal orientation, or, approximately 90° elbow flexion for the vertical orientation. Participants were instructed to maintain consistency in their technique when performing the screwdriving task. Six of the twelve participants tested the screwdriving task from the vertical orientation; the others from the horizontal orientation. The orientation and sequence of the handles were randomly assigned to each participant in this study.

At the end of each trial, participants reported their subjective discomfort ratings for the handle using a 7-point scale. The scale anchors were as follows: (most uncomfortable, 7; somewhat uncomfortable, 5; moderately uncomfortable, 3; and no discomfort, 1). To reduce the effect of muscle fatigue, two minutes of rest time was provided between trials.

2.4. Data analysis

Mixed models (Proc Mixed, SAS® Version 9.1, SAS Institute Inc., Cary, NC, USA) were used to analyze the dependent variables in the screwdriving task. Handle surface, lateral cross-sectional shape and longitudinal cross-sectional shape were fixed, within-subjects variables. Workstation orientation was a fixed, between-subjects variable. Subject was a random variable nested within workstation orientation. In the analysis of individual phalangeal segment force individual finger (index, middle, ring, and little) and phalangeal segment (distal, middle, proximal, and metacarpal phalangeal) were treated as fixed within-subject variables. The dependent variables were number of screw rotations, screw-insertion time, total/individual phalangeal segment force, axial screwdriving force, and subjective discomfort.

A simple algorithm was employed to identify peaks in the axial force time series that corresponded to each tightening rotation of the screw. This algorithm utilized the Labview "Threshold Peak Detector" function which specifies minimum amplitude, and a minimum number of consecutive data points that must exceed this amplitude, to constitute a valid peak. The local maximum axial force for each screw rotation was visually identifiable (see Fig. 1) and the number of peaks detected by the algorithm matched the number of rotations for the complete screw insertion (see Fig. 1, which clearly illustrates 11 peaks corresponding to 11 screw-tightening rotations). The axial driving force associated with each trial was expressed as the average of the peak axial driver forces (averaged over all screw-tightening rotations) detected by the algorithm. The total finger force was also calculated as the sum of all phalangeal segment forces associated with the peak axial driver force in the trial. This measure was also expressed as the average of the measures captured at the peaks corresponding to each screw rotation. Individual phalangeal segment forces and their contribution to the total finger force were also recorded. Screw-insertion time was calculated beginning at the instant the subject began inserting the screw and ended when the screw head was flush with the face of the wooden board.

The average peak axial driving forces associated with the insertion of a screw were measured from the force platform. The individual phalangeal segment forces and total finger force (sum of all 16 individual sensors) associated with the axial force were measured with the force glove system. The percentage contribution of each phalangeal segment and each finger to the total finger force during the screwdriving task was also analyzed.

3. Results

3.1. Subjective discomfort rating

Statistical analysis for the evaluation of subjective discomfort ratings in the screwdriving task indicated that the main effects of longitudinal cross-sectional shape and lateral (long-axis) shape were significant ($p<0.01$ and $p=0.02$, respectively). See ANOVA summary in Table 3.

Among the longitudinal cross-sectional shapes, the results of contrasts showed that participants reported significantly less discomfort for circular (mean 2.70) and

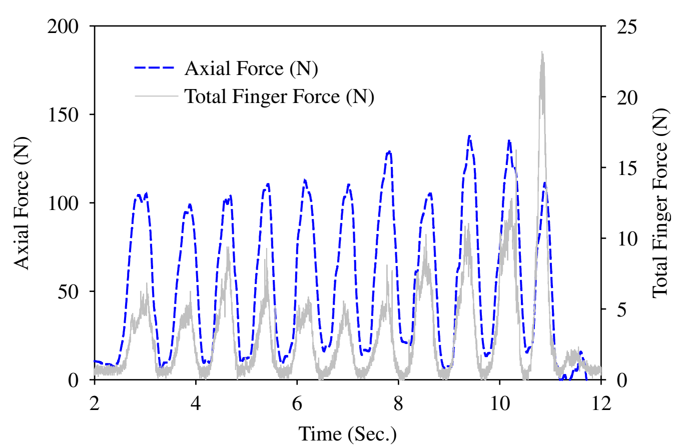


Fig. 1. Axial force and total finger force in a screwdriving trial. There are 11 clearly delineated peaks in axial force, reflecting 11 individual tightening rotations.

hexagonal (2.76) handles than triangular handles (3.78). Among the lateral cross-sectional shapes, participants rated double frustum and cone handles (both 2.72) as associated with less discomfort than cylindrical (3.25) and reversed double frustum (3.63) handles. These findings suggest that combinations of circular and hexagonal handles with double frustum and cone handles were associated with less discomfort than other handle combinations (see Fig. 2). Although the orientation and surface material were not statistically significant, participants rated the vertical orientation and rubber-surface material with lower levels of discomfort than the horizontal orientation and plastic surface material.

3.2. Number of rotations and screw-insertion time

There were no significant factors for the number of tightening rotations required to insert the screw or the screw-insertion time (see Table 3). The average number of rotations and task time were 14.6 rotations and 9.5 s for inserting a screw. Although the effect of orientation was not significant, the average number of tightening rotations

Table 3
(a) ANOVA summary table (p-values) for subjective discomfort rating, number of screw tightening rotations, screw insertion time, peak axial driving force, and total finger force

	Subjective discomfort rating			Number of rotations			Screw-insertion time			Peak axial driving force			Total finger force		
	df	F	p	df	F	p	df	F	p	df	F	p	df	F	p
Orientation (O)	1	0.24	0.636	1	0.58	0.463	1	2.87	0.121	1	4.90	0.051	1	1.26	0.288
Surface (S)	1	0.44	0.522	1	3.06	0.111	1	2.65	0.134	1	0.04	0.854	1	2.51	0.144
Longitudinal shape (LO)	2	6.83	**0.005**	2	2.13	0.145	2	0.39	0.682	2	1.87	0.180	2	18.50	**0.001**
Lateral shape (LA)	3	3.79	**0.020**	3	1.77	0.173	3	2.44	0.083	3	0.87	0.467	3	7.41	**0.001**
O × S	1	0.04	0.849	1	1.68	0.224	1	3.08	0.110	1	0.01	0.943	1	0.84	0.382
O × LO	2	0.21	0.811	2	0.07	0.931	2	1.34	0.285	2	4.21	**0.030**	2	6.69	**0.006**
S × LO	2	0.21	0.812	2	0.88	0.431	2	0.17	0.848	2	0.05	0.953	2	3.17	0.063
LO × LA	6	1.70	0.137	6	0.33	0.917	6	0.69	0.661	6	0.51	0.797	6	0.25	0.957
O × LA	3	0.40	0.756	3	0.29	0.829	3	0.39	0.764	3	0.18	0.911	3	2.78	0.058
S × LA	3	0.42	0.743	3	0.60	0.619	3	0.37	0.773	3	2.49	0.079	3	0.30	0.828
O × S × LO	2	0.57	0.575	2	1.02	0.377	2	0.50	0.612	2	0.12	0.887	2	1.28	0.300
O × S × LA	3	1.03	0.392	3	0.79	0.511	3	0.27	0.849	3	0.13	0.942	3	0.68	0.569
O × LO × LA	6	0.69	0.658	6	0.63	0.706	6	0.91	0.496	6	1.71	0.134	6	1.29	0.275
S × LO × LA	6	0.34	0.915	6	1.84	0.107	6	2.02	0.077	6	0.50	0.804	6	0.32	0.925
O × S × LO × LA	6	0.49	0.814	6	0.75	0.609	6	0.89	0.511	6	1.17	0.334	6	2.12	0.065

(b) ANOVA summary table (p-values) for individual phalangeal segment force

	Individual phalangeal segment force		
	Df	F	p
Orientation (O)	1	1.29	0.282
Surface (S)	1	3.08	0.109
Longitudinal shape (LO)	2	20.42	**0.001**
Lateral shape (LA)	3	7.35	**0.001**
Finger (F)	3	13.22	**0.001**
Phalange(Ph)	3	19.33	**0.001**
O × S	1	1.02	0.336
O × LO	2	7.28	**0.004**
S × LO	2	3.16	0.062
O × LA	3	2.79	0.057
S × LA	3	0.38	0.770
LO × LA	6	0.21	0.973
F × O	3	1.20	0.327
F × S	3	2.20	0.107
F × LO	6	3.41	**0.005**
F × LA	9	1.95	0.053
Ph × O	3	1.69	0.190
Ph × S	3	1.50	0.234
Ph × LO	6	2.24	**0.049**
Ph × LA	9	1.94	0.054
F × Ph	9	2.85	**0.005**

and screw-insertion time in the horizontal orientation (15.3 rotations and 10.7 s) were greater than those in the vertical orientation (14.0 rotations and 8.4 s). For the lateral-shape handles, results of contrasts indicated that screw-insertion time for the reversed double frustum handle (10.0 s) was significantly longer ($p < 0.05$) than that for the cone (9.2 s) and double frustum (9.3 s) handles.

3.3. Peak axial driving force and total finger force

The interaction effect between longitudinal cross-sectional shape and orientation was statistically significant on the peak axial driving forces ($p = 0.03$). In the analysis of

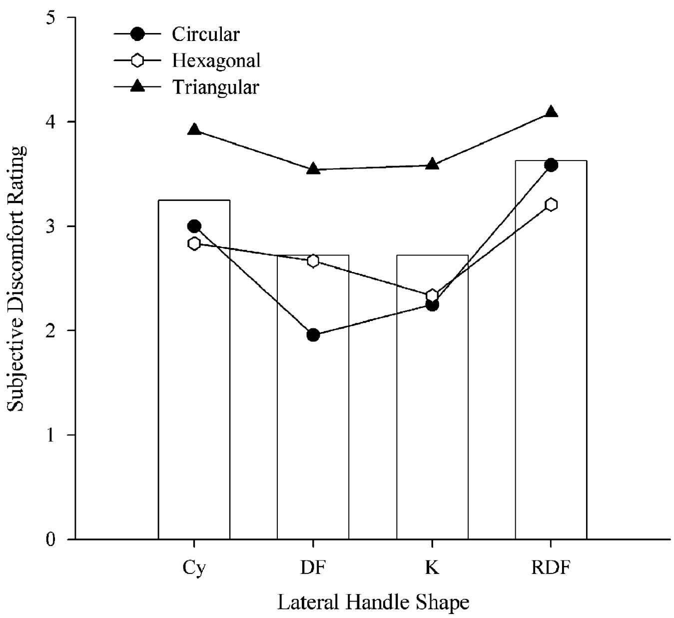


Fig. 2. Subjective discomfort ratings for longitudinal cross-sectional and lateral-shape handles. Vertical bars represent the significant main effect for lateral long-axis shape. The line graph portion shows the significant longitudinal cross-sectional shape main effect (Cy, cylindrical; DF, double frustum; K, cone; RDF, reversed double frustum).

peak axial driving force, the horizontal orientation (82.0 N) was associated with higher axial screwdriving force than the vertical orientation (60.1 N), however this main effect of orientation was associated with a p-value of 0.051. Peak axial driving forces were 85.4, 84.1, and 76.4 N for circular, hexagonal, and triangular handles, respectively, in the horizontal workpiece orientation, and 57.5, 60.6, and 62.1 N, respectively, in the vertical workpiece orientation.

The main effects of longitudinal cross-sectional shape and lateral (long-axis) shape were statistically significant ($p < 0.05$) on the total finger force (see Tables 3 and 4). For longitudinal cross-sectional shape handles, circular handles were associated with the least total finger force (23.6 N) of all the handles, followed by hexagonal (27.9 N) and triangular (30.5 N). For the lateral shape, cylindrical (24.4 N) and double frustum handles (25.7) showed less total finger force than cone (29.9 N) and reversed double frustum (29.3 N) handles. Fig. 3 indicates that a circular shape with double frustum handle was associated with the least total finger force in screwdriving. The interaction of workpiece orientation and longitudinal cross-sectional shape also had a significant effect ($p < 0.01$) on total finger force. The triangular handle shape seemed more affected by workpiece orientation (24.5 N in the horizontal vs. 36.5 N in the vertical) than the circular (21.5 N vs. 25.7 N) or hexagonal (25.4 N vs. 30.6 N) longitudinal shapes.

3.4. Individual phalangeal segment forces

Significant main effects of longitudinal cross-sectional shape, lateral shape, finger, and phalange (all $p < 0.01$) and interaction effects of orientation × longitudinal cross-sectional shape on the individual phalangeal segment forces were found in the screwdriving task (see Table 3b). Main effects of longitudinal cross-sectional and lateral shape, and interaction effects of orientation × longitudinal cross-sectional shape and orientation × lateral shape on the individual phalangeal segment force showed similar trends

Table 4
Summary of mean finger and phalangeal forces and percentage contributions to total finger force

	Total finger force (N)	Mean forces of fingers (N) and percentage contributions (%)				Mean forces of phalanges (N) and percentage contributions (%)			
		Index	Middle	Ring	Little	Distal	Middle	Proximal	Meta
Longitudinal-shape handle									
C	23.6^{A}	3.6 (15.1%)	7.7 (32.7%)	8.1 (34.3%)	4.2 (17.9%)	11.4 (48.4%)	4.7 (20.0%)	3.1 (13.1%)	4.4 (18.6%)
H	27.9^{B}	4.2 (15.1%)	9.7 (34.7%)	9.6 (34.5%)	4.4 (15.8%)	12.8 (46.1%)	6.1 (22.0%)	3.5 (12.6%)	5.4 (19.3%)
T	30.5^{C}	4.5 (14.9%)	11.0 (36.0%)	10.6 (34.7%)	4.4 (14.4%)	13.2 (43.2%)	7.5 (24.5%)	4.0 (13.1%)	5.9 (19.2%)
Lateral-shape handle									
Cy	24.4^{A}	3.7 (15.2%)	7.6 (31.0%)	8.7 (35.6%)	4.4 (18.2%)	11.1 (45.3%)	4.8 (19.5%)	3.3 (13.4%)	5.3 (21.7%)
DF	25.7^{A}	4.1 (16.1%)	8.3 (32.3%)	8.8 (34.1%)	4.5 (17.4%)	11.5 (44.9%)	6.1 (23.8%)	3.4 (13.4%)	4.6 (17.9%)
K	29.9^{B}	4.2 (13.9%)	11.1 (36.9%)	10.4 (34.8%)	4.3 (14.3%)	14.2 (47.3%)	7.3 (24.3%)	3.7 (12.4%)	4.8 (16.0%)
RDF	29.3^{B}	4.4 (14.9%)	10.9 (37.2%)	9.9 (33.7%)	4.2 (14.2%)	13.1 (44.9%)	6.3 (21.5%)	3.7 (12.7%)	6.1 (20.9%)
Mean	27.4	4.1^{A} (15.0%)	9.5^{B} (34.6%)	9.4^{B} (34.5%)	4.3^{A} (15.9%)	12.5^{A} (45.7%)	6.1^{B} (22.4%)	3.5^{B} (12.9%)	5.2^{B} (19.0%)

Top number in cell represents force in Newtons; bottom number represents the percentage contribution to the total finger force (alphabetic letters represent groupings by statistical significance).

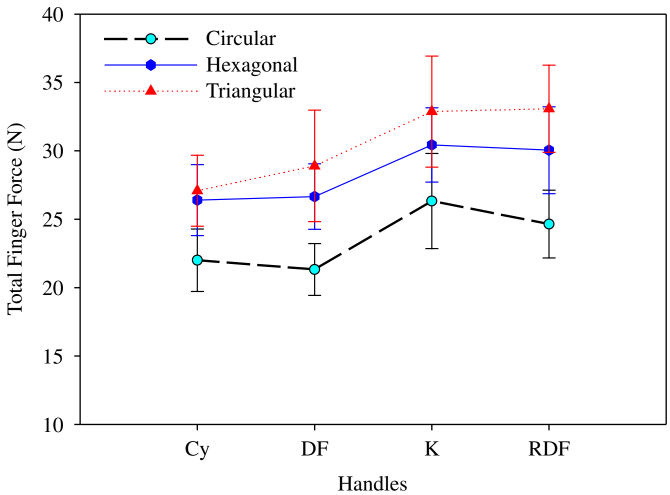


Fig. 3. Total finger force for longitudinal and lateral cross-sectional-shape handles (Cy, cylindrical; DF, double frustum; K, cone; RDF, reversed double frustum handles).

with the analysis of total finger force. Other significant ($p<0.05$) interactions included finger × longitudinal cross-sectional shape, finger × phalange, and phalange × longitudinal cross-sectional shape.

In the analyses of the contribution of individual fingers to the total finger force (see Table 4), the middle (mean 9.5 N, 34.6% of total finger force) and ring (mean 9.4 N, 34.5%) fingers were more dominant fingers than the index (mean 4.1 N, 15.0%) and little (mean 4.3 N, 15.9%) fingers. There were no significant differences between the index and little fingers, and between the middle and ring fingers. In the assessment of the contribution of the phalangeal segments to the total finger force, the forces were mainly exerted by the distal phalange (mean 12.5 N, 45.7%), followed by the middle (mean 6.1 N, 22.4%), metacarpals (mean 5.2 N, 19.0%), and proximal (mean 3.5 N, 12.9%) phalanges.

4. Discussion

In the analyses of handle shapes, participants rated the discomfort lower with the circular (C) and hexagonal (H)-shaped handles relative to triangular (T) longitudinal cross-sectional-shaped handles, and double frustum (DF) and cone (K)-shaped handles relative to cylindrical (Cy) and reversed double frustum (RDF) lateral-shaped handles. Among combinations of longitudinal and lateral shapes, circular with double frustum handles exhibited the least discomfort. In addition, circular with double frustum handles also exhibited the least amount of total finger force in screwdriving, followed by circular with cylindrical handles. This finding is similar to that reported by Kong et al. (in press) in the analysis of subjective discomfort ratings and total finger force in a maximum static screwdriver torque task. Reversed double frustum handles exhibited the greatest discomfort and a longer insertion time than the other handles.

In general, the vertical workpiece orientation was associated with less axial screwdriving force than the horizontal orientation though this difference did not reach a 0.05 statistical significance level. This finding may be explained by participant's use of their own body mass to transfer downward force against the screwdriver handle in the horizontal workpiece orientation. In this manner, participants may have used their body weight passively, resulting in more axial screwdriving force in the horizontal orientation. In a previous study (Örtengren et al., 1991), axial screwdriving forces were also measured with a force transducer and reported as 101 and 120 N for vertical and horizontal orientations, respectively. Since the Örtengren et al. (1991) study examined different screws (Phillips #2 and TORX T25), screwdrivers (Bahco Ergo 8155), and participants (electrical installation workers) a direct comparison of these axial force values with those measured in the present study is not possible. However, the trends in vertical and horizontal work orientations regarding axial force levels (i.e., workpiece with horizontal orientation associated with higher axial driving force) are consistent between these studies.

Magill and Konz (1986) and Kong et al. (in press) reported a greater preference for rubber-surface handles and a better torque performance in studies of maximum static screwdriver torque capability. In the present study, however, rubber-surface handles were associated with only slightly preferable subjective discomfort ratings than plastic handles, and no significant differences in the number of rotations, screw-insertion time, axial force, and finger force were observed. Thus, it is noted that the effects of surface material on the perception of discomfort as well as performance may be more apparent in the production of near-maximum static screwdriver torque than in a dynamic screwdriving task which involves submaximal grip force and torque levels.

In the present study, total and individual finger/phalange forces were measured by the hand force measurement system to investigate individual phalangeal force distributions and identify the finger segments that contributed most influentially to the total grip force for driving a screw. The total finger forces were in the ranges of 22–37 N for the various screwdriver handles. Overall, triangular handles were associated with the highest total finger force for driving a screw followed by the hexagonal and circular handles. This is similar to the findings of a study of maximum screwdriver torque (Kong et al., in press). In the maximum screwdriver torque study the circular with cylindrical or cone-shape handles were associated with the least total finger force. The circular with cylindrical or double frustum handles were associated with the lowest total finger force in the dynamic (submaximum) screwdriving task of the present study.

This study showed that the average percentage contribution of each finger to total finger force was 15.0%, 34.6%, 34.5%, and 15.9% for the index, middle, ring, and little fingers; and 45.7%, 22.4%, 12.9%, and 19.0% for the distal, middle, proximal phalanges, and metacarpal head, respectively. The major difference in the distribution of finger force between that in the exertion of maximum static screwdriver torque and that in submaximal dynamic screw insertion is that in maximum screwdriving torque (Kong et al., in press) the main contributions were made by the index, middle, and ring fingers (28.1%, 39.3%, and 26.5%), whereas in the submaximal case the grip forces are mainly exerted by the middle and ring fingers (34.6% and 34.5%). In the dynamic submaximal case it appears that the index and little fingers contributed mainly to the guiding and balancing of the screwdriver handles and the middle and ring fingers had a more substantial contribution in gripping and turning. The generation of maximum static screwdriving torque, logically, involves greater recruitment of all fingers relative to submaximal dynamic screwdriving.

There are some limitations of the hand force measurement system as it was applied to quantify hand contact forces on the screwdriver handles in the present study. First, the measure of total finger force may not be equivalent to the true total contact force in the task, because of incomplete coverage of the force sensors on the palmar areas in contact with the screwdriver handle. Even though sensors were placed over the principal points of hand contact there were palmar regions that made contact with the screwdriver handle under which there was no sensor coverage. Thus, the true total hand force in the screwdriving tasks was likely to be underestimated by the force glove system. A second limitation of the force glove system is the fact that the glove and sensor material might alter the frictional conditions between the hand and screwdriver handles. Thus, when wearing the force glove the ratio of the total finger force to axial screwdriver force or torque may be different than the ratio of the total finger force to axial force or torque in the bare-handed condition.

Although the force glove system possesses these limitations, there are advantages to this system in applied studies of the grasping force distribution on hand tools. The force glove system allows for easy repositioning and replacement of individual sensors based on the user's hand size by 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 applied to evaluate any type of tool handle, of any shape, size, or material. The sensor technology is also relatively inexpensive, compared to other commercially available systems for pressure/force mapping. When an individual sensor fails or is damaged, which occurs more frequently during exertions of high levels of grip force, it can easily be replaced with a new sensor.

In summary, screwdriver handles designed with combinations of circular longitudinal cross-sectional shape with double frustum lateral (long-axis) shape are recommended over the other designs tested for minimizing discomfort of use and finger force in submaximal dynamic screwdriving tasks.

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