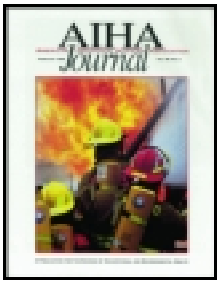

American Industrial Hygiene Association Journal
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/aiha20

EFFECT OF TOOL SHAPE AND WORK LOCATION ON PERCEIVED EXERTION FOR WORK ON HORIZONTAL SURFACES

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Published online: 04 Jun 2010.

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Thirty subjects drove screws into perforated sheet metal mounted on a horizontal surface using three air-powered tools that varied in shape (right-angle, in-line, and pistol-shaped). The four horizontal work locations ranged from 13–88 cm in front of the body and were placed at 25 cm intervals. The vertical placement of the horizontal beam was at midthigh, elbow, and midchest height. Subjects drove 25 screws at each tool/work location combination before rating that condition using the Borg 10-point ratio rating scale. The ratings of perceived exertion increased with increasing horizontal distance from the body. When tool shape was not considered, the perceived exertion was virtually equal for driving screws at midthigh or elbow height. The ratings at midchest height were significantly higher than elbow and midthigh height. When tool shape was taken into account, subjects perceived less exertion driving screws with the pistol-shaped tool at midthigh height. The in-line and right-angle tools had the lowest ratings of perceived exertion for driving screws at elbow and midchest height.

The objective of this study was to examine the effects on perceived exertion of various horizontal work locations, which varied in vertical position and tool shape combinations. Subjects drove screws into a horizontal work surface which was positioned at three vertical positions. As the work location changed, so did the postural configuration of the subject as he/she used tools of varying shapes to drive screws. By exploring the relationship between work location and tool shape, workstation design guidelines may be developed.

Partial funding and support for this research was provided by Ford Motor Company, a National Institute for Occupational Safety and Health traineeship grant, a National Needs fellowship and gifts from private industry.

Despite the widespread use of hand tools throughout a variety of industries, specific quantitative workstation design guidelines are not available. Knowledge of biomechanics, anthropometry, and scattered epidemiology studies are often used as justification for workplace recommendations aimed at minimizing the risk of developing work-related disorders such as carpal tunnel syndrome, tendinitis, or a low-back injury. This study utilizes a psychophysical methodology to explore the differences between various horizontal work-location/tool-shape combinations. In combination with existing data, specific hand-tool/work-location design guidelines can be developed that will minimize perceived exertion and have the potential to reduce the incidence of work-related musculoskeletal disorders.[1–7] Previous studies have utilized a similar psychophysical methodology to develop guidelines for manual materials-handling tasks.[8–16]

Powered screwdrivers are used extensively in automotive manufacturing and other industries. Consequently, driving screws with air-powered drivers has been used in several experiments to examine the effects of vertical work location, horizontal work location, tool shape, and work frequency on ratings of perceived exertion.[5–7] This study examines the effect of horizontal work location, tool shape, and vertical position of the horizontal beam on subject ratings of perceived exertion using the Borg 10-point ratio rating scale.

MATERIALS AND METHODS

Subjects drove screws into perforated sheet metal that was mounted on a horizontal surface. Three differently shaped air-powered tools were used to drive the screws at four horizontal locations. The horizontal beam was placed at three vertical positions. After driving screws with each tool/work location combination, subjects rated the perceived exertion of each task using Borg's 10-point ratio rating scale.[17,18]

FIGURE 1a. Subject driving screws with a pistol screwdriver at 38 cm with the horizontal surface placed at midthigh height.

FIGURE 1b. Subject driving screws with an in-line screwdriver at 38 cm with the horizontal surface placed at elbow height.

Subjects

Thirty subjects (15 males and 15 females) were chosen for this study based on a power approach utilizing data from two previous pilot studies.[7] The subjects were university students who were paid for their participation. Their ages ranged from 18 to 23 years and their stature spanned from 157 cm to 192 cm, including people as tall as a 99th percentile U.S. civilian male and as short as a 23rd percentile U.S. civilian woman.[19]

Equipment

The four horizontal work locations were 13, 38, 63, and 88 cm from the edge of the beam, and subjects were instructed to stand directly in front of the beam. The horizontal surface was positioned vertically at each subject's midthigh (67.3–85.1 cm; Mean = 75.7 ± 3.8 cm), elbow (95.3–123.2 cm; Mean = 108.9 ± 6.1 cm), and midchest height (114.3–146.1 cm; Mean = 130.2 ± 8.2 cm). Subjects drove screws only at the first three horizontal locations when the beam was placed at midchest height; most people could not reach the furthest location of 88 cm at the highest vertical position. The vertical position of the beam was determined by body landmarks to minimize the differences in the ratings of perceived exertion that were due primarily to anthropometry.

Subjects used a pistol-shaped tool (Atlas Copco, model no. A 780002; 1600 revolutions/min), a right-angle tool (Stanley, model no. A30LQATA-30F2; 1600 revolutions/min), and an in-line tool (Stanley, model no. A 30NRT-18; 1700 revolutions/min) to drive screws at all work locations. Each tool had a mass of 1.1–1.4 kg, a shut-off clutch, and the torque was set to 3.2 Nm. All three screwdrivers had phillips magnetic bits. The distance from the center of the handle to the bit was 21.6 cm for the right-angle tool, 23.5 cm for the pistol tool, and 20.3 cm for the in-line tool. The air pressure was set to 620.5 kPa. Figure 1a-c shows a subject driving screws with the three tools and with the horizontal beam positioned at the three vertical positions.

Eighteen-gauge perforated metal with a hole size of 0.28 cm was mounted on the horizontal surface. Subjects used number six slotted hex-head sheet metal screws (1.9 cm in length). A computer beep that sounded every seven seconds signaled subjects to begin driving a screw.

FIGURE 1c. Subject driving screws with a right-angle screwdriver at 38 cm with the horizontal surface placed at midchest height.

Procedure

The Borg 10-point category ratio rating of perceived exertion[17,18] was the dependent variable. The scale was developed while studying both short-term (less than 1 min) and long-term (several minutes) exercise on the bicycle ergometer,[18] and has been used in ergonomic investigations in studies of heavy aerobic work and tasks that consist of short-term static work.[18] In a previous investigation,[7] the Borg 10-point category ratio rating scale was compared with two visual analog scales, and the scales were comparable.

Subjects were to imagine that they were working on an assembly line driving screws into sheet metal as part of their job. Their workload was based on a normal eight-hour shift that would allow them to go home without feeling uncomfortable, strained, or tired. After driving 25 screws with a particular work location/tool combination, subjects were asked to rate the combination for a normal eight-hour work day. A work segment of 25 screws for each work location/tool combination was selected to simulate, in a short time period, the screw-driving segment of a manufacturing employee's work cycle.

TABLE I. Average Borg Ratings for all Three Tools at all Work Locations (n = 30)

Vertical Position and Horizontal Location	*Pistol Ratings*	*In-Line Ratings*	*Right-Angle Ratings*
Midthigh Height			
1 (13 cm)	2.5 ± 1.6	3.8 ± 1.5	3.6 ± 2.1
2 (38 cm)	3.0 ± 1.8	3.9 ± 1.3	3.9 ± 2.0
3 (63 cm)	3.8 ± 1.9	4.9 ± 1.9	4.9 ± 2.4
4 (88 cm)	5.8 ± 2.2	6.3 ± 2.0	6.4 ± 2.2
Elbow Height			
1 (13 cm)	3.5 ± 1.9	2.5 ± 1.4	2.7 ± 1.9
2 (38 cm)	3.7 ± 1.9	2.7 ± 1.3	3.2 ± 2.0
3 (63 cm)	4.7 ± 1.7	4.1 ± 1.7	4.3 ± 1.7
4 (88 cm)	7.4 ± 2.0	7.2 ± 1.9	6.7 ± 1.9
Midchest Height			
1 (13 cm)	4.8 ± 1.8	3.2 ± 1.7	4.3 ± 1.9
2 (38 cm)	5.5 ± 1.5	4.0 ± 2.0	4.5 ± 2.0
3 (63 cm)	7.4 ± 1.7	6.3 ± 2.1	6.4 ± 2.1

Three experimental sessions that lasted from an hour to an hour and a half were used in this study. The first meeting was a learning session in which subjects were taught how to use the tools and allowed to practice driving screws. Subjects also became familiar with the horizontal work locations, vertical work heights, work pace, and the rating scale. They were allowed to use one or two hands when operating the tools. Anthropometric data and background information regarding each subject's medical and work history was collected during the first session. Data was collected during the next two sessions, in which subjects drove screws using each tool/work location combination. The presentation of the vertical position of the horizontal surface, the horizontal work locations, and the tool shape was randomized.

Analysis of variance (and the comparable nonparametric test, Kruskal-Wallis), the Scheffé F-test (and the comparable nonparametric test, Wilcoxon signed-rank test) and the Fisher PLSD[19] test were used to analyze the data. StatView™,[20] Systat™,[21] and SAS™[22] were the statistics software packages used.

RESULTS AND DISCUSSION

Average perceived exertion by work location for the three vertical positions of the horizontal beam are contained in Table I. Perceived exertion ranged from a low of 2.5 for driving screws with a pistol-shaped tool at 13 cm with the beam at midthigh height (2.5 ± 1.6) or for driving screws with an in-line driver at 13 cm with the beam at elbow height (2.5 ± 1.4), to a high of 7.4 for driving screws with the pistol tool at 88 cm at elbow height (7.4 ± 2.0) and at 63 cm with the beam positioned at midchest height (7.4 ± 1.7) (see Table I).

Table II displays the results from the three-factor analysis of variance (each subject served as a block); transformations were not applied to the Borg ratings before performing the analyses. The three independent variables for this study were the horizontal work location, vertical position of the

TABLE II. Levels of Significance from ANOVA of Borg Ratings of Perceived Exertion

Source of Variance	*DF*	*F-Value*	*Significance*
Horizontal Work Location	3	133	0.0001
Vertical Position of the Horizontal Surface	2	17	0.0001
Tool Shape	2	2	0.1260
Horizontal Work Location × Vertical Height	5	23	0.0001
Horizontal Work Location × Tool Shape	6	0.5	0.8017
Vertical Height × Tool Shape	4	13	0.0001
Horizontal Work Location × Vertical Height × Tool Shape	10	0.3	0.9783

horizontal beam, and tool shape. Horizontal work location and the vertical position of the horizontal beam were significant main effects ($p < 0.0001$). The significant interactions were between horizontal location and vertical position of the beam ($p < 0.0001$) and between tool shape and vertical position of the beam ($p < 0.0001$). Since one of the independent variables, tool shape, was not a main effect, the position of the work, both vertical and horizontal, is the most important factor in determining the rating of perceived exertion. For the work locations studied, there was no specific tool shape preferred overall. The preferred tool shape was dependent on the work location (both vertical and horizontal), which varied greatly in this study.

As the distance between the body and the work location increased, the ratings of perceived exertion increased (see Table I). In examining the effect of the vertical position of the horizontal beam, overall, ratings of perceived exertion were higher for driving screws at midchest height than at either elbow or mid-thigh height (see Figure 2). The ratings of perceived exertion from the pistol tool were 8–52% lower across all horizontal work locations at midthigh height (see Table I). In contrast, for driving screws at elbow and midchest height, the ratings for the pistol tool were 3–50% higher than the ratings for the in-line and right-angle tools. The horizontal work location and vertical position interaction (see Figure 2) is seen at 88 cm where the ratings of perceived exertion were noticeably higher at elbow height as compared to midthigh height.

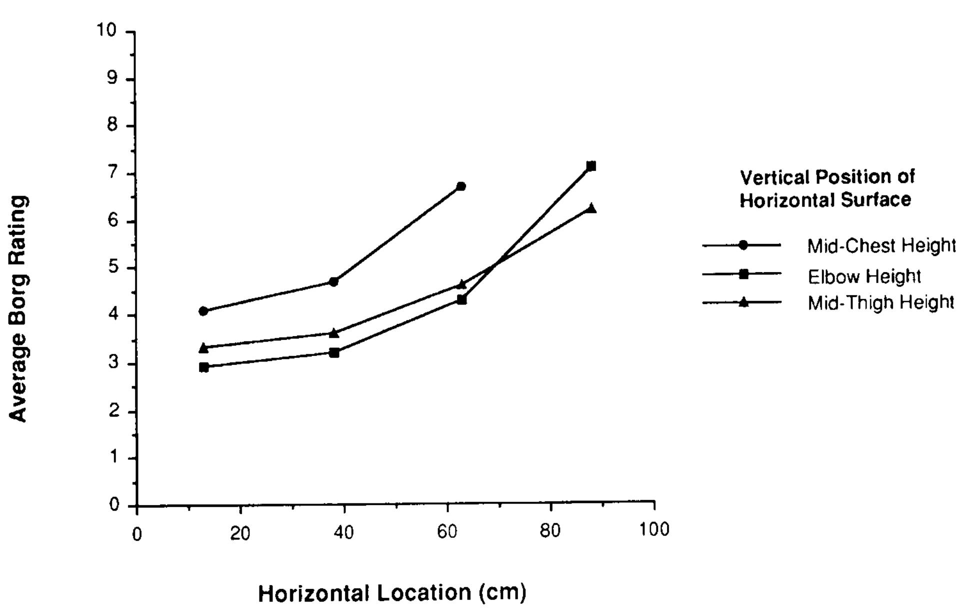

FIGURE 2. Interaction between the horizontal work location and the vertical position of the surface.

Anthropometry Effect

In a previous investigation, ratings of perceived exertion for the shortest subjects (stature ranged from 155–163 cm) were at least one-and-a-half times larger than the ratings that were reported by the tallest subjects (stature ranged from 181–189 cm) for driving screws at 191 cm on a vertical surface and at 88 cm on a horizontal surface positioned at elbow height.[6,7] In this present experiment, the horizontal beam was positioned vertically at body landmarks to minimize the effect of anthropometry on subject's rating of perceived exertion for the various work combinations. An analysis of variance for each work location/tool combination according to stature revealed that anthropometry was not a significant factor in determining the ratings of perceived exertion for each of the work combinations that were studied ($p > 0.05$). However, the ratings for the tallest subjects were always less than for the shortest subjects at the furthest horizontal location, when arm length was most important. Consequently, adjustable workstations can provide accommodation for workers who vary in stature, but there were still tasks that were perceived as easier for the taller subjects. The subjects were placed into groups according to stature, similar to the groups used in previous studies.[6,7] Subjects were categorized in the following manner: Group 1, 157–165 cm; Group 2, 166–171 cm; Group 3, 172–180 cm; and Group 4, 181–192 cm.

Gender Effect

Gender differences are often explored by researchers. In the past, stature was found to be a significant variable in determining the rating of perceived exertion for various screw-driving tasks.[6,7] In the present study, a t-test was used to compare the ratings for the various work combinations from the males and the females. Tables III and IV report the significant gender differences. Although there are gender differences at selected work locations, although there is no consistent trend. For all conditions studied, the ratings from the females were greater than the ratings from the males. This may be due to females possessing less upper-body strength than males. However, upper-body strength was not measured in this study. It is important to note that the same tool would be selected for all work combinations by both males and females based on the ratings of perceived exertion. For example, for both males and females, the pistol tool received lower ratings of perceived exertions for driving screws with the horizontal beam positioned at midthigh height.

TABLE III. Average Borg Ratings for all Tools Combined Given While Driving Screws at the Four Horizontal Work Locations (n = 30)

Distance/Location		All Vertical Positions	Vertical Position of the Horizontal Surface: Midchest Height 130.2±8.2 cm 114–146 cm	Elbow Height 108.9±6.1 cm 95–123 cm	Midthigh Height 75.7±3.8 cm 67–85 cm
1 (13 cm)	Pooled	3.4 ± 1.9	4.1 ± 1.9	2.9 ± 1.8	3.3 ± 1.8
	Male	3.1 ± 1.8*	3.9 ± 1.7	2.4 ± 1.6*	2.9 ± 1.8*
	Female	3.8 ± 1.9*	4.3 ± 2.1	3.4 ± 1.8*	3.6 ± 1.8*
2 (38 cm)	Pooled	3.8 ± 1.9	4.7 ± 1.9	3.2 ± 1.8	3.6 ± 1.8
	Male	3.5 ± 1.9*	4.6 ± 1.9	2.5 ± 1.6*	3.3 ± 1.7*
	Female	4.2 ± 1.9*	4.8 ± 2.0	3.9 ± 1.8*	3.9 ± 1.8*
3 (63 cm)	Pooled	5.2 ± 2.2	6.7 ± 2.0	4.3 ± 1.7	4.6 ± 2.1
	Male	4.7 ± 2.1*	6.3 ± 1.9*	3.7 ± 1.4*	4.1 ± 1.9*
	Female	5.7 ± 2.2*	7.1 ± 2.0*	5.1 ± 1.7*	5.0 ± 2.2*
4 (88 cm)	Pooled	6.6 ± 2.1		7.1 ± 1.9	6.2 ± 2.1
	Male	5.9 ± 1.8*		6.1 ± 1.4*	5.8 ± 2.1
	Female	7.3 ± 2.1*		8.1 ± 1.9*	6.5 ± 2.1

*Implies a significant difference ($p < 0.05$) between the ratings from the males and the females

Horizontal Work Location

For all three vertical positions of the horizontal beam, the ratings of perceived exertion increased with each incremental increase in horizontal work location (see Table I). The ratings increased 63–145% from the 13 cm work location to the 88 cm work location for each vertical position of the horizontal surface. Table III contains the ratings of perceived exertion for the four horizontal work locations with all of the vertical positions of the beam combined and for each of the vertical positions of the surface, individually. Pair-wise comparisons (Scheffé F-Test, $p > 0.05$) revealed that the ratings at 13 cm and 38 cm were not significantly different from each other, that the ratings at 63 cm were significantly larger (Scheffé F-Test, $p < 0.05$) than the ratings at the closest two locations, and that the ratings at 88 cm were significantly larger than the ratings from the other horizontal locations. Subjects perceived the same level of exertion between 13–38 cm (ratings increased 9–14%), but the perceived exertion significantly increased at each new work location when driving screws beyond 38 cm (see Table I and Table III). The ratings increased 28–43% between the 38 cm and the 63 cm work locations and the ratings increased 35–61% between the 63 cm and the 88 cm horizontal work locations (see Table III).

Ulin, Snook, Armstrong, and Herrin[6] reported the same significant subgroups of work locations for driving screws on a horizontal surface placed at elbow height. Also, another study showed[5] that, regardless of work pace, the ratings of perceived exertion were greater (21%) when subjects drove screws with their arms fully extended on a horizontal beam as opposed to driving screws with the lower arm perpendicular to the torso. In the present study, regardless of the vertical position of the horizontal surface, as the distance between the body and the horizontal work location increased, the rating of perceived exertion increased. Driving screws close to the body creates moments at the elbow, shoulder, and hip that are relatively low. To drive screws at 63 cm and 88 cm, the arms must be extended and the torso flexed. These postures create larger resultant moments at the elbow, shoulder, and hip and could lead to localized fatigue.[23] Consequently, it appears that psychophysical data are consistent with predictions based on biomechanics data; as the work location moves farther away from the body, greater moments are created at body joints and the ratings of perceived exertion increase.

Vertical Position of the Horizontal Surface

Table IV displays the ratings of perceived exertion at the three vertical positions of the horizontal beam for all tools combined and for each of the tools individually. The ratings of perceived exertion are virtually equal for driving screws at elbow and midthigh height when tool shape is not considered. However, the ratings at midchest height are significantly higher (Scheffé F-test, $p < 0.05$) than the ratings at midthigh or elbow height where, regardless of the tool/work location combination, perceived exertion was decreased by 16–31%. Working above midchest height has been associated with fatigue and shoulder disorders.[23–27] Driving screws at midchest height creates a larger moment at the shoulder than driving screws at elbow or midthigh height and partially explains the increased ratings of perceived exertion at this elevation.

TABLE IV. Average Borg Ratings For all Horizontal Locations Combined While Driving Screws with Three Tools at the Three Vertical Positions of the Horizontal Surface (n = 30)

Vertical Position of the Beam		*All Tool Shapes*	*Tool Shape* *Pistol Ratings*	*In-Line Ratings*	*Right-Angle Ratings*
Midchest Height	Pooled	5.2 ± 2.2	5.9 ± 2.0	4.5 ± 2.3[a]	5.1 ± 2.2[a]
130.2 ± 8.2 cm	Male	4.9 ± 2.1*	5.7 ± 1.8	4.3 ± 2.2	4.7 ± 2.1
114–146 cm	Female	5.4 ± 2.3*	6.1 ± 2.1	4.6 ± 2.4	5.4 ± 2.3
Elbow Height	Pooled	4.4 ± 2.4	4.8 ± 2.4	4.1 ± 2.5[a]	4.2 ± 2.4[a]
108.9 ± 6.1 cm	Male	3.7 ± 2.1*	4.1 ± 2.2*	3.3 ± 1.9*	3.6 ± 2.1*
95–123 cm	Female	5.1 ± 2.6*	5.5 ± 2.5*	4.9 ± 2.6*	4.9 ± 2.5*
Midthigh Height	Pooled	4.4 ± 2.2	3.8 ± 2.2[a]	4.7 ± 2.0	4.7 ± 2.4
75.7 ± 3.8 cm	Male	4.0 ± 2.2*	3.1 ± 2.0*	4.7 ± 2.0	4.4 ± 2.2
67–85 cm	Female	4.7 ± 2.3*	4.5 ± 2.2*	4.7 ± 2.0	5.0 ± 2.5

*Implies a significant difference ($p < 0.05$) between the ratings from the males and the females

[a]Implies a significant difference ($p < 0.05$) between the ratings for that tool shape and other tool shapes that are not similarly marked

Tool Shape

Tool shape alone does not account for much of the variance in the ratings of perceived exertion (see Table II). When separated based only on the type of tool used (see Table IV), the ratings from the three tool groups are indistinguishable (Scheffé F-Test, $p > 0.05$). No specific tool shape received a significantly lower rating and, consequently, it is reasonable to assert that a single tool shape was not appropriate for all of the various work combinations studied in this experiment. Considering the wide range of horizontal work location/vertical position combinations, this result is not surprising. Researchers have found that tools must be chosen and modified based on each specific workstation.[28,29]

It should be noted that because of the tool shape, different reaction forces were transmitted to the subjects' hands. The large distance between the hand and the bit of the right-angle tool also may have reduced the reaction at the hands and the force required to oppose the tool. Likewise, the short distance between the hand and the bit of the in-line tool may have increased the reaction force felt by the subject.

Vertical Position and Tool-Shape Interaction

When tool shape was examined in combination with the vertical position at which the horizontal beam was positioned, a significant interaction was present (see Table II). At midthigh height, the ratings of perceived exertion from the pistol tool (see Table IV) were significantly lower (24%) than the ratings from the other two tools (Scheffé F-Test, $p < 0.5$). However at this low height, the ratings from the in-line and the right-angle tools were indistinguishable (Scheffé F-Test, $p > 0.05$).

When the horizontal beam was placed at the subject's elbow height, the in-line and the right-angle tools received the lowest ratings (14–17% lower than the pistol ratings) and these ratings were not significantly different (Scheffé F-Test, $p > 0.05$). However, the ratings from the pistol-shaped tool were significantly higher than the ratings from the other two types (Fisher PLSD, $p < 0.05$).

With the beam positioned at midchest height, the ratings from both the in-line and the right-angle tools were significantly lower (16–31%) (see Table IV) than the ratings from the pistol shaped tool (Scheffé F-Test, $p < 0.05$); these ratings also were indistinguishable (Scheffé F-Test, $p > 0.05$).

Considering only the vertical position of a horizontal work surface, the lowest ratings of perceived exertion at midthigh height came after using the pistol tool, and the ratings from the in-line and the right-angle tools were indistinguishable and lower than the pistol ratings when driving screws at elbow height and above.

In a similar previous study,[6] as in this study, tool shape was a significant factor in an analysis of variance for each of the vertical positions of the horizontal surface, individually ($0.0001 < p < 0.07$). Overall, the ratings of perceived exertion in the previous study[6] were lowest (0–70% lower than ratings from the pistol tool) for the in-line and right-angle tools when the beam was positioned at elbow height. The ratings of perceived exertion for the in-line and right-angle tools ranged from 2.3 ± 1.2 to 7.3 ± 2.3.

Different postures were required for driving screws at the specified horizontal work locations when the beam was placed at the three vertical positions. Even though specific work postures for each work combination were not coded, general postures that were used to perform the specified tasks were observed. Driving screws at the two closest horizontal locations (13 cm and 38 cm) provided the clearest picture of the different postures subjects assumed to drive screws at the three vertical positions, and these positions will be used in the following postural analysis (see Figures 1a-c).

At midthigh height, the pistol tool received the lowest ratings of perceived exertion, and subjects could drive screws using this tool with little or no wrist deviation, wrist flexion or extension, shoulder flexion or abduction, or elbow flexion or abduction. The distance from the third metacarpal to the pistol tool bit (25 cm) gave subjects an extra vertical distance between their hand and the work surface. Consequently, while driving screws with the pistol tool at midthigh height, less torso flexion was necessary. Driving screws with the in-line and right-angle tools at midthigh height caused some wrist deviation, but generally kept the wrist, elbow, and shoulder in relatively neutral postures compared to driving screws with the pistol tool; however, more forward bending was required. This extra torso flexion may be the main contributor to the increased ratings of perceived exertion, since torso flexion has been associated with low back pain and/or injuries[30,31] and creates large moments and forces at the L5/S1 disc.[32]

When the horizontal surface was placed at elbow height, the right-angle and the in-line tools had the lowest ratings of perceived exertion. Driving screws with the in-line and right-angle tools at this vertical position caused little or no wrist deviation, wrist flexion or extension, shoulder flexion or abduction, or elbow flexion. Wrist deviation and shoulder abduction are the postures subjects were forced to use while driving screws with the pistol tool, and consequently, the ratings were higher after using the pistol tool at elbow height. Both wrist deviation and shoulder abduction have been linked to the occurrence of upper-extremity cumulative trauma disorders.[29,33,34]

Driving screws at midchest height required the same basic postures as driving screws at elbow height, but the arms were raised higher. Working with elevated arms also has been linked to the occurrence of upper-extremity cumulative trauma disorders.[35–39] Consequently, the ratings of perceived exertion are higher at midchest height than elbow height, and the relative preference between the tools follows the same pattern: the pistol tool received higher ratings of perceived exertion than the in-line or right-angle tools.

Vertical Position and Horizontal Work Location Interaction

There was no significant difference between the ratings at midthigh and elbow height for each of the first three work locations (13–63 cm) (Scheffé F-Test, $p > 0.05$). However, the ratings at midchest height were significantly higher (41–52%) than the ratings at midthigh and elbow height for each of the first three horizontal work locations (Scheffé F-Test, $p < 0.05$).

The greatest effect for the interaction between the vertical position and the horizontal work location was at the furthest work location (see Figure 2). At 88 cm, there was a significant difference (Scheffé F-Test, $p < 0.05$) between the ratings of perceived exertion at midthigh and elbow height; the ratings at midthigh height (6.2 ± 2.1) were lower than the ratings at elbow height (7.1 ± 1.9). To drive screws at 88 cm with the beam placed at elbow height, subjects' arms were fully extended and they had to stretch to drive the screws. Positioning the beam at midthigh height allowed the subjects to alleviate some of the stress on the arms by bending forward slightly. The rating of perceived exertion[17,18,40] allows subjects to integrate signals from all parts of the body into one single response. For driving screws at 88 cm, it appears that mild torso flexion offsets severe shoulder flexion/abduction and, consequently, the ratings of perceived exertion are lower at midthigh height than at elbow height. Gallagher and Unger[41] studied manual lifting in restricted postures (stooped and kneeling) and concluded that when a larger mass of skeletal muscles are used, an individual can lift a heavier load. In particular, they found that lifting capacity was greater in the stooped posture and the metabolic costs were greater for the kneeling posture. Lifting in the kneeling posture required subjects to primarily use their arms, while in the stooped posture, subjects could utilize the muscles in both their back and their upper body.

RECOMMENDATIONS

Based on this study and previous research, general design guidelines for workstations that include the use of hand tools can be postulated to reduce the occurrence of overexertion injuries, fatigue, and localized discomfort. Previous research has shown that the risk of back injuries increases as psychophysical guidelines are exceeded,[1–4] that subjective ratings of body discomfort are consistent with objective fatigue data for various hammering tasks,[42] and that workstations can be improved based on body-part discomfort data.[43,44]

This study demonstrated that one tool shape was not appropriate for all positions on a horizontal work surface. An analysis of variance revealed that the ratings of perceived exertion were due primarily to horizontal work location, vertical position of the horizontal surface, the interaction between horizontal work location and vertical position of the horizontal surface, and the interaction between the vertical position of the horizontal surface and tool shape. Specific workstation design guidelines are listed below and can be used as directing principles when setting up a work area.

1. Repetitive horizontal work, such as a screw-driving task, should be placed within 38 cm of the operator. As the work location moved to 63 cm and 88 cm, the ratings increased significantly (Scheffé F-test, $p < 0.05$).
2. Based on this study, horizontal work should be placed at elbow height or below. For all work locations and tool shapes combined, the ratings of perceived exertion for driving screws at midchest height were significantly higher (41–52%) (Scheffé F-test, $p < 0.05$) than the ratings at elbow and midthigh height. Even though working at midthigh height may cause forward bending, overall this requires less effort than working with the arms at midchest height.
3. For horizontal work at elbow height or above, in-line or right-angle tools should be used. When the beam was positioned at elbow or midchest height, the ratings for these tools were 14 to 31% lower than the pistol-tool ratings, and there was no detectable difference between the ratings from the in-line or right-angle tools (Scheffé F-test, $p > 0.05$).
4. For horizontal work at midthigh height, the pistol tool should be used. For driving screws at midthigh height, the ratings of perceived exertion from the pistol tool were 24% lower than the ratings from the other tools.
5. Working at 88 cm in front of the body should be avoided, but if it is necessary to do so, the horizontal surface should be positioned at midthigh height and the pistol tool should be used. The ratings suggest

that positioning the beam at midthigh height allows subjects to alleviate some of the stress on their arms by bending forward slightly.

These guidelines should by applied with an understanding of the experimental methods. For example, a short test period, relatively low torque tools (3.2 Nm), and only one screw size, metal thickness, and hole size were used in this study. Experimental results may change as various work parameters are altered. The goal of this research was to develop workstation design guidelines that minimize the risk of work-related disorders such as upper-extremity cumulative trauma disorders or low-back injury from developing in industrial workers. Further research is needed to determine if workstations designed using the principles from this and related studies actually reduce the incidence of work-related disorders.

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