Evaluation of an adjustable support shoulder exoskeleton on static and dynamic overhead tasks.

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Introduction: Overhead tasks increase the risk of work related musculoskeletal disorders to industrial workers. A shoulder supporting exoskeleton with adjustable and angle dependent torque (referred to as shoulderX in this paper for brevity) was designed and built at the University of California Berkeley Human Engineering and Robotics Laboratory for workers performing overhead tasks. shoulderX was designed specifically to reduce the exposure to large muscle exertion forces on the shoulder complex from overhead work. **Methods:** We evaluated shoulderX by measuring the muscle activation of the upper trapezius (UT), anterior deltoid (AD), triceps long head (TR), and infraspinatus (IF) during static and dynamic overhead tasks. Thirteen male subjects with experience in the construction or manufacturing industries were recruited to perform overhead tasks using light (.45 kg) and heavy (2.25 kg) weight tools with four exoskeleton support levels (0, 8.5, 13.0, 20.0 Nm peak torque). **Results:** During all conditions, the wearer's shoulder flexor muscle activity of UT, AD were reduced with increasing strength of shoulderX by up to 80%. Subjects unanimously preferred the use of shoulderX over the unassisted condition for all task types (static and dynamic overhead tasks) and tool weights (.45 kg and 2.25 kg). **Conclusion:** shoulderX reduces the wearer's primary muscle activity in overhead static and dynamic work and results in a more desirable and balanced pattern of shoulder complex activation. This investigation indicates that shoulderX reduces the risk of work related shoulder injuries during overhead tasks.

DOI 10.1177/1541931218621184

INDRODUCTION

In 2011, the shoulder was involved in 13% of all work related musculoskeletal disorder (WMSD) cases reported in the United States and the average amount of missed time due to a shoulder WMSD was 23 lost workdays [Bureau of Labor Statistics, 2012]. Overhead work has been identified as a category of tasks with especially high risk of WMSDs [NIOSH, 1997]. To mitigate risk of injury, the load lifted or duration of the task must be reduced, or the amount of rest breaks increased [Chengalur, 2004].

Exoskeleton technology has the potential to reduce exposure to heavy exertion forces thereby reducing risk of WMSDs. The torque effects of the ABLE upper limb exoskeletons have been evaluated in the automotive industry [Sylla, 2014] which show that the sum of the joint torques are reduced by up to 38.9% for an overhead screwing task. An additional study on the personal ergonomic device (PED) upper limb exoskeleton identified an 86% productivity increase for welding tasks and a 26-53% increase in productivity for painting tasks as measured by a welding/painting simulator [Butler, T.,2016]. However, to date the effects of a shoulder supporting exoskeleton on muscle activation have not been presented. This study aims to compare the changes in shoulder muscle activation for a dynamic screwing-type task as well as a static welding-type task between an unassisted condition and when supported by various settings of a novel shoulder support exoskeleton, shoulderX.

shoulderX DESIGN

Over many years, a shoulder supporting exoskeleton device has been developed at the University of California, Human Engineering Laboratory to support the shoulder muscles during tasks that require repetitive or sustained arm elevation. Based on observations and interviews with construction, manufacturing, and other specialized laborers we established three main design requirements for our device.

1. Support the shoulder against gravitational forces during elevated postures for light to medium weight tools and eliminate support during neutral postures
2. Allow unrestrained rotation and full range of motion to secondary joints of the shoulder and spine.
3. Permit all work activities to be carried out safely and without discomfort.

In order to achieve these design requirements for a majority of workplace tasks and worker sizes the following hardware specifications were defined:

1. Allow for exoskeleton support torque to be easily adjusted for each arm.
2. The frame dimensions should adjust to fit 5-95% of the US population.
3. A trained user should be able to don and doff the device in under one minute.
4. No tools should be needed to adjust the device.
5. Device contact points should be sufficiently padded and allow heat transfer between the user and exoskeleton.
6. The exoskeleton profile should be minimized so that the device may be worn under outer clothing such as a welding apron.
7. Device weight should be minimized.

Figure 1a shows the moments about the shoulder from gravitational loads as well as the exoskeleton support. The exoskeleton provides an adjustable torque to the operator's shoulder, applied as a force (F) to the upper arm, to counteract the forces of gravity due to the weight of the arm and tool (G) that would otherwise be supported by muscle forces (F_M). The exoskeleton's torque profile is designed to provide a peak torque at 90 degrees of shoulder flexion (θ), when the moment arm (l_G) of the shoulder load is greatest, and automatically reduce support as the arm is lowered. The primary exoskeleton components, Figure 1b, consist of an actuator that generates the supportive toque and a frame that couples to the wearer and distributes reaction forces to the upper arm, shoulders, and hips.

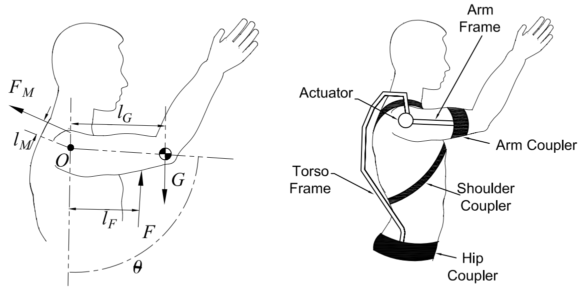

Figure 1. (a)Forces at shoulder from gravitational load and exoskeleton support (b) primary exoskeleton components.

To best suit each wearer's needs, the exoskeleton, shown in Figure 2, is adjustable in both size and strength. To accommodate a range of user and tool weights, the supportive torque can be continuously adjusted between 8.5 Nm and 20.0 Nm of peak torque by means of an adjustment knob. A majority of working postures is allowed by the frame through two degrees of freedom at the spine (twisting and lateral flexion), and three degrees of freedom at the shoulder (vertical, horizontal, internal/external rotation). The device can be custom fit to each wearer through adjustments of hip width, hip depth, torso height, shoulder width, shoulder depth, and arm length and attached to the body with a belt and set of shoulder straps. When properly adjusted, shoulderX will balance the gravitational load of the arm and tool during working postures above 20 degrees of elevation and transfer a majority of the reaction forces to the wearer's hips. During neutral postures when the wearer's arms are resting at his/her sides the exoskeleton does not provide support, allowing free motion.

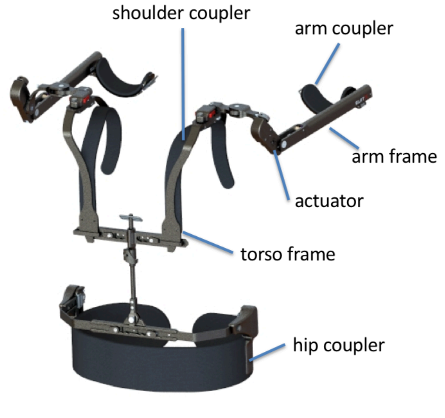

Figure 2. Shoulder supporting exoskeleton (shoulderX).

METHODS

Participants

Thirteen male subjects with experience in construction or manufacturing industries were recruited for participation in this within-subjects intervention study of cross over design. All subjects were right handed with average (standard deviation) age 37(13) yrs., weight 81.2(14.5) kg., and height 1.83(.08) meters. During their daily occupations, unassisted, the subjects reported an average of 11 (10) hours of overhead work per week with post-work soreness occurring 44 (23) percent of the time at the shoulders. This suggests that the study population is representative of those that would use and benefit from the device in their daily work. The subjects provided informed consent, approved by the Investigational Review Board of the University of California, Berkeley.

Procedure

Study tasks, shown in Figure 3, were performed against a ceiling with height set so that each subject was at 90 degrees of shoulder flexion (θ) when the tip of the drill was positioned to the workspace. A static task consisted of tracing a series of lines held up to the ceiling by the non-dominant arm, requiring from the dominant arm a constant shoulder angle as the elbow/wrist was used to follow the tracing with the drill. A dynamic task consisted of inserting and removing a series of screws, requiring the wearer to alternate between raising the arm to the celling and lowering the arm to get screws from a waist-mounted tool bag. For each task type (i.e. either dynamic or static), subjects used both a light weight (0.45 kg) drill and a heavy weight (2.25 kg) drill. Subjects completed two thirty-second trials for each task type and tool weight under conditions of no support, low support (8.5 Nm peak torque), medium support (13.0 Nm peak torque) and high support (20.0 Nm peak torque) bilaterally provided by shoulderX. Task type was first randomized, the light tool always being used first to reduce onset of fatigue, and then each of the four support conditions randomized for a total of 16 conditions per subject.

Figure 3. Experimental setup.

Data Acquisition

Subjects were instrumented with Noraxon mini DTS electrodes, the locations first lightly abraded with rubbing alcohol for a clean signal (Noraxon MyoMuscle, Scottsdale, AZ). Electrodes were applied to the upper trapezius (UT) and anterior deltoid (AD) representing agonist muscles acting to keep the arm raised to the work space. The infraspinatus (IF) was measured to represent a rotator cuff muscle acting to stabilize the shoulder girdle. The triceps long head (TR) muscle was also measured as an antagonist acting to extend the shoulder. The measured muscles are identified in Figure 4. Care was taken so that the exoskeleton frame did not contact the electrodes. For each of the measured muscles three maximum voluntary contractions were elicited, the largest of which was taken as the muscle's highest value of activation (Kendall, 1993). EMG data was captured for each of the two thirty-second trials of the 16 experimental conditions. After each set of four support level conditions, within task type and tool weight, subjects were asked to rate their most and least preferred support settings.

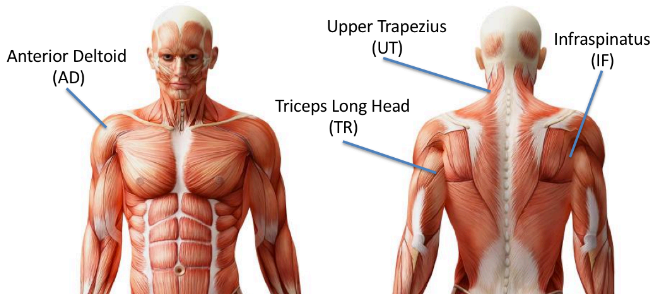

Figure 4. Muscles Measured.

Data Analysis

Noraxon MR3.10 software was used for data capture and processing. Raw data was first rectified to a single polarity to ensure the signal did not average to a zero value. Data was then smoothed with a root mean square algorithm (100ms window) to best display the shape of the activation pattern. Data was finally normalized as a percentage of maximum voluntary contraction (MVC) to provide for a standard comparison between individuals. For all conditions the data was put through an amplitude probability distribution function (APDF) analysis in Matlab (The Math Works Inc) and quantified based on the 50th percentile activation in order to describe mean muscle activation. Values of muscle activation were averaged across all subjects under each condition and were compared using Sata (StataCorp.) by using repeated measures analysis of variance and the Tukey post-hoc test with statistical significance defined as $p<0.05$.

RESULTS

Mean muscle activation, as a percentage of maximum voluntary contraction, is shown in Figure 5 though Figure 9 for each level of exoskeleton support. Values are the average of all thirteen subjects.

Anterior deltoid activation vs exoskeleton support level is shown in Figure 5. Unassisted, anterior deltoid activation is approximately 16% of MVC for the light tool and 20% MVC for the heavy tool. For the light tool, anterior deltoid activation was reduced by an average of 32% at the low support setting, 54% at the medium support setting, and 80% at the high support setting, compared to the unassisted condition. For the heavy tool AD activation was similarly reduced by 24%, 43% and 64% through the low, medium, and high support settings. Results for AD activation are statistically significant between all support levels.

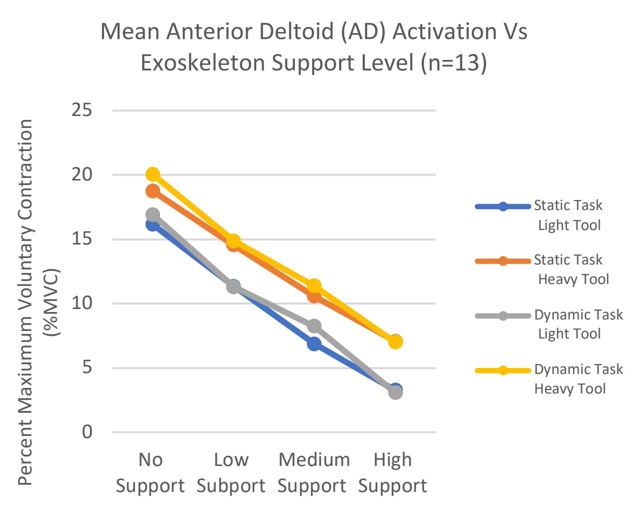

Figure 5. Anterior Deltoid Activation vs Support Level.

Upper Trapezius activation vs exoskeleton support level is shown in Figure 6. Unassisted upper trapezius activation is similar to the anterior deltoid, approximately 15% for the light tool and 20% for the heavy tool. The high support setting yielded the greatest reduction in UT activation of 46% for the light tool and 42% for the heavy tool. The medium & low support settings similarly reduced UT activation by 39% & 23% for the light tool and 27% & 18% for the heavy tool. Results for UT activation are statistically significant between all support levels.

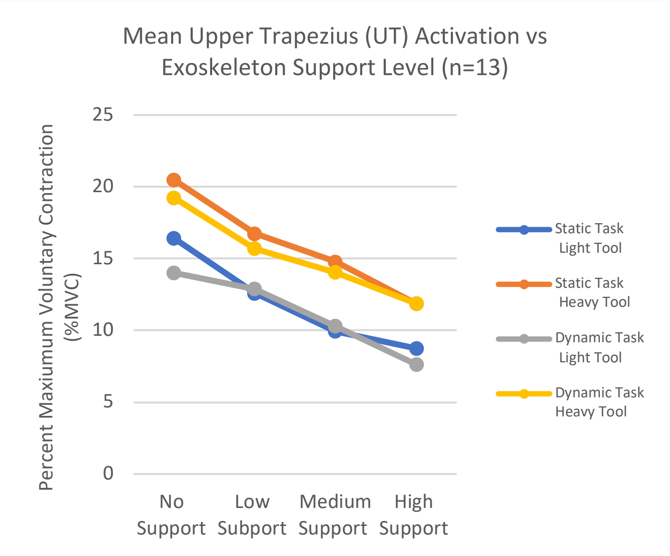

Figure 6. Upper Trapezius Activation Vs Support Level.

Triceps long head activation vs exoskeleton support level is shown in Figure 7. Unassisted triceps activation is between 3-5% of maximum voluntary contraction, much less than agonist muscle levels. With increasing exoskeleton support triceps activation increases, significant only for the high support setting at 2-4% MVC higher than the unassisted condition. Results for TR activation are statistically significant only between the high support setting and the no, low, medium support settings.

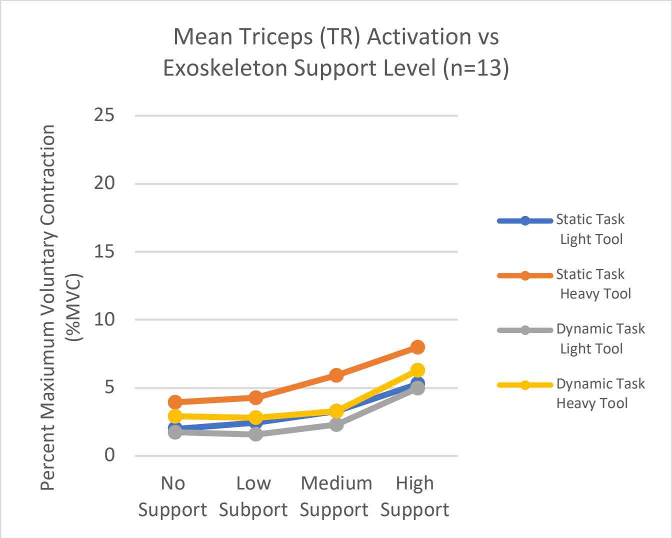

Figure 7. Triceps Long Head Activation Vs Support Level.

Infraspinatus activation vs exoskeleton support level is shown in Figure 8. Unassisted levels of activation are approximately 13% for the heavy tool and 7% for the light tool. With increasing exoskeleton support, mean infraspinatus activation decreases significantly between the unassisted case compared to the medium and high support settings. The medium support setting resulted in the greatest decrease in IF activation for all but the static-heavy condition with reductions up to 24%.

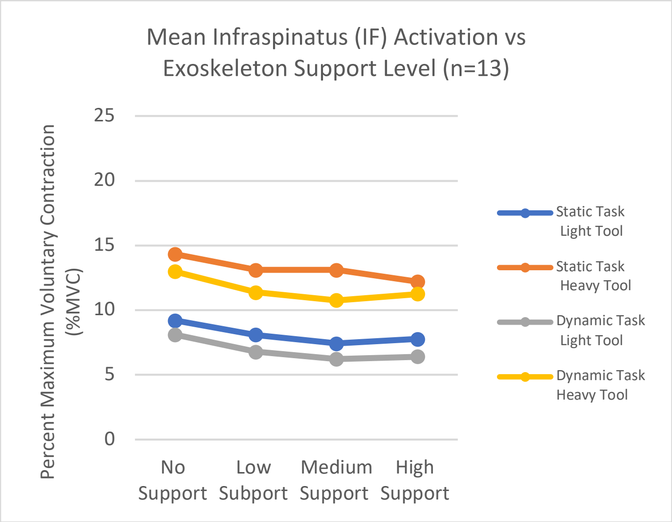

Figure 8. Infraspinatus Activation Vs Support Level.

Support preference results are summarized below for the light tool (Table 1) and heavy tool (Table 2) as the percentage of responses each support level was identified as the most preferred or least preferred. Input for both task types is included for each of the tables. For all task types and tool weights, subjects unanimously preferred use of the exoskeleton over the unassisted condition. Preference of the specific exoskeleton support setting varied between individuals with a bias toward the higher settings for heavier weight tools.

Light Tool	Support Level			
	No	Low	Medium	High
Most Preferred	0%	25%	75%	0%
Least Preferred	25%	0%	0%	75%

Table 1. Support Preference Results for Light Tool

Heavy Tool	Support Level			
	No	Low	Medium	High
Most Preferred	0%	16%	63%	21%
Least Preferred	58%	0%	5%	37%

Table 2. Support Preference Results for Heavy Tool

DISCUSSION

In the unassisted conditions muscle activation patterns are what would be expected for an overhead task. The unassisted level of agonist UT and AD activation is highest, and within the range shown to impair circulation and possibly lead to increased levels of fatigue [Hagberg, M., 1984]. The upper trapezius and anterior deltoid were significantly affected by tool weight but not by task type, while the infraspinatus and triceps were significantly affected by both task type and tool weight. The lack of significant difference between task types for the agonist activation may be attributed to the periodic flexion-relaxation when raising and lowering the arm averaging to that of the statically held posture. This is deemed acceptable as each task was designed to represent workplace scenarios as closely as possible, the lack of significance indicating the device may be equally applicable to static or dynamic tasks.

The primary shoulder flexor, the anterior deltoid, was most affected by the shoulderX support under all conditions of task type and tool weight. Anterior deltoid activation significantly decreased with the use of the exoskeleton as well as between each level of support. As this is the primary muscle used in the studied tasks, such a reduction may lead to increased stamina or decreased risk of injury.

With increasing exoskeleton support, mean upper trapezius activation similarly decreased. In addition to holding the shoulder in a flexed position, it is hypothesized that UT activation also represents a component of load transfer between the shoulder complex and the spine. The reduced UT activation may indicate reduced spinal loading as the exoskeleton frame transfers the reaction forces past the shoulders and to the hip belt. If true, the exoskeleton may provide benefits to the back/spine as well as the shoulder complex.

Without measuring antagonist extensor muscles, it would seem that increasing exoskeleton support levels would continue to reduce shoulder muscle activation with no consequence. Looking at the TR, responsible in part for extending the shoulder opposite of the direction of exoskeleton supporting torque, the highest support setting muscle activation is significantly increased relative to the unassisted, low support, and medium support settings. For the measured population it can then be concluded that there is a threshold between the medium and high settings where the exoskeleton support becomes undesirably strong for the average first time user. This threshold may be influenced by user size, tool weight, or the user's inherent familiarity in moving with the added support. While there are not enough participants to correlate subject weight with increased triceps activation, preference results shown in Table 1 and Table 2 support the idea that tool weight influences the threshold at which the exoskeleton supporting torque becomes too strong. For the light tool the high setting was identified as most preferred by 0% of the users and the least preferred by 75% of users, while for the heavy tool the high setting was more favorably reviewed with 21% of responses identifying it as most preferred and 37% as least preferred. Finally, triceps average muscle activation had a high standard of deviation across all measurements, indicating that there was a large spectrum of responses between individual users. The 37% of users who most preferred the high setting may have adapted to working with the added exoskeleton support more quickly, while other users unnecessarily fought the support. With an extended training period it is thought that all users will better adapt to moving with the added support, reducing triceps activation and increasing the favorable view of the highest support setting. Even with the increase in triceps activation at the high setting, the resultant muscle activation pattern becomes more balanced between measured shoulder flexors and extensors. Similar activation across all muscle groups may further prevent fatigue or injury, as well as benefit overall shoulder posture.

Finally, the infraspinatus may be used as a measure of shoulder stability, related to activation of both flexor and extensor muscle groups. This reduction of infraspinatus activation indicates relief not only to the shoulder flexor muscles, but also to the rotator cuff. This decrease in rotator cuff activation supports the conclusion that the exoskeleton support will reduce the risk of shoulder WMSD, which often manifests at the rotator cuff. With increased durations of training with the exoskeleton it is expected that rotator cuff activation will be further decreased as subjects learn to operate the device with reduced extensor activation, as discussed above.

For the studied tasks all users preferred use of the exoskeleton over the unassisted condition. The most preferred support level varied between subjects, with the medium support condition favored most. In addition to tool weight, support level preference may also vary based on the task, subject size, or general level of fatigue. For a given task and tool, a subject may prefer a lower support setting in the morning and a higher setting in the afternoon as they tire, or may decide to more heavily work agonist vs antagonist muscles to balance daily muscle use. A study of longer duration may both bias support preference to the higher support ranges as users adapt to the support, as well as identify changes in support preference throughout the workday. If given more time to properly adapt to the device, an equivalent experiment with a self-selected support setting may allow subjects to optimize muscle activation of the shoulder flexors, extensors, and stabilizers.

CONCLUSION

The shoulder support exoskeleton significantly reduces muscle activity of shoulder flexors and stabilizers during overhead work. Due to the variability of tool weights, worker sizes, and personal preference, it is important that the exoskeleton support be adjustable in order to optimize the benefit to and acceptance of workers. This investigation determines that the exoskeleton reduces the force related risk for shoulder work related musculoskeletal disorders. The effects of exoskeleton shoulder support may dramatically alter the manner in which overhead work is performed in many industries, both to reduce strain on the workers and increase overall productivity.

Notice of Conflict of Interest: Logan Van Engelhoven, Homayoon Kazerooni, and Nathan Poon hold patents for the technology through UC Berkeley and are working to commercialize the device through a university partnership with US Bionics (dba suitX) and hold stock options in the company.

This study is funded in part by the Centers of Disease Control and Prevention (CDC) through the Southern California NIOSH Education and Research Center (SCERC) Pilot Project Research Training Program.

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