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An electromyographic study of maximum torques and upper extremity muscle activity in simulated screwdriving tasks

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Abstract

The effects of workstation and tool handle design on strength and upper extremity muscle activity during a simulated manual screwdriving task were examined. Fifteen male participants performed maximal (100%) and submaximal (75% and 50%) exertions with a screwdriver using postures frequently observed in industry. Investigators varied handle height, reach distance, handle diameter, and handle orientation during the experiment. The activity of the anterior deltoid, triceps brachii, biceps, extensor digitorum, flexor digitorum superficialis and flexor pollicis longus was monitored using surface electromyography (EMG). The ratio of normalized EMG activity to torque produced during the exertion was computed for each muscle under each condition. The results indicated that increased torque capability was associated with the use of a larger (3.7 cm), vertically oriented handle. EMG/torque ratio generally increased as handle height was increased, reach distance and handle diameter were reduced, and the handle orientation was changed from vertical to horizontal. This study supports the premise that workstations and tools can be configured to maximize worker capabilities while minimizing the potential for muscle strain and fatigue. These data may be useful to job analysts for assessing the relative demands of construction and assembly work.

Relevance to industry

These data can be used by job analysts to grade the level of muscle activity required by screwdriving tasks (relative to similar exertions in different postures), and to justify workstation changes to reduce muscular stress on the upper extremities.

Keywords: Surface electromyography (EMG); Upper extremity musculoskeletal disorders; Torque; Posture

1. Introduction

A routine service function of the National Institute for Occupational Safety and Health (NIOSH) is the conduct of worksite studies to evaluate potential

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health hazards under its Hazard Evaluation and Technical Assistance (HETA) program. When the hazard specified in an HETA request is excessive physical demands or biomechanical loads, and the suspected health outcome is upper extremity musculoskeletal disorders, a detailed job evaluation is performed (Habes and Putz-Anderson, 1985). This evaluation consists of an analysis of job attributes which may contribute to the development of tendinitis, tenosynovitis, carpal tunnel syndrome, and other musculoskeletal injuries. Of primary interest are the frequency and duration of manual activities, the occurrence of awkward postures, and the level of muscle activation required to perform the job. Frequency, duration and posture can be measured through direct observation or a review of video records of a job. Muscle usage is more difficult to assess in field settings, and estimates are frequently based on the appearance of effort and the size and weight of objects handled. To increase the reliability of risk assessments in ergonomic studies, estimates of muscle activity must be based on more objective criteria.

An easier way to obtain information about the effort requirements of manual tasks is to simulate these activities in the laboratory. In the laboratory, electromyography (EMG) has frequently been used to assess the effects of workplace layout and tool design on the upper extremity musculature (Ayoub and Lo Presti, 1971; Tichauer, 1978; Strasser, 1991; Freivalds and Eklund, 1993). During isometric contractions, there are well-defined relationships between the amplitude of the EMG signal and the magnitude of voluntary muscle activity (Dempester and Finerty, 1947; Inman et al., 1952; Lippold, 1952). Through careful recording and processing techniques, EMG can provide information about the relative activation of individual muscle groups during select work activities. This information is useful to job designers from several standpoints; specifically, investigators can more easily identify probable sites of overexertion injury, and analysts can use these data to identify tools, workstations, equipment items, etc., to relieve stress at a particular anatomical location without adversely impacting work output.

In this study, EMG was used to measure the activity of upper extremity muscles while subjects performed exertions with a screwdriver, similar to those required by many common industrial tasks. The objective of this research is to provide data that can be used by job analysts to assess and compare the biomechanical demands on the upper extremity when observing workers engaged in similar tasks at a worksite. In addition, this information will provide a quantitative basis for recommending interventions such as tool substitution and workstation redesign.

2. Materials and methods

2.1. Subjects

Fifteen males between the ages of 18 and 30 yr (mean age = 26.4 yr) were recruited from a temporary employment agency to participate in this experiment. All participants described themselves as right-handed, and free of known musculoskeletal impairments. At the beginning of each test session, informed consent was obtained and anatomic measurements of the hand and arm were made. All procedures were approved by the NIOSH Human Subjects Review Board (HSRB).

2.2. Experimental task

Participants were asked to apply a series of exertions to a standard screwdriver handle (straight longitudinal contour, round cross-section with grooved surface) with the right hand in postures frequently observed in the construction and manufacturing trades. The handle was attached to the actuator shaft of the LIDO WorkSET II work simulator system (Fig. 1). Four factors were varied during the experiment:

1. Height of the handle – positioned at elbow or shoulder height.
2. Distance of the handle away from the body – full or half reach.
3. Handle orientation – positioned with the long axis of the handle perpendicular (vertical) or parallel (horizontal) to the floor.
4. Handle diameter – 3.7 cm (larger) or 2.9 cm (smaller) diameter.

Handle height was defined in a way that would allow the segment joining the wrist and shoulder, or wrist and elbow to remain parallel to the floor during

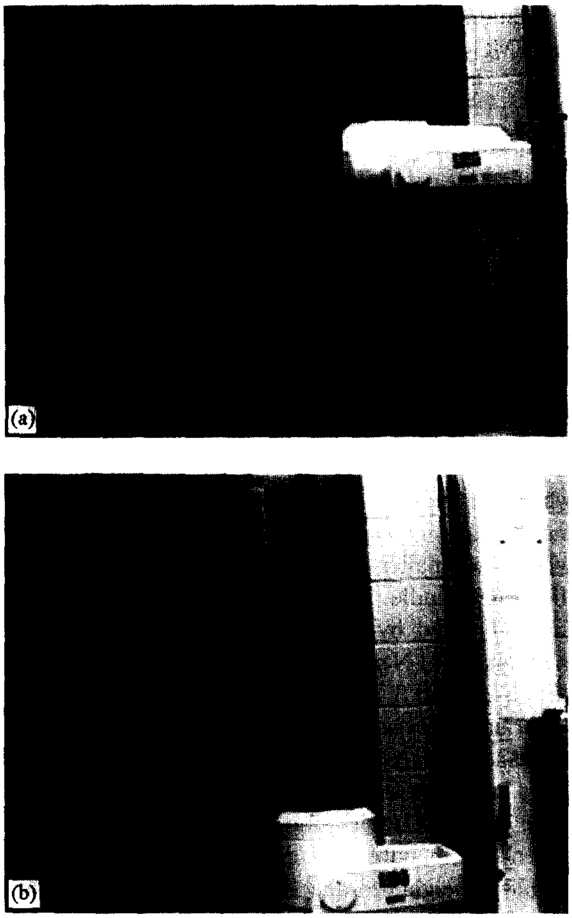

Fig. 1. Subject performing simulated work task with (a) handle oriented horizontally at shoulder height, and (b) handle oriented vertically at elbow height.

task execution. If the handle was positioned horizontally (Fig. 1a), the long axis of the handle was aligned with either the elbow or shoulder. If the handle was oriented vertically (Fig. 1b), the topmost point (end) of the handle was positioned so as to be level with the elbow or shoulder. Full reach distance was defined as the distance from the front of the participant's toes to the front end of the handle when the handle was grasped with the arm fully outstretched at shoulder height. Half reach distance was defined as half of full reach distance.

2.3. Procedure

Each participant performed isometric maximum (100%) and submaximum (75% and 50% of maximum) torque exertions using all treatment combinations (total = 16) in random order. Torque output was measured by the LIDO WorkSET II system. Handle height and orientation were adjusted using the actuator height adjustment mechanism and by rotating the actuator unit in its yoke until the shaft pointed straight up (vertical orientation) or was positioned parallel to the floor (horizontal orientation). The workset was programmed for isometric exercise to permit assessment of torque at each test condition. For each trial, participants were asked to stand in front of the workstation, with the handle positioned in a sagittal plane with the participant's right shoulder. Participants were instructed to grip the handle with the right thumb aligned with the long axis at the 12 o'clock (horizontal handle) or 6 o'clock (vertical handle) position, and to attempt to turn the handle in a clockwise direction. During maximum exertions, participants were instructed to exert as much torque as possible for a 5 s period. Maximum strength measurements were repeated three times for each condition, with 1 min of rest provided between exertions. During submaximal exertions, participants were asked to slowly apply torque to the tool handle while watching the workset's biofeedback display. The display showed both a desired torque exertion level (either 75% and 50% of the torque produced during maximal exertion) and the torque actually exerted. When the two values matched, participants were asked to hold the exertion for a 5 s period. Each submaximal exertion was repeated twice. A 3 min rest period was provided after each set of exertions (between conditions) to avoid fatigue.

2.4. Dependent variables

Maximum torque (i.e., strength) was recorded from the workset's biofeedback display (hidden from the participant's view) after each maximal (100%) exertion. The average torque during the three maximum efforts at each condition was computed, and the resulting value was used to establish the required exertion level during the subsequent submaximal contractions (i.e., the level of torque was set to 75% and 50% of this value).

Six channels of EMG from the anterior deltoid, the long head of the biceps, the triceps brachii, the flexor digitorum superficialis, the extensor digitorum, and the flexor pollicis longus were recorded during the middle 3 s of each 5 s exertion (maximal and submaximal). These muscles were chosen because of their size, their actions in supporting the arm in various postures, their proximity to the surface of the skin, and the susceptibility of the muscle or its tendons to overexertion injury. EMG was monitored using silver/silver-chloride surface electrodes mounted in a lightweight plastic housing with preamplification circuitry (inter-electrode distance = 2 cm). The electrodes were positioned over the anterior deltoid, biceps, triceps brachii, flexor digitorum superficialis, and extensor digitorum in the configuration recommended by Zipp (1982). Electrode placement over the belly of the flexor pollicis longus muscle was determined by palpation of the muscle while the subject resisted extension of the thumb. Amplification and root-mean-square (RMS) processing of the EMG signals was provided by the 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. RMS values were calculated using an 11.75 ms time constant. The processed EMG was sampled at 175 Hz and stored by microcomputer using a 12-bit analog-to-digital converter and LabTech Notebook© data acquisition software.

2.5. Research design

Due to technical difficulties, EMG data from one participant was not used. To permit comparisons among individuals and activities, EMG values for each muscle were normalized to the highest amplitude observed from that muscle during any of the isometric exertions. Because the torque produced by maximal exertions under different conditions varied, the ratio of the normalized EMG to the torque produced during the corresponding exertion (also normalized) was computed and used in subsequent analyses. Relatively high levels of muscle activity associated with relatively low levels of torque production will result in ratios > 1.0.

Multivariate analysis of variance (MANOVA) with univariate repeated-measures tests was used to assess the significance of handle height, reach distance, handle orientation and handle diameter on the maximum torque produced under each condition and the EMG/torque ratio for each muscle group.

3. Results

3.1. Torque

Maximum torque (i.e., strength) for each treatment combination is shown in Fig. 2. As reported by others (Pheasant and O'Neill, 1975; Mital and Sanghavi, 1986), torque was strongly dependent on handle height, $F(1,14) = 35.40$, $p < 0.01$; handle orientation, $F(1,14) = 6.54$, $p = 0.02$; and handle diameter, $F(1,14) = 67.53$, $p < 0.01$. Torque was greater when participants used the larger (3.7 cm) handle; mean torque increased by 23% from 3.16 to 3.89 N m when the smaller (2.9 cm) handle was replaced by the larger handle. These torque values closely match those reported by Mital and Sanghavi (1986), i.e., 3.24 and 3.71 N m, for males performing exertions with a 2.9 and 3.7 cm handle, respectively.

Orientation had an effect on torque strength when the handle was positioned at shoulder height, but not when it was positioned at elbow height, $F(1,14) = 5.79$, $p = 0.03$ (interaction of height and orientation). When the handle was positioned horizontally at shoulder height, torque levels were approximately 13% less than those recorded when the handle was oriented vertically or positioned at elbow height. Reach distance had no significant effect on torque output, $F(1,14) = 0.92$, $p = 0.35$.

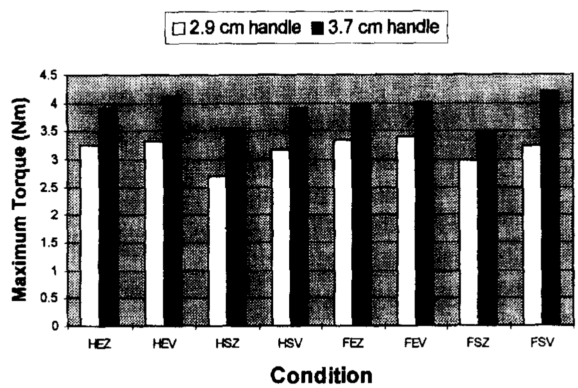

Fig. 2. Mean torque strengths for different treatment combinations (H = half reach, F = full reach, E = elbow height, S = shoulder height, Z = horizontal orientation, V = vertical orientation).

3.2. Muscle EMG / torque ratio

3.2.1. Handle effects

The EMG/torque ratio for all muscle groups was significantly affected by the position of the handle during the experiment (see Tables 1 and 2).

Although no muscle was affected by all of the variables examined in this experiment, each factor had a significant effect on the EMG/torque ratio for at least two muscle groups, and one variable (handle diameter) had an influence on the EMG/torque ratio for all muscles. Where their effects were significant, factors tended to influence the EMG/torque ratio for different muscles in the same manner. For instance, raising the handle from elbow to shoulder height tended to increase EMG/torque ratios, while enlarging the handle diameter reduced these values. The magnitude of these effects was not always uniform across conditions; a number of significant interactions were noted. For example, raising the handle height had a 3.5 times greater effect on the EMG/torque ratio for the deltoid and biceps when the handle was positioned at full reach distance vs. half reach distance. Similarly, orienting the handle in a horizontal position had a 3 times greater influence on the triceps and flexor pollicis longus when the handle was positioned at shoulder height vs. elbow height. In general, the condition which came closest to minimizing the EMG/torque ratio for all muscle groups simultaneously was that where the larger

Table 1
Repeated measures ANOVA results

	Anterior deltoid	Triceps brachii	Biceps brachii	Extensor digitorum	Flexor digitorum superficialis	Flexor pollicis longus
Exertion: $F(2,12)$	**6.53**	**11.13**	3.20	**32.51**	**21.86**	**11.10**
p	**= 0.01**	**< 0.01**	> 0.05	**< 0.01**	**< 0.01**	**< 0.01**
Height: $F(1,13)$	**24.60**	**9.98**	**13.21**	**5.32**	1.44	0.81
p	**< 0.01**	**= 0.01**	**= 0.01**	**= 0.04**	> 0.05	> 0.05
Reach: $F(1,13)$	0.04	3.25	**9.33**	1.85	**9.73**	0.75
p	> 0.05	> 0.05	**< 0.01**	> 0.05	**= 0.01**	> 0.05
Orientation: $F(1,13)$	1.39	**11.58**	**26.76**	0.04	**18.92**	**18.73**
p	> 0.05	**< 0.01**	**< 0.01**	> 0.05	**< 0.01**	**< 0.01**
Diameter: $F(1,13)$	**18.69**	**9.00**	**26.04**	**25.77**	**72.35**	**23.38**
p	**< 0.01**	**= 0.01**	**< 0.01**	**< 0.01**	**< 0.01**	**< 0.01**
Exertion * height: $F(2,12)$	3.31	**5.76**	**6.19**	0.04	0.16	1.56
p	> 0.05	**= 0.02**	**= 0.01**	> 0.05	> 0.05	> 0.05
Exertion * reach: $F(2,12)$	1.81	3.88	**5.60**	0.00	**6.71**	1.69
p	> 0.05	> 0.05	**= 0.02**	> 0.05	**= 0.01**	> 0.05
Exertion * orientation: $F(2,12)$	0.99	2.25	**6.81**	1.01	2.75	2.49
p	> 0.05	> 0.05	**= 0.01**	> 0.05	> 0.05	0.05
Exertion * diameter: $F(2,12)$	0.61	0.80	1.04	**4.72**	0.74	0.48
p	> 0.05	> 0.05	> 0.05	**= 0.03**	> 0.05	> 0.05
Height * reach: $(F1,13)$	**15.60**	1.03	**9.71**	0.00	2.94	0.98
p	**< 0.01**	> 0.05	**< 0.01**	> 0.05	> 0.05	> 0.05
Height * orientation: $F(1,13)$	0.07	**4.86**	0.01	4.14	1.04	**8.13**
p	> 0.05	**= 0.05**	> 0.05	> 0.05	> 0.05	**= 0.01**
Height * diameter: $F(1,13)$	3.29	**5.47**	3.12	1.10	0.30	0.29
p	> 0.05	**= 0.04**	> 0.05	> 0.05	> 0.05	> 0.05
Reach * orientation: $F(1,13)$	**7.40**	2.67	0.59	1.81	0.43	0.18
p	**= 0.02**	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05
Reach * diameter: $F(1,13)$	1.13	0.00	0.62	0.42	0.57	1.71
p	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05
Orientation * diameter: $F(1,13)$	0.00	1.28	**4.88**	1.32	3.47	1.10
p	> 0.05	> 0.05	**= 0.05**	> 0.05	> 0.05	> 0.05

Note: Bold indicates effect is significant at alpha = 0.05. N/A = not applicable

Table 2
Factors affecting EMG/torque ratio

Muscle group	Height	Reach	Orientation	Diameter	Exertion
Deltoid	+159% (half reach) +47% (full reach)			−22%	−30% (50–75%) −19% (75–100%)
Triceps	+35%		+65% (shoulder height) +23% (elbow height)	−15% (shoulder height) −5% (elbow height)	+17% (50–75%, shoulder height) +39% (50–75%, elbow height)
Biceps	+62% (half reach) +16% (full reach)	−32% (shoulder height) −5% (elbow height)	+91%	−21%	
Flexor digitorum superficialis		−13%	+20%	−15%	+10% (50–75%) −11% (75–100%)
Extensor digitorum	+7%			−23%	−10% (50–75%) −17% (75–100%)
Flexor pollicis longus			+31% (shoulder height) +10% (elbow height)	−18%	−12% (75–100%)

Note: (1) Plus indicates increase in factor (i.e., raising handle height from elbow to shoulder, increasing reach distance from half to full, changing handle orientation from vertical to horizontal, maximum, increasing handle diameter, or increasing exertion level from 50 to 75%, or 75 to 100% of maximum) results in increase in EMG/torque ratio
(2) Minus indicates increase in factor results in decreased EMG/torque ratio

(3.7 cm) diameter handle was used in the vertical orientation, at elbow height and full reach distance. In this position, EMG/torque ratio was minimized in the biceps, 7% greater than the minimum for the flexor pollicis longus, 9% greater than the minimum for the anterior deltoid, 10.6% greater than the minimum for the flexor digitorum superficialis, 12.8% greater than the minimum for the extensor digitorum, and 13.5% greater than the minimum for the triceps.

3.2.2. Exertion level effects

Exertion level had a significant effect on the EMG/torque ratio for all muscle groups except the biceps (see Tables 1 and 2). In general, increases in exertion level caused a decrease in the EMG/torque ratio, although the EMG/torque ratio increased with increasing exertion levels in the triceps. In the flexor digitorum superficialis, the ratio increased by 10% as the exertion level increased from 50% to 75%, and then declined 11% as exertion levels climbed from 75% to 100%, so that the mean EMG/torque ratios for 50% and 100% exertions were virtually the same (1.03 vs. 1.01). Although the effect of exertion level was not significant in the biceps, exertion level did interact significantly with reach distance, height and handle orientation (Fig. 3). As shown, the effect of increasing reach distance and handle height was 4.5 and 3.7 times greater, respectively, at 50% of maximum exertion than at 100% of maximum exertion. Conversely, changing the handle orientation from vertical to horizontal had a 55% greater effect at maximum exertion than at 50% of same.

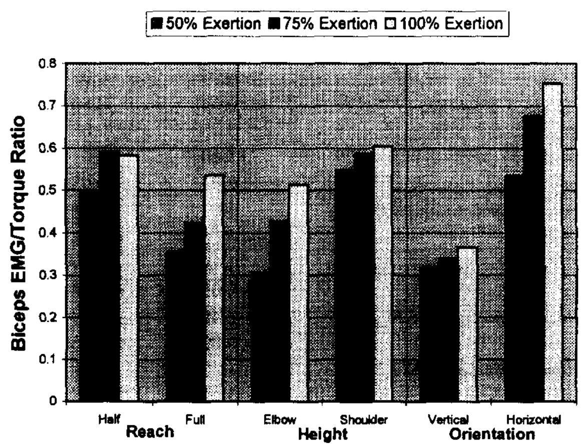

Fig. 3. Mean biceps EMG/torque ratio for different exertion levels.

4. Discussion and conclusions

The relationship between the force output of an exertion and muscle activity is not constant – the relationship can be influenced by muscle length, the fiber composition of the muscle, the nature of the contraction (concentric vs. eccentric), and the activity of neighboring synergist and antagonist muscle groups (LeVeau and Andersson, 1992; Kumar, 1996). Recognizing that this relationship is subject to change, we used the ratio of normalized muscle activity (EMG) to torque produced as an "efficiency" measure: the smaller the ratio, the less muscle activation required to produce a desired level of torque output. Based on this value, our results suggest that workstations can be configured to maximize strength and biomechanical advantage while minimizing muscular effort. In this study, this goal was best achieved when work was positioned at elbow height and a vertically oriented, larger diameter tool handle was used. Changes from this configuration resulted in increased muscle activity that was not related to increased torque output. For example, raising the handle from elbow to shoulder height did not result in greater torque strength, but did result in a substantial increase in deltoid activity, probably because of the increase in the moment about the shoulder as the hand was raised. Likewise, substituting the smaller handle for the larger handle caused little change in muscle activity, but the decrease in handle diameter resulted in less torque generation for the same level of muscular effort.

The recommendations resulting from this study are not unique; previous studies support the use of cylindrical handles approximately 4 cm in diameter, and it is well accepted that work surfaces should be positioned at or slightly below elbow height (Chaffin and Andersson, 1991). However, engineers often face difficulties in justifying capital expenditures for changes in existing equipment, since the magnitude of the expected improvement is usually unknown. Based on this or similar data, engineers can predict how proposed changes might impact the musculoskeletal system, and make better judgements as to whether changes will satisfy health and safety objectives. For example, lowering work surfaces from shoulder to elbow height might be justified based on the number of muscle groups impacted, or the magnitude of the change in muscle activity relative to torque output (up to 61% reduction for the deltoid, up to 38% reduction for the biceps). Likewise, these data suggest that reach distance is not an important determinant of muscular stress in screwdriving tasks, and that expenditures to alter the reach distance may not be justified.

The change in EMG/torque ratio with changing exertion level was somewhat surprising – generally, we expected torque and EMG activity to increase proportionately under the same working conditions. However, the relationship between normalized muscle activity and torque output is not always linear, particularly at or near maximal exertion levels (Lawrence and DeLuca, 1983). Furthermore, if the primary function of a muscle is to support a specific posture and not to generate torque, changing the torque level would have little effect on the activity of the muscle. As torque level increases, the ratio will appear to decline. Finally, there is some evidence that tool users tend to grip tool handles more forcefully than necessary to prevent slippage, and that this phenomenon is more apparent at lower exertion levels (Grant, 1994). Hence, muscle activity in the forearm would tend to be greater than expected at lower torque levels, resulting in an apparent decline in EMG/torque ratio with increasing exertion.

This study represents a partial exploration of the upper extremity musculature; other muscles such as the coracobrachialis, pectoralis major, pronator teres may be active during screwdriving tasks. Nonetheless, it is plausible that the approach used in this study could be applied to evaluate the suitability of accommodations for injured workers, and to identify appropriate job rotation schemes. For job rotation to be an effective control measure for upper extremity musculoskeletal disorders, tasks included in the rotation should stress different portions of the musculoskeletal system. Rotating workers from one assembly task to another may not be an effective control measure if both positions require activation of similar muscle groups.

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