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Effectiveness of a handle flange for reducing manual effort during hand tool use

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Abstract

Forceful manual exertion is a risk factor for upper extremity musculoskeletal disorders. Mechanical considerations and previous research suggest this risk can be reduced by redesigning tools to decrease manual effort. This study sought to determine whether adding a flange to handles would reduce grip force requirements by providing an additional source of coupling between the hand and handle. In the first of two experiments, participants grasped and *lifted* handles with and without a flange at the *top* lip of the handle. In the second experiment, participants grasped and *pulled* handles with and without a flange at the *bottom* edge of the handle. Each task was performed at three levels of weight or resistance. Grip force was measured using a strain gage mounted inside the handles. Electrical activity (EMG) of select forearm muscles was also monitored using surface electrodes. The main finding was that adding a flange to the handle did not significantly reduce the grip force required to perform either task. However, grip force significantly increased with increased weight or pull resistance. The study indicates that reducing tool weight should be a primary objective for reducing the risk of fatigue and injury during hand tool use.

Relevance to industry

Many workers are at risk for upper extremity musculoskeletal disorders due to forceful manual exertions during tool use. Previous research suggests this risk can be reduced by modifying the handle design. This study indicates that providing a flanged handle may not be an effective intervention for reducing manual effort, at least not in light industrial tasks.

Keywords

Handle design; Hand tool; Grip force; Manual effort; Electromyography

1. Introduction

Workers who routinely use hand tools subject their hands to a variety of mechanical forces. Forceful exertion, especially if repetitive, can cause damage to underlying structures such as tendons, tendon sheaths, and nerves (Armstrong et al., 1987). Data from previous studies have demonstrated a strong association between cumulative trauma disorders (CTDs) such as tendinitis and carpal tunnel syndrome, and forceful manual exertions during work activities (Falck and Aarnio, 1983; Silverstein et al., 1986; Smith et al., 1977; Thompson et al., 1951).

Tool design is an important determinant of force requirements in manual work. Grip force is largely generated through contractions of muscles in the forearm, with muscle forces transferred to the fingers via the flexor tendons. Numerous biomechanical studies indicate that the ability to generate grip force depends on grip configuration, hand and wrist anthropometry, and the

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alignment of the hand and forearm during the exertion (Eastman Kodak, 1986; Fransson and Winkel, 1991; Grant et al., 1992; Terrell and Purswell, 1976). To the extent that handle shape, size and weight can affect these variables, it is believed that hand tool design can significantly impact manual performance and biomechanical stress and strain on the upper extremity.

To reduce the risk of trauma from excessive biomechanical stress, a number of specific guidelines for the design of various hand tools have been proffered (most recently, see Mital and Kilbom, 1992). Investigators have shown some of these suggestions to be effective in reducing manual effort in certain tasks. Miller et al. (1971) modified the handles of a pair of surgical bayonet forceps to increase the surface area available for the surgeon's thumbs and fingers. The modified forceps resulted in lower levels of flexor muscle activity than the original design. Armstrong et al. (1982) redesigned a poultry knife to reduce biomechanical stress during thigh boning tasks. The blade was reoriented perpendicular to the handle to reduce wrist deviation, the handle diameter was enlarged to better fit users' hands, and a strap was placed around the handle to allow grip relaxation between cuts. Laboratory evaluation indicated that the proposed knife required less grip force and resulted in less forearm muscle fatigue than standard knives (Armstrong et al., 1982). Knowlton and Gilbert (1983) demonstrated that bending the handle of a hammer to minimize ulnar deviation of the wrist reduced muscle fatigue during hammering tasks. EMG studies by Johnson (1988) indicated that adding (a) a vinyl sleeve and (b) a brace to the handle of a powered screwdriver could reduce operator effort during tool use. Johnson noted that the vinyl sleeve simultaneously increased the diameter of the tool handle and increased the coefficient of friction between the handle and the palm of the hand. Similarly, the brace allowed the arm to absorb the torque of the tool at shutoff, reducing the manual force required to grip the tool.

One recommendation suggested by Greenberg and Chaffin (1977) and Cochran and Riley (1986) is that tools for exerting force across the breadth of the hand should be designed with a flanged handle or tang to prevent the hand from slipping during the exertion. Mechanical considerations further suggest that handles which allow contact between the handle and the side of the hand should require less grip force to manipulate than handles which allow only frictional coupling between the palm and handle surfaces (Chaffin and Andersson, 1991).

Nonetheless, the utility of a flange for reducing grip exertion has not been adequately investigated. The purpose of this study was to evaluate the utility of adding a flange to one end of a cylindrical handle as a method for reducing applied grip force. The flange was intended to improve the effectiveness of hand/handle coupling by providing a surface barrier perpendicular to the lateral surface of the hand. In the first experiment, participants were required to grasp and *lift* handles with and without a flange located at the top of the handle. In the second task, participants were required to grasp and *pull* handles with and without a flange at the bottom of the handle. These tasks were selected as representative of a number of manual handling and assembly tasks in industry.

2. Materials and methods

2.1. Subjects

Thirty right-handed males between the ages of 18 and 30 years were recruited from a temporary employment agency to participate in this study (15 in each of two experiments). All participants were free of known musculoskeletal impairments. At the beginning of each test session, informed consent was obtained and right hand length and breadth of each participant was measured. These data are summarized in Table 1.

Table 1

Characteristics of study participants

	Age (years)	Hand length (cm)	Hand breadth (cm)
Experiment I (Lift task)			
Mean	24.8	19.9	8.9
Std. Dev.	3.6	1.2	0.4
Experiment II (Pull task)			
Mean	24.4	19.4	8.8
Std. Dev.	4.2	1.2	0.5

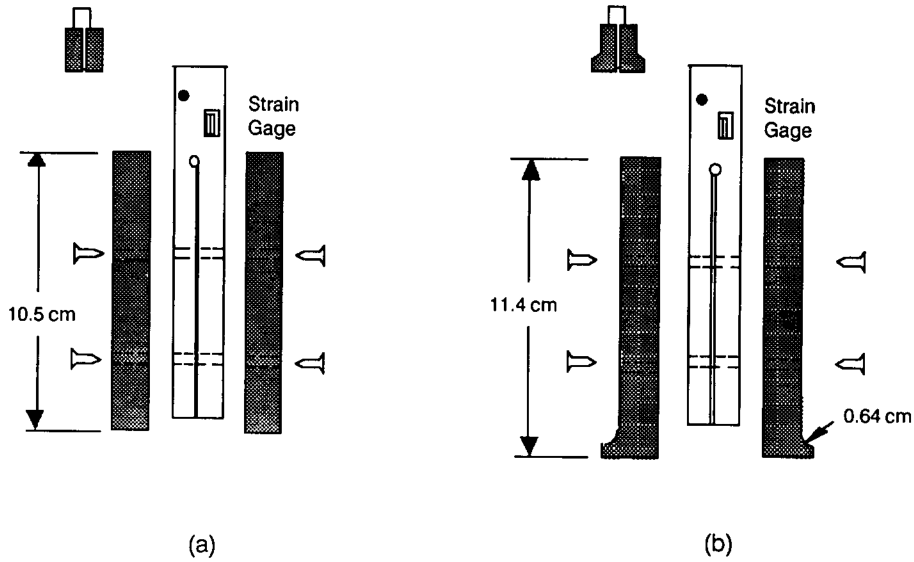

Fig. 1. Test handles.

2.2. Test apparatus

The test handles were constructed using an aluminum rectangular bar (2.5 cm [length] × 1.3 cm [width] × 14 cm [height]) instrumented with a strain gage. The configuration used to mount the strain gage is described by Pronk and Niesing (1981). Curved aluminum half-shells were attached to the short sides of the bar with set screws to form each handle (Fig. 1). The design allowed investigators to change the shape of the handle and the orientation of the flange for different experimental tasks or conditions. In both experiments, a straight, 3.8 cm diameter cylindrical handle (shell height = 10.5 cm) was compared to a 3.8 cm diameter flanged cylindrical handle (shell height = 11.4 cm). As shown in Figure 1, the flange had a 0.64 cm radius of curvature, and a height of 0.5 cm. The diameter of the flanged handle at the base of the flange was 4.8 cm. In the lift task, the flange was located at the top of the handle, adjacent to the index finger and thumb. In the pull task, the flange was located at the bottom of the handle, adjacent to the base of the palm and little finger (Fig. 2).

The weight of the tool handle was varied using two methods. In the lift task a small plastic box (7 cm [length] × 7 cm [width] × 9 cm [height]) was clamped to the bottom of the tool handle. Rectangular lead blocks were added to or removed from the box to change the weight of the handle. Three handle weights were evaluated: 0.5 kgf (light), 1.1 kgf (medium), and 2.3 kgf (heavy). In the pull task, the handle was suspended above the work station by a rope. The rope passed over a series of pulleys, including a pulley tied to a metal can, before attaching to a fixed metal pole. During the experiment, the metal can was lifted off the ground each time the participant pulled on the handle. Weights were added to the can (1.1, 2.3, and 3.4 kgf) to alter the rope tension required to lift the can.

2.3. Experimental tasks

Two tasks were devised to compare the flanged handle to a straight handle, and to evaluate the

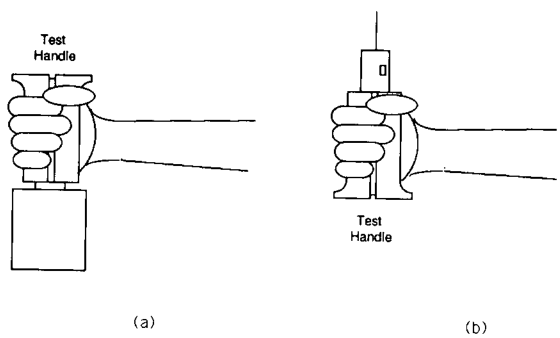

Fig. 2. Location of flange during work tasks. (a) Experiment 1: Lift task. (b) Experiment 2: Pull task.

effect of the different handle weights/resistances on grip force exertion. The tasks were intended to simulate (a) a material transfer task involving a lifting motion and (b) an assembly operation using a suspended tool, requiring a pulling motion. Descriptions of the tasks and the associated work stations are provided below.

Experiment 1: Lift task. In the first experiment, participants were seated in front of a table with a 56 cm diameter circular platform centered on the top of the work surface. The work station configuration is shown in Fig. 3. Two receptacles were located at opposite ends of the horizontal axis of the platform, separated by a center-to-center distance of 42 cm. At the beginning of each trial, the test handle was positioned upright in the receptacle on the right side of the work table.

During the experiment, participants were instructed to grasp the handle with the right hand using a power grip, and lift and move the handle from the initial position on the right side of the platform to the receptacle on the left. After completing this task, participants simultaneously pushed two palm buttons located on opposite sides of the platform, causing the platform to rotate 180 degrees. The task was repeated once every five seconds for a total of 30 cycles (2.5 minutes).

Experiment 2: Pull task. In this experiment, participants were seated at a work station positioned in front of a free-standing pulley system (Fig. 4). The pulley system was constructed using a Baltimore Therapeutic Equipment (BTE) work simulator with the exercise head set in the free-turning dynamic mode. The rope, pulley, spool and 101.6 cm extension pole were standard BTE attachments (parts 191 and 191B). The test handle was suspended from the rope, 42.6 cm above the table surface, in line with the participant's right shoulder. Chair and table height were adjusted for each participant.

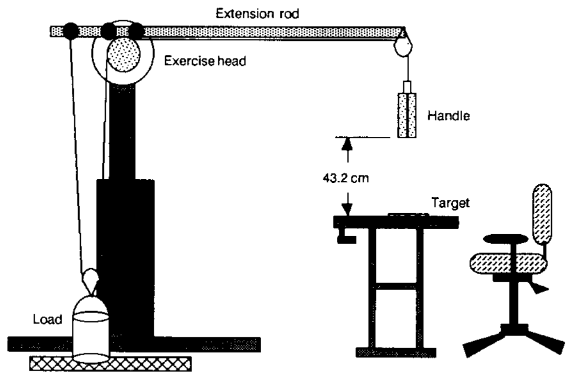

Fig. 4. Power tool assembly workstation (Experiment 2).

During the work task, participants grasped the handle with the right hand using a power grip and pulled it down to a target marked on the work table. This position was maintained briefly (approximately one second); then the handle was returned to its starting position and released. The task was repeated once every five seconds for a total of 30 cycles (2.5 minutes per condition).

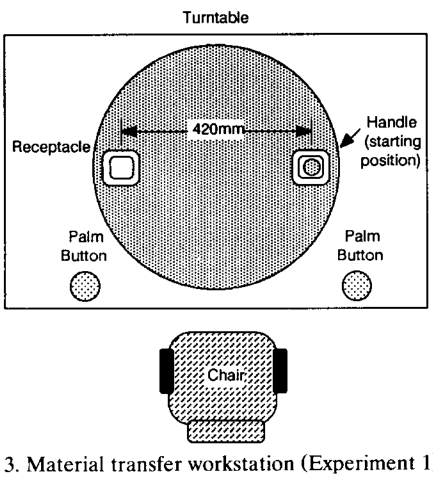

Fig. 3. Material transfer workstation (Experiment 1).

2.4. Test procedure

Before the work task was initiated, isometric strength tests were conducted to measure the participant's maximum grip compression strength. Tests were conducted using the test handles while the participant sat in the same posture as in the experiment. In the lift task, the handle was positioned on top of the table in the right receptacle; in the pull task, the handle was temporarily lowered to a position 5.1 cm above the table. Standard strength testing procedures were used to determine maximum voluntary contraction (MVC) of muscles controlling grip (Caldwell et al., 1974). Grip strength measurements were repeated three times with each handle used in the experiment (i.e., handles with no flange and flange at top in

Experiment 1; handles with no flange and flange at bottom in Experiment 2). One minute of rest was allowed between exertions. Because subsequent analyses found that the presence of a flange had no effect on MVC, the average of all six trials (three with flange, three without) was recorded as the participant's maximum grip strength.

The task was demonstrated before the beginning of each session, and participants were given an opportunity to practice the task before data collection was initiated. During the work periods, an electronic timer was used to cue the start of each five-second work cycle. Participants were instructed to move smoothly and keep pace with the beats of the timer. Each participant performed the task using all six shape/resistance combinations presented in a random order. A three-minute rest period was provided between each 2.5 minute work period.

2.5. Dependent variables

Grip compression force and right forearm EMG were recorded during all strength tests and throughout each work period. Grip compression force applied along the length of the handle was assessed using the strain gage mounted in the handle. Power and amplification for the strain gage was provided by a Force Monitor© (Prototype Design, Ann Arbor, MI). Right forearm EMG was monitored using surface electrodes positioned over the flexor pollicis longus, flexor digitorum superficialis, and extensor digitorum muscles in the configuration recommended by Zipp (1982). The three channels of EMG data were collected using a Therapeutics Unlimited (TU) Model 544 Electromyographic System©. A high-pass filter with a cut-off frequency of 20 Hz was used to remove low frequency noise from the EMG signals. Root mean square (RMS) values were calculated using an 11.75 ms time constant. Strain gage output and processed EMG were sampled at 175 Hz and stored by microcomputer using a 12-bit analog-to-digital converter and LabTech Notebook© data acquisition software.

2.6. Research design

A complete within-subject, repeated-measures design (2 × 3) was used to analyze the data from each experiment. Multivariate analysis of variance (MANOVA) with univariate repeated-measures tests was used to assess the significance of the main effects (handle shape and weight/resistance) and interactions. Degrees of freedom were adjusted to correct for violations in the ANOVA assumptions due to the repeated measures (Geisser and Greenhouse, 1958). Dependent variables included:

(1) average grip force for each condition;
(2) peak grip force for each condition, determined by averaging the peak grip force exerted in each of the thirty task cycles;
(3) flexor pollicis longus EMG (average RMS for each condition);
(4) flexor digitorum superficialis EMG (average RMS for each condition), and
(5) extensor digitorum EMG (average RMS for each condition).

To permit comparison of values across conditions, grip force and EMG values were normalized using the following formula (Marras, 1992):

$$\frac{(\text{Average Task Value} - \text{Baseline Value})}{(\text{MVC Value} - \text{Baseline Value})}$$

Baseline values were set equal to zero for average and peak grip force normalization. Normalized values are expressed as a percent.

3. Results

Normalized peak and average grip force levels for the lifting and pulling tasks are plotted in Figs. 5 and 6 respectively. In both tasks, increased handle weight produced corresponding increases in force exertion. In the lifting task, peak grip forces ranged from 12.4% to 32.7% of MVC. Average grip forces ranged from 6.6% to 19.2% of MVC. The relationship between force and tool weight was statistically significant, $p < 0.0002$ (Table 2). In the pulling task, peak force levels ranged from 12.6% to 21.6% of MVC, while average force levels ranged from 5.1% to 11.6% of MVC. The relationship between pull resistance and force was also statistically significant, $p < 0.0001$ for both variables (Table 3). The presence of the flange did not significantly affect peak or average grip force in either task, nor

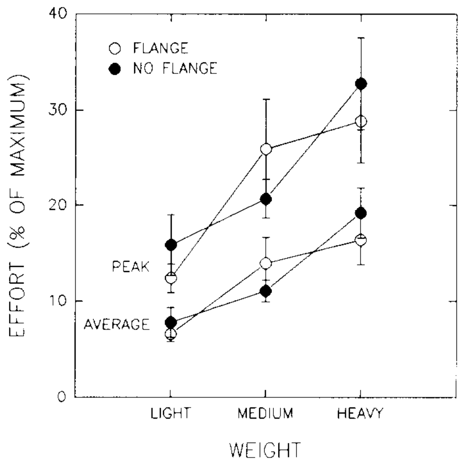

Fig. 5. Peak and average grip force levels for Experiment 1: Lift task ($n = 15$ subjects).

were any significant interactions between weight and handle flange observed.

Normalized EMG activity in the three forearm muscle groups is plotted in Fig. 7. As indicated in the graphs, the lifting task was associated with substantially higher levels of muscle activity than the pulling task. Muscle activity values during the lifting task ranged from 14.1% to 19.2% of MVC in the flexor pollicis longus, 8.9% to 16.24% of MVC in the flexor digitorum superficialis and 38.7% to 48.0% of MVC in the extensor digitorum. Activity levels during the pulling task ranged from 3.5% to 8.7% of MVC in the flexor pollicis longus, 2.2% to 7.7% of MVC in the flexor digitorum superficialis, and 5.6% to 11.5% of MVC in the extensor digitorum. The differences in muscle activity can be explained by the different movement patterns required by each task. The pulling task involved only vertical movement of the handle in the plane of the right shoulder. The

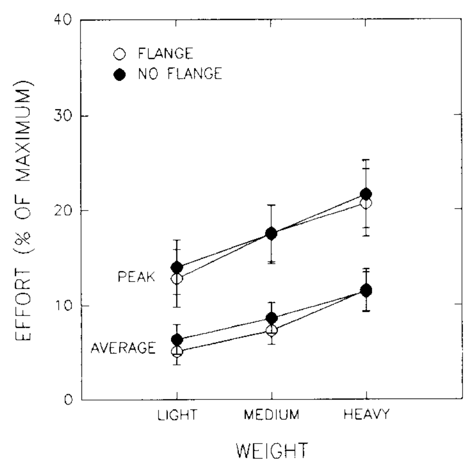

Fig. 6. Peak and average grip force levels for Experiment 2: Pull task ($n = 15$ subjects).

Table 2

Univariate repeated measures ANOVA-lifting task

Source	*df*	*ss*	*ms*	*F*	$p > F$ [a]
Peak force					
Handle	1	0.00100	0.00100	0.76	0.4007
Error (handle)	12	0.01573	0.00131		
Weight	2	0.36181	0.36181	21.9	0.0002
Error (weight)	24	0.19818	0.19818		
Handle × weight	2	0.03438	0.3438	2.67	0.0951
Error (handle × weight)	24	0.15470	0.15470		
Average force					
Handle	1	0.00026	0.00026	0.51	0.4905
Error (handle)	12	0.00620	0.00052		
Weight	2	0.14562	0.07281	23.5	0.0001
Error (weight)	24	0.07425	0.00309		
Handle × weight	2	0.01131	0.00565	3.08	0.0673
Error (handle × weight)	24	0.04404	0.00183		
Flexor pollicis longus					
Handle	1	0.00002	0.00002	0.06	0.8100
Error (handle)	12	0.00600	0.00040		
Weight	2	0.04774	0.02387	9.73	0.0012
Error (weight)	24	0.07361	0.00245		
Handle × weight	2	0.00211	0.00106	1.27	0.2897
Error (handle × weight)	24	0.02486	0.00082		
Flexor digitorum superficialis					
Handle	1	0.00425	0.00425	4.88	0.0431
Error (handle)	12	0.01305	0.00087		
Weight	2	0.05281	0.02641	10.2	0.0010
Error (weight)	24	0.07740	0.00258		
Handle × weight	2	0.00093	0.00047	0.38	0.6723
Error (handle × weight)	24	0.37120	0.00124		
Extensor digitorum					
Handle	1	0.00154	0.00154	0.40	0.5364
Error (handle)	12	0.05781	0.00385		
Weight	2	0.11635	0.05818	6.19	0.0063
Error (weight)	24	0.28195	0.00940		
Handle × weight	2	0.00367	0.00184	0.24	0.7014
Error (handle × weight)	24	0.22647	0.00755		

[a] Greenhouse-Geisser conservative degrees of freedom were used for all repeated measures tests in the analyses of variance.

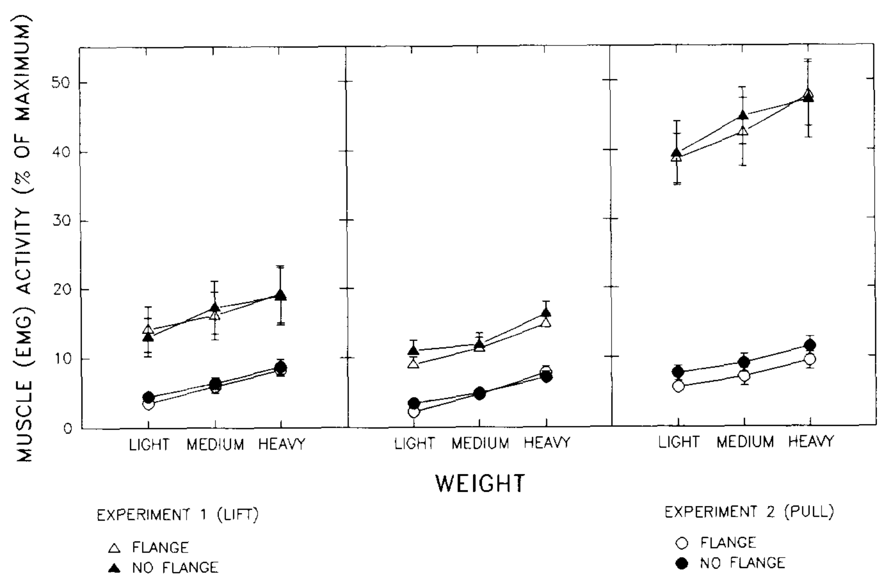

Fig. 7. Forearm EMG activity for Experiment 1: Lift task ($n = 15$ subjects); and Experiment 2: Pull task ($n = 15$ subjects).

lifting task required both vertical and transverse movement of the handle across the body. Because the movement pattern was more complex, the extensor digitorum and flexor pollicis longus muscles were more active in stabilizing the wrist during the lifting task. The activity of the flexor digitorum superficialis remained proportional to the measured grip force in both tasks. Increased handle weight produced strongly significant increases in muscle activity. In both tasks, the relationship between weight and muscle activity was significant in all muscle groups ($p < 0.005$ for all cases, see Tables 2 and 3).

The presence of the flange had little effect on forearm EMG. Flexor digitorum superficialis activity was slightly reduced with use of the flanged handle in the lifting task (mean difference = 1.33% of MVC), and extensor digitorum activity was slightly reduced with use of the flanged handle in the pulling task (mean difference = 2.0% of MVC). No other significant effects attributable to the handle flange were observed. Likewise, there were no significant interactions between weight and handle type.

4. Discussion and conclusions

In this study, manual exertion was significantly related to the weight but not to the type of handle. Therefore, the results of this study indicate that adding a flange to the design of a handle may not be an effective method for reducing manual force during tool use, at least not under favorable environmental conditions where load levels are relatively light. In this study, participants performed the task for short periods of time (2.5 minutes). Temperature and humidity were controlled. Although exertion varied with handle weight, average force levels did not exceed 20% of maximum, and in only one condition (lifting task, heavy load) did peak force levels exceed 30% of maximum. Under similar conditions, where grip force requirements are well within the capability of most workers, a handle flange is likely to have little effect on grip force exertion.

Industrial settings, however, are frequently vulnerable to environmental effects. If the coefficient of friction between the hand and handle is reduced through tool handle wear, perspiration, use of work gloves, or accumulation of lubricant on the handle surface, the grip force needed to maintain a frictional coupling between the hand and handle surface can dramatically increase. Power tools are frequently heavy and produce torque. Under conditions where the handle is likely to become slippery and the operator fatigued, allowing tool users to rest the side of the hand against a flange may provide some benefit.

Table 3

Univariate repeated measures ANOVA-pulling task

Source	*df*	*ss*	*ms*	*F*	$p > F$ [a]
Peak force					
Handle	1	0.00102	0.00102	0.85	1.3730
Error (handle)	14	0.01691	0.00121		
Weight	2	0.09014	0.04507	23.0	0.0001
Error (weight)	28	0.05481	0.00196		
Handle × weight	2	0.00065	0.00032	0.28	0.6600
Error (handle × weight)	28	0.03233	0.00115		
Average force					
Handle	1	0.00152	0.00152	2.37	0.1460
Error (handle)	14	0.00899	0.00064		
Weight	2	0.05086	0.02539	21.5	0.001
Error (weight)	28	0.03315	0.00118		
Handle × weight	2	0.00112	0.00056	1.31	0.2780
Error (handle × weight)	28	0.01197	0.00043		
Flexor pollicis longus					
Handle	1	0.00086	0.00086	1.47	0.2461
Error (handle)	14	0.00824	0.00059		
Weight	2	0.03034	0.01517	40.6	0.0001
Error (weight)	28	0.01046	0.00037		
Handle × weight	2	0.00015	0.00007	0.12	0.7999
Error (handle × weight)	28	0.01746	0.00062		
Flexor digitorum superficialis					
Handle	1	0.00015	0.00015	0.50	
Error (handle)	14	0.00410	0.00029		0.4900
Weight	2	0.03232	0.01616	44.5	
Error (weight)	28	0.01017	0.00036		0.0001
Handle × weight	2	0.00122	0.00061	3.01	
Error (handle × weight)	28	0.00569	0.00020		0.0763
Extensor digitorum					
Handle	1	0.00905	0.00905	16.8	0.0011
Error (handle)	14	0.00754	0.00054		
Weight	2	0.02207	0.01103	15.8	0.0001
Error (weight)	28	0.01959	0.00070		
Handle × weight	2	0.00001	0.00000	0.02	0.9646
Error (handle × weight)	28	0.00518	0.00019		

[a] Greenhouse-Geisser conservative degrees of freedom were used for all repeated measures tests in the analyses of variance.

Pilot laboratory data indicates that a flange may indeed reduce grip force when the coefficient of friction between the hand and handle is severely degraded. Providing a flange may also allow the user to change finger and hand positions (i.e., shift the load onto different muscle groups) between exertions without releasing the object. Finally, the addition of a flange may be useful for safety reasons not examined in this study. If slipping between the hand and handle does occur, the flange may prevent release of the tool and guard the hand from contact with sharp surfaces.

Increased manual exertion with added tool weight has been previously demonstrated (Grant et al., 1992; Lyman and Groth, 1958). This study suggests that tool weight should be minimized to reduce exertion. According to Eastman Kodak (1986) power grip forces should not exceed 2.2 kgf during repetitive handling tasks. This value represents 20% of the isometric grip strength of the average woman when the hand is in its optimum posture for force exertion. Because peak grip forces and forearm EMG levels exceeded this value in the lifting task, it is possible that the tool weights evaluated in this experiment would have eventually resulted in muscle fatigue, and are inappropriate for long-term, continuous use.

In work situations where tool weight cannot be reduced, or the tool is used with the arm raised in flexion or abduction, a tool balancer device or padded arm support should be provided to reduce the load moment on the shoulder (Chaffin and Andersson, 1991). Johnson and Childress (1988) concluded that if a tool is used in a vertical orientation with a properly adjusted tool balancer, tool weight does not appear to affect manual effort. Increasing the coefficient of friction between the handle and the hand may also reduce grip force requirements. Materials such as vinyl rubber and adhesive tapes have been suggested as handle coverings to reduce manual exertion (Buchholz et al., 1988). Under heavy loading conditions, replacing a low-friction handle with a high-friction handle has been found to result in a 16–42% reduction in grip force used to handle various objects (Johnson, 1988; Frederick, 1990). However, because the ability of the hand to withstand frictional forces is limited, reducing tool weight is probably a more effective approach to reducing grip force requirements. As smaller components and stronger, lighter materials are developed, their applications in tool design should be investigated.

In summary, a flange may be an effective device for reducing grip force when exertion is increased by a poor hand/handle coupling. However, providing a lightweight handle with good surface characteristics should be the primary approach to reducing manual exertion during tool use.

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