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The Impact of Passive Shoulder Exoskeletons on Muscle Activity During Simulated Aircraft Manufacturing Squeeze Riveting Tasks

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Abstract: Squeeze riveting in aircraft manufacturing is often a two-armed operation setting rivets at heights from below the elbow to above a worker's head utilizing a pneumatic riveting tool. Occupational shoulder injuries have been associated with working with hands above the head, 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 shoulder exoskeletons on shoulder and torso muscle activation compared to no exoskeleton during simulated squeeze riveting tasks. Squeeze riveting tasks were performed by 16 aircraft workers wearing three different passive shoulder exoskeletons. The tasks included simulating two-second duration squeeze riveting of 16 sequential rivets on an upper horizontal stringer (50.8 cm above the shoulder) as well as along a lower stringer (36 cm below the upper stringer). 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 Tukey HSD post-hoc tests were performed assessing differences in percent MVC due to exoskeletons. For riveting along the upper stringer, most exoskeletons significantly decreased the left- and right-side percent MVC of the anterior deltoid (9%-17%), medial deltoid (8%-11%), whereas fewer exoskeletons reduced the latissimus dorsi (2%-3%). For riveting along the lower stringer most exoskeletons decreased the left- and right-side percent MVC of the anterior deltoid (3%-7%), medial deltoid (2%-3%), whereas one exoskeleton reduced the right latissimus dorsi (3%). Greater benefit from the exoskeletons to both anterior and medial deltoids appeared to be gained during squeeze riveting along the upper stringer compared to squeeze riveting along the lower stringer. While these laboratory results are encouraging, these exoskeletons must be evaluated in worksite studies to better assess their efficacy.

Keywords: Passive Shoulder Exoskeleton, Electromyography, Squeeze Riveting

1. Introduction

Aircraft manufacturing involves utilization of hand tools to perform many tasks such as drilling and countersinking holes for rivets, sanding, and riveting and bucking to set rivets. Given the size of the aircraft manufactured, some of the tasks involve working at locations above shoulder level. 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). 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. 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). 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. Depending on the rivet size, material, and location of the rivets to be set, sometimes larger and heavier riveting tools such as pneumatic squeeze riveting tools are used. These tools are hand-held and often used at locations ranging from below the elbow to above the head. Since passive shoulder exoskeletons have the potential to reduce muscular demands during overhead work, the objective of this study was to assess the impact of three different passive upper limb exoskeletons on shoulder and torso muscle activity during simulated horizontal squeeze riveting tasks similar to those found in an aircraft manufacturing environment, utilizing experienced aircraft manufacturing participants.

2. Methods

2.1 Participants

The participants for this study consisted of 16 (8 males, 8 females) experienced employees recruited from a Midwest U.S. aircraft manufacturing facility. The mean (SD) age, height, weight, and years of experience was 44.3 yrs (11.0), 181.2 cm (5.1), 104.8 kg (14.8) and 18.0 yrs (7.2), respectively for the male participants, and 47.0 yrs (11.4), 162.4 cm (5.7), 69.7 kg (13.6) and 19.3 yrs (11.4), respectively for the female participants.

2.2 Experimental Equipment

Three different passive shoulder exoskeletons were utilized in this investigation, including an Evo (Ekso Bionics, Richmond, CA, USA), a Skelex 360XFR (Skelex, Rotterdam, The Netherlands), and a Paexo (Ottobock, Duderstadt, Germany). 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 squeeze riveting task vertical locations were attained for each participant by use of an adjustable structure which housed a simulated aircraft fuselage panel. This simulated fuselage panel contained horizontal metal stringers with rivets lined along the stringers. 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 2.7 kg pneumatic squeeze riveting tool connected to an air hose and performed the simulated squeeze riveting tasks. When participants squeezed the trigger of the squeeze riveting tool a voltage signal was sent to the data acquisition system to mark the riveting start time. The duration of the riveting for each rivet was set to two seconds to simulate the typical time it takes to complete setting a rivet with the tool. This time on the rivet was determined based on discussions with aircraft manufacturing personnel.

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, body mass) were recorded followed by the application of the EMG electrodes. The electrode sites were scrubbed with alcohol wipes to reduce resistance and applied using standardized procedures (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. Each MVC exertion was separated by one minute of rest.

Following the MVC exertions, the simulated aircraft fuselage panel was adjusted based on the participants anthropometry to ensure consistent vertical heights of the upper stringer and lower stringer across participants. The upper stringer height was set such that the midpoint of the upper stringer was 50.8 cm above the standing participants acromion process whereas the midpoint of the lower stringer was 36 cm below the upper stringer. Thus, riveting along the upper stringer was at an overhead position whereas riveting along the lower stringer was slightly above the standing shoulder height. After the simulated fuselage panel was set up for the participant the experimental riveting tasks were demonstrated to the participants, including the starting point, use of the squeeze rivet and direction of movement of the squeeze rivet gun. 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 three 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. 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.

The participants started with their arms hanging down to their side, then raised their arms to begin the simulated squeeze riveting tasks, commencing with the upper stringer. The participants started on the left side of the upper stringer and moved the tool left to right along the stringer completing eight sequential rivets, spending two seconds on a rivet before moving on to the next rivet. The EMG data collection began when the participants positioned the tool on the first rivet and ended after the last of the eight rivets was completed. Once the eight rivets were completed on the left side of the stringer the participants moved the squeeze rivet tool to the right side of the upper stringer and moved right to left completing the eight sequential rivets, again spending two seconds on each rivet. This procedure was repeated for riveting on the lower stringer.

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, 4^{th} 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 muscle to determine the percent MVC for that particular muscle.

It was of interest to determine if passive shoulder exoskeletons have an impact on the shoulder and torso muscles during horizontal squeeze riveting tasks. As such, the EMG activity of the muscles were evaluated during the two second period that the squeeze rivet gun was on each rivet, while riveting on the upper stringer and lower stringer. For each rivet the start of the two second period on the rivet was identified by the time marker generated when participants squeezed the trigger. Thus, the mean percent MVC EMG of this two second rivet time period was analyzed for all right and left side muscles.

Figure 1. Upper stringer

Figure 2. Lower stringer

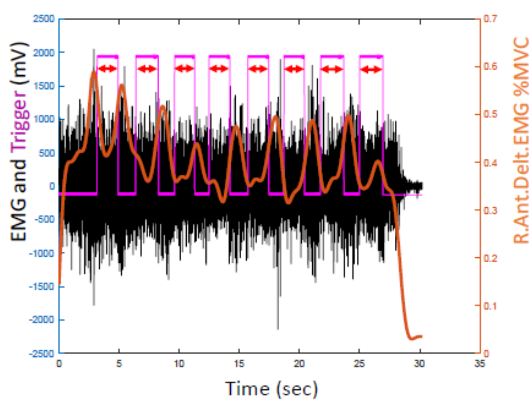

Figure 3. EMG data analysis of horizontal squeeze riveting exertions

2.5 Statistical Analysis

A one-way within-subjects ANOVA was performed for each stringer and muscle combination to determine if exoskeletons had an impact on the normalized percent MVC muscle activity during the actual time the squeeze riveting tool was on the rivet. The independent variable was the exoskeleton condition, and the dependent variable was the mean of the peak normalized EMG signals (percent MVC) while riveting. For all ANOVAs performed, significant exoskeleton effects ($p \leq 0.05$) were investigated via a Tukey HSD assessing all exoskeleton condition pairwise comparisons.

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3. Results

The mean (SD) percent MVC muscle activity as a function of stringer level, muscle and exoskeleton condition across all 16 participants is shown in Table 1. Shaded columns in Table 1 identify muscles that were significantly impacted by exoskeletons ($p \leq 0.05$). For riveting along the upper stringer, exoskeletons significantly impacted the right and left side anterior deltoids, medial deltoids, and latissimus dorsi. For riveting along the lower stringer, exoskeletons significantly impacted the right and left side anterior deltoids and medial deltoids, as well as the right latissimus dorsi. For each stringer level tested Tukey follow-up post-hoc test results are also shown in Table 1, where exoskeletons with the same letters are not significantly different from each other.

To assist in visually demonstrating where differences in the mean percent MVC muscle activity were present when wearing an exoskeleton compared to not wearing an exoskeleton, the mean difference of each exoskeleton compared to not wearing an exoskeleton are shown in Figure 4 for riveting along the upper stringer and in Figure 5 for riveting along the lower stringer.

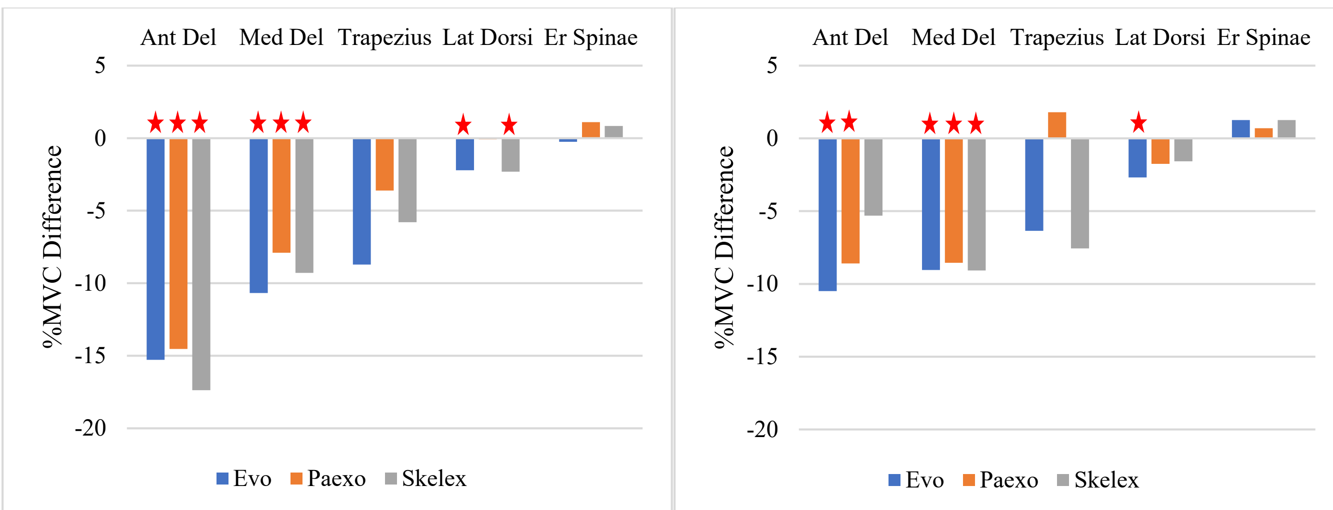
As shown in Figure 4 (left- and right-side muscles in Figure 4a and Figure 4b, respectively) for squeeze riveting along the upper stringer, the anterior deltoid was consistently reduced by the use of exoskeletons for both left-side (15% to 17%) and right-side (9% to 10%). The medial deltoid percent MVC was consistently reduced by exoskeletons on the left-side (8% to 11%) and the right-side (9%), whereas fewer exoskeletons reduced the latissimus dorsi percent MVC (2% to 3%). For squeeze riveting on the lower stringer (left-side and right-side muscles shown in Figure 5a and Figure 5b, respectively), the anterior deltoid was consistently reduced by the use of exoskeletons for both left-side (5% to 7%) and right-side (2% to 3%), and one exoskeleton resulted in a 3% reduction of the latissimus dorsi percent MVC.

Table 1. Mean (Standard Deviation) percent MVC muscle activity as a function of stringer location, muscle, and exoskeleton condition. Shaded columns represent significant exoskeleton effects on percent MVC muscle activity where exoskeletons with the same letters within a significant muscle column indicate no significant difference between the exoskeleton conditions.

Upper Stringer										
Exoskeleton	Left Side Muscles					Right Side Muscles				
	Ant Delt p<.001	Med Delt p<.001	Trapez p=.150	Lat Dorsi p=.008	Er Spinae p=.316	Ant Delt p=.005	Med Delt p<.001	Trapez p=.234	Lat Dorsi p=.010	Er Spinae p=.922
None	^{A}40.5 (23.7)	^{A}26.8 (8.2)	40.2 (22.3)	^{A}17.8 (7.2)	10.6 (4.9)	^{A}32.0 (22.5)	^{A}24.4 (14.6)	47.0 (29.8)	^{A}16.9 (8.7)	12.8 (5.8)
Evo	^{B}25.2 (14.8)	^{B}16.1 (8.5)	31.4 (16.7)	^{AB}15.6 (7.4)	10.3 (6.0)	^{B}21.5 (17.5)	^{B}15.4 (9.0)	40.7 (28.9)	^{B}14.2 (8.7)	14.1 (10.8)
Paexo	^{B}26.0 (13.5)	^{B}18.9 (11.3)	36.5 (20.2)	^{AB}17.7 (8.5)	11.7 (5.9)	^{B}23.4 (17.7)	^{B}15.9 (9.1)	48.9 (33.2)	^{AB}15.2 (9.6)	13.5 (6.9)
Skelex	^{B}23.1 (13.9)	^{B}17.5 (8.0)	34.4 (22.3)	^{B}15.5 (6.7)	11.4 (5.8)	^{AB}26.7 (22.6)	^{B}15.3 (9.4)	39.5 (24.7)	^{AB}15.3 (9.0)	14.1 (11.8)
Lower Stringer										
Exoskeleton	Left Side Muscles					Right Side Muscles				
	Ant Delt p<.001	Med Delt p=.005	Trapez p=.143	Lat Dorsi p=.078	Er Spinae p=.636	Ant Delt p=.005	Med Delt p=.002	Trapez p=.200	Lat Dorsi p=.012	Er Spinae p=.801
None	^{A}16.2 (9.1)	^{A}7.4 (6.1)	23.7 (16.7)	11.7 (7.5)	13.3 (9.2)	^{A}13.7 (7.7)	^{A}8.7 (6.9)	27.4 (22.7)	^{A}13.1 (9.3)	14.7 (9.2)
Evo	^{B}10.8 (6.3)	^{B}4.9 (3.7)	19.4 (14.2)	10.4 (5.0)	12.3 (6.0)	^{AB}11.4 (9.1)	^{B}6.4 (4.7)	24.1 (19.7)	^{AB}11.1 (7.5)	13.8 (8.8)
Paexo	^{B}11.1 (7.7)	^{AB}5.5 (5.7)	20.9 (13.2)	11.0 (5.6)	12.8 (5.5)	^{B}9.8 (7.7)	^{B}6.4 (4.6)	29.7 (27.0)	^{AB}11.9 (9.9)	15.2 (8.7)
Skelex	^{B}9.6 (6.8)	^{B}4.3 (3.7)	19.2 (14.2)	10.2 (5.6)	13.8 (6.3)	^{B}10.7 (9.2)	^{B}5.7 (5.0)	25.3 (23.3)	^{B}10.1 (6.0)	15.2 (11.1)

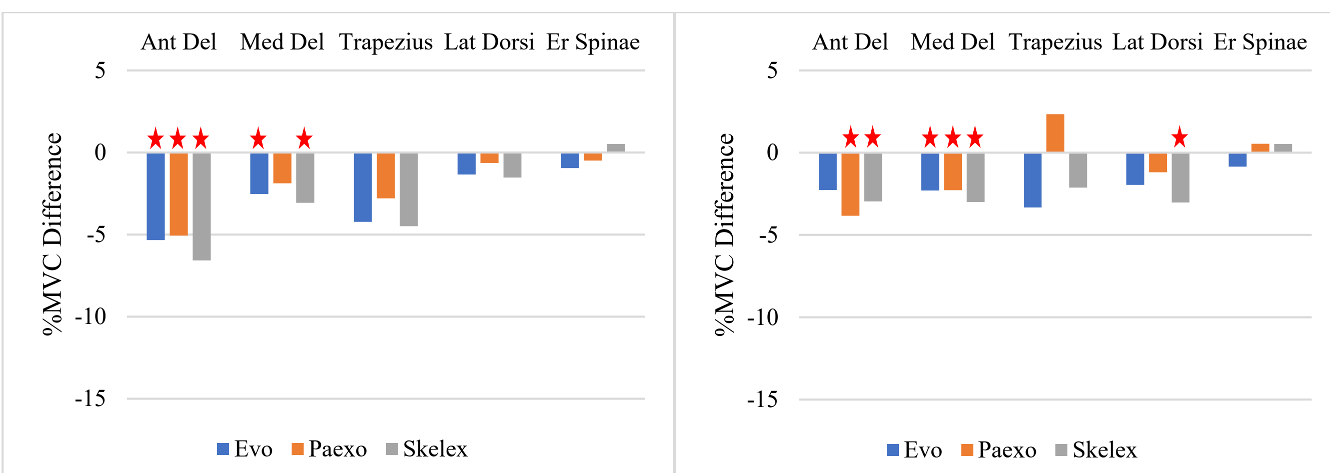
4. Discussion

This study investigated the impact of different passive shoulder exoskeletons on shoulder and torso muscle activity performing tasks designed to mimic squeeze riveting in aircraft manufacturing, utilizing experienced aircraft manufacturing employees. Squeeze riveting is often a two-armed operation which requires manipulation of the pneumatic riveting tool to place the jaws of the tool on the rivet head and hold the tool on the rivet as the tool squeezes and sets the rivet. As such, there is a static muscular exertion component during this riveting process and to some extent when moving the squeeze riveting tool to the next adjacent rivet. Additionally, this riveting process can occur at heights ranging from below elbow height to well above the employee's head, thus, there is an overhead component to this process that requires muscular exertions of the shoulder and torso to utilize a sometimes heavy pneumatic squeeze riveting tool.



(a) (b)

Figure 4. Mean percent MVC difference between exoskeleton and no exoskeleton conditions during squeeze riveting on upper stringer for (a) left-side muscles, and (b) right-side muscles. Red stars indicate significant difference between exoskeleton and no exoskeleton percent MVC.



(b) (b)

Figure 5: Mean percent MVC difference between exoskeleton and no exoskeleton conditions during squeeze riveting on lower stringer for (a) left-side muscles, and (b) right-side muscles. Red stars indicate significant difference between exoskeleton and no exoskeleton percent MVC.

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The major findings of this study are similar to previous research on passive shoulder exoskeletons during simulated overhead drilling and wiring tasks, which consistently found a decrease in anterior deltoid muscle activity (Kim and Nussbaum, 2019) as well as decreases in muscular demand on the anterior and medial deltoid muscles as presented in a review of studies (McFarland and Fischer, 2020). This study also found, consistent with other studies, little to no impact on other muscles investigated, including the lumbar erector spinae muscle activity (Alabdulkarim et al, 2019; Kim and Nussbaum, 2019). This suggests, at least for this type of task, the force/load may not necessarily be transferred to other torso and shoulder muscles unlike findings from other studies (de Vries and de Looze, 2019).

Most exoskeletons tested in this study benefited the anterior and medial deltoids, and to some extent the latissimus dorsi, at both horizontal stringer heights investigated. However, a greater decrease in muscle activation was realized for utilizing the riveting tool along the upper stringer (overhead height, Figure 4) compared to utilizing the riveting tool along the lower stringer (slightly above shoulder height, Figure 5). Wearing exoskeletons resulted in significant mean decreases in right and left anterior deltoid muscle activation of 15.4% and 9.6%, respectively, at the upper stringer compared to 5.7% and 3.5% for the right and left side, respectively, at the lower stringer. A similar pattern resulted for the medial deltoid, with significant mean decreases of 9.3% and 8.9% wearing exoskeletons, respectively, along the upper stringer, with lower significant mean right and left medial deltoid decreases of 2.8% and 2.5%, respectively, when riveting along the lower stringer. These differences in the magnitude of reduction as a function of vertical stringer height are consistent with findings from Kim and Nussbaum (2019) who found greater reduction of shoulder muscle activation for drilling and wiring tasks at the overhead level compared to performing these tasks at the shoulder level. The differences in the magnitude of muscle activity reductions utilizing exoskeletons as a function of task height likely resulted from a combination of two factors. First, greater shoulder muscle activity was required to raise the arms and utilize the squeeze riveting tool at the overhead height of the upper stringer compared to the lower stringer (see Table 1 %MVC's for no exoskeleton condition), thus, exoskeletons may provide a larger benefit since the no-exoskeleton condition starts from a larger level of muscle loading. Second, the shoulder flexion angles where the maximum support is provided from the exoskeletons may be for larger shoulder flexion angles than smaller shoulder flexion angles. The Evo exoskeleton shoulder angle support level was set such that the maximum support occurred at 115° shoulder flexion, whereas the shoulder angle support level profiles for the Skelex and Paexo are unknown and likely proprietary manufacturer information. Thus, while exoskeletons resulted in decreases in muscle activation levels at both stringer heights, larger benefits were realized at the higher vertical heights.

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 squeeze riveting tasks, where the actual duration and location of tasks may vary in an actual work environment. Finally, 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 right and left sides during simulated squeeze riveting tasks, and the overhead squeeze riveting location (upper stringer) realized greater benefit than squeeze riveting just above shoulder level (lower stringer) in terms of reducing shoulder muscular demand. While these laboratory results are encouraging in terms of reducing muscular demand, these exoskeletons must also be evaluated in worksite studies to better assess their efficacy.

5. References

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