Getting a Grip on Grip Force Estimates

A valuable tool for ergonomic evaluations

By Jeffrey S. Casey, Raymond W. McGorry and Patrick G. Dempsey

THE DEVELOPMENT OF musculoskeletal disorders (MSDs) in today's workplace has become a substantial loss source in industry. This is evidenced in congressional hearings on the relationship between specific work/task actions and MSDs (Michael 1). As a result, the need to identify and quantify risk factors for the development of MSDs has become more important. It has also become more difficult due to the diversity of jobs and, more specifically, to different configurations of a given job.

Force, repetition and posture have been identified as three risk factors associated with the incidence of MSDs (Silverstein, et al 779; Silverstein, et al 343; Putz-Anderson 21; OSHA). The National Research Council and Institute of Medicine identified forceful and repetitive hand motions as risk factors for the development of carpal tunnel syndrome (NRC-IM 1). It has also been reported that industrial workers who move their hands and wrists repeatedly and/or forcefully are susceptible to cumulative trauma disorders (CTDs) (Silverstein, et al 779; Silverstein, et al 343). Excessive grip force may be a risk factor for the development of MSDs in the hand, wrist, forearm and shoulder as well.

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In jobs that require repetitive gripping, an ergonomic evaluation should include a measure or estimation of the applied grip force. For example, many jobs within the meatpacking industry are hand-intensive and require considerable force (e.g., cutting tasks). OSHA has developed an ergonomic management guideline for that industry which suggests that tools and handles be selected to minimize excessive gripping in jobs where CTD risk factors include forceful exertions performed by an individual using the tools (OSHA 1).

SH&E professionals can use various observational methods to quantify posture (Karhu, et al 199; Karhu, et al 13; Priel 570; Persson, et al 1). Similarly, repetition can be measured using a time-and-motion study (Armstrong, et al 325). However, direct measurement of applied forces and grip forces, with or without hand tools, can be difficult without sophisticated equipment. Consequently, practitioners often resort to

Table 1
Subject Demographic & Anthropometric Data

	Mean (s.d.)	Range
Age (years)	43.9 (12.9)	25 - 64
Height (cm)	181.1 (8.2)	167.5 - 193.5
Weight (kg)	91.3 (41.7)	77.11 - 122.47
Elbow height (cm)	115.7 (5.1)	108 - 124.5
Hand length (cm)	19.2 (1.4)	16.5 - 21.3
Hand & breadth (cm)	9.0 (0.4)	8.2 - 9.8

n =16
Anthropometric data were collected according to the MIL STD (1988).

Table 2
Skill Level as Reported by Subjects

Tool	Skill Level	Most Recent Use
Screwdriver	5 - Professional	14 - Week
	8 - Skilled	2 - Month
	3 - Novice	
Ratchet	4 - Professional	6 - Week
	7 - Skilled	7 - Month
	5 - Novice	1 - Six months
		1 - Year
		1 - Never

other methods. For example, the weight of the tool or objects may be used as a surrogate for direct force measurements. This approach can be problematic, however, because the task dynamics and tool/object surface can influence the grip force used (Grant 549).

One approach to estimate force exertions is to use psychophysical methods where the worker estimates the forces being exerted. This method has traditionally been performed using a Borg scale or rating of perceived exertion (RPE) scale, where workers are asked to estimate their force exertion on an anchored scale. The American Conference of Governmental Industrial Hygienists (ACGIH) recently developed a threshold limit value (TLV) for the hand activity level of all mono-task jobs in which a similar set of motions or exertions are performed repeatedly (ACGIH 110); a trained observer is used to determine the ratings.

The hand dynamometer has long been used to measure maximum voluntary contraction (MVC) (Caldwell, et al 201). This device has also been used for field estimation of a task's grip force requirements. However, the accuracy of these estimates has not been well-documented. The limited study detailed here focused on the subject's ability to replicate, with a hand dynamometer, the grip force used to perform a specific task, and to provide some insight into the factors that may influence these estimates by workers. Its purpose was to test the hypothesis that the accuracy of grip force estimates is influenced by reported skill level and by the grip requirements of the experimental tasks. Three tasks with varying handle orientations and direction of force application, and operators at three levels of experience were used to test the hypothesis.

Study Methodology
Subjects

Eighteen healthy males between the ages of 18 and 65 participated in the study. Subjects were recruited by newspaper advertisement from the local community. No hand tool experience was specified or required. All responders who met the exclusion criteria—no recent hand, wrist, forearm or upper arm injuries—were accepted. Prior to each test session, the experimental protocol and the purpose of the experiment were explained to subjects. Each subject gave informed written consent for participation (as approved by the Institutional Review Committee for the Protection of Human Subjects). In addition, age, height, weight, elbow height and general hand anthropometry data were gathered (Table 1). Sixteen subjects completed the study; two subjects were dropped after a short period because of difficulties in compliance with or understanding of instructions for the experimental protocol. The subjects also subjectively rated their skill level or experience using the screwdriver and ratchet, and also reported when they last used the respective tools (Table 2).

Hardware

Handle. The core of the test handle was instrumented with six strain gauges mounted on three beams designed to measure grip force. Three strain gauges were mounted to one end of the handle core to measure the horizontal, vertical and axial moments acting on tool ends fitted to the handle. The handle was molded from polyurethane to fit around the instrumented core. [Further details on the fabrication technique, and the specifications and performance of this hardware can be found in McGorry 271.]

The handle was 3 cm in diameter and 10.16 cm in length. A single handle was used for the three experimental tasks in order to control for the potential effects of handle shape, diameter and texture. A different tool end was attached to the handle for each task. The tool ends were a fitting to accept screwdriver bits, the head of a ratchet and a weight hanger. Photo 1 shows the experimental handle with a segment removed to reveal the instrumented handle core.

Dynamometer. A hydraulic hand dynamometer (Baseline®, FEI, Irvington, NY) was modified to accept a pressure transducer (model number PX236-0306, Omega Corp., Stamford, CT). Calibration was performed to allow for determination of grip force from the output of the pressure transducer (Photo 2).

Rotational Resistance Device. A particle brake was used to control resistance to rotary motion in the screwdriver and ratchet tasks. Changing the voltage supplied to the brake varies the magnetic forces acting on iron particles that surround the brake's output shaft. In turn, this varies the friction on the shaft and, thus, the resistance to motion. The voltage setting for each of the four resistance levels for the screwdriver and ratchet tasks was determined by calibration. The vertical position (elbow height) and orientation of the brake's input shaft were adjusted for each task for each subject. The input shaft had a chuck that accepted the screw and the ratchet extension.

Photo 1 (far left): Experimental handle configured as a screwdriver. One handle segment is removed to reveal the instrumented core.
Photo 2 (left): Hand dynamometer. A pressure transducer was inserted between the dynamometer body and dial gauge.

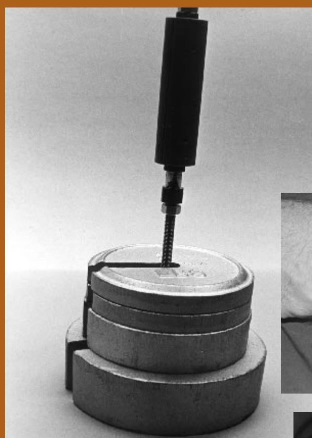


Photo 3 (clockwise from right): Screwdriver task apparatus.
Photo 4: Ratchet task apparatus.
Photo 5: Lift-and-carry task apparatus.

Experimental Protocol

Three tasks were selected for investigation: a screwdriver task, a ratchet task and a lift-and-carry task. These tasks were chosen because they require use of a power grip while applying a force in very different ways. The screwdriver task requires a power grip while applying torque about the long axis of a tool. The ratchet task requires a power grip while using the handle as a lever arm to apply torque. The lift-and-carry task requires use of a power grip on a vertically oriented handle, so that the force is directed down the long axis of the handle, normal (perpendicular) to the gripping force.

Before each of the three randomly presented tasks, the subject had a brief practice session at the highest and lowest experimental resistance levels to become familiar with the equipment and protocol. The subject was then instructed in the procedure for estimating grip force with the hand dynamometer, which was to be performed following two replications of each experimental condition. The instructions were: "Grip the handle with the same force you just used while you performed the task."

Subjects were verbally cued to perform a two-second ramp up to the estimated force level, followed by a sustained grip at that estimated level for three seconds. A custom software program developed for acquiring the grip force estimates was based on the MVC protocol proposed by Caldwell (Caldwell 201). A ±15-percent variance from the mean during the three seconds of sustained grip estimate period was used as criterion for acceptance of a trial, based on recommendations for finger strength measurements (Berg, et al 191). The estimation protocol was repeated, and when two estimates with averages within ±15 percent were collected, the mean of the two values was saved as the estimated grip force for that test condition. A protocol requiring two consistent repetitions of the grip force estimate was utilized, based on recommended protocols for psychophysical investigations (Snook and Ciriello 1197).

After the practice session was completed, the test session began. Two replications of each randomly presented test condition were followed by estimation of grip forces with the hand dynamometer. This procedure was repeated until all test conditions of the task were completed. The procedure was repeated for the remaining two tasks. A description of the three experimental tasks follows.

Screwdriver Task

One of three randomly selected Phillips head screwdriver bits—29.6, 33.6 and 40.6 cm in length—was inserted into the fitting on the instrumented handle. A machine screw was placed in the particle brake chuck, and the height of the screw was adjusted to the subject's elbow height. Subjects were instructed to perform 10 turns of the screwdriver through a comfortable working range. While performing this task, subjects were permitted to use their other hand to guide—but not support—the shaft of the screwdriver bit. Subjects used a parallel grip facing the particle brake. The task was randomized between length (short, medium and long bit) of screwdriver and torque level (resistance level 1 to 4) and each combination of the task was performed twice. Photo 3 depicts the screwdriver task apparatus.

Ratchet Task

The head of a 3/8-in. (9.5 mm) drive hand ratchet was attached to the instrumented handle. The overall length of the assembled ratchet was 18.4 cm. A ratchet extension with a universal joint was placed in the particle brake chuck. The universal joint provided a "sloppy" joint that required the subject to firmly grip the ratchet in order to "turn the bolt" rather than simply pulling or pushing the handle. The ratchet joint was placed at elbow height for each subject. Subjects were instructed to perform 10 turns of the "bolt" in the horizontal plane. The clockwise turns were from approximately 12 o'clock to 6 o'clock and vice versa for the counterclockwise direction. The task was randomized between direction and resistance level (1 to 4), and each combination of the task was performed twice. Photo 4 shows the ratchet task apparatus.

Lift-and-Carry Task

A plate and hanger for carrying slotted calibration weights was attached to the instrumented handle. A small cloth "curtain" was draped around the weights to prevent the subject from seeing them. Four weight levels were used: 3.6, 5.4, 7.2 and 9 kg. The table height was adjusted to locate the center of the handle at elbow height. Using a power grip, and maintaining approximately a right-angle elbow bend, the subject lifted and carried the apparatus over a 20 cm high obstacle a distance of 150 cm, to a target circle approximately 20 cm in diameter. The task was randomized between weights, and each subject performed each loading condition twice. Photo 5 shows this apparatus.

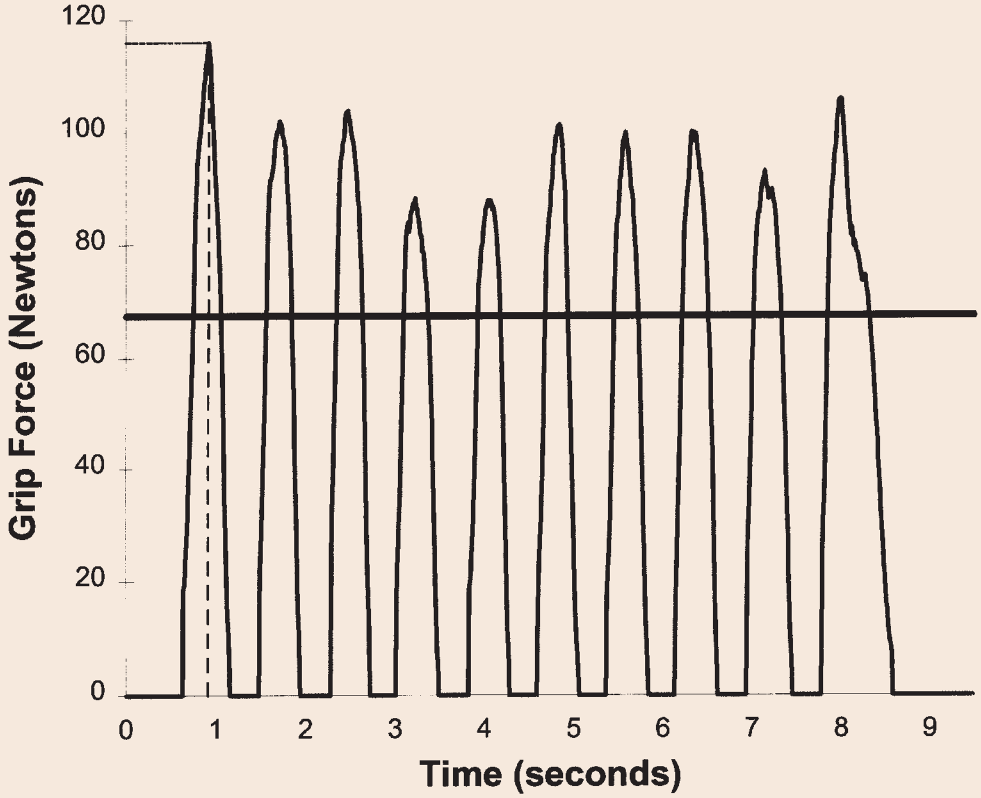
Data Analysis

Signals from the six handle strain gauges and the three strain gauges at the tool end of the instrumented core were sent to an analog-to-digital converter, sampled at 100 Hz and stored in the computer. Conversion factors were applied to the data. For each data point, an average for the six grip channels and the moment applied by the tool was computed. Data from several lift-and-carry trials were examined and a grip force threshold of 18.6 Newton (N) was selected to denote the active phase of the lift. For the screwdriver and ratchet tasks, a threshold of 0.56 Newton-meters (Nm) for the applied moment was used to denote the active phase of tool use. Data points with grip force values exceeding the threshold level were included in the trial data. Mean and peak values were calculated for each trial, and the average for the two trials of each condition was calculated. Mean and peak grip forces were determined for the active phases of all conditions for 16 subjects. Figures 1, 2 and 3 are examples of the applied grip force exerted during the tasks. The grip force estimate was determined by calculating the mean value for the three-second isometric phase of the estimate for each trial, then averaging the values for the two trials for each condition.

The error between estimated grip force and actual average grip force was calculated by taking the difference between these values. It was expressed as a percentage of the actual value; a positive value indicated an overestimate of the actual value, a neg-

Figure 1

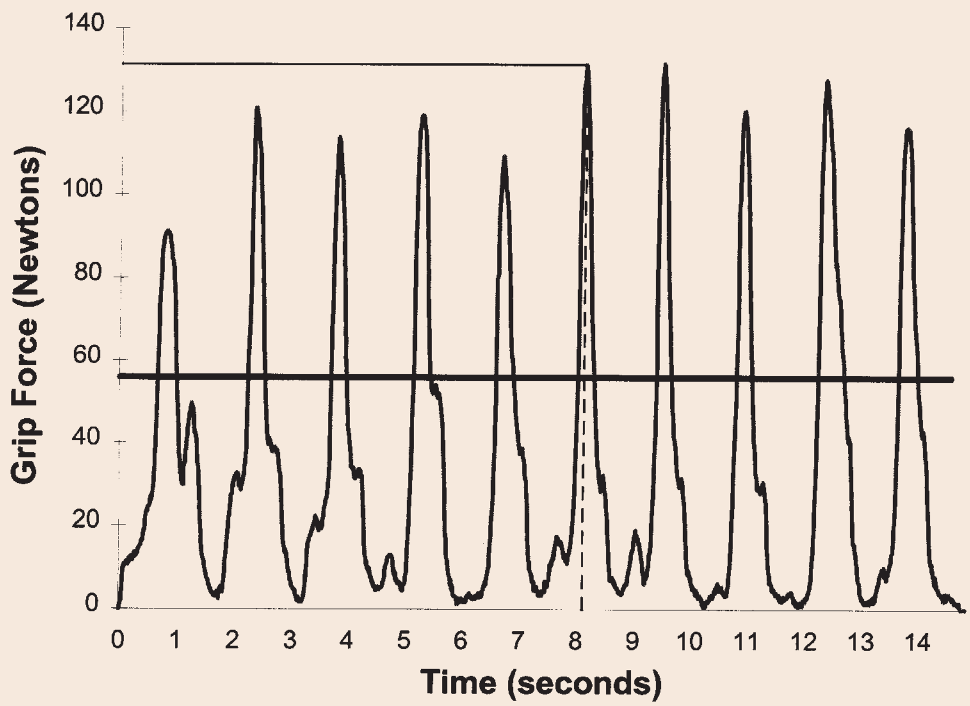
Grip Force During the Screwdriver Task



Grip force during the screwdriver task, with a 1.5 Nm average moment. The dashed line marks the peak force; the thick straight line indicates the average grip force.

Figure 2

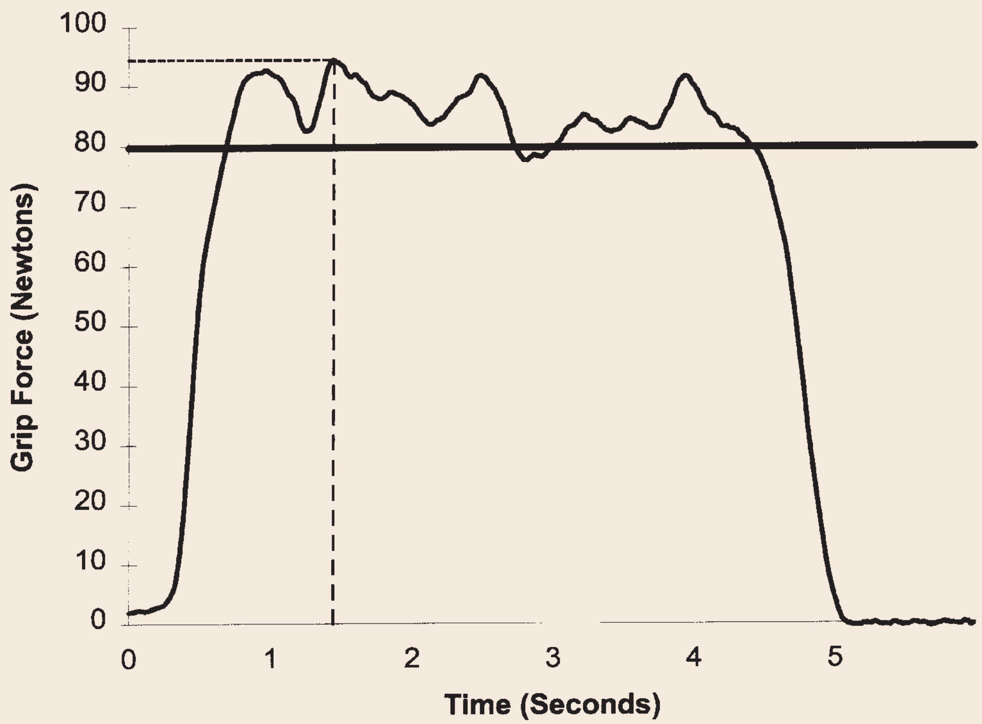
Grip Force During the Ratchet Task



Grip force during the ratchet task, with a 5.3 Nm average moment. The dashed line marks the peak force; the thick straight line indicates the average grip force.

Figure 3

Grip Force During the Lift & Carry Task



Grip force during the lift-and-carry task, with a 7.2 kg load. The dashed line marks the peak force; the thick straight line indicates the average grip force.

ative value an underestimate. The error between the estimate and peak grip force was calculated in the same manner. This approach allows for comparisons across subjects by eliminating the effects of individual differences between subjects.

Study Results

Table 3 presents average and peak task grip forces, set resistance levels and dynamometer grip force estimates for the trials of all 16 subjects. Set resistance is the resistance level set with the particle brake for the screwdriver and ratchet tasks, and the weight for the lift-and-carry tasks, as controlled by the experimenter. Average task grip force is the mean value of the actual grip force exerted during the active phase of a task. Peak task grip force is the maximum value exerted during the active phase. The dynamometer estimate value represents the average grip force estimation values for each task for all 16 subjects.

Table 4 presents the mean percent estimation error between the dynamometer estimate and the actual average task grip force and the peak task grip force for all trials, for each subject. A large between-subject variation was observed in the estimates, as compared to the average grip force value, ranging from approximately 80 percent overestimation to 53 percent underestimation. The range of the estimation error was less when the estimate was compared to the peak grip force, ranging from approximately 11 percent overestimation to 74 percent underestimation.

Table 3

Average & Peak Grip Force & Estimates for All Subjects, Grouped by Task & Force Level

Task	Force Level	Set Resistance Mean (s.d.)	Average Task Grip Force Mean (s.d.)	Peak Task Grip Force Mean (s.d.)	Dynamometer Estimate Grip Force Mean (s.d.)
Screwdriver n = 191		**(Nm)**	**(N)**	**(N)**	**(N)**
	1	0.34 (.02)	78.1 (6.5)	141.2 (11.1)	82.8 (15.2)
	2	0.63 (.03)	103.1 (4.9)	181.0 (9.6)	110.3 (15.6)
	3	1.07 (.06)	140.7 (5.5)	241.4 (10.3)	131.1 (16.4)
	4	1.57 (.06)	183.0 (6.3)	306.2 (11.5)	163.5 (16.3)
Ratchet n = 128		**(Nm)**	**(N)**	**(N)**	**(N)**
	1	2.1 (0.5)	114.7 (11.5)	218.8 (15.7)	96.7 (10.8)
	2	2.9 (0.7)	137.9 (8.9)	265.2 (13.0)	118.9 (13.5)
	3	4.0 (1.0)	164.7 (9.4)	310.8 (11.1)	149.5 (15.2)
	4	5.3 (1.2)	193.1 (11.6)	365.4 (15.4)	163.3 (16.7)
Lift & Carry n = 64		**(N)**	**(N)**	**(N)**	**(N)**
	1	38.1 (0)	115.0 (12.9)	197.8 (17.6)	99.7 (13.1)
	2	55.8 (0)	134.9 (11.5)	210.8 (15.9)	123.2 (15.04)
	3	73.4 (0)	165.4 (9.9)	247.6 (15.2)	154.8 (15.2)
	4	91.1 (0)	188.1 (13.4)	269.0 (19.0)	182.7 (19.6)

Mean (standard deviation).
Average grip force, peak grip forces and dynamometer estimate in Newtons (N). Set resistance for lift task in N. Set resistance for screwdriver and ratchet in Newton-meters (Nm). n is the total number of trials evaluated for each tool.

Estimate errors were then compiled from the data of all 16 subjects. The overall group percent estimation error of the peak grip force was 45.4 percent (s.d. = 31.2 percent) underestimate, as compared to a 4.8 percent (s.d. = 49.4 percent) underestimate of the average grip force. Data were then grouped by self-reported skill level (professional, skilled, novice) and task (screwdriver, ratchet, lift-and-carry), and the percent estimation error calculated for each group. In all cases, the error was much less when the estimates were compared to the average grip forces exerted. Table 5 presents the results of the analysis comparing estimates to the average and peak grip forces.

Discussion

The quality and accuracy of a measurement tool for evaluating a given workstation or job has become increasingly important when quantifying risk of MSDs. The hand dynamometer has been used to estimate the level of force exerted during a given task. This laboratory evaluation of the accuracy of grip force estimates in three different tasks produced some interesting results that should prove useful to SH&E professionals.

Subjects received simple instructions: "Grip the handle with the same force you just used while you performed the task." When the difference between the estimate and the peak and average grip force used was examined, it was consistently found that the difference between the estimate and the average grip force was much smaller than the difference from the peak grip force (-4.8 percent and -45.4 percent, respectively). This suggests that the instructions elicited the correct response from subjects and that subjects, as a group, were fairly accurate at estimating the average grip forces used during the tasks.

It should be noted, however, that the subjects, as a group, did not estimate the peak grip forces used, which is the estimate typically desired in an ergonomic evaluation. In retrospect, an experimental protocol could have been designed to examine whether subjects are able to differentiate between the average and peak grip force applied.

The finding of large between-subject variation in the estimate error warrants further discussion. This variance suggests that some individuals are much better at producing an accurate psychophysical estimate than others.

In this study, three subjects had average estimates within five percent of the average grip force they produced, while two subjects had estimates that were 65 percent greater than the average value; four had underestimates of nearly one half of the average value. This finding suggests that reliance on just a few subjects (workers) could lead to erroneous results. A mean of a larger sample size, 16 subjects in this study, produced an average grip force estimate with an overall mean error of approximately five percent underestimation. Statistically, a marginally more accurate grip force estimate might be anticipated with larger sample sizes. From the practitioner's perspective, however, it is informative that a sample size of 16 could be expected to provide a reasonably accurate grip force estimate in tasks similar to those evaluated in the experiment.

Table 4

Overall Percent Estimation Error by Subject

Subject	% Estimation Error Average Grip Force	% Estimation Error Peak Grip Force
1	79.9	3.6
2	65.0	11.3
3	39.8	-16.3
4	-51.9	-71.1
5	7.6	-40.1
6	4.8	-40.2
7	25.2	-34.3
8	-52.9	-74.2
9	-48.2	-70.4
10	-32.6	-62.2
11	7.0	-38.8
12	-28.8	-62.2
13	-3.3	-48.0
14	-4.0	-46.3
15	-38.8	-64.2
16	-46.3	-72.9

Percent estimation error = (actual grip force - estimate) / actual grip force, expressed as a percentage. A negative value represents an underestimation.

Table 5

Comparison of Percent Estimation Error by Skill Level, Task & Overall

Grouping	n	% Estimation Error Average Grip Force	% Estimation Error Peak Grip Force
Overall	383	-4.8 (49.4)	-45.4 (31.2)
By Skill Level			
Professional	88	6.7 (55.3)	-43.3 (30.0)
Skilled	155	-15.8 (32.8)	-53.9 (17.8)
Novice	76	4.6 (66.2)	-36.0 (45.8)
By Task			
Screwdriver	191	-0.7 (55.5)	-41.9 (35.2)
Ratchet	128	-10.7 (40.1)	-54.0 (20.9)
Lift and Carry	64	-5.5 (46.4)	-38.7 (32.5)

Percent estimation error = (actual grip force - estimate) / actual grip force, expressed as a percentage. A negative value represents an underestimation. n is the total number of trials evaluated for each skill level and for each tool.

In jobs that require repetitive gripping, an ergonomic evaluation should include a measure or estimation of the applied grip force.

The analysis of estimate error when grouped by skill level and by task produced interesting results. Subjects who considered themselves to be professional or skilled with the ratchet or screwdriver were not more accurate than their novice counterparts. Those with experience misestimated by 6.7 percent and -15.8 percent, as compared to the 4.6 percent estimation error of the novices. This suggests that the ability to estimate is not a reflection of familiarity. Lifting was not included as a "skilled" task as it was assumed that all individuals regularly experience simple lifting tasks in their daily lives.

Estimate accuracy was also found to vary with the task performed. When the tasks were performed, subjects had estimation errors of -0.7 percent with the screwdriver task; -10.7 percent with the ratchet task; and -5.5 percent for the lift-and-carry task.

Although the differences between tasks were relatively small, some observed differences may be due to the fact that although all three tasks required use of a power grip, force was applied in very different ways. The screwdriver task required gripping while applying torque about the long axis of a tool, which would be expected to produce a relatively uniform shear force at the hand-tool interface. The lift-and-carry task required a power grip on a vertically oriented handle under an axial load; it would also produce a relatively uniform shear force at the interface. By contrast, the ratchet task required a power grip applied to a handle used as a lever arm. The perception of greater pressure against one surface of the handle than against the opposite side might account for the tendency to overestimate.

Another possibility is that different upper extremity muscles unrelated to grip might be used, or used in different ways in the three tasks. These differences may interfere with or modify perception of the grip force. The overall stresses of the task, such as those felt in a muscle of the shoulder involved in stabilizing the arm during one task, might influence perception of muscles acting at the hand.

It should be noted that these stated reasons for the observed differences are conjecture and are not supported by experimental evidence. The authors offer them to emphasize that estimates of perceived grip force may also be influenced by the nature of the task itself—a factor that should be considered when evaluating data.

Conclusion

Results of this study represent one of the few efforts to quantify the accuracy of estimates of grip force. A positive attribute of this study was the ability to quantify both grip forces applied during a task and during the estimate protocol itself. Another strength was the ability to investigate tasks that require different loading characteristics. One weakness was that the subject population probably varied more in skill level with the tools than might be expected in an industrial worker population, although the results did not suggest that estimate accuracy varies systematically with skill level.

In conclusion, the study provided several insights that should be considered by SH&E professionals interested in grip force estimation as part of an ergonomic analysis.

If giving a simple instruction for eliciting an estimate, where peak or average grip force is not specified, it should be assumed that the response will more accurately represent the average value. It was also found that the ability to make accurate estimates may vary among individuals. Based on these findings, practitioners evaluating the grip force requirements of a job should collect estimates from as many workers as possible in order to improve estimate accuracy. Finally, the relationship of the grip force about the handle to the direction of the force or torque applied during the task should be considered when evaluating the accuracy of a grip force estimate. ■

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