



Overhead drilling: Comparing three bases for aligning a drilling jig to vertical

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ABSTRACT

Problem: Drilling overhead into concrete or metal ceilings is a strenuous task done by construction workers to hang ductwork, piping, and electrical equipment. The task is associated with upper body pain and musculoskeletal disorders. Previously, we described a field usability evaluation of a foot lever and inverted drill press intervention devices that were compared to the usual method for overhead drilling. Both interventions were rated as inferior to the usual method based on poor setup time and mobility. **Method:** Three new interventions, which differed on the design used for aligning the drilling column to vertical, were compared to the usual method for overhead drilling by commercial construction workers ($n = 16$). **Results:** The usual method was associated with the highest levels of regional body fatigue and the poorest usability ratings when compared to the three interventions. **Conclusion:** Overall, the 'Collar Base' intervention design received the best usability ratings. **Impact on Industry:** Intervention designs developed for overhead drilling may reduce shoulder fatigue and prevent subsequent musculoskeletal disorders. These designs may also be useful for other overhead work such as lifting and supporting materials (e.g., piping, ducts) that are installed near the ceiling. Workplace health and safety interventions may require multiple rounds of field-testing prior to achieving acceptable usability ratings by the end users.

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1. Introduction

Increasing hours per day of overhead work is strongly associated with shoulder pain and disorders among construction workers (Holmstrom, Lindell, & Moritz, 1992; Welch, Hunting, & Kellogg, 1995). One of the most physically demanding tasks in commercial construction is overhead drilling into concrete or metal ceilings to attach anchors bolts for hanging pipes, sheet metal ducts, cable trays, and other mechanical equipment (NIOSH, 2002). The work is done by plumbers, pipefitters, fire sprinkler installers, electricians, carpenters, and sheet metal workers. The usual method involves standing on a ladder or a scissor lift and holding a hammer drill overhead to drill the holes (Fig. 1). The anchor bolts are inserted and seated with a hammer, then the ladder or scissor lift is moved to the next anchor bolt location. The drill and bit weigh 20 to 40 N. Typically, the upward force applied during drilling is 300 N and it takes approximately 45 seconds to drill a hole (Rempel, Star, Barr, Blanco, & Janowitz, 2010). The upward force on the drill is transmitted through the wrists, shoulders, and back (Anton, Shibley,

Fethke, & Hess, 2001). Drilling overhead also carries the risks of falling from height and exposure to silica dust, noise, and hand vibration.

Previously, we reported on the development and evaluation of two interventions for overhead drilling: an inverted drill press (Fig. 2) and a foot lever design [Generation 1 designs] (Rempel, Star, Gibbons, Barr, & Janowitz, 2007; Rempel, Star, Barr, Gibbons, & Janowitz, 2009). These interventions were compared to the usual method for overhead drilling by 24 commercial construction workers performing their regular overhead drilling work. While both interventions were perceived to be less fatiguing (the inverted drill press design was less fatiguing than the foot lever design) than the usual method for overhead drilling, the usual method was still preferred over the intervention designs based on the usability ratings of set-up time and time to move between holes. The construction workers recommended a number of design modifications, including a faster method of moving between holes.

In this phase of the project, the inverted drill press intervention design was modified, based on worker feedback, to improve mobility and to allow the drilling column to be rapidly aligned to vertical. Commercial construction workers used three new intervention designs [Generation 2] and the usual method to carry out their regular overhead drilling. The three interventions differed on the design used to aligning the drilling column to vertical. The long-term objectives of this research are to develop interventions for overhead drilling that will reduce the risk factors for upper body musculoskeletal disorders while not interfering with productivity.

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Fig. 1. An example of the usual method for overhead drilling. The upward forces applied to the drill are typically 200 to 400 N.

2. Method

2.1. Sites and Subjects

Commercial construction sites in the greater Portland, OR area, where overhead drilling into concrete or metal was to be performed, were identified with outreach to electrical, plumbing, and sheet-metal contractors and unions. Subjects were commercial construction workers who anticipated spending at least one day of work performing overhead drilling work. The study was approved by the University of California at San Francisco Committee on Human Research.

2.2. Generation 2 Device Designs

Of the two Generation 1 designs developed in the prior study, the inverted drill press design (Fig. 2) was selected over the foot-lever design to become the mechanism for raising the drill for the Generation 2 designs. This selection was based on the reduced leg fatigue and better usability characteristics of the inverted drill press design compared to the foot lever design (Rempel et al., 2009). The primary problems identified with the Generation 1 intervention devices compared to the usual method were reduced productivity due to set-up time and poor device mobility. The base of the Generation 1 devices was a flat metal plate with wheels that only engaged when the column was tilted. Therefore, once the device was close to the drilling location, the device was moved by kicking and sliding it until the drill bit was aligned with the mark on the ceiling.

To improve mobility, three different rolling bases were developed to accompany the inverted drill press column. Each base used a different method to align the column to vertical. Small bubble levels were secured to the column to check vertical alignment. Rapid vertical alignment of



Fig. 2. Generation 1 inverted drill press intervention design using a rotating handle and linear gear to raise the inner (silver) column. At the base of the column is a yellow metal plate and at the top a black saddle that holds a rotary hammer drill. The depth stop is taped to the drill.

the column prior to raising the drill could improve the accuracy of the device and reduce setup time. If the column was truly vertical, target marks could be placed on the floor instead of the ceiling, thereby improving productivity and further reducing fall risk by eliminating the requirement of marking the ceiling prior to drilling.

The three bases were named: Collar Base, Adjustable Castor Base, and Spring Base (Fig. 3). The Collar Base allowed the column to tilt freely within an opening set by the size of a collar at the top of the base. A horizontal plate wrapped around the column and two butterfly nuts locked the column to the collar when it was vertical. The Adjustable Castor Base was aligned to vertical by adjusting the height of each wheel with a knob on a threaded bolt. The Spring Base allowed the operator to step on the base and tilt the column to the correct angle by compressing springs set between the base and the castors. All bases used four double-locking swivel castors with solid rubber tread measuring 12.7 cm in diameter and 3.2 cm in width (Colson, EcoForma, Jonesboro, AK). The castors could be locked with the foot.

The new bases also allowed drilling to be done close to walls. Often overhead drilling occurs at a time in construction when the walls are still unfinished and the studs are exposed. The intervention devices allowed the drill column to be moved close to a wall because one leg of the base could be set between wall studs.

2.3. Outcome Measures

The *single device questionnaire* was completed by a subject after each device was used in order to assess ease of use, fatigue (5 body regions), safety, and usability. Usability was assessed for various characteristics (accuracy, control, stability, aesthetics, durability, and handling). Ease of



Fig. 3. The three different bases tested with the inverted drill press: (upper left) Adjustable Castor Base - the height of each wheel is adjusted separately to align the column to vertical; (upper right) Spring Base - the column can be tilted in different directions by compressing springs set above each castor; (lower left) Collar Base (red) with inverted drill press column (yellow) and saddle with drill; and (lower right) close up of the Collar Base. Bubble levels on the column or base are used to align the column to vertical.

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 questions were answered using discrete 0, 1, 2, 3, 4, 5 point scales with word anchors at 0 (e.g., easy, excellent, no fatigue) and 5 (e.g., difficult, poor, very fatigued). The questionnaire also solicited positive and negative features of the device and suggestions for improving the device design.

At the end of the workday, subjects completed a *comparison questionnaire* to rank order the devices on the following usability characteristics: setup, moving, ease of use, accuracy, work speed, comfort, and overall.

2.4. Field-Testing

Each construction worker evaluated all of the intervention devices and their usual method while performing their scheduled overhead drilling tasks. For each subject the order of device testing was randomized. A workday was selected where it was likely that the construction worker would be spending all day doing the same type of overhead drilling. Therefore, the conditions of drilling (e.g., height, platform [ladder or scissor lift], hole diameter, hole depth, number of holes) were the same for each drilling method.

Prior to testing, each subject received a five minute training on how to use the intervention, change the bit, move the device, lock the wheels, align the column to vertical, advance the drill toward the ceiling, and retract the column. The researcher administered the questionnaires, noted the type of ceiling, the platform used (e.g., floor, ladder, scissor lift), the number of holes drilled, the bit diameter, the hole depth, the environment, and unusual barriers encountered during testing.

2.5. Analysis

Outcome measures were compared between devices with the Friedman chi-square test. Significant findings were followed-up with the Tukey test to adjust for multiple comparisons.

3. Results

The trades of the 16 construction workers who participated in the study were: 9 electricians, 2 plumbers, and 5 carpenters. Two were apprentices and 14 were journeymen. All were male; one was Hispanic, one was Black, and the rest were White. The mean age was $42 (\pm 10)$ years, the mean height was $178 (\pm 8)$ cm, and the median number of years in the trade was $12 (\pm 9)$. For the usual method, 5 subjects used a ladder and 11 used a scissor lift (Fig. 4). Subjects used each of the methods for 1 to 2 hours.

The outcome measures are summarized in Table 1. The Adjustable Castor Base inverted drill press or the Collar Base inverted drill press were rated as easier to use than the Spring Base inverted drill press or the usual method for *setting up*, *moving to the next hole*, *making adjustments*, *activating the drill*, and *drilling/vibration*. There were no differences between the methods for *knowing when drilling is complete*. For the usability evaluation, one or more of the three intervention devices received better ratings than the usual method for *control*, *stability*, *durability*, and *handling*.

The average levels of perceived fatigue were lower in all five body regions for the Adjustable Castor Base inverted drill press and the Collar Base inverted drill press when compared to the usual method (Table 1).

When rank ordering (Table 1) the drilling methods, the Collar Base intervention was most preferred across all evaluation categories: setup (64%), moving (60%), ease of use (70%), accuracy (73%), work-speed



Fig. 4. Adjustable Castor Base intervention being used in a scissor lift to drill into a ceiling.

Table 1
Mean usability ratings, fatigue scores and summary rankings for the three interventions and the usual method for overhead drilling (N = 16). The lowest (i.e., best) significant values are marked as bold.

	Drilling Method								p-value ^a	Significant pairs ^b
	Adj Castor Base		Collar Base		Spring Base		Usual Method			
	mean	SD	mean	SD	mean	SD	mean	SD		
Ease of... (0 = easy, 5 = difficult)										
Setting up	1.14	1.03	0.80	0.53	2.00	0.96	1.86	1.29	p = 0.01	CS
Moving to next hole	0.93	0.83	0.70	0.56	1.33	0.93	1.71	1.20	p = 0.03	CU
Making adjustments	1.00	0.88	1.00	0.68	2.17	0.91	1.79	1.12	p = 0.003	AS, CS
Activating drill	0.50	0.76	0.80	0.66	1.33	1.22	1.86	1.46	p = 0.009	AS, AU
Drilling - vibration	0.50	0.65	0.60	0.58	1.17	1.20	3.00	1.36	p < 0.001	AU, CU
Knowing when drilling is complete	1.14	1.03	0.70	0.69	1.67	0.51	1.36	1.08	p = 0.052	
Usability (0 = excellent, 5 = poor)										
Accuracy	1.14	0.66	1.30	0.69	1.50	1.09	1.64	1.28	p = 0.47	
Control	0.71	0.73	1.10	0.47	0.83	0.25	1.68	0.95	p = 0.007	AU, SU
Stability	1.07	0.62	0.90	0.47	1.50	0.52	2.36	1.06	p < 0.001	AU, CU
Looks - Aesthetics	1.07	1.00	1.30	0.79	1.67	0.85	1.64	1.01	p = 0.25	
Durability	0.93	0.73	0.90	0.61	1.67	0.85	1.71	1.38	p = 0.01	CS
Feel Handling	1.14	0.66	1.00	0.68	1.83	0.73	2.57	0.94	p < 0.001	AU, CU
Fatigue (0 = none, 5 = very)										
Neck	1.29	1.20	1.40	1.05	2.00	0.88	2.93	1.44	p = 0.003	AU, CU
Shoulder	0.64	0.74	0.90	1.00	0.83	0.73	3.71	1.20	p < 0.001	AU, CU, SU
Hands and forearm	0.79	0.80	1.00	0.88	0.67	0.75	3.58	1.36	p < 0.001	AU, CU, SU
Low back	0.79	0.80	1.10	1.00	1.33	0.85	3.00	1.24	p < 0.001	AU, CU
Leg	0.64	0.74	0.90	1.07	0.67	0.75	2.14	1.23	p = 0.001	AU, CU, SU
Comparison Ranking (1 = best, 4 = worst)										
Set-Up	1.93	0.83	1.64	0.92	2.50	1.38	2.50	1.16	p = 0.01	CS
Moving	1.93	0.83	1.64	0.92	2.50	1.38	2.57	1.09	p = 0.006	CS, CU
Ease of Use	1.93	0.83	1.45	0.82	2.50	1.38	2.79	0.97	p < 0.001	CS, CU
Accuracy	2.14	0.95	1.36	0.67	3.00	1.10	2.43	0.94	p = 0.002	CS, CU
Work speed	2.00	0.88	1.64	0.81	2.83	1.17	2.71	0.99	p = 0.001	CS, CU
Comfort	1.71	0.61	1.45	0.82	2.67	1.21	3.14	0.77	p < 0.001	AS, AU, CS, CU
Stability	1.71	0.73	1.73	0.79	2.83	1.17	3.00	0.88	p < 0.001	AS, AU, CS, CU
Adjusting	2.21	0.97	1.64	0.81	3.00	1.10	2.43	1.02	p = 0.03	CS
Overall	1.86	0.53	1.36	0.81	2.67	1.21	3.00	0.88	p < 0.001	AU, CS, CU

^a Friedman chi-square test.

^b Tukey test (A = Adj Castor Base, C = Collar Base, S = Spring Base, U = Usual Method).

(55%), comfort (73%), stability (45%), adjusting (55%), and overall (82%). The Adjustable Castor tied for most preferred for the categories of comfort, stability, and overall. The usual method and the Spring Base intervention were the least preferred across the categories, with the usual method being the least preferred for the overall rating.

From the open-ended questions, the most positive comments were for the Collar Base intervention and the Adjustable Caster Base interventions. Subjects found the Spring Base intervention not as durable, difficult to stabilize, and cumbersome to adjust. The Collar Base was reported to be more stable, easier to move, more durable, and handled better than the other methods. The Adjustable Caster Base performed better on uneven surfaces than the Collar Base because the caster heights could be adjusted to keep all four wheels on the ground whereas the four wheels of the collar base would rock in those conditions. The Adjustable Castor Base required that the subject kneel or bend over in order to turn the castor height adjustment knobs, a process that was slow. Some subjects complained about thumb fatigue with the momentary action switch used on the intervention devices.

With the Collar Base intervention, the column was easier to align to vertical and lock. The adjustment was done at waist level and the bubble levels were at eye height. Compared to the usual method of drilling, the inverted drill press design required less force to raise and to drill. For all three interventions, the increased distance from the drill to the construction worker decreased the dust, noise, and vibration exposure that were problematic with the usual method for drilling. Rolling the devices to the locations where the holes were to be drilled was generally easy. However, moving over obstacles on the ground, such as cords or debris, would slow down the process. In all the testing done, the ceiling height exceeded the inverted drill presses maximum working height of 3.5 m, so subjects added a fixed extension to the column shaft in order to reach ceiling heights of up to 4.7 m or they used the interventions in a

scissor lift. Although functional, the column extensions were heavy and in many cases, with the extension in place, the device had to be tipped over to maneuver around overhead obstacles.

Subjects made numerous suggestions for improving the designs of the intervention devices. These included using wheels with improved bearings (i.e., less slop); larger wheels; air or foam filled tires to move over small obstacles; a hand wheel with a revolving handle instead of the three spokes handle for cranking the column upward; cover pinch points; improve cord management, change drill on-off switch to one with less force to activate; add method to switch drill into reverse; move hand controls to lower height; score the column at eye level so that drilling depth can be monitored without looking up; mount a laser near the drill in order to target marks on ceiling; better stop to know when drill depth was achieved; and add a light near the drill in order to better view the ceiling.

4. Discussion

The changes incorporated into the Generation 2 overhead drilling devices reversed the negative assessment of the Generation 1 designs and led to better usability ratings when compared to the usual method. The design changes that helped improve usability ratings included adding casters, decreasing the device weight, and modifying the design to decrease the setup time. Overall, the Collar Base design received the best usability ratings while the Spring Base design and usual method received the lowest usability ratings. Subjective fatigue ratings were the lowest for the Collar Base and Adjustable Castor Base designs in comparison to the usual method. Finally, in the comparison rankings, the Collar Base design was rated the best followed by the Adjustable Collar Base. The Spring Base and usual method received the lowest rankings.

The Collar Base was the preferred method for aligning the column to vertical. The primary problem with the Adjustable Caster base design was that it was more fatiguing and took extra time than the other methods to repeatedly bend over to adjust the wheels. The Spring Base was difficult to maintain in a vertical orientation while advancing the drill upward toward the ceiling. Although a four wheel base provides a larger floor contact area for preventing tipping, the construction workers recommended that a three wheel base, with larger distance between wheels, would be just as stable and would have less wobble on an uneven surface.

There was some concern that use of the interventions would lead to more neck extension and neck fatigue associated with looking up at the ceiling. However, this was not the case — neck fatigue was greatest with the usual method. Some of the recommended changes to the Generation 2 designs, such as scoring the column to monitor drilling depth, could lead to even less neck extension.

4.1. Summary

The field-testing of the first intervention designs for overhead drilling was critical to improving the usability of the Generation 2 devices. The changes that most improved usability were the addition of castors and decreasing the weight to improve mobility. Adding design features to allow the column to be aligned to vertical also improved usability. Experienced workers played 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 nuances and the obvious advantages and disadvantages of its application (Schneider, 2006). Additional, relatively minor changes to the Generation 2 devices were recommended by the construction workers in the study. These recommendations should be incorporated into a new prototype and field-tested (Rempel et al., 2010). A lesson from this study is that intervention devices designed to improve health and safety in the construction sector should be evaluated by construction workers familiar with the work and tested in diverse field settings.

5. Impact on Industry

Few interventions have been developed for reducing upper extremity musculoskeletal disorder risk factors associated with overhead work in construction. This study demonstrates the feasibility of developing an intervention device for overhead drilling that can reduce shoulder fatigue. The 'Collar Base' design may be useful for other overhead construction activities such as lifting and supporting building materials (e.g., piping, ducts) that are installed near the ceiling. Finally, the study demonstrates the value of several rounds of redesign and usability testing at real workplace settings before settling on a final design.

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