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Preferred Tool Shapes for Various Horizontal and Vertical Work Locations

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Thirty-six subjects rated seven vertical and four horizontal positions after driving 25 screws at each of these work locations. The four horizontal work locations ranged from 13 to 88 cm and the seven vertical work locations ranged from 38 to 191 cm. Pneumatic tools (torque set to 3.2 Nm) with three varying shapes (pistol, in-line, and right-angle) were used to drive the screws into perforated sheet metal. Before rating each work combination with the Borg ten-point ratio rating scale, subjects were asked to imagine that they were an assembly line worker who was required to drive screws at that work location and with that particular tool for 8 hours. The work location/tool combination that received the lowest ratings of perceived exertion for the vertical surface were given after using the pistol tool to drive screws between 114 and 140 cm. Using the right-angle or the in-line tool to drive screws at distances between 13 and 38 cm received the lowest ratings of perceived exertion on the horizontal surface. The results compare favorably with predictions from biomechanics and anthropometric data. **Ulin, S.S.; Snook, S.H.; Armstrong, T.J.; Herrin, G.D.: Preferred Tool Shapes for Various Horizontal and Vertical Work Locations. Appl. Occup. Environ. Hyg. 7(5): 327–337; 1992.**

Introduction

Specialized hand tools have been developed to help workers perform a wide variety of tasks. Powered screwdrivers allow auto workers to assemble components to an automobile, pliers are used by electronics assemblers to easily position wires, and knives are manipulated by meat processors to perform the necessary cutting operations. When the hand tool decreases the effort a worker must exert to perform a task, that operation can be completed in a shorter amount of time and with greater precision. Consequently, hand tools significantly affect productivity and product quality. At the same time, the use of hand tools may result in excessive levels of ergonomic stress on the user.(1–3) This may contribute to chronic muscle, tendon, and nerve disorders,(4–10) thereby decreasing the quantity and quality of the worker's output. Unfortunately, dose–response studies are not available that can be used to develop health standards for all aspects of selection and use of hand tools. An alternative is the use of psychophysical methods to assess workers' perceived stress while performing specific operations.

Psychophysical methods have been used extensively to analyze and improve manual operations. In particular, psychophysical methods have been used to estimate the lifting capacity of the working population.(11–20) This approach has also been used to determine the patient's perceived exertion during exercise stress tests,(21) to establish appropriate levels of arm elevation,(22) to understand postural discomfort,(6,23,24) to modify exercise intensity to the correct level,(25) to estimate physical endurance,(26) and to determine preferred vertical work locations.(27)

The objectives of the present study are to examine the effect of work orientation, work location, and tool shape on subject ratings of perceived exertion using the Borg ten-point ratio rating scale.(25) The results will also be compared with predictions based on biomechanics and anthropometric data.

Materials and Methods

Subjects drove screws into perforated sheet metal at seven vertical and four horizontal work locations using three different pneumatic tools. Borg's ten-point, ratio rating scale was used by the subjects to assess perceived exertion for each work location/tool combination. Perceived exertion was then analyzed as a function of work location, tool shape, and stature.

Thirty-six (18 males and 18 females) university students were recruited through advertisement in a university publication. The number of subjects needed was based on a power calculation using statistics from a pilot study.(27) All of the subjects never or rarely used hand tools, so they were not biased by past experience. An initial training session was conducted in which the subjects learned how to use the tools and became familiar with the experimental protocol. The other two sessions were used for data collection of the subjects' ratings of each tool/work location combination on either the horizontal or the vertical orientation. Subjects were required to drive 25 screws at each work location before determining a rating for that tool/

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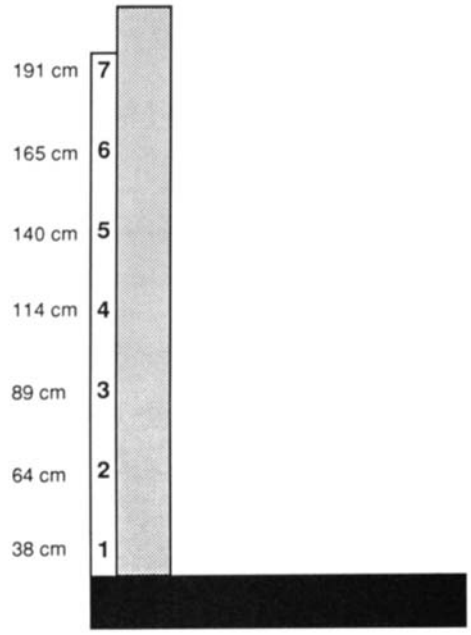

FIGURE 1a. Vertical beam with seven work locations.

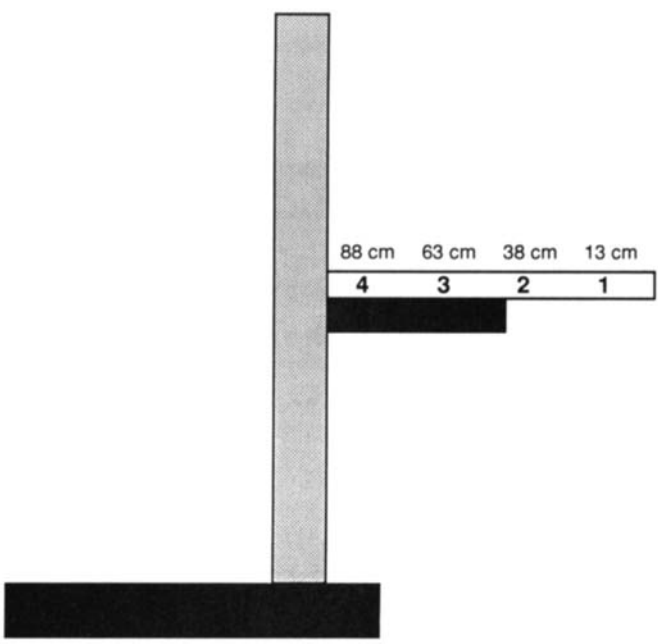

FIGURE 1b. Horizontal beam with four work locations.

work location combination. A computer beep, which sounded every 7 seconds, was the signal for subjects to begin driving the next screw. All three tools were used by the subjects at all of the horizontal and vertical work locations. The presentation of the work orientations, work locations, and the tools were all randomized.

The independent variables for this experiment included work orientation, work location, and tool shape. The work orientations included both a horizontal and a vertical work surface (Figure 1), with the perforated sheet metal mounted on to each surface. The seven vertical work locations ranged from 38 to 191 cm with each zone at approximately 25 cm intervals (Figure 1a). For the horizontal orientation, the four work locations ranged from 13 to 88 cm at 25 cm intervals, and the beam was placed just below the subject's elbow height (Figure 1b). Subjects used a pistol, an in-line, and a right-angle pneumatic screwdriver at each horizontal and vertical work location (Figure 2). The torque was set to 3.2 Nm and number six, slotted, hex-head screws were used. An Atlas Copco pistol-shaped tool (Model no. A 780002, mass = 1.1 kg) a Stanley right-angle tool (Model no. A 30LQATA-30F2, mass = 1.2 kg), and a Stanley in-line (Model

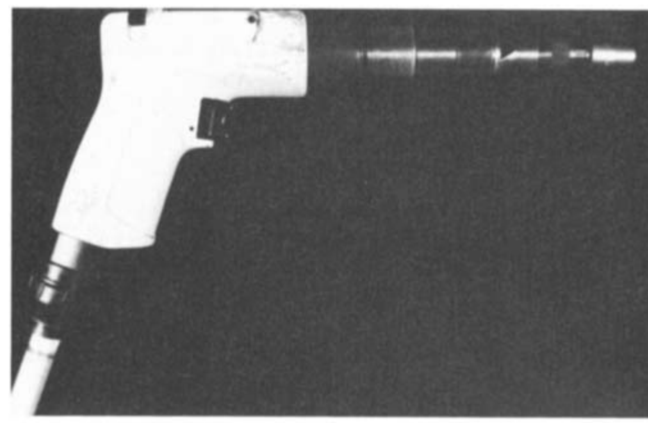

FIGURE 2a. Pistol tool.

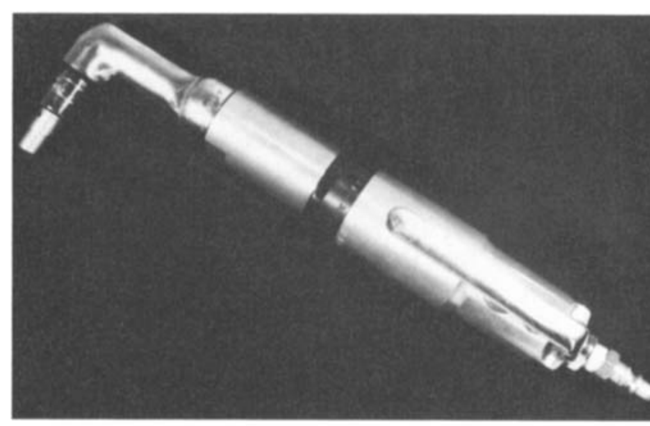

FIGURE 2b. Right-angle tool.

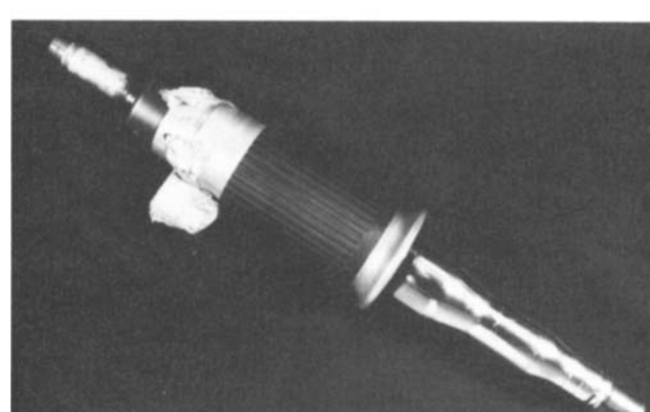

FIGURE 2c. In-Line Tool.

no. A 30NRT-18, mass = 1.1 kg) tool were used. Each screwdriver had a magnetic bit. These tools represent the basic shapes of pneumatic screwdrivers that are used in industry, and the effects of work location should generalize to other brands of tools of similar shape.

Two dependent variables were studied. The first dependent variable was the Borg rating of perceived exertion.(25) Subjects were asked to rate each tool/work location combination using Borg's ten-point ratio rating scale based on using that particular tool at the given work location for a normal 8-hour workday. The second dependent variable was the actual position on the horizontal or vertical beam at which subjects felt would be their most preferred location for driving screws for a normal 8-hour day. After driving screws at all of the horizontal or vertical work locations with a particular screwdriver, subjects were asked to demonstrate with the tool in hand, their preferred location for driving screws for a normal 8-hour workday.

Three independent variables, work orientation, work location, and tool shape, were manipulated as subjects drove screws at a fixed work pace. The impact of each of the independent variables, both individually and combined, on the dependent variables was explored. Also, the psychophysical ratings for various work locations were compared with predictions from anthropometric and biomechanics data.

One-, two-, and three-factor analyses of variance (ANOVA) and the comparable nonparametric tests (Kruskal-Wallis and Friedman),(28) in conjunction with multiple range tests,(29) were used to test the difference in the ratings from the various work location/tool combinations. ANOVA was also used to test the effect of stature on the ratings of perceived exertion, and a paired t-test(28) was selected to compare predicted work heights with the demonstrated preferred work heights. Statistical analyses were run with StatView™(30) and Systat™(31) computer software packages.

Results and Discussion

Tables I, IIa, and IIb list the ratings of perceived exertion for the three tools on both work surfaces and at the seven vertical and four horizontal work locations. On the horizontal surface, the right-angle tool ratings of perceived exertion were the lowest (3.7 ± 2.3), while on the vertical surface, the pistol tool had the lowest ratings of perceived exertion (4.8 ± 2.4) (Table I). When the ratings from both work orientations are examined more closely, the lowest ratings of perceived exertion on the vertical surface were at 114 cm (3.4 ± 1.7), whereas, the highest ratings were at 38 (7.0 ± 2.1) and 191 cm (6.8 ± 2.5), the lowest and highest work locations, respectively. At the lowest vertical work location, the ratings from the three tools are fairly similar (6.9–7.1); however, at 114 cm, the ratings given after using the pistol tool (2.4 ± 1.2) are considerably lower than the ratings from the other two tools (3.9 ± 1.7 and 1.8). Moving up to the highest work locations of 165 and 191 cm, the right-angle tool received the lowest ratings of perceived exertion (6.4 ± 2.3), but the pistol tool ratings (6.7 ± 2.6) were relatively close. The lowest ratings of perceived exertion on the horizontal surface were at the closest work locations of 13 and 38 cm (3.1 ± 1.7 and 1.8), and the ratings increased as the work location moved farther away from the subject. At the closest work location, the ratings from the right-angle tool were lower (2.3 ± 1.2), but the in-line tool's ratings were just slightly higher (2.9 ± 1.8). As the work locations moved farther away from the subject to 38, 63, and 88 cm, the ratings from the right-angle tool were considerably lower than the ratings from the other two tools.

TABLE I. Average Borg Ratings Given While Driving Screws with Three Tools on Different Surfaces (n = 36)

Orientation	Pistol Ratings	In-Line Ratings	Right-Angle Ratings
Horizontal	5.1 (± 2.5)	4.6 (± 2.6)	3.7(± 2.3)
Vertical	4.8 (± 2.4)	5.4 (± 2.5)	5.1 (± 2.3)

Note: 0 = Nothing at all and 10 = very, very hard on the Borg 10-point ratio rating scale.

TABLE IIa. Average Borg Ratings Given While Driving Screws with Three Tools at the Seven Vertical Locations (n = 36)

Level	Location	Pooled Ratings	Pistol Ratings	In-Line Ratings	Right-Angle Ratings
7	191 cm	6.8 (± 2.1)	6.7 (± 2.6)	7.3 (± 2.5)	6.4 (± 2.3)
6	165 cm	5.1 (± 2.2)	4.9 (± 1.9)	5.8 (± 2.4)	4.5 (± 2.0)
5	140 cm	3.8 (± 1.8)	3.2 (± 1.4)	4.4 (± 2.1)	3.7 (± 1.6)
4	114 cm	3.4 (± 1.7)	2.4 (± 1.2)	3.9 (± 1.8)	3.9 (± 1.7)
3	89 cm	4.1 (± 1.7)	4.0 (± 1.4)	4.0 (± 2.0)	4.3 (± 1.7)
2	64 cm	5.6 (± 2.1)	5.4 (± 2.1)	5.5 (± 2.0)	5.9 (± 2.2)
1	38 cm	7.0 (± 2.1)	6.9 (± 1.9)	6.8 (± 2.5)	7.1 (± 2.1)

Note: 0 = Nothing at all and 10 = very, very hard on the Borg 10-point ratio rating scale.

TABLE IIb. Average Borg Ratings Given While Driving Screws with Three Tools at the Four Horizontal Locations (n = 36)

Level	Location	Pooled Ratings	Pistol Ratings	In-Line Ratings	Right-Angle Ratings
1	13 cm	3.1 (± 1.8)	3.9 (± 1.9)	2.9 (± 1.8)	2.3 (± 1.2)
2	38 cm	3.1 (± 1.7)	3.8 (± 1.9)	3.3 (± 1.7)	2.3 (± 1.1)
3	63 cm	4.6 (± 1.9)	5.3 (± 2.0)	4.7 (± 1.9)	3.8 (± 1.6)
4	88 cm	7.0 (± 2.3)	7.3 (± 2.3)	7.3 (± 2.3)	6.3 (± 2.3)

Note: 0 = Nothing at all and 10 = very, very hard on the Borg 10-point ratio rating scale.

Work Orientation

Work orientation was found to be a significant factor in determining perceived exertion in the one-, two-, and three-factor ANOVAs (Table III) and the comparable nonparametric statistics (Kruskal-Wallis and Friedman) ($p = 0.0001$). Similar results were found by Schoenmarklin and Marras.(32) They found a significant orientation effect between hammering on a bench (horizontal surface) and a wall (vertical surface). The present experiment cannot discriminate between ratings of perceived exertion for the two orientations when using the pistol tool (difference in the ratings between the two work orientations is 0.27), but it can discriminate between the ratings for orientation when using the right-angle and in-line tools (difference in the

TABLE III. Analysis of Variance

	Significance
Independent Variables	
Orientation	0.0001
Work location	0.0001
Tool shape	0.0633
Orientation × Work location	0.0001
Orientation × Tool shape	0.0001
Work location × Tool shape	0.0995
Orientation × Work location × Tool shape	0.9579
Vertical Surface	
Work location	0.0001
Tool shape	0.0021
Work location × Tool shape	0.0338
Horizontal Surface	
Work location	0.0001
Tool shape	0.0001
Work location × Tool shape	0.7839
Dependent Variable	
Borg rating of perceived exertion	

ratings between the two work orientations is 1.43 for the right-angle tool and 0.84 for the in-line tool).

Work Location

Work location was a significant variable in the one-, two-, and three-factor ANOVAs (Table III) and the comparable nonparametric tests ($p = 0.0001$). For the vertical orientation, the highest ratings of perceived exertion occurred when subjects drove screws at the top (6.8 ± 2.5) and bottom (7.0 ± 2.1) of the beam (Table IIa). The work locations of 114 cm (3.4 ± 1.7) and 140 cm (3.8 ± 1.8) received the lowest ratings of perceived exertion for driving screws. Subjects rated the lowest location of 38 cm fairly high, regardless of what tool they were using (Table IIa). At the highest location of 191 cm, ratings were almost two to three times higher than the ratings at 114 cm and 140 cm. These results support an earlier study[27] which examined subject ratings that were given after driving screws at the same seven vertical locations with a pistol-shaped tool. In this previous experiment, the same work locations with the greatest and smallest ratings of perceived exertion were identified. Specifically, the minimum, average, Borg rating was 2.7 ± 1.4 at the 114-cm elevation, and the ratings increased to 7.9 ± 1.7 and 6.7 ± 2.5 at 38 and 191 cm, respectively. In yet another study, workers in an automotive trim line were asked to assess their own tools and workstations.[33] The preferred work height ranged from 102 to 153 cm.

For the horizontal orientation, as the work locations moved further away from the body, the ratings increased (Table IIb). The ratings at 88 cm are two to three times higher than the ratings for the 13- and 38-cm distances, depending on which tool was being used. These results agree with the data reported by Armstrong *et al.*[33] In that study, workers rated the use of hand tools within 38 cm in front of the body significantly more comfortable than work locations from 38 to 76 cm.

The work locations can be placed into subgroups whose mean ratings are not significantly different according to the Newman-Keuls multiple range test ($p = 0.05$).[29] Figure 3 graphically portrays the groupings of the vertical work locations for all three tools. The Newman–Keuls test was used to identify subgroups of work locations that were not significantly different than each other, based on the Borg rating at each work location. On the vertical surface, the ratings from the pistol tool led to the formation of four subgroups. The highest levels of perceived exertion were for the 38-cm and 191-cm elevations. The ratings given after driving screws at the 64-cm and 165-cm elevations were smaller than the ratings for working at the extremes, followed by the ratings at 89 cm and 140 cm. The lowest levels of perceived exertion occurred when working at the 114-cm and 140-cm elevation.

The ratings that were given after using the in-line tool on the vertical surface were combined into four groups. These were less distinct than the subgroups created based on the mean ratings while using the pistol tool. The 38-cm and 191-cm elevations caused the highest ratings of perceived exertion. The mean ratings at 38 and 165 cm were not significantly different, and likewise, the mean ratings at 64 and 165 cm were not significantly different. Driving screws at the 89, 114, and 140 cm created the lowest ratings of perceived exertion. Figure 3 portrays the subgroups that were created.

Three subgroups were formed based on the ratings given after using the right-angle tool (Figure 3). The highest ratings of perceived exertion were given after driving screws at 38 and 191 cm, followed by the mean ratings at 64 cm and 191 cm, and the mean ratings for each pair were not significantly different than each other. The lowest ratings were given after working at 89, 114, 140, and 165 cm. The right-angle tool has the widest range of preferred work locations, and this may be due to the large distance between the hand and the bit which allowed subjects to maneuver the tool and drive the screws easily. The large

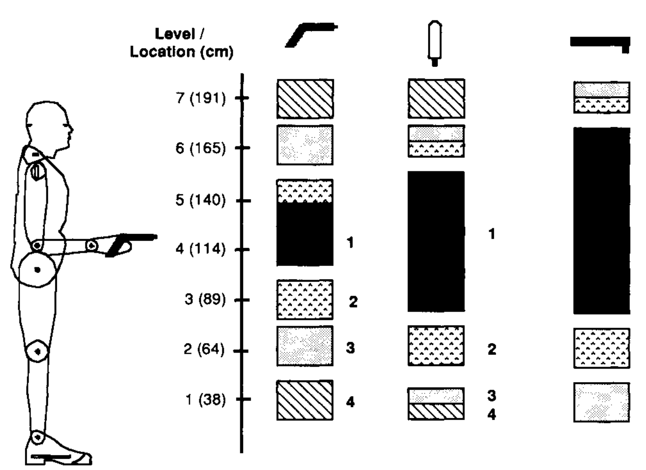

FIGURE 3. Subgroups of vertical work locations. *Note:* Subgroups created according to the Newman–Keuls multiple range test ($p = 0.05$) and ordered from lowest to highest mean Borg rating of perceived exertion. Similar shading defines the subgroups and indicates that the mean values at the work locations are indistinguishable (Newman–Keuls multiple range test, $p = 0.05$).

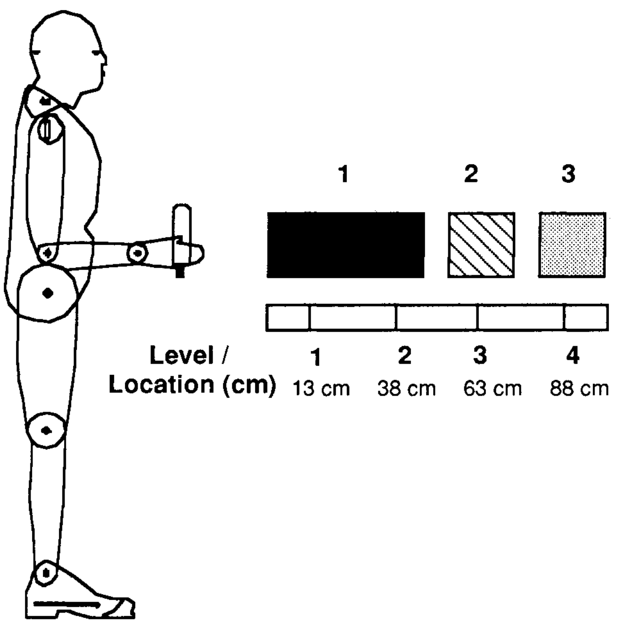

FIGURE 4. Subgroups of horizontal work locations. *Note:* Subgroups created according to the Newman–Keuls multiple range test ($p = 0.05$) and ordered from lowest to highest mean Borg rating of perceived exertion. Similar shading defines the subgroups and indicates that the mean values at the work locations are indistinguishable (Newman–Keuls multiple range test, $p = 0.05$).

distance between the hand and the bit may have also reduced the reaction at the hands and the force required to oppose the tool.

The three subgroups formed from the ratings given for driving screws on the horizontal beam were the same for all three tools according to the Newman–Keuls multiple range test ($p = 0.05$) (Figure 4).[29] Driving screws at 13 cm and 38 cm in front of the body received the lowest ratings of perceived exertion. Driving screws at 63 cm was considered harder, while the 88-cm location was rated the hardest place to drive screws on the horizontal beam.

Tool Shape

Varying the tool shape to reduce postural stresses has been discussed by others.[1–3,32] Tichauer[1] bent the handles on pliers so that workers could use a neutral wrist posture to complete their tasks. In a poultry processing plant, Armstrong *et al.*[3] introduced knives with blades mounted on to pistol-shaped handles so that wrist deviation would be minimized as workers cut in a vertical plane. Tool shape also affected subjects' ratings significantly in this experiment as demonstrated by the one-, two-, and three-factor ANOVAs (Table III) and the comparable nonparametric statistics. Post hoc analyses, the Scheffé F-test and the Newman–Keuls multiple range test, were used to test the mean ratings to see if it is possible to determine which tool shape was most preferred for the various work locations.

Because of the wide variety of vertical work locations, the Borg ratings of perceived exertion were examined to determine which tool received the lowest ratings at each work location. The mean Borg ratings for the three tools were not significantly different ($p > 0.05$) at the 38-, 64-, and 89-cm elevations (Table IIa). Driving screws at the lowest elevations forced the subjects to bend over. Consequently, their ratings were based on both the stress to the torso and to the upper extremities. Even though varying forearm postures are required to operate the three tools, there was not a distinguishable difference between the ratings from the three tools. Therefore, it is postulated that the discomfort associated with torso flexion was the main factor in determining the rating of perceived exertion at the three lowest vertical work locations. To drive screws at 114 cm and above, subjects could stand erect and the major work stress is associated with the forearm posture required to operate the tool. At 114 cm, the pistol-shaped tool received lower ratings of perceived exertion (2.4 ± 1.2) than both the in-line (3.9 ± 1.8) and the right-angle (3.9 ± 1.7) tools ($p < 0.05$). For driving screws at 140 and 165 cm, there was no significant difference ($p > 0.05$) between the mean Borg ratings for the pistol-shaped (3.2 ± 1.4 and 4.9 ± 1.9) and the right-angle tools (3.7 ± 1.6 and 4.5 ± 2.0), but these ratings were significantly lower ($p < 0.05$) than the ratings for the in-line tool (4.4 ± 2.1 and 5.8 ± 2.4). At 191 cm, there was not a significant difference ($p > 0.05$) among the ratings for the three tools. Although, the average ratings were slightly lower (the difference in the ratings between the tools range from 0.3 to 0.9) when subjects used the right-angle tool at the 165- and 191-cm elevations as compared with the ratings given when subjects used the pistol-shaped or the in-line tool (Table IIa).

Next, the ratings given after driving screws on the horizontal surface were examined. At 13 cm in front of the body, the ratings from the in-line (2.9 ± 1.8) and the right-angle (2.3 ± 1.2) tools were significantly lower than those from the pistol-shaped tool (3.9 ± 1.9, $p < 0.05$). For the next two work locations (38 and 63 cm), the lowest ratings of perceived exertion were from the right-angle tool ($p < 0.05$). At the 88-cm location, there was no significant difference between ratings among the tools (Table IIb).

As discussed earlier, after driving screws at the extreme points of the vertical (38, 64, 89, and 191 cm) and the horizontal (88 cm) beam, there was not a significant difference ($p = 0.05$) between the ratings from the three tools. At these work locations, subjects' ratings were primarily based on work location, not the type of tool that they were using. It is hypothesized that large physical demands on the whole body, not only the upper extremities, were required to drive screws at the extreme points. Consequently, the effort exerted by the hand and arm is only one part of the strain and is integrated into the ratings of perceived exertion along with signals from other body parts. Therefore, it was not possible to discriminate between the ratings from the varying tools at the extreme points of the vertical and horizontal surfaces.

Demonstrated Preferred Work Location

After driving screws at all of the horizontal or vertical work locations with one of the three tools, subjects were

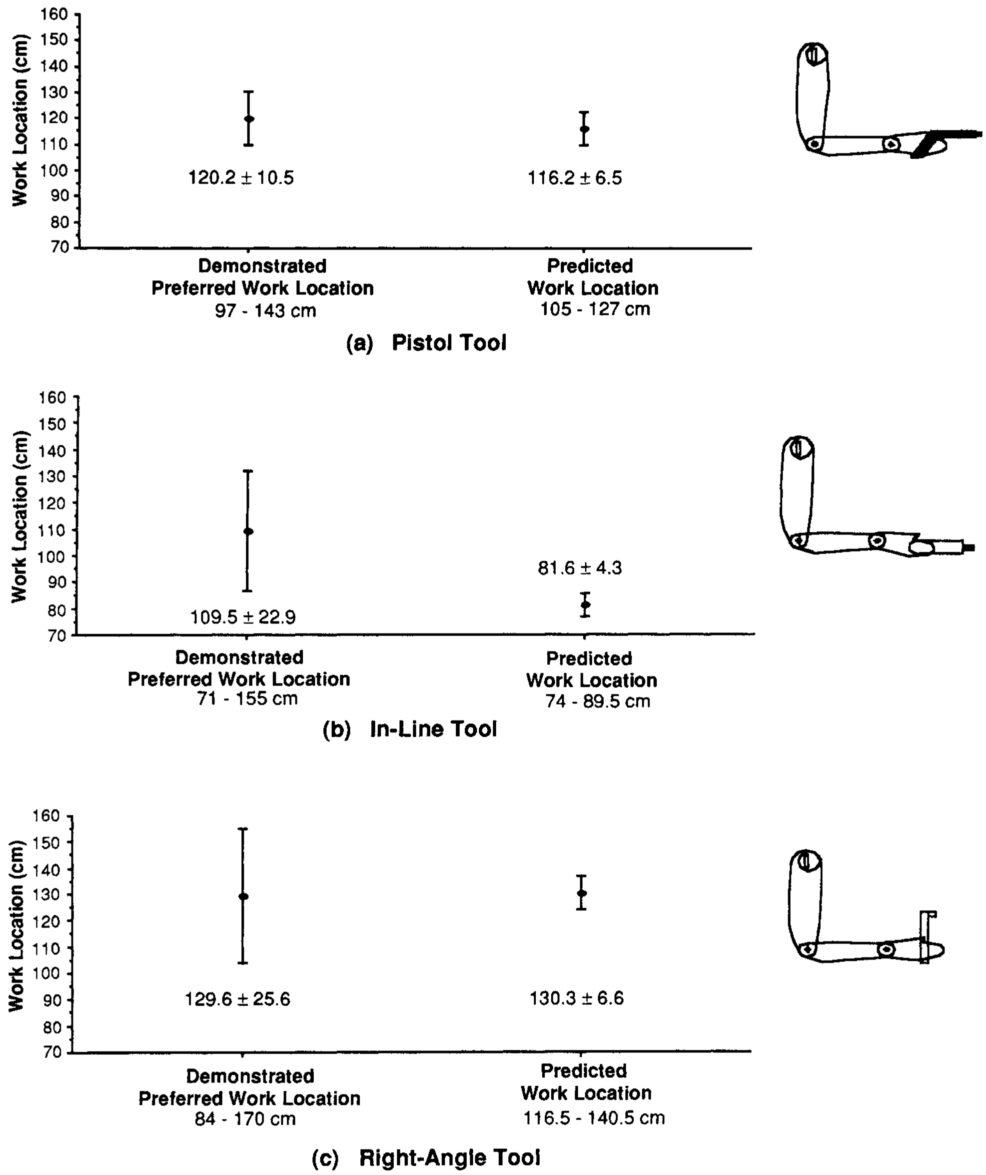

FIGURE 5. Preferred and predicted work heights for using three tools on a vertical work surface.

asked to demonstrate the position they would choose to drive screws with that particular tool for an 8-hour workday. They could choose any point on the beam, since they were not restricted to the defined work locations. If the method of adjustment was being used, subjects would be asked to drive screws at that location and then revise their decision as necessary. This approach has been used by Snook[14] to estimate acceptable loads to lift for given frequencies and locations.

After using the pistol tool on the vertical work orientation, the Borg ratings given by the subjects were lowest at 114 cm (2.4 ± 1.2) and 140 cm (3.2 ± 1.4); consequently, these locations were considered to be the most preferred vertical work locations. The demonstrated preferred work locations with the pistol tool ranged from 97 to 143 cm (120.2 ± 10.5 cm) (Figure 5a), and 88.9 percent of the subjects chose a position on the sheet metal that lies in the range of 114 to 140 cm. When subjects used the in-line tool on the vertical work surface, 89 cm (4.0 ± 2.0), 114 cm (3.9 ± 1.8), and 140 cm (4.4 ± 2.1) received the lowest ratings of perceived exertion. The demonstrated preferred work locations with the in-line tool ranged from 71 to 155 cm (109.5 ± 22.9 cm) (Figure 5b), and 72.2 percent of the subjects chose a preferred position that lies in the range of 89 to 140 cm. As presented earlier, the Borg ratings revealed that the in-line tool is not the preferred tool for use on the vertical work surface; therefore, subjects were forced to identify a work location for driving screws even though they would never choose that tool for the given work situation. The Borg ratings given after subjects used the right-angle tool were lowest at 89 cm (4.3 ± 1.7), 114 cm (3.9 ± 1.7), 140 cm (3.7 ± 1.6), and 165 cm (4.5 ± 2.0). The demonstrated preferred positions ranged from 84 to 170 cm (129.6 ± 25.6 cm) (Figure 5c), and 91.7 percent of the demonstrated positions were in the range of 89 to 165 cm.

A large percentage of the demonstrated work locations on the horizontal beam were between the areas of 13 and 38 cm, and these two work locations received the lowest ratings. For example, 83.3 percent of the demonstrated positions with the pistol tool (30 ± 10.6 cm), 86.1 percent with the in-line tool (24.4 ± 10.1 cm), and 91.7 percent with the right-angle tool (29.8 ± 9.7 cm) were within the range of 13 to 38 cm (Figure 6).

Predictions Based on Theoretical Arguments

Proposed work locations based on anthropometric data and theoretical arguments were compared to the Borg ratings and the demonstrated preferred work locations. Postural criterion for desirable work location/tool combinations that minimize physical stress according to current biomechanical and postural theories(2,7–9,34–36) are listed in Table IV. Subject anthropometric data were used to predict the proper work height when using the three tools on both the vertical and the horizontal surface.

TABLE IV. Postural Criterion

Torso
Minimize mild flexion/extension
Avoid severe flexion
Upper Arm/Shoulder
Avoid working above shoulder height
Minimize flexion/extension and abduction/adduction
Lower Arm/Elbow
Minimize forearm rotation
Attempt to keep elbow close to torso
Wrist/Hand
Minimize extension
Avoid radial/ulnar deviation, flexion, and hyperextension

Vertical Surface, Pistol Tool

To predict a subject's preferred work height while using

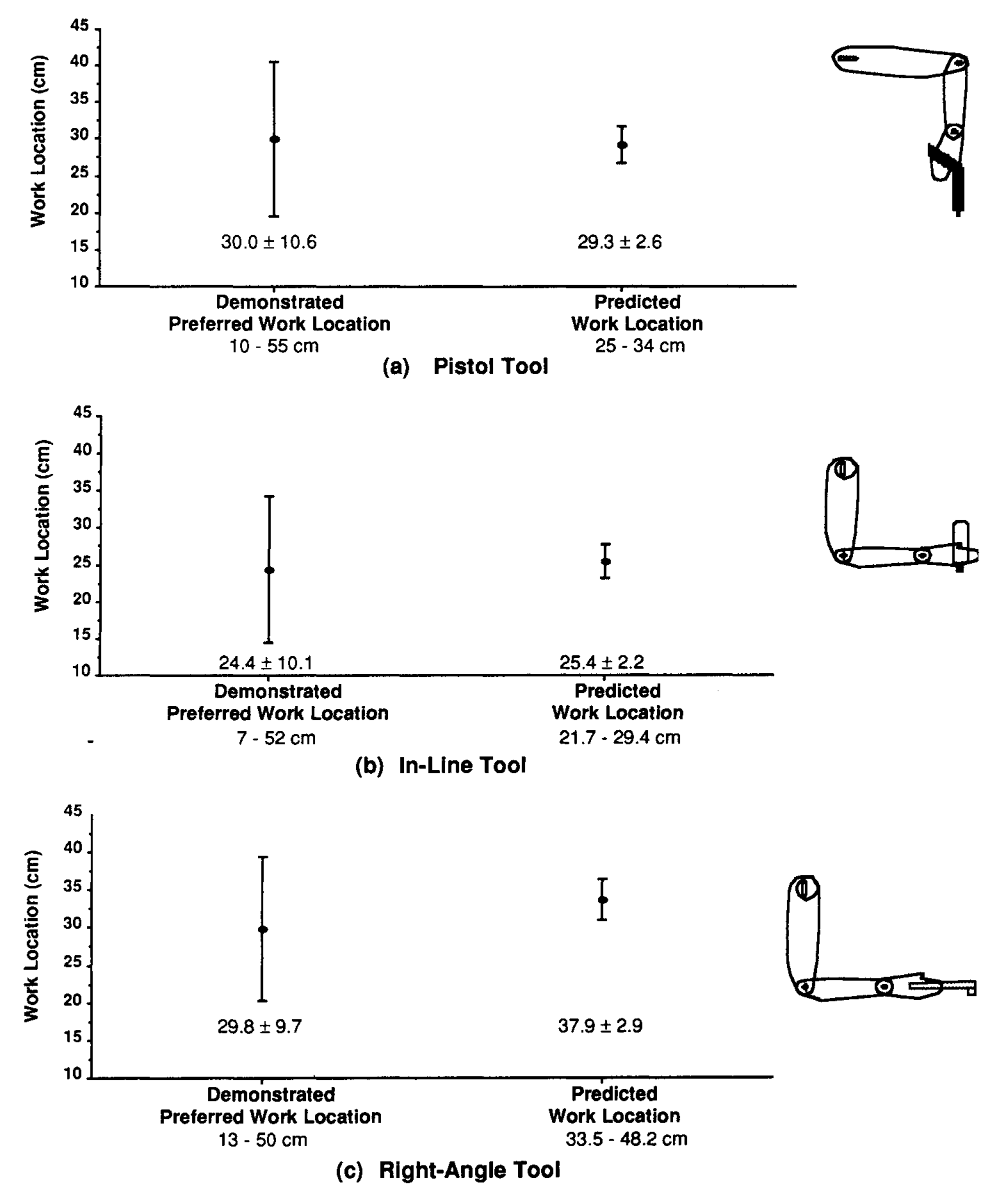

FIGURE 6. Preferred and predicted work heights for using three tools on a horizontal work surface.

the pistol tool, the vertical distance from the center of the grip to the bit was added to the subject's elbow height (these measurements were collected during the first experimental session).[27,34] Of the predicted work heights (105–127 cm; 116.2 ± 6.5 cm), 83.4 percent fell within 10 cm of the 114-cm elevation, the position that received the lowest Borg ratings, and is, consequently, the "ideal" location for driving screws on a vertical work surface with a pistol-shaped tool. The paired t-test revealed that, overall, the predicted work heights from the subjects' anthropometric data were significantly lower (4.0 cm) than the subjects' demonstrated preferred work locations (p = 0.02) (Figure 5a). The predicted work heights may be lower than the demonstrated preferred work locations because subjects may prefer slightly higher work locations to minimize neck flexion, or subjects prefer working closer to eye height,[37] or subjects may have adjusted their preferred location to match the predicted work height more closely if they had been asked to drive screws at their chosen location and were then allowed to modify their initial work location selection.

Vertical Surface, In-Line Tool

As shown in Table IIa, the ratings were higher for the in-line tool on the vertical beam than for the other two tools at 114 to 191 cm. The Borg ratings for 89 to 140 cm led to the formation of the subgroup with lowest ratings of perceived exertion for driving screws with the in-line tool on the vertical work surface. Based on the Borg ratings, the predicted position for driving screws with the in-line driver on the vertical beam is elbow height. Even though this work height causes ulnar wrist deviation, less neck flexion is required to see the work than when driving screws at positions lower than elbow height. When work heights for this position are predicted using the subjects' elbow height as the predicted work location, 83.3% (74–89.5 cm; 81.6 ± 4.3 cm) of the predictions are within 10 cm of the 114-cm work location, which agrees favorably with the Borg ratings (Table IIa). The paired t-test revealed that the predicted location for driving screws with the in-line tool was significantly lower (27.9 cm) than the demonstrated work location (p = 0.0001) (Figure 5b). Since the ratings for the in-line tool were higher than the other two tools for driving screws at 114 to 191 cm, subjects would probably not choose this tool to drive screws on the vertical surface, and this may explain the large difference in the two values. Also, subjects may prefer to drive screws closer to eye height at a position that is closer to the optimal point for foveal vision.[37]

Vertical Surface, Right-Angle Tool

The predicted preferred location for driving screws with the right-angle tool on a vertical surface was calculated by adding the subject's elbow height to the distance from the center of the subject's grip to the bit. In this position, wrist deviation is negligible and neck flexion is minimized since the work is positioned above elbow height. The predicted work locations ranged from 116.5 to 141.5 cm (130.3 ± 6.6 cm) (Figure 5c), which are within the range of Locations 4 (114 cm) and 5 (140 cm) on the vertical beam. As was discussed earlier, work Locations 4 and 5 are in the center of the range of preferred locations for using the right-angle tool on the vertical surface. There was not a significant difference between the predicted and demonstrated work locations (paired t-test, p = 0.6633).

Horizontal Surface, Pistol Tool

Predictions based on anthropometric and biomechanics data were also calculated for using the three tools on the horizontal surface. To use the pistol tool on the horizontal beam, the upper arm and elbow are elevated and the wrist is deviated. This tool/orientation combination is often used as an example of "poor" workstation design.[4] The Borg ratings from the subjects also agree with this recommendation. This pistol tool was the least preferred tool for working on the horizontal surface which was placed right below elbow height, and the calculated predictions for using the pistol tool are not significantly different than demonstrated preferred work locations (paried t-test, p = 0.5) (Figure 6a).

Horizontal Surface, In-Line Tool

The predictions for using the in-line tool on the horizontal surface are not significantly different than the demonstrated preferred work locations (paired t-test, p = 0.252). The predicted work locations (21.7–29.4 cm; 25.4 ± 2.2 cm) were based on the location of the center of the grip when the forearm is postioned 60 degrees from the torso and the upper arm lies next to the torso. All of the predicted work locations were less than 38 cm, which agrees with the Borg ratings that indicated the subjects preferred driving screws at 13 cm (2.9 ± 1.8) and 38 cm (3.3 ± 1.7) (Figure 6b).

Horizontal Surface, Right-Angle Tool

The predicted locations for using the right-angle tool on the horizontal surface were established by determining how the tool could be held to minimize wrist deviation. This is accomplished by moving the upper arm slightly out from the body and then placing the lower arm and hand at approximately 30 degrees from the torso. When preferred work location predictions are calculated based on this posture, 95.1 percent of the predictions (33.5–48.2 cm; 37.9 ± 2.8 cm) are within 5 cm of the 38-cm work location (Figure 6c). The predicted work locations are larger (8.1 cm) than the demonstrated preferred work locations (paired t-test, p = 0.0001). There was a very large range in the demonstrated work locations (13–50 cm). Some subjects preferred to drive screws with the tool very close to the body and others preferred to drive screws with the lower arm out farther. If subjects had been required to drive screws at their chosen location and then revise their decision, the results may have been clearer.

Effect of Anthropometry on Subject Ratings

Because in many cases the subject preferences were

TABLE V. Average Borg Ratings Given While Driving Screws on the Vertical Surface with Three Tools and the Subjects Categorized According to Stature (n = 36)

			Stature			
Tool	Level	Location	155–163 cm (n = 9)	164–172 cm (n = 9)	173–180 cm (n = 10)	181–189 cm (n = 8)
Pistol	7	191 cm	9.4 (± 1.0)	6.7 (± 2.0)	5.2 (± 1.7)	5.4 (± 2.9)
	4	114 cm	2.8 (± 1.5)	2.4 (± 1.0)	2.4 (± 1.4)	2.0 (± 0.5)
	1	38 cm	7.4 (± 1.9)	6.3 (± 2.6)	6.9 (± 1.2)	7.0 (± 1.9)
In-Line	7	191 cm	0.3 (± 0.9)	7.9 (± 2.3)	6.5 (± 2.2)	5.6 (± 2.9)
	4	114 cm	4.3 (± 2.5)	3.9 (± 1.5)	4.4 (± 1.9)	2.8 (± 0.7)
	1	38 cm	7.2 (± 2.2)	6.3 (± 3.1)	7.3 (± 2.2)	6.4 (± 2.5)
Right-Angle	7	191 cm	8.8 (± 1.2)	6.8 (± 1.9)	5.3 (± 1.8)	4.8 (± 2.1)
	4	114 cm	4.2 (± 1.6)	4.5 (± 2.2)	3.6 (± 1.9)	3.5 (± 1.2)
	1	38 cm	7.2 (± 2.3)	7.3 (± 2.2)	7.2 (± 2.0)	6.9 (± 2.2)

Note: 0 = Nothing at all and 10 = very, very hard on the Borg 10-point ratio rating scale.

similar to the anthropometric predictions, subjects were assigned to four groups based on stature to examine the quantitative effect of anthropometry on the Borg ratings. The stature descriptions of the four groups are contained in Tables V and VI along with the ratings for each of the groups. For the vertical surface, no significant difference was found ($p > 0.05$) among the ratings from the different stature groups at the 38-cm and 114-cm work locations for all three tools. At the highest work location (191 cm), the Borg ratings from the short subjects (stature range, 155–163 cm) were significantly higher ($p < 0.05$) than the ratings given by the taller subjects (173–189 cm) when using all three tools. The average Borg ratings given by the shortest subjects (stature range, 155–163 cm) for this location were almost twice (Table V) the ratings given by the tallest subjects (stature range, 181–189 cm). This agrees with the results reported by Ulin *et al.*[27] In this previous experiment, subject ratings of driving screws with a pistol tool at 38 and 114 cm when the subjects were categorized according to stature were not significantly different ($p > 0.05$). In contrast, the Borg ratings (8.3 ± 3.0) from the shortest subjects (stature range, 155–164 cm) at 191 cm were nearly twice as large as the Borg ratings (4.3 ± 1.2) from the tallest subjects (stature range, 182–199 cm).

Similar effects of anthropometry were also found for the horizontal orientation. No significant difference ($p > 0.05$) was found between the Borg ratings given by the four stature groups of subjects after driving screws at 13 and 38 cm. Significant differences ($p < 0.05$) were found between the Borg ratings at 88 cm. For all three tools, the Borg ratings given by the shortest subjects (stature range, 155–163 cm) were at least 1.5 times larger (Table VI) than the ratings given by the taller subjects (stature range, 173–189 cm). Analysis of variance demonstrated that stature, not gender, was the significant factor in determining the ratings of perceived exertion at the highest vertical and furthest horizontal locations.

Summary

Psychophysical methods have previously been used to develop workstation design guidelines for manual materials handling tasks.[11–20] This research methodology provides workstation design guidelines that are based on a healthy subject population performing a controlled task for a short amount of time. Previous research has shown

TABLE VI. Average Borg Ratings Given While Driving Screws at the Four Horizontal Locations with Three Tools and Subjects Categorized According to Stature (n = 36)

			Stature			
Tool	Level	Location	155–163 cm (n = 9)	164–172 cm (n = 9)	173–180 cm (n = 10)	181–189 cm (n = 8)
Pistol	1	13 cm	3.7 (± 2.3)	3.7 (± 2.1)	4.4 (± 1.8)	3.8 (± 1.9)
	2	38 cm	4.0 (± 2.2)	4.0 (± 2.0)	4.1 (± 1.9)	2.9 (± 1.5)
	3	63 cm	5.9 (± 2.4)	5.3 (± 1.7)	5.4 (± 1.9)	4.3 (± 2.1)
	4	88 cm	8.9 (± 1.8)	7.8 (± 2.3)	6.4 (± 2.0)	5.9 (± 2.1)
In-Line	1	13 cm	3.2 (± 2.1)	2.6 (± 1.5)	3.2 (± 1.6)	2.6 (± 2.0)
	2	38 cm	4.2 (± 1.7)	3.3 (± 1.8)	3.2 (± 1.8)	2.4 (± 0.9)
	3	63 cm	5.1 (± 1.6)	5.4 (± 2.4)	4.7 (± 2.0)	3.6 (± 0.7)
	4	88 cm	8.7 (± 2.1)	8.1 (± 2.3)	6.6 (± 1.9)	5.9 (± 2.3)
Right-Angle	1	13 cm	2.5 (± 1.2)	2.4 (± 0.5)	2.6 (± 1.6)	1.8 (± 1.1)
	2	38 cm	2.8 (± 1.3)	2.3 (± 0.9)	2.5 (± 1.1)	1.7 (± 1.1)
	3	63 cm	4.3 (± 1.0)	4.4 (± 2.3)	3.6 (± 1.3)	3.0 (± 1.1)
	4	88 cm	8.2 (± 2.0)	6.6 (± 1.6)	5.4 (± 1.6)	5.0 (± 1.9)

Note: 0 = Nothing at all and 10 = very, very hard on the Borg 10-point ratio rating scale.

that the risk of back injuries increases as psychophysical guidelines are exceeded,[14,38–40] that subjective ratings of body discomfort are consistent with objective fatigue data for various hammering tasks,[32] and that workstations can be improved based on body-part discomfort data.[23,24] Consequently, it is hypothesized that the workstation design guidelines suggested by this research will also reduce the risk of work-related disorders, fatigue, and localized discomfort.

Several workstation design guidelines that apply to the types of tools studied can be formulated based on this research.

1. Driving screws at 114 cm was the preferred vertical work location for all tools and for people of all stature because the ratings of perceived exertion at 114 cm were lower (the Borg ratings ranged from 2.4 ± 1.2 to 4.4 ± 2.1) than all other work locations, and approximately one-half of the ratings at 38 cm and 191 cm (the Borg ratings ranged from 6.4 ± 2.3 to 7.3 ± 2.5).
2. For driving screws at 114 cm on the vertical surface, the pistol-shaped screwdriver is the most preferred tool because it requires less perceived exertion (2.4 ± 1.2) than the other two tools.
3. The right-angle tool had the largest range of preferred vertical work locations (based on the subgroups that were created according to the Newman–Keuls multiple range test) and included work locations spanning from 89 to 165 cm.
4. For driving screws at 191 cm, the right-angle tool received slightly lower ratings of perceived exertion (6.4 ± 2.3) than the other two tools (7.3 ± 2.5 and 6.7 ± 2.6).
5. The preferred work locations for driving screws on the horizontal work surface for people of varying stature and for using all three tools are at 13 cm and 38 cm (the Borg ratings ranged from 2.3 ± 1.2 to 3.9 ± 1.9) because the ratings of perceived exertion were lower and at least one-half of the ratings at 88 cm (the Borg ratings ranged from 6.3 ± 2.3 to 7.3 ± 2.3).
6. The pistol-shaped tool (the Borg ratings ranged from 3.9 ± 1.9 to 7.3 ± 2.3) was the least preferred tool for driving screws at all horizontal work locations when the work surface is placed at elbow height (the Borg ratings for the in-line and right-angle tools ranged from 2.3 ± 1.2 to 7.3 ± 2.3).
7. For driving screws close to the body at the 13-cm horizontal work location, the preferred tools were the in-line and the right-angle tools (the Borg ratings ranged from 2.3 ± 1.3 to 2.9 ± 1.8), since they had the lowest ratings of perceived exertion and the ratings for those two tools were not significantly different.
8. For driving screws beyond 13 cm in front of the body (38, 63, and 88 cm) on a horizontal work surface placed at elbow height, the right-angle tool (the Borg ratings ranged from 2.3 ± 1.1 to 6.3 ± 2.3) is the most preferred tool according to the ratings of perceived exertion (the Borg ratings for the pistol and in-line tools ranged from 3.3 ± 1.7 to 7.3 ± 2.3).
9. At the highest vertical work location of 191 cm, the Borg ratings from the short subjects (stature range, 155–163 cm) were almost twice the ratings given by the tallest subjects (stature range, 181–189 cm). For driving screws at 88 cm on the horizontal surface, the Borg ratings from the short subjects were at least 1.5 times larger than the ratings given by the tallest subjects.

Conclusions

Postural considerations of manual work were studied using a psychophysical methodology in order to identify preferred work combinations. This research focussed on three different-shaped pneumatic tools that were used by subjects to drive screws on both a horizontal and vertical work surface at various work locations. The results can be used as guidelines for choosing tools for specific workstations or as a rationale for redesigning an existing workstation. Although, in most cases, the results agree favorably with predictions based on anthropometric and biomechanics data, additional research is needed to demonstrate that workstations which are designed based on psychophysical, anthropometric, and biomechanics data actually reduce the incidence of work-related disorders.

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