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A universal rig for supporting large hammer drills: Reduced injury risk and improved productivity

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ABSTRACT

Drilling holes into concrete with heavy hammer and rock drills is one of the most physically demanding tasks performed in commercial construction and poses risks for musculoskeletal disorders, noise induced hearing loss, hand arm vibration syndrome and silicosis. The aim of this study was to (1) use a participatory process to develop a rig to support pneumatic rock drills or large electric hammer drills in order to reduce the health risks and (2) evaluate the usability of the rig. Seven prototype rigs for supporting large hammer drills were developed and modified with feedback from commercial contractors and construction workers. The final design was evaluated by laborers and electricians ($N = 29$) who performed their usual concrete drilling with the usual method and the new rig. Subjective regional fatigue was significantly less in the neck, shoulders, hands and arms, and lower back when using the universal rig compared to the usual manual method. Usability ratings for the rig were significantly better than the usual method on stability, control, drilling, accuracy, and vibration. Drilling time was reduced by approximately 50% with the rig. Commercial construction contractors, laborers and electricians who use large hammer drills for drilling many holes should consider using such a rig to prevent musculoskeletal disorders, fatigue, and silicosis.

1. Introduction

Drilling into concrete is a physically demanding task associated with exposure to hand vibration, noise, silica dust and high forces to the upper body. These exposures are associated with whole body fatigue, upper body musculoskeletal disorders, hand arm vibration disorders, noise induced hearing loss, and silicosis (Flanagan et al., 2006; Herberts et al., 1984; Miranda et al., 2008; Palmer et al., 2000; Edwards and Holt, 2006; Shepherd et al., 2009; Balmes, 2007). In commercial construction, drilling holes into concrete is a common task for placing anchor bolts or for setting rebar for retrofitting and seismic upgrades, e.g., dowel and rod drilling (Fig. 1). For example, approximately 25,000 1″ diameter, 12″ deep holes were drilled recently on a sound wall expansion job in the Bay Area. On a concrete bridge structural upgrade, laborers drilled 5000 1″ diameter holes each 12″ deep. The work is usually done with large (10–36 lb) pneumatic rock drills or electric hammer drills. The work is exhausting; high forces are required to both support the drill and to push the drill into the concrete and these high forces and handle vibration are transmitted through the hands, arms, shoulders and back (Hagberg, 1981). The typical hand vibration levels are 8–16 m/s^2 for hammer drills and 14–20 m/s^2 for pneumatic rock drills (Griffin et al., 2006) – much higher vibration levels than most vibrating hand tools.

Many trades drill into concrete or stone, especially laborers (814,470), brick and block masons (57,090), cement masons (135,200), carpenters (567,820), electricians (519,850), and plumbers (340,370) [BLS employment numbers 2012]. In 2012 the nonfatal injury rate for highway, street and bridge construction (NAICS 2373) was 4.2 per 100 FTE, and for foundation, structure and building exterior (NAICS 2381) was 4.7; both were well above rates for all construction (3.7) and for all of private industry (3.4) (BLS, 2014). Although many of these are traumatic injuries, many are also sprains and strains associated with tool use.

Devices to support smaller hammer drills for just overhead drilling have been developed (Rempel et al., 2010) and commercialized (e.g., DrillRite, Telpro Inc, Grand Forks, ND). In addition, large air powered devices have been developed for supporting and simultaneously driving multiple pneumatic rock hammers into concrete for tarmac, highway, and structural upgrades (e.g., E-Z

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Fig. 1. Usual method for drilling with a 36 lb pneumatic rock drill to drill hundreds of holes for structural upgrade to concrete columns supporting train tracks.

Drill Inc, Stillwater, OK; Minnich Manufacturing Inc, Mansfield, OH). However, no smaller support devices exist for use from the ground, scaffolding or scissor lifts with easy manual advancement of the drill and easy adjustment of drilling height and angle.

The goal of the current study was to use a participatory process with construction workers to develop a new rig to support large hammer drills and evaluate the productivity, fatigue and usability in comparison to the usual method for drilling in commercial construction settings. Other aims were to reduce exposure to hand vibration and respirable silica dust. The intention was to design a universal rig that could use pneumatic rock drills or electric hammer drills of many sizes and shapes. The long-term aim of this line of research is to develop interventions for concrete drilling and grinding that will reduce fatigue, risk factors for upper extremity musculoskeletal disorders, and respirable silica dust exposure while not interfering with productivity.

Previously, we demonstrated that an early version of the universal drilling rig, when used with a pneumatic rock drill, reduced mean respirable silica dust from 0.68 to 0.30 mg/m^3 (the NIOSH REL (recommend exposure limit) is 0.05 mg/m^3; NIOSH, 2002). Drilling with the rig and dust control reduced the level to 0.04 mg/m^3 (Cooper et al., 2012).

2. Methods

2.1. Study sites and subject recruitment

Commercial construction sites where drilling into concrete with large electric or pneumatic hammer drills was to be performed were identified with outreach to general, highway and electrical contractors. Full-time construction workers who would be drilling for one or more days were recruited to the study. The construction workers performed their usual work and received their usual pay during their participation in the study. The study was approved by the university committee on human research.

2.2. Participatory feedback: design of the universal drill rig

The first prototype was designed by the researchers and included a base with wheels, a 5′ double vertical strut column, a carriage that rode up and down the column, a barrel attached to the carriage that could be adjusted to different heights and angles with bolt pins. The barrel had a sliding tube system that extended with a cranked linear gear (12:1). At the end of the barrel was a saddle that held the drill. A cable wrapped around the drill trigger and activated the drill when remotely tensioned. Thus, drilling could be done from horizontal to vertical and at different heights. The drill saddle was secured to the barrel with a spring mount so that drill vibration was dampened between the carriage and the saddle (Fig. 2).

The rig went through seven design modifications based on observations of use in the field, feedback from construction workers, and observed wear patterns on the rig. After each worker used the rig a short questionnaire was administered that used open ended questions to ask about the positive and negative features of the rig and recommended changes to improve the design. Bushings were added to the main drive axle/gearbox interface to improve serviceability of wearing parts. An electric winch was added to raise and lower the carriage, barrel and drill based on feedback that it was heavy to lift by hand and took too long. The carriage attachment to the vertical column was replaced with a brake caliper to allow the barrel to be rapidly rotated and securely locked at any angle over a 360° range. This change was made because the prior process for changing the drilling angle was slow and had discrete locking locations that limited the selection of drilling angles. Rolling bearings were added to the sliding tubes in the barrel because near full extension extending or retracting the drill required high crank forces to overcome sliding friction. The saddle was redesigned to accommodate almost any drill because the drills used by contractors varied widely in manufacturer and size. The design of the drill trigger activation mechanism was changed to improve reliability. A T-bar was added to the end of the barrel to allow simultaneous drilling with 2 drills. This was recommended by the electrical workers in order to drill two aligned holes for brackets and improved productivity. The rig was designed to be modular so that the base could be changed and the rig could be used in a scissor lift. The dimensions and weight of the final rig were: 20″$W \times$ 32″$L \times$ 68″H at 215 lbs (Fig. 3).

2.3. Field testing

The commercial construction workers who participated in the field study were union laborers ($N = 22$) and electricians ($N = 7$). All were male journeymen with 1–38 years of experience in the trade. Eighteen were Hispanic, seven were White, two were Asian and one was Black. The mean age was 40 (±9) years, the mean height was 175 (±9) cm, and the mean body mass was 86 (±14) kg. Participants reported that they typically used a hammer drill 4 days per month (range 1–15 days).

The field data collection was carried out at commercial construction sites that involved structural upgrades (e.g., dowel and rod) or drilling holes for large anchor bolts. The holes for structural

Fig. 2. Construction workers using early versions of the universal rig with an electric hammer drill on a stadium upgrade (left) and a pneumatic rock drill on a train tower (right).

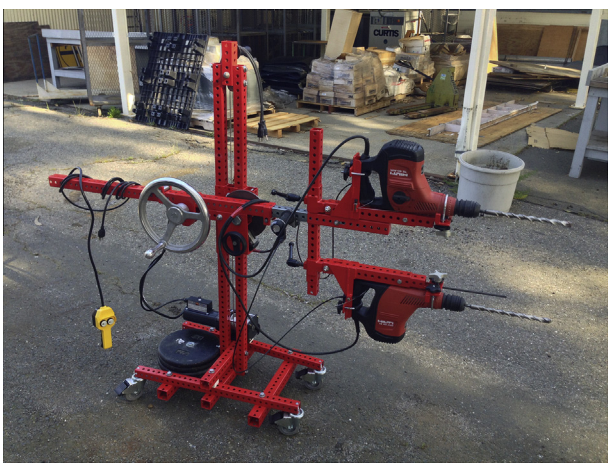

Fig. 3. Final design of universal drilling that can drill 2 holes simultaneously into concrete. Drills are supported in saddles that are attached to a T-bar mounted to the end of the barrel. Turning the round aluminum handle advances the activated drills into concrete. The small black round handle locks the barrel at the desired angle. The barrel is raised and lowered on the vertical columns with an electric winch.

upgrades are typically 7/8″ in diameter and 4–12″ deep. After all the holes are drilled, they are filled with epoxy and rebar is inserted. Concrete is then poured next to the old structure to increase the overall stability of the structure. This work was done at a highway sound wall, a highway bridge, a sports stadium, train towers and a commercial office building. The holes were drilled horizontally, vertically or at other angles. The drilling was done from the ground, from a scaffold and in a scissor lift. Drilling height was anywhere from knee to the shoulder height. Electric hammer drill or pneumatic rock drills were used and the drills weighed between 12.5 and 36 lbs. The electrical workers drilled 3″ deep holes for ¾″ anchor bolts into the ceiling of a tunnel for hanging 6″ conduit.

A workday was selected for testing where the construction worker would be spending a full day drilling hundreds of holes in relatively the same way. Subjects spent half of the day drilling with the rig and half of the day drilling with the usual method (order randomized). This ensured comparison of the two methods under identical drilling conditions (e.g., ceiling height, scissor vs. floor, diameter and depth of holes). At the beginning of the day, each participant completed a brief *demographic* questionnaire to assess age and construction experience. After each method of drilling was completed, the participant completed a *device* questionnaire to assess usability and fatigue. Usability was rated for various features, such as setting up, moving to next hole, drilling, accuracy, control, stability, and vibration; each on a 6-point scale from 0 = poor to 5 = excellent. Fatigue was rated for neck, shoulders, hands and forearms, low back and legs; each on a 6-point scale from 0 = no fatigue to 5 = very fatigued. The questionnaire also solicited positive and negative features of the device.

Prior to using the drilling rig workers received a 10 min training where they were trained how to move and set up the rig, adjust the height and angle, set up dust capture, lock the wheels, turn on the drill, advance the drill, and retract the drill.

When permitted by the construction site owner, contractor and participant the drilling was videotaped for approximately 8 holes and the video was later analyzed to estimate productivity (time to drill one hole) and duty cycle for drilling (e.g., % time drilling).

2.4. Laboratory analysis of handle vibration and hand force

In a laboratory setting, drill handle vibration acceleration magnitude was measured and interpreted according to ISO and EU standards (ISO 28927-6&10 (old ISO 8662-3); CEN/TR 15350:2006). Tri-axial accelerometers were calibrated (PCB Piezotronics shaker 394C06) and attached to the tool at the locations of the primary handgrip or hand contact and the signals were stored on a PC (Larson Davis, HVM100). An electric hammer drill (Hilti, TE40) was used with a ¾″ concrete bit. Three experienced construction workers drilled ten 5″ deep holes horizontally into a concrete block with and without the universal rig.

Hand forces applied during vertical and horizontal drilling with and without the rig were estimated using empiric data and modeling. Three experienced construction workers drilled vertically into concrete block using the usual method with an electric hammer drill (Hilti, TE40) and a 5/8″ concrete bit. Upward thrust force while drilling was measured while subjects stood on an electronic force plate (Acculab Digital Scale, Bradford, MA) and the data were sampled at 25 Hz on a laptop computer. Subjects were instructed to drill at their usual rate. The drill, bit and subject weight were subtracted from the force data to calculate applied upward force during drilling. To estimate the hand force during the usual method of vertical drilling the drilling force was added to the drill and bit mass (12.5 lb). To estimate the hand force during horizontal drilling the drilling force was summed with the drill and bit mass using the square root of the sum of the squared forces. To estimate the hand force for vertical drilling using the rig the combined drill, column and saddle mass (35.9 lb) were added to the drilling force and multiplied by 1/12 (the mechanical advantage of the linear gear). To estimate the hand force for horizontal drilling using the rig, the drilling force was summed with the rig column friction force (5.0 lbf) and multiplied by 1/12.

The required shoulder force for vertical drilling, as a percent of strength (%MVC) was modeled for the median 25th percentile female (3DSSPP, U. Michigan) and evaluated against maximum effort fatigue curves in the literature (Potvin, 2012) using the observed duty cycle for drilling.

2.5. Data analysis

To calculate productivity, the videotapes were evaluated frame-by-frame to identify the drilling time for each hole. If rebar was struck during drilling, and the drill was repositioned, the hole was not counted. Drilling time was measured for five typical holes. Productivity data was measured for both the usual method and drilling with the rig. Although not always achieved, the intention was to compare the two methods of drilling done by the same worker while drilling the same hole diameter and depth at a similar location relative to the body (e.g., shoulder or waist height). Other work not involving drilling (e.g., moving between holes, talking to other workers, inserting anchors, taking breaks) was not included in the productivity analysis.

The effects of drilling method on subjective ratings and productivity measures were statistically tested using repeated measures ANOVA and differences were considered significant if $p < 0.05$ (SAS, v 9.2, Cary, NC). Dependent variables were tested for normality. Differences in handle vibration between methods were also evaluated with repeated measures ANOVA.

3. Results

The usability and fatigue ratings for the usual method of drilling and the rig are summarized in Figs. 4 and 5. Drilling with the rig was rated superior to the usual method on usability measures of *drilling*, *accuracy*, *control*, *stability*, *and vibration*. The mean levels of perceived fatigue were lower in all five body regions when drilling with the rig compared to the usual method but the differences were significant for four body regions: neck, shoulders, hands and forearms, and low back. Importantly, all significant findings were in the same direction, that is, the rig performed better than the usual method.

Video productivity analysis was available for six subjects who performed similar drilling activities using both the usual method and the rig (Fig. 6). Three subjects drilled with pneumatic rock drills and three subjects drilled with large electric hammer drills; in both groups drilling was faster with the rig. The mean drilling time, combining data from both pneumatic and electric drilling, to use the full sample of six, was reduced by approximately 50% (103.3 s (±50.8)

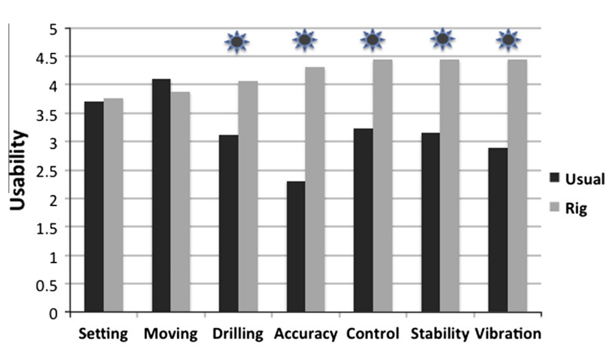

Fig. 4. Mean usability ratings (0 = poor, 5 = excellent) comparing the usual manual method of drilling to drilling with the rig ($N = 27$). Significantly different ratings ($p < 0.05$) for those who drilled with both methods are marked with a '⁎' ($N = 16$).

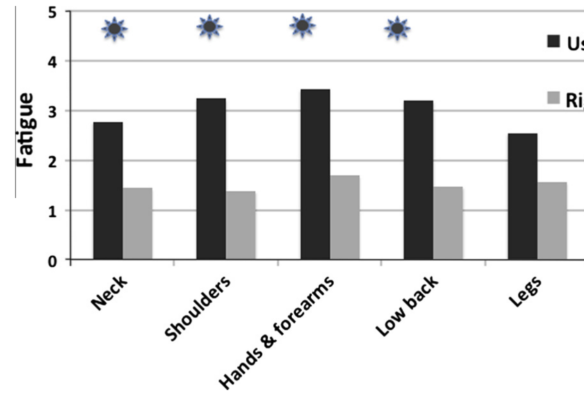

Fig. 5. Mean self-reported fatigue ratings (0 = no fatigue; 5 = very fatigued) in five body regions after drilling with each method for 2 or more hours ($N = 29$). Significantly different ratings ($p < 0.05$) for those who drilled with both methods ($N = 16$) are marked with a '⁎'.

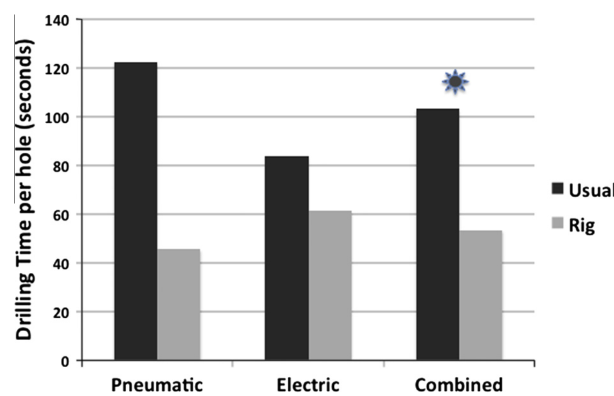

Fig. 6. Productivity: mean drilling time per hole comparing the usual method to drilling with the universal rig during identical drilling conditions in the field. When combined ($N = 6$), productivity was significantly better ($p = 0.03$) with the rig when compared to the usual method.

vs. 53.6 s (±24.6); $p = 0.036$)) with the rig. Duty cycle for drilling was measured from videos for an average of 5 holes per person for 14 workers drilling with the usual method and 17 workers drilling with the rig. The mean duty cycle for drilling with the usual method was 73% (±23%) and for the rig was 57% (±24%).

A laboratory study evaluated handle vibration while 3 construction workers drilled into concrete using the usual method and the universal rig (International Orgnanization for Standardization, 2011). The mean handle vibration during drilling was higher with the usual method than with the rig (9.04 (±0.81) vs. 3.26 (±0.03) m/s^2; $p = 0.007$).

The estimated hand force while drilling vertically was greater with the usual method than the rig (58.3 (±5.8) vs. 6.8 (±0.5) lbf). Similarly, for horizontal drilling, the estimated hand force for the usual method was higher than the rig (47.5 (±5.8) vs. 4.2 (±0.5) lbf).

4. Discussion

A rig for supporting large hammer drills was developed and refined based on worker feedback. The rig was evaluated by constructions workers performing their usual work and found to improve usability and regional body fatigue when compared to the usual method for drilling. Very importantly, from the contractors' perspective, productivity was also improved with the rig.

The participatory design process with construction workers performing their usual tasks was critical to improving usability. During development, seven different prototype rigs were built with incremental improvements based on observations of use in the field or recommendations from workers. This feedback led to improvements in the gearing system, the addition of an electric winch for height adjustment, modifications to allow for drilling with two drills simultaneously and other important changes.

The final design rig was tested by 29 commercial construction workers who found that the usability with the rig was better than the usual method on drilling, accuracy, control, and stability. While the rig has wheels and is easy to move around a construction site with a smooth floor, it weighs 215 lbs and requires a lift or ramp to deliver. The base is detachable so that the rig can be used on a scissor lift or scaffold. The extra time for setup makes the rig most useful when drilling many holes (e.g., greater than 20).

The reduction in regional body fatigue with the final design rig is likely due to the reduced hand forces and reduced time required for drilling compared to the usual method (Anton et al., 2001). For vertical drilling, the mean estimated hand force was reduced from 58.3 to 6.8 lbf. The shoulder muscle forces required for vertical drilling with the usual method were compared to drilling with the rig for the 25th percentile female using a static strength prediction program (3DSSPP, v.6.0.2, University of Michigan, Ann Arbor, MI). 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 59% of strength (e.g., maximum voluntary contraction (MVC)) and when drilling with the rig was 10% of strength. Applying the shoulder force data and the observed duty cycle to the maximum effort equation of Potvin (2012) reveals that drilling would be fatiguing with the usual method but not with the rig.

Construction workers reported less hand vibration when using the rig compared to the usual method. A laboratory study evaluated handle vibration with an electric hammer drill comparing the usual method to the rig and found a mean reduction from 9.04 to 3.26 m/s^2. Using the EU 2002 Physical Agents Directive action value of 2.5 m/s^2, this difference in handle vibration translates to an increase in permitted drilling time per day from 37 min to 4 h and 42 min (European Community Directive, 2002; Griffin et al., 2006; HSE, 2005; ACGIH, 2013). It is likely that the impact of vibration reduction with the rig would be even greater if measured with pneumatic rock drills.

Several limitations of this study should be noted. While the study included participants from a variety of trades who used several types of large hammer drills in varied workplace settings there were no female participants. We sought female construction workers to participate but there were none at the study sites. It may be that women select out of this particular type of work because of the physical demands. Because the rig requires less hand and arm loads it may allow more women and men to use large hammer drills. The rig might also allow workers with upper body and back injuries to return to work earlier than usual.

The field-testing of prototype drilling rigs by experienced construction workers and their feedback on design was key to improving the usability of the rig. Experienced construction workers and contractors are experts in the work and can identify the advantages or disadvantages of various design features of safety interventions (Schneider, 2006). They are the ones most impacted by work design and can identify the settings where a drill rig may be beneficial or an unwanted intrusion.

5. Conclusion

A rig for supporting large hammer drills was designed and improved using a participatory process in the field involving commercial construction workers. The final rig design allowed workers to drill one or two holes simultaneously, at different heights and angles with improved productivity and reduced regional fatigue compared to the usual method. The key design elements that reduced fatigue were the support structure that transferred drill weight and drilling force to the floor; the linear gear that reduced hand force during drilling; and the spring dampener that reduced hand vibration. Other features that improved usability and productivity were good mobility with appropriate wheels; methods for rapidly adjusting drilling height and angle; the reduced hand forces; and effective dust capture. New interventions for improving the health and safety of construction tasks should undergo multiple rounds of field-testing with experienced workers in order to optimize the tool's usability and productivity.

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