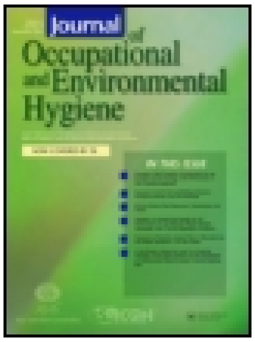

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Field Evaluation of a Modified Intervention for Overhead Drilling

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Drilling holes into concrete or metal ceilings is one of the most physically demanding tasks performed in construction. The work is done overhead with rotary impact hammer drills that weigh up to 40 N. The task is associated with pain and musculoskeletal disorders at the wrist, forearm, shoulder, and back. The mechanism of injury is thought to be the high forces and non-neutral shoulder and wrist postures applied during drilling. Previously, we described a field study of a foot lever and inverted drill press intervention devices that received poor usability ratings compared with the usual method for overhead drilling based on problems with mobility and productivity. Using a participatory intervention model, feedback from construction workers (N = 13) was used to develop a new intervention design that incorporated a wheeled tripod base and a unique method of aligning the drilling column to vertical. A different group of construction workers (N = 23) evaluated usability and fatigue of the new device during their regular overhead drilling in comparison with the usual method. Four of 12 usability ratings were significantly better with the intervention device compared with the usual method. Subjective shoulder fatigue was less with the new intervention (1.1 vs. 3.3; scale 0 to 5; p < 0.001). This difference was supported by objective outcome measures; the mean hand forces during drilling were 26 N with the intervention compared with 245 N with the usual method. The percentage of time with the shoulder flexed or abducted to more than 60 degrees was less with the intervention compared with the usual method (21 vs. 40%; p = 0.007). There was significantly less head extension with the intervention compared with the usual method. There were no significant differences in overall productivity between the two methods. This study demonstrates that a new intervention device for overhead drilling has improved usability and subjective fatigue ratings compared with the usual method. These improvements are most likely due to the reduced hand forces, reduced shoulder abduction and flexion, and reduced drilling time.

Keywords construction, ergonomics, overhead, shoulder, tool

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INTRODUCTION

The construction sector in the United States has the highest rates of non-traumatic soft tissue injuries to the neck, back, and upper extremities.(1) Shoulder pain and disorders among construction workers are associated with overhead work,(2–5) and the risk increases with increasing hours of overhead work per day.(6,7) One of the most physically demanding tasks in construction is overhead drilling into concrete or metal ceilings for the attachment of anchor bolts to hang pipes, sheet metal ducts, cable trays, and other mechanical equipment.(8) The usual method for overhead drilling involves applying a sustained upward, over shoulder push with one or both hands on a vibrating hammer drill with a mass of 2 to 4 kg (Figure 1). The high, applied forces are transmitted through the hands, arms, shoulders, and back. The work is done on a ladder or scissor lift. Other risks of the task include falling from heights and exposure to silica dust, noise, and vibration.

Devices and jigs to assist with overhead drilling have been developed on an ad hoc basis at construction sites to reduce shoulder loading, but none of these efforts have led to a commercial product. Furthermore, none of these interventions have been evaluated for usability or their effects on arm and shoulder loads. One device, a vertical support stand, which linked a bolt gun to a holster on the worker's belt, was demonstrated to be an effective shock dampener and reduced perceived hand-arm loads.(9)

Previously, we reported on the development and evaluation of two interventions for overhead drilling: an inverted drill press and a foot lever design intervention.(10,11) These interventions were compared with the usual method for overhead drilling by commercial construction workers performing their regular overhead drilling work. While both interventions were perceived to be less fatiguing than the usual method (the inverted drill press design more so than the foot lever design), the usual method was still preferred over the intervention designs based on shorter setup time, time to move between holes, and accuracy. The construction workers recommended

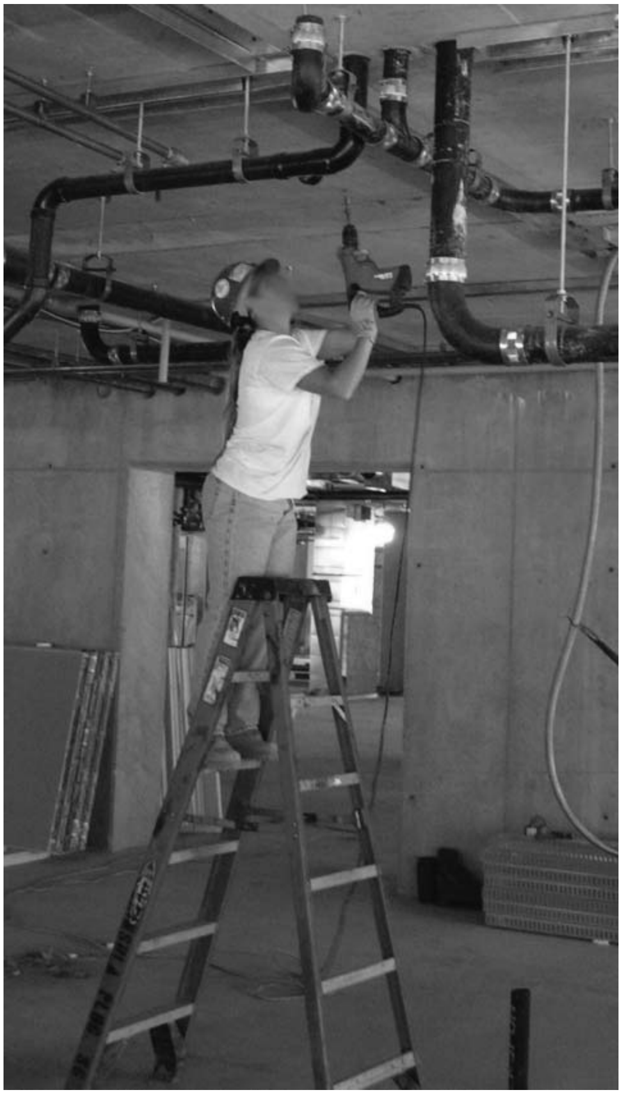

FIGURE 1. Usual method for drilling overhead into concrete ceilings for placing anchor bolts

a number of design modifications, including a faster method of moving between holes and a method for knowing when the proper hole depth had been reached. The study did not include objective measures of productivity, arm loads, or shoulder postures.

Current Study

The goal of the current study was to evaluate a modified overhead drilling device to assess usability, fatigue, objective measures of musculoskeletal risk (drilling duration, arm loads, shoulder posture), and productivity as used in commercial construction settings. The prior inverted drill press design was modified, based on worker feedback, to improve setup and movement times and to further reduce musculoskeletal loads. The long-term aim of this line of research is to develop interventions for drilling that will reduce fatigue and risk factors for upper extremity musculoskeletal disorders while not interfering with productivity. Secondary aims are to reduce fall risk and exposure to noise, vibration, and silica dust.

METHODS

Study Sites and Subject Recruitment

Focus group evaluations of device designs by construction workers were carried out at union halls and at contractor offices. Subsequently, the new device was evaluated in the field at commercial construction sites in Oregon and Washington. Sites where overhead drilling into concrete or metal was to be performed were identified with outreach to electrical, plumbing, and sheet metal contractors. Full-time construction workers who were to be performing overhead drilling for one or more days were identified and recruited to the study. The participation rate was 100%, and construction workers received their usual pay during their participation in the study. The study was approved by the University of California at San Francisco Committee on Human Research.

Participatory Feedback: Design Changes to the Intervention Device

Three groups of four to five commercial construction workers (N = 13) from the plumbing, electrical, or sheet metal trades were invited to meet at their local union hall or at their contractor offices to review the recommendations for changes to the original device designs that were compiled in the prior study.[11] They then provided feedback on the recommended design changes.

Of the two interventions developed in the prior study, the inverted drill press design was selected over the foot lever design to become the mechanism for raising the drill based on the reduced muscular fatigue and better usability characteristics. Based on the feedback, the column of the new intervention device was built from three, steel square tubes of consecutively smaller sizes that were nested one within the other. The nested columns are lowered or raised by cranking hand wheels that operate linear gears set along inset tracks in the columns. The column is inserted into a rolling tripod base. The base has three 18 cm diameter, air-filled, locking wheels that are 76 cm apart. The device has a resting height of 2 m so that it can be moved through a door and can be extended to a working height of 4.7 m (Figure 2). One leg of the tripod based can be positioned between wall studs to drill close to an unfinished wall.

Different rotary hammer drills can be attached to the top of the innermost column by securing them to a drill saddle. The saddle is hinged to allow the operator to flip the drill down to change the bit or set the depth rod (Figure 3). The drill trigger is activated with a Velcro strap, and the drill is plugged into an outlet whose power is controlled by the operator through a switch located on the column near the D-handle. When drilling in a scissor lift, the tripod base is replaced with a 25 cm diameter plastic plate (Figure 4). The column used in the scissor lift uses two nested columns and has a resting height of 2 m and extends to 2.75 m.

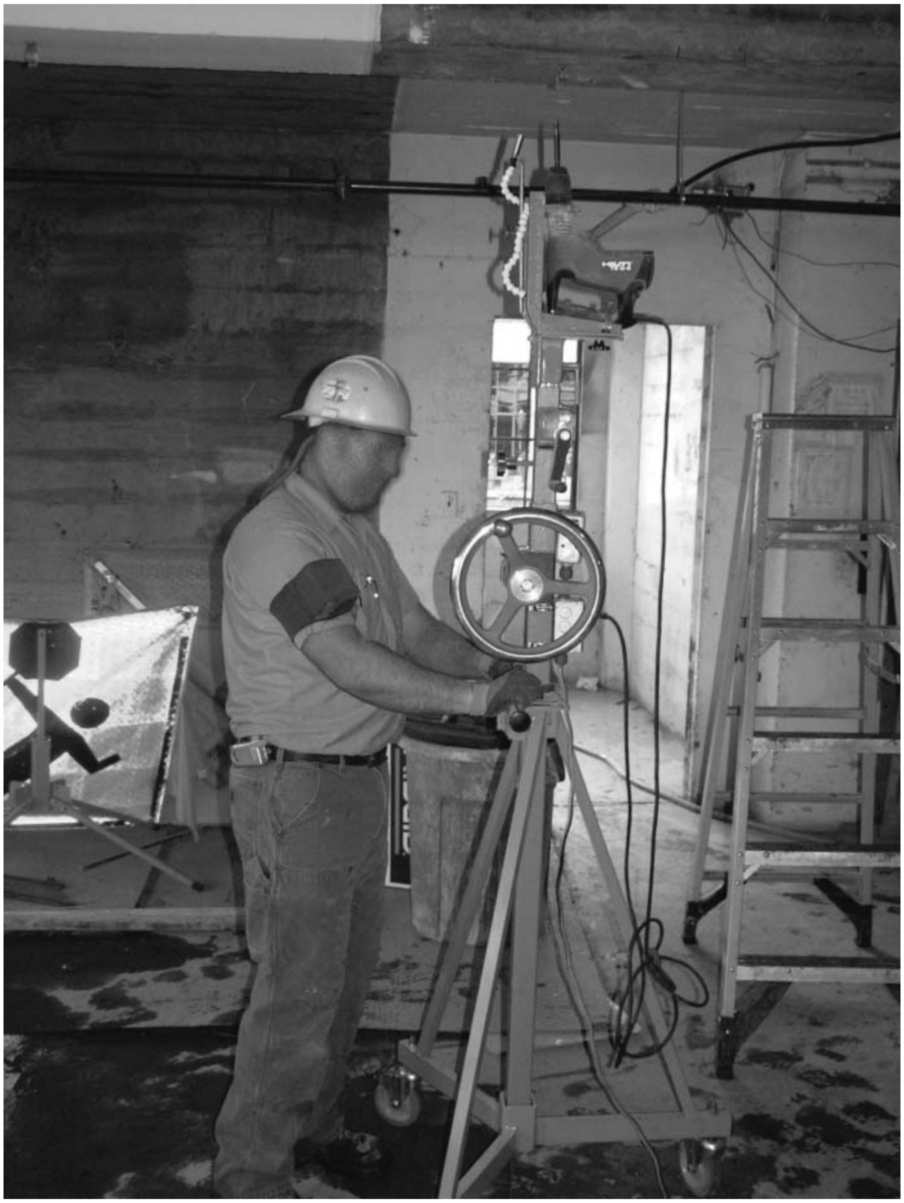

FIGURE 2. New intervention design with wheeled tripod base. Column extends from 2 to 4.7 m. Inclinometer box is attached to upper arm for continuously recording shoulder posture.

The rolling tripod base includes a new collar design that allows the column to be rapidly aligned to vertical. The collar at the top of the tripod base allows the column to tilt freely within an opening (±2.5°) set by the size of a collar (Figure 3). A horizontal plate wraps around the column, and two butterfly nuts lock the column to the collar when it is vertical. Small bubble levels secured to the column are used to determine when it is vertical.

Once the column is vertical, target marks can be placed on the floor instead of the ceiling. This feature may improve productivity and reduce fall risk by eliminating the need to climb a ladder to mark the ceiling before drilling. As far as we are aware, this is a unique method for aligning a column to vertical and has not been used before in a jig that supports construction equipment.

Field Testing

The trades of the 23 construction workers who participated in the field study were: carpenters (9), electricians (6), plumbers (3), laborers (3), and sheet metal workers (2). Five were apprentices and 18 were journeymen; one worker was female and two were left-handed. One worker was Hispanic and the rest were Caucasian. The mean age was 38 (±12) years, the mean height was 180 (±8) cm, the mean mass was 93 (±17) kg, and the median time in the trade was 14 (±10) years. Participants reported drilling overhead for a mean of 5.4 (±7.5) days per month.

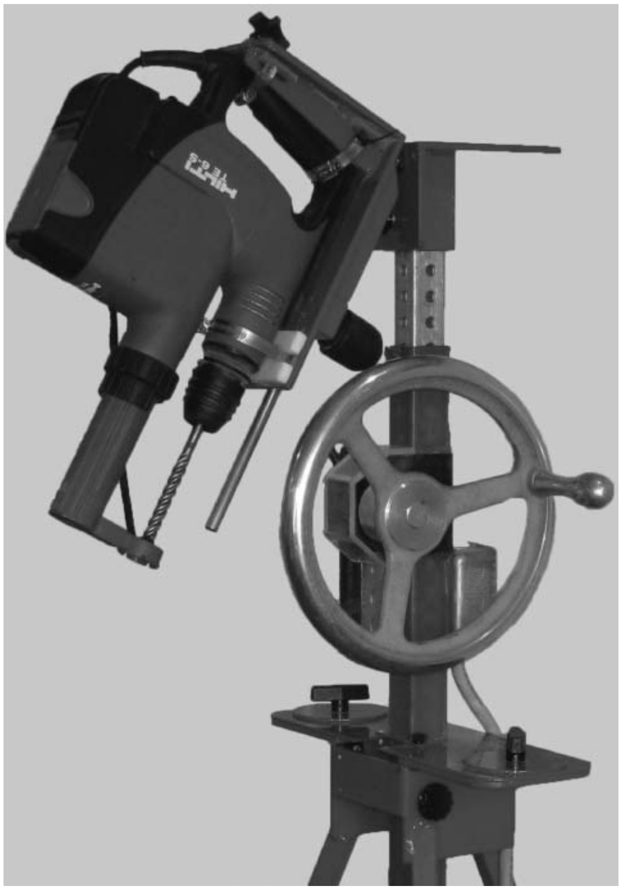

FIGURE 3. Hinged saddle allows the drill to be flipped over to change bits or to adjust the depth gauge. A dust collection system is attached to the drill. The hand wheel is turned to advance the drill toward the ceiling. The collar on top of tripod base allows the column to be tilted (± 2.5°) in order to align it to vertical. Once set to vertical, the column is locked in place with the black T-handles.

A workday was selected for testing where it was likely that the construction worker would be spending all day doing the same type of overhead drilling. The planned duration of overhead drilling was split in two, and the intervention device was used for half the work and the usual method for the other half. Therefore, for each subject, the conditions during drilling (e.g., ceiling height, scissor vs. floor, diameter, and depth of holes) for the two methods were identical. The order of testing was random.

The field data collection was carried out at commercial construction sites, and the tasks involved drilling holes for installing anchors for hanging conduit, cable trays, pipes, and struts. Construction workers used the appropriate intervention device for the task: for ceiling heights of 4.7 m or less the rolling tripod base was used, and for taller ceilings the scissor lift was used. The ceiling heights ranged from 3 to 12 m. During drilling, 15 participants used a scissor lift for both methods of drilling, and the other 8 participants used a ladder with the usual method or drilled from the ground with the intervention device. Each method was used for a mean of 3 (±1.8) hr, and the mean number of holes drilled using each method was 47 (±25).

Generally, the holes were drilled consecutively, but sometimes the process was interrupted by laying out and marking the position of the next holes. The same hammer drill was used for all work (TE-6S Roto-hammer; Hilti, Inc., Tulsa, Okla.). The holes drilled were 9 to 16 mm in diameter and between 50 and 100 mm deep. All ceilings were concrete except one, which was metal.

On the morning of testing, participants completed a brief *demographic* questionnaire. After each method of drilling was performed, a short *device* questionnaire was completed by the participant to assess ease of use, usability, safety, and fatigue (five body regions) using a discrete 0, 1, 2, 3, 4, 5 point scale with word anchors at 0 (e.g., easy, excellent, no fatigue) and 5 (e.g., difficult, poor, very fatigued). Usability was assessed for various characteristics (accuracy, control, stability, aesthetics, durability, and handling). Ease of use was assessed for various actions (setting up, moving to next hole, fine positioning, activating drill, drilling/vibration, and knowing when drilling is complete). The questionnaire also solicited positive and negative features of the device and suggestions for improving the device design.

Prior to use of the intervention device, participants received a 5-min training where the researcher demonstrated how to change the bit, move the device, lock the wheels, align the column to vertical, advance the drill toward the ceiling, and retract the column. Participants were also advised not to stare at the ceiling during drilling but to look at the score marks on the column to follow the hole depth during drilling.

When permitted by the construction site owner (N = 19), participants were videotaped to measure productivity. The participants' (N = 16) right shoulder posture was recorded with two small inclinometers with data loggers (Virtual Corset; MicroStrain, Williston, Vt.) (sampling rate 7.5 Hz). Technical problems prevented the extraction of posture data for three participants. These inclinometers were attached to the upper arm to record shoulder posture relative to gravity (Figure 2).[12] Upper arm motion in the anterior direction is referred to as flexion and motion in the lateral direction as abduction. Upper arm inclinometer data were collected during the last hour for each drilling method during the data collection period when the worker would be most familiar with the method. The inclinometers were calibrated at the beginning of each data collection period by having subjects stand upright and place their upper arm in three postures (0 degrees flexion/abduction; 90 degree abduction; 90 degrees flexion).

To measure head extension, an inclinometer was attached to the back of a special safety helmet (N = 7).[12] The helmet was tightly secured to the head. The neutral (0 degree) flexion/extension posture was set by having the participant stand and look at the horizon.[13]

Hand forces applied during drilling were measured for only three subjects because the measurement method interfered with work. The measurements were done only for workers who were working in a scissor lift because the scale could not

FIGURE 4. The intervention design used in a scissor lift. The wheeled base is replaced with a round plastic disk.

be placed under a ladder. Upward thrust force while drilling using the usual method was measured while the subjects stood on an electronic force plate (Acculab Digital Scale, Bradford, Mass.), and the data were sampled at 25 Hz on a laptop. Subjects were instructed to drill at their usual rate. The subject's weight was subtracted from the force data to calculate applied upward force. The mass of the drill with dust collector and bit was 4.6 kg. To measure hand forces when using the intervention device, subjects pulled on the hand wheel handle with a digital force gauge (DFM 50; Chatillon, Largo, Fla.) while drilling at their usual rate.

Data Analysis

To calculate productivity, the videotapes were evaluated frame by frame to identify the four subtasks associated with the drilling of each hole. The subtasks were *targeting* (moving the device, ladder, or scissor lift to the next drilling site), *approach* (cranking the drill up toward the drill mark on the ceiling or climbing up the ladder), *drilling* (drilling into the ceiling), and *departure* (cranking the drill down or climbing down the ladder). Other work not involving these subtasks (e.g., talking to other workers, inserting anchors, marking holes, taking a break) was not included in the productivity analysis.

The videotape recordings were synchronized with the inclinometer data so that shoulder and head posture data could be time marked by subtask. For shoulder posture, a flexion/abduction value was calculated for each data point by taking the larger value of the abduction or flexion angle. Flexion and abduction contribute similarly to shoulder muscle loads and increasing angles of flexion or abduction relative to gravity are associated with increasing shoulder muscle activity since these muscles act to counter gravity applied to the arm.[14] One method for evaluating risk for shoulder disorders is to compare percentage time that the shoulder is flexed/abducted to values over 60 or 90 degrees. These are commonly used thresholds for shoulder posture risk assessment based on increased muscle loading and risk of musculoskeletal disorders.[15–19]

Similarly, the percentage of time that the head was in more than 0 or 15 degrees extension was compared between drilling methods.[20] Head extension of more than 0 degrees was associated with neck pain in one of the few prospective studies to evaluate the effect of head posture on subsequent neck/shoulder symptoms.[21] Others have used a head extension threshold of more than 15 degrees.[13,19]

The effects of drilling method on subjective ratings and objective outcome measures were evaluated using repeated measures ANOVA, and differences were considered significant if $p < 0.05$ (SAS, v. 9.2). Dependent variables were tested for normality. For the subjective ratings, the model included the order by condition interaction term. However, none of these interaction terms were significant for any of the outcome measures.

TABLE I. Usability and Fatigue Ratings – Mean (SD) (N = 23)

	Usual Method	Intervention	P-value
Ease of. . . (0 = easy, 5 = difficult)			
Setting up	0.8 (0.9)	1.0 (0.8)	p = 0.36
Moving to next hole	0.8 (0.9)	0.9 (0.9)	p = 0.82
Making adjustments	1.1 (1.3)	1.2 (0.9)	p = 0.69
Activating drill	1.2 (1.1)	1.0 (0.9)	p = 0.56
Drilling – vibration	2.3 (1.1)	0.8 (1.0)	p < 0.001
Knowing when drilling is complete	1.0 (1.3)	0.8 (1.2)	p = 0.62
Usability (0 = excellent, 5 = poor)			
Accuracy	1.2 (0.9)	1.3 (1.0)	p = 0.55
Control	1.6 (1.2)	1.0 (0.8)	p = 0.05
Stability	1.7 (1.2)	1.0 (0.8)	p = 0.03
Looks – aesthetics	1.7 (1.0)	1.1 (0.8)	p = 0.06
Durability	1.3 (1.0)	1.1 (0.8)	p = 0.52
Feel – handling	2.3 (1.1)	1.2 (0.7)	p < 0.001
Fatigue (0 = none, 5 = very)			
Neck	2.6 (1.5)	1.8 (1.3)	p = 0.01
Shoulder	3.3 (1.2)	1.1 (1.0)	p < 0.001
Hands and forearm	3.6 (1.0)	0.8 (0.8)	p < 0.001
Low back	2.9 (1.3)	0.9 (0.9)	p < 0.001
Leg	1.7 (1.3)	0.9 (1.1)	p = 0.003

RESULTS

The usability and fatigue ratings for the usual method of drilling and the intervention device are summarized in Table I. The intervention device was rated superior to the usual method on the usability measures of *drilling/vibration*, *stability*, and *feel/handling*. The mean levels of perceived fatigue were significantly lower in all five body regions for the intervention device compared with the usual method. With a $p < 0.05$ threshold we would have expected one significant finding out of the 17 tests, but not eight. Importantly, all eight significant findings were in the same direction; that is, the intervention device performed better than the usual method.

For the intervention device, there was a trend for productivity to improve during the first 5 to 15 holes (Figure 5). Productivity measures (e.g., mean time per hole by subtasks) and total time per hole are presented in Table II. There was no significant difference in total time per hole between the usual method and the intervention device ($p = 0.61$). However, the subtasks *approach* and *departure* were significantly faster with the usual method.

Shoulder posture data were collected for a mean of 13 (±5) holes per person (Table III). The shoulder was flexed or abducted to over 60 degrees for 40% of the time while *drilling* with the usual method compared with 21% of the time when drilling with the intervention ($p = 0.007$). There was a similar trend for the shoulder flexed or abducted to over 90 degrees.

The percentage of time that the head was in extension of more than 0 degrees, across all subtasks, was greater for the usual method than the intervention (Table III) ($p = 0.005$). During the *drilling* subtask, when the greatest force is applied

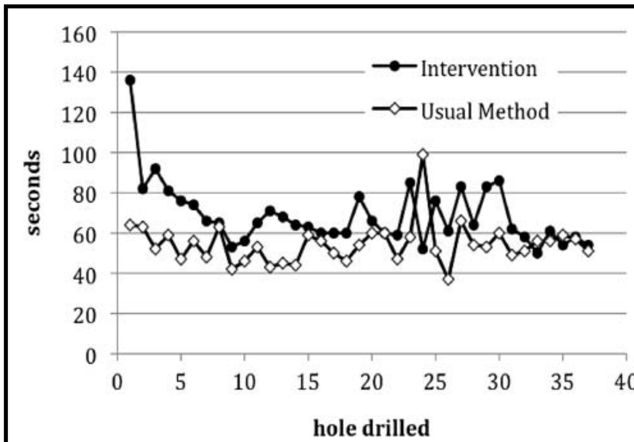

FIGURE 5. Typical pattern of time to complete each hole (time includes all subtasks) for one subject. Note improvement in productivity during the first nine holes with the intervention.

TABLE II. Productivity – Mean Time in Seconds per Hole (SD) by Subtasks (N = 19)

	Usual Method	Intervention	P-value
Target	13.5 (19.4) sec	16.2 (11.5) sec	p = 0.47
Approach	13.0 (13.7) sec	19.6 (16.3) sec	p = 0.004
Drill	46.4 (30.4) sec	36.4 (14.7) sec	p = 0.12
Departure	5.8 (5.7) sec	11.2 (9.2) sec	p = 0.003
Total	78.6 (62.8) sec	83.5 (37.4) sec	p = 0.61

by the shoulder muscles, the head was in less extension with the intervention. There were similar findings when the threshold for head extension was greater than 15 degrees. Head posture was measured for a mean of 15 (±7) holes drilled per person.

The mean applied upward hand force during drilling (included mass of drill and bit) was 245 (±11) N. The mean hand force applied to the handle of the hand wheel when drilling with the intervention device was 26.3 (±3.3) N.

The construction workers who used the intervention device in the field made recommendations for additional changes to the design. The time to raise and lower the column (e.g., *approach* and *departure* subtasks) could be reduced by providing fast and slow gear settings. The fast setting would be used for *approach* and *departure* subtasks, and the slow setting would be used for *drilling*. Productivity and fatigue might be improved further by replacing the linear gear with a power driven column (e.g., pneumatic cylinder or screw drive).

TABLE III. Shoulder Abduction/Flexion (N = 16) and Head Extension (N = 7) Postures – Mean Percentage Time (SD) by Subtasks

	Usual Method	Intervention	P-value
Shoulder abduction/flexion > 60°			
Target	23 (15) %	23 (14) %	p = 0.89
Approach	32 (24) %	22 (19) %	p = 0.06
Drill	40 (29) %	21 (19) %	p = 0.007
Departure	35 (32) %	27 (24) %	p = 0.26
All subtasks	33 (21) %	23 (17) %	p = 0.04
Shoulder abduction/flexion > 90°			
Target	12 (13) %	6 (6) %	p = 0.06
Approach	13 (14) %	5 (7) %	p = 0.03
Drill	16 (20) %	3 (6) %	p = 0.007
Departure	17 (20) %	5 (10) %	p = 0.03
All subtasks	13 (15) %	5 (6) %	p = 0.01
Head extension > 0°			
Target	74 (20) %	86 (5) %	p = 0.14
Approach	80 (12) %	84 (9) %	p = 0.07
Drill	90 (6) %	79 (9) %	p = 0.003
Departure	85 (17) %	87 (12) %	p = 0.72
All subtasks	88 (7) %	81 (8) %	p = 0.005
Head extension > 15°			
Target	60 (22) %	67 (8) %	p = 0.29
Approach	68 (14) %	71 (8) %	p = 0.53
Drill	78 (9) %	67 (11) %	p < 0.001
Departure	79 (18) %	69 (17) %	p = 0.34
All subtasks	76 (8) %	68 (8) %	p = 0.001

DISCUSSION

As far as we are aware, this is the first study to evaluate the effects of a new method for overhead drilling on head and shoulder postures. The usability ratings of the new design were better than or the same as the usual method. The ratings were an improvement from the negative ratings received during testing of the first iterations of the intervention.[11] Construction workers reported less vibration exposure and better handling and stability with the new device. Most importantly, the improvements in usability were made without an overall loss in productivity.

Perceived fatigue ratings in the five body regions were lower for the intervention device than the usual method. The improvement in the subjective shoulder fatigue ratings were supported by reductions in the objective risk factors of applied force and percentage time in non-neutral shoulder postures. While the shoulder abduction/flexion was significantly reduced across all subtasks with the new method compared with the usual method, the largest reduction in shoulder flexion/abduction was during drilling. The postures for this subtask are more important than the postures during the other subtasks because this subtask is associated with the largest shoulder muscle loads. In addition, the actual time drilling was less with the new method, although this difference was not significant.

Another important risk factor reduced during drilling was the required hand force. Directly comparing hand forces, however, may be an oversimplification because the usual method involves pushing upward with the hand above the shoulder while the intervention involves pushing and pulling the hand wheel handle just below the level of the shoulder with the arm outstretched. The shoulder muscle forces required to accomplish these tasks were compared for the 50th percentile male using the static strength prediction program from the University of Michigan (3DSSPP, v.6.0.2; University of Michigan, Ann Arbor, Mich.). The measured forces and the arm postures that were typically observed on the videotapes were entered into the program.

The program predicted that the shoulder muscle force required to drill with the usual method was 90% of strength (e.g., MVC, maximum voluntary contraction), while 15% of strength was required to push or pull the hand wheel handle on the intervention device. The force values presented may not be representative of all construction workers because they were measured with only three subjects. When drilling with the usual method, the shoulder moment and muscle loads can be reduced by moving the ladder so that the drill is close to the shoulder.[22]

For both drilling methods, the head was in extension most of the time. There was some concern that use of the intervention device may lead to more neck extension and neck fatigue due to looking up at the ceiling during targeting and drilling. However, this was not the case; more neck fatigue was reported and more neck extension was measured while drilling with the usual method. Neck fatigue while drilling with the usual method is likely to be increased by the higher shoulder muscle tension required to stabilize the shoulder during drilling.

Several limitations of this study should be noted. While the study included participants from a variety of trades performing overhead drilling in many settings, there were very few female participants. Based on the 3DSSPP analysis, it is likely that many women and men without strong shoulders would be too weak to drill repeatedly with the usual method. Therefore, these construction workers might benefit more from use of the intervention device than indicated by the study findings. The device might also improve the return to work time and rehabilitation for construction workers being treated for shoulder injuries.

Another limitation of the study is that the mean duration of exposure to each method of drilling was only 3 hr. A longer duration of exposure (e.g., for several weeks) may lead to better familiarity with the device and improved productivity and usability outcomes. Finally, the reported shoulder postures are the upper arm angle relative to gravity not the upper arm angle relative to the torso. This measure may reflect the shoulder muscle loads but not the anatomical loads (e.g., compression at the acromion) unless the subject torso was upright.

Field testing by experienced construction workers and their feedback on design was vital to the development of this new intervention device. It is difficult to anticipate how intervention devices designed to improve health and safety will perform and be received without their testing in varied settings by different trades. Experienced workers play a key role in the process because they are the most impacted by the intervention; they are experts in the work and they can identify both the nuanced and the obvious advantages and disadvantages of its application.[23] Incorporating their recommended changes made during the evaluation of the early versions of the device led to a design with significantly improved usability ratings.

CONCLUSION

In conclusion, an intervention device was developed using a participatory process that led to a design that was demonstrated to reduce fatigue, shoulder flexion/abduction, and arm forces while not interfering with productivity. Although not measured in this study, the use of this device is also likely to reduce fall risk and reduce exposure to noise, silica dust, and hand vibration by moving the drill away from the worker.

The important design elements for minimizing fatigue included design features that reduced the required hand forces (hand wheel with linear gear); reduced shoulder flexion/abduction especially during the high force drilling subtask (height of hand wheel); and reduced the time performing the high force drilling subtask (linear gear). The important design elements for improving usability and maintaining productivity included improving the mobility of the device with appropriate wheels and adding a system to rapidly align the drilling column to vertical. The methods used in this study may be useful for the development of other jigs, for use in construction, that are designed to prevent musculoskeletal disorders.

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