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The Effect of Passive Shoulder Exoskeletons on Shoulder and Torso Muscle Electromyographic Activity During Simulated Overhead Drilling Tasks

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Abstract: Occupational shoulder injuries have been associated with working with hands above the head, either repeatedly or with sustained durations. Passive shoulder exoskeletons have gained interest within the manufacturing sector with the prospect of reducing shoulder injuries. The objective of this study was to assess the impact of four different passive shoulder exoskeletons on shoulder and torso muscle activation compared to no exoskeleton during overhead drilling. Simulated overhead drilling tasks were performed by 17 aircraft workers wearing four different passive shoulder exoskeletons. The drilling task postures included 1) upper arm horizontal, elbow 90°, push the drill vertically, and 2) upper arm horizontal, elbow 135°, push the drill horizontally. Electromyographic signals from bilateral pairs of the anterior and medial deltoids, trapezius, latissimus dorsi, and erector spinae were captured and normalized to maximum voluntary contractions (MVC). Repeated measures one-way ANOVAs followed by a Dunnett's post-hoc test comparing each exoskeleton to the no-exoskeleton condition for the difference in percent MVC were performed for the drilling exertions and time-between drilling exertions. For the vertical drilling exertions (Task 1), all exoskeletons significantly decreased the dominant and non-dominant medial deltoid percent MVC during drilling exertions and time between exertions, and consistently reduced the dominant anterior deltoid for the time-between drilling exertions. For the horizontal drilling exertions (Task 2), the majority of the exoskeletons decreased the dominant and non-dominant anterior and medial deltoids percent MVC, for the drilling exertions and time-between drilling exertions. Greater benefit to both anterior and medial deltoids appeared to be gained during horizontal drilling exertions compared to vertical drilling exertions. While these laboratory results are encouraging in terms of reducing muscular exertions, these devices must be evaluated in worksite studies to better assess their efficacy.

Keywords: passive shoulder exoskeletons, electromyography, drilling tasks

1. Introduction

Work-related musculoskeletal disorders (WMSDs) of the shoulder, such as rotator cuff tendinitis, shoulder pain and bicipital tendinitis, contribute to lost-time and elevated medical-related costs for companies engaged in manual work activities. The U.S. Bureau of Labor Statistics (BLS, 2020) reported that 14.9% of lost-time cases in 2019 involved the shoulder region, and although lost-time shoulder cases were less than half of lost-time back cases (3.9 vs. 9.6 cases per 10,000 FTE) shoulder cases resulted in approximately three times the duration of lost-time compared to cases involving the back (22 days vs. 7 days). Dunning et al (2010) found that total workers compensation cost for claims involving the shoulder ranked second behind claims involving the lumbar spine. Epidemiological investigations have shown that work involving sustained and/or repeated arm elevation and working with the elbows above shoulder level increases the risk for WMSDs of the shoulder (Waersted et al, 2020; van der Molen et al, 2017), where moderate evidence for an exposure-response relationship exists between intensity level and duration of arm elevation (Waersted et al, 2020).

Recent advances in wearable technology have resulted in the development and strong interest in wearable exoskeletons to assist the users with their manual work activities. According to de Looze et al (2016) "an exoskeleton can be described as a wearable, external mechanical structure that enhances the power of a person". Passive exoskeletons utilize materials, springs or dampers with the ability to store energy harvested by human motion, ultimately using this to support a posture or motion (de Looze et al, 2016). As interest in these upper limb exoskeletons rises, studies are being conducted to assess the effectiveness in reducing the mechanical loading on the shoulders while performing overhead work. Numerous laboratory studies have been performed assessing the impact of various passive upper limb exoskeletons on simulated occupational tasks such as overhead drilling (Alabdulkarim and Nussbaum, 2019; Kim and Nussbaum, 2019) and overhead wiring (Kim and Nussbaum, 2019), with most studies showing reduced shoulder muscle activity utilizing the exoskeletons.

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A recent systematic review of the passive upper limb exoskeleton research literature found moderate evidence that passive upper limb exoskeletons reduce muscular demands for overhead work, particularly to muscles responsible for shoulder elevation (e.g., anterior deltoid, medial deltoid) (McFarland and Fischer, 2019), and that research quality can be improved by including samples representative of industrial workers. Given that many laboratory studies were performed using one passive upper limb exoskeleton as well as participants not representative of industrial workers, the objective of this study was to assess the impact four different passive upper limb exoskeletons on shoulder and torso muscle activity during two simulated overhead drilling tasks similar to that found in an aircraft manufacturing environment, utilizing experienced aircraft manufacturing participants.

2. Methods

2.1 Participants

The participants for this study consisted of 17 (9 males, 8 females) experienced employees recruited from a local aircraft manufacturing facility. The mean (SD) age, height, weight, and years of experience was 43.0 yrs (7.5), 177.9 cm (14.1), 108.0 kg (21.1) and 21.7 yrs (8.1), respectively for the male participants, and 44.1 yrs (7.8), 162.0 cm (5.3), 71.7 kg (13.1) and 15.6 yrs (7.0), respectively for the female participants.

2.2 Experimental Equipment

Four different passive shoulder exoskeletons were utilized in this investigation, including an EksoVest (Ekso Bionics, Richmond, CA, USA), a Skelex 360XFR (Skelex, Rotterdam, The Netherlands), a Paexo (Ottobock, Duderstadt, Germany), and a ShoulderX (SuitX, Emeryville, CA, USA). While each of these exoskeletons had differences in design, attachment methods to the users, adjustment capabilities to fit users of different anthropometries, as well as how to set different resistance levels, similarities among the exoskeletons included a waist belt, arm cuffs to support the arms, as well as connections to attach the exoskeleton to the torso.

Electromyographic (EMG) muscle activity was collected using a Noraxon TeleMyo G2 2400R telemetry 16-channel EMG system (Noraxon USA, Inc., Scottsdale, AZ) sampled at 1,200 Hz, utilizing pre-gelled bipolar Ag/AgCl (2-cm spacing) electrodes. The experimental postures were attained for each participant by use of an adjustable structure that also contained a rigid surface utilized to push the drill against. This structure was adjustable vertically and horizontally to account for participants' differing anthropometry and to allow consistent elbow and shoulder postures for each participant (Figure 1 and Figure 2). Participants utilized a 0.5 kg pistol grip drill connected to an air hose and performed the drilling exertions by inserting the drill into a fabricated drill guide with a built-in calibrated load cell to measure drilling push force, where the real-time drilling force exerted was displayed visually to participants during the experimental trials.

2.3 Experimental Procedure

Upon arrival to the laboratory, participants were briefed on the study objectives and protocol, and signed an informed consent form approved by the Wichita State University Institutional Review Board for Human Subjects Research. Demographic (age, years of aircraft manufacturing experience) and anthropometric dimensions (e.g., stature, weight) were recorded followed by the application of the EMG electrodes. The electrode sites were scrubbed with alcohol wipes to reduce resistance and applied using the standardized procedures by Zipp (1982) for the right and left sides of the anterior deltoid, medial deltoid, trapezius, latissimus dorsi, and the lumbar erector spinae muscles, with a ground reference electrode secured over the dominant lateral olecranon. Following the application of the EMG electrodes static maximum voluntary contractions (MVC) were elicited from each of the muscles by performing two five-second exertions against manual resistance provided by the research assistants, where each exertion was separated by one minute of rest.

Following the MVC exertions the testing structure was adjusted for the participant to achieve the specific elbow and shoulder postures for both drilling tasks investigated. Specifically, Task 1 consisted of the upper arm in a horizontal position (90° shoulder flexion) and the elbow flexed 90° (Figure 1) and Task 2 consisted of the upper in a horizontal position (90° shoulder flexion) and the elbow in 135° extension (Figure 2). During the testing, participants pushed the drill vertically in Task 1 and horizontally in Task 2. After the testing structure was set up for the participant the experimental tasks were demonstrated to the participants, including the upper extremity postures to use, the direction of the push force, the use of the drill and drill guide and the targeted push forces, whereupon the participants were allowed to practice the experimental tasks until they achieved familiarity.

The no-exoskeleton condition was always the first condition the participants completed, followed by the four exoskeletons in a randomized order. The no-exoskeleton was always the first condition to allow participant feedback (not reported here) for each of the exoskeletons in comparison to the no-exoskeleton condition. The order of the tasks was also randomized for each exoskeleton. For the exoskeleton conditions, participants were fitted to each per manufacturer's instructions, and the resistance levels of each exoskeleton was adjusted such that arms could be held (without effort) in 90° abduction, 90° elbow flexion.

For each task-exoskeleton experimental trial, the participant started with their arms hanging down to their side, then raised arms to insert drill in drill guide against the test structure, performed five consecutive two-second 111 ± 22 N push force exertions with one-second of no force (remove the push force) in between each push force exertion, then lowered their arms to their side ending the experimental trial. This target push force was based on discussion with aircraft manufacturing personnel regarding their drilling training protocol.

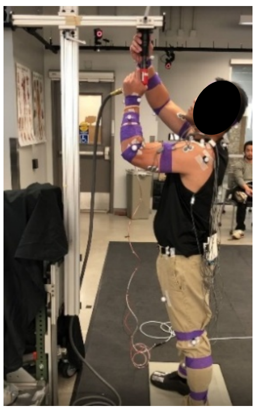


Figure 1. Task 1 postures

Figure 2. Task 2 postures

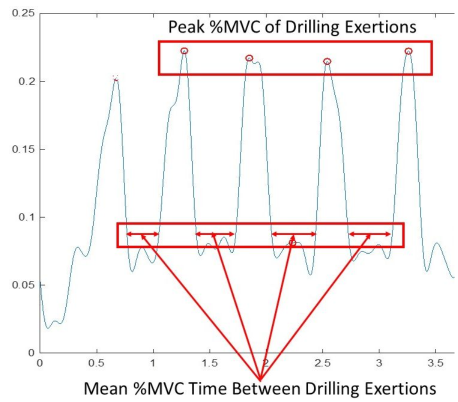


Figure 3. EMG data analysis of drilling exertions and time between drilling exertions

2.4 Data Analysis

The raw EMG signals for all MVC and experimental trials were processed by scripts written in MATLAB (MathWorks, Natick, MA), where the signals were rectified and low pass filtered (3 Hz cutoff, 4th order Butterworth) to create linear envelopes. Each experimental trial processed EMG signal was then divided by the peak processed EMG value from the MVCs for each particular muscle to determine the percent MVC for each muscle.

Drilling tasks in aircraft manufacturing consist of the actual time to drill a hole for a rivet (approximately two seconds) and the time to move the drill to the next adjacent drilling location (approximately one second). As such, both portions of the experimental trial (drilling exertion, time-between drilling exertion) were investigated separately for the impact of exoskeletons on the muscles investigated. The EMG signals from both experimental tasks were separated into drilling exertion and time-between drilling exertion portions, where the transition from exertion to time-between exertion was determined by the time corresponding to 45% of the peak exertion force across all five exertion trials. Thus, when a drilling exertion reached 45% of the peak exertion force this time determined the transition from a drilling exertion to the time-between drilling exertion, and vice versa (Figure 3). Finally, the mean of the peak percent MVC EMG for drilling exertions two through five represented the drilling exertion percent MVC whereas the mean of the mean percent MVC EMG for the four time-between drilling exertions represented the time-between drilling percent MVC.

2.5 Statistical Analysis

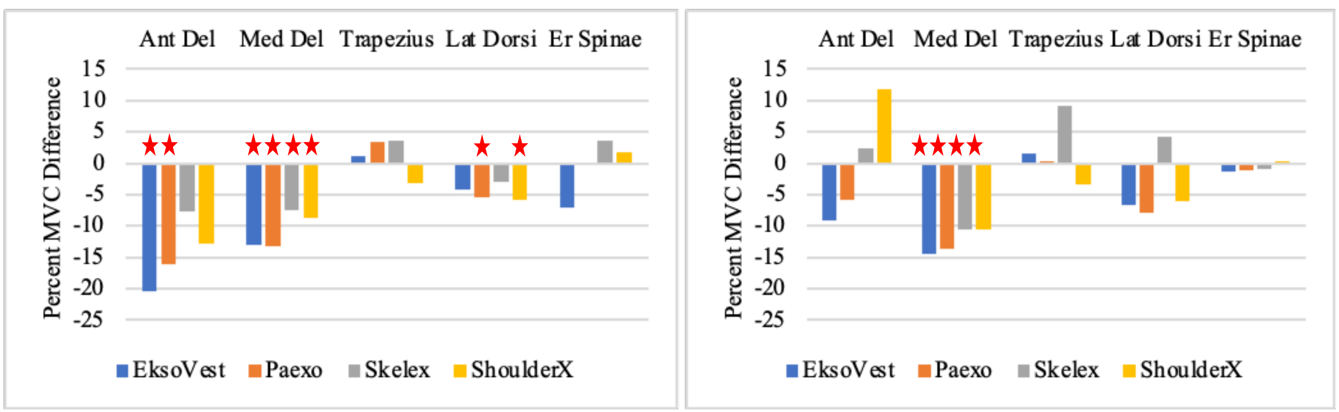
For each task and muscle combination a one-way repeated measures ANOVA was performed to determine if exoskeletons had an impact on the normalized percent MVC. For the drilling exertions the independent variable was the exoskeleton condition, and the dependent variable was the mean of the peak drilling exertion normalized EMG signals (percent MVC). For the time-between drilling exertions the independent variable was again the exoskeleton condition whereas the dependent variable was the mean of the mean normalized EMG signals (percent MVC). For all ANOVAs performed, significant exoskeleton effects ($p \leq 0.05$) were investigated via a Dunnett post-hoc test, utilizing the no-exoskeleton condition as the comparison condition. The rationale for this post-hoc test was to determine if any of the exoskeletons had a statistically significant impact the muscle activation compared to not wearing an exoskeleton rather than investigate statistical differences between exoskeletons themselves.

3. Results

The absolute difference in percent MVC for each exoskeleton from the no exoskeleton condition for Task 1 (vertical drilling exertions) and Task 2 (horizontal drilling exertions) are shown in Figures 4 and 5, and Figures 6 and 7, respectively.

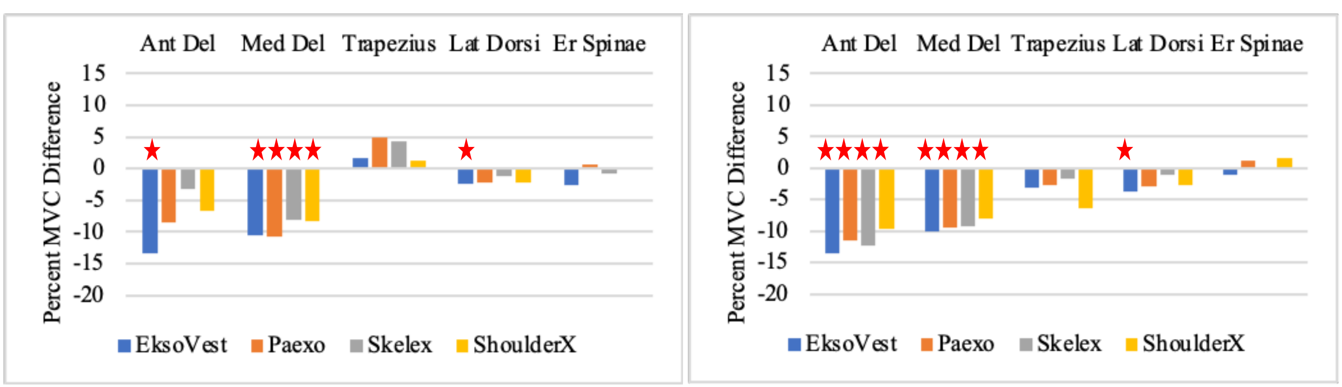
As shown in Figure 4 for the drilling exertions in the vertical direction, the medial deltoid was consistently reduced by the use of exoskeletons for both non-dominant (7% to 13%, Figure 4a) and dominant sides (11% to 14%, Figure 4b), and the non-dominant anterior deltoid (16% to 20%) and latissimus dorsi (6%) decreased significantly for two of the four exoskeletons (Figure 4a). For the time-between drilling exertions for Task 1, all four exoskeletons significantly decreased the dominant side (Figure 5b) anterior deltoid (10% to 14%) and medial deltoid (8% to 10%), whereas the exoskeletons resulted in a decrease in percent MVC primarily for the medial deltoid (8% to 11%, Figure 5a) on the non-dominant side.

As shown in Figure 6 for the drilling exertions in the horizontal direction (Task 2), all exoskeletons reduced the percent MVC for the non-dominant (Figure 6a) anterior deltoid (19% to 26%) and medial deltoid (7% to 9%), whereas the majority of exoskeletons reduced the dominant (Figure 6b) anterior deltoid (16% to 19%) and medial deltoid (13% to 17%). For the time-between drilling exertions for Task 2 (Figure 7), all four exoskeletons significantly decreased the non-dominant (Figure 7a) anterior deltoid (16% to 18%) and medial deltoid (4% to 5%), as well as the dominant (Figure 7b) anterior deltoid (8% to 11%) and medial deltoid (5% to 8%).



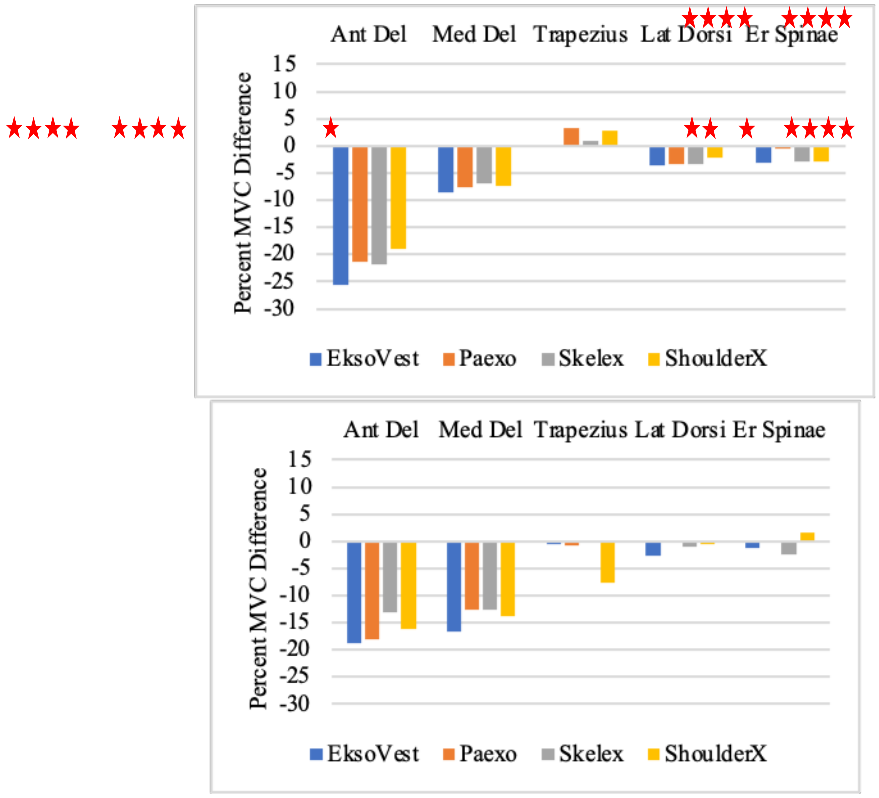
(a) (b)

Figure 4: Mean percent MVC difference between exoskeleton and no exoskeleton conditions during drilling exertions for vertical drilling (Task 1) for (a) non-dominant side muscles, and (b) dominant side muscles. Red stars indicate significant difference between exoskeleton and no exoskeleton percent MVC.



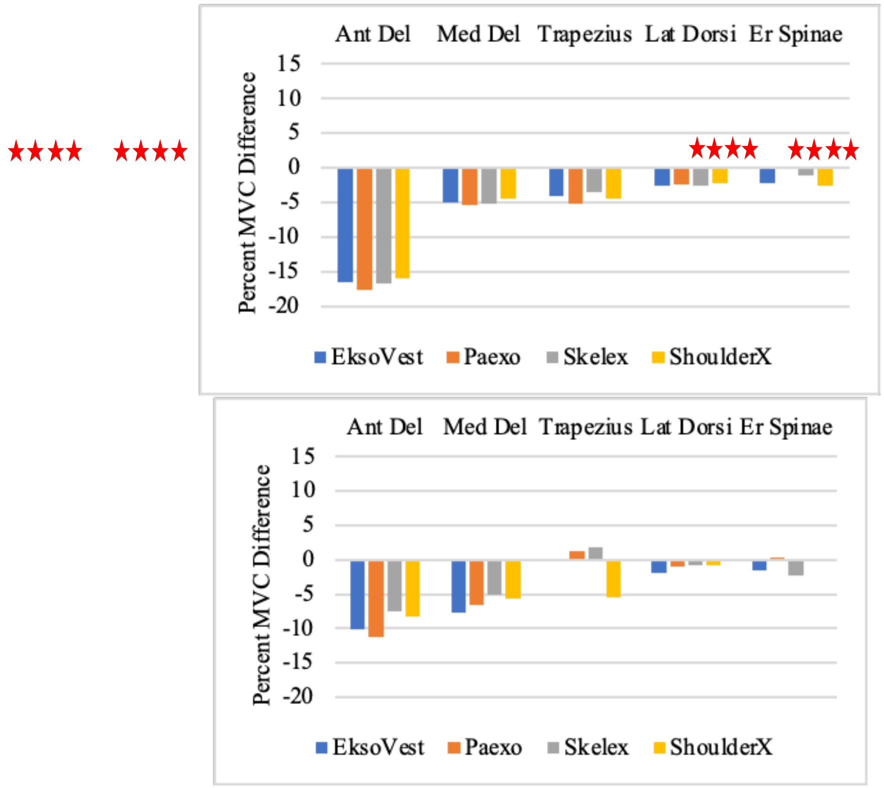
(a) (b)

Figure 5: Mean percent MVC difference between exoskeleton and no exoskeleton conditions for the time-between drilling exertions for vertical drilling (Task 1) for (a) non-dominant side muscles, and (b) dominant side muscles. Red stars indicate significant difference between exoskeleton and no exoskeleton percent MVC.



(a) (b)

Figure 6: Mean percent MVC difference between exoskeleton and no exoskeleton conditions during drilling exertions for horizontal drilling (Task 2) for (a) non-dominant side muscles, and (b) dominant side muscles. Red stars indicate significant difference between exoskeleton and no exoskeleton percent MVC.



(a) (b)

Figure 7: Mean percent MVC difference between exoskeleton and no exoskeleton conditions for the time-between drilling exertions for horizontal drilling (Task 2) for (a) non-dominant side muscles, and (b) dominant side muscles. Red stars indicate significant difference between exoskeleton and no exoskeleton percent MVC.

4. Discussion

This study investigated the impact of different passive shoulder exoskeletons on shoulder and torso muscle activity from tasks designed to mimic drilling tasks in aircraft manufacturing utilizing aircraft manufacturing employees with experience performing these types of drilling tasks. Where differences in muscle activity utilizing exoskeletons were found, most exoskeletons resulted in similar difference magnitudes compared to not using an exoskeleton.

The major findings of this study are similar to previous research on passive shoulder exoskeletons during overhead drilling, which consistently found a decrease in anterior deltoid muscle activity (Kim and Nussbaum, 2019; Alabdulkarim and Nussbaum, 2019; Alabdulkarim et al, 2019), as well as decreases in muscular demand on the anterior and medial deltoid, as presented in a review of studies (McFarland and Fischer, 2019). This study also found, consistent with other studies, little to no impact on other muscles investigated, including no significant impact on the lumbar erector spinae muscle activity (Alabdulkarim et al, 2019; Kim and Nussbaum, 2019), suggesting the force/load may not necessarily be transferred to other torso and shoulder muscles.

Drilling tasks in aircraft manufacturing is often a two-armed operation with one arm utilizing the drill and the other arm positioning and holding a drill guide. The drilling task also consists of the drilling exertion and the time to move the drill to the next adjacent drilling location. Most of the exoskeletons resulted in reduced muscle activity during the actual drilling and also during the time between drilling exertions (mimicking moving to the next drill hole location), thus, passive exoskeleton usage has the potential to reduce muscle fatigue from tasks consisting of drilling exertion and holding the arms and tools up when moving to the next drill hole location.

Most exoskeletons benefited the anterior and medial deltoids in both tasks investigated. However, a greater decrease in muscle activation was typically realized for horizontal drilling exertions compared to vertical drilling exertions for the anterior deltoid (Figure 4a vs. Figure 6a; Figure 4b vs. Figure 6b), whereas the muscle activation reduction was of similar magnitude in vertical and horizontal drilling exertions for the medial deltoid. This difference is likely due to the benefit the exoskeletons provide holding the arms up and reducing anterior deltoid muscular demand while pushing the drill forward, whereas the exoskeletons likely added less benefit to the anterior deltoid when pushing the drill upward. The exoskeletons also provided more benefit for the non-dominant anterior deltoid for horizontal drilling than vertical drilling during the time-between drilling exertions (Figure 7a vs. Figure 5a), which may be due to differences in non-dominant arm posture when holding the drill guide drilling horizontally versus vertically.

This study should be viewed with several methodological limitations. First, this was a controlled laboratory study with short term exposures, thus, long term impact on muscular demands and outcomes cannot be determined. Second, these were simulated drilling tasks, where the actual duration and location of tasks may vary in an actual work environment. Third, other factors that may be important in determining exoskeleton benefit were not studied, including duration of use, long-term comfort, or possible limitations of motion.

In conclusion, this study found that multiple passive shoulder exoskeletons consistently resulted in less anterior and medial deltoid muscular activation for both dominant and non-dominant sides, during the drilling exertions as well as the time-between the drilling exertions. While these laboratory results are encouraging in terms of reducing muscular demand, these exoskeletons must be also be evaluated in worksite studies to better assess their efficacy.

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