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Three passive arm-support exoskeletons have inconsistent effects on muscle activity, posture, and perceived exertion during diverse simulated pseudo-static overhead nutrunning tasks

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ABSTRACT

Arm-support exoskeletons (ASEs) are an emerging technology with the potential to reduce physical demands during diverse tasks, especially overhead work. However, limited information is available about the effects of different ASE designs during overhead work with diverse task demands. Eighteen participants (gender-balanced) performed lab-based simulations of a pseudo-static overhead task. This task was performed in six different conditions (3 work heights × 2 hand force directions), with each of three ASEs and in a control condition (i.e., no ASE). Using ASEs generally reduced the median activity of several shoulder muscles (by ~12–60%), changed working postures, and decreased perceived exertion in several body regions. Such effects, though, were often task-dependent and differed between the ASEs. Our results support earlier evidence of the beneficial effects of ASEs for overhead work but emphasize that: 1) these effects depend on the task demands and ASE design and 2) none of the ASE designs tested was clearly superior across the tasks simulated.

1. Introduction

Shoulder work-related musculoskeletal disorders (WMSDs) continue to be a major health problem, which accounted for 5.4% (~50,000) of all occupational injuries in the U.S. and involved a median of 28 lost workdays in 2020 (U.S. Bureau of Labor Statistics, 2021). Shoulder WMSD claims can also be more costly than others, with a mean incurred cost of $22,916 (Washington State Dept. of Labor and Industries, 2021). Earlier work has indicated that overhead work – often defined as work performed at or above acromion height (Bjelle et al., 1981) – is an important risk factor for shoulder WMSDs (Grieve and Dickerson, 2008; Punnett et al., 2000; Roquelaure et al., 2009). However, overhead work is an intrinsic part of many tasks in some industry sectors (e.g., automotive manufacturing and construction), and it can be challenging to eliminate many overhead tasks. Diverse interventions have been introduced to reduce worker exposures to overhead tasks (e.g., Asensio-Cuesta et al., 2012; Ferguson et al., 2012; Lowe et al., 2017; Rempel et al., 2010), yet the prevalence of shoulder WMSDs suggests that additional interventions are needed.

Arm-support exoskeletons (ASEs) – designed to reduce loads on the shoulder, especially during overhead work – are a promising technology that has received considerable attention to mitigate WMSD risks involved during overhead work. Earlier studies have examined several commercially available ASEs during diverse overhead tasks, finding that ASEs can reduce shoulder muscle activity and fatigue (e.g., Alabdulkarim and Nussbaum, 2019; Butler, 2016; Gillette et al., 2022; Kim et al., 2018a; Maurice et al., 2020; Schmalz et al., 2019; Van Engelhoven et al., 2019), as stated in a recent review (Moeller et al., 2022). For example, use of ASEs during simulated overhead tasks reduced the mean activity of shoulder muscles by 45–62% (Huysamen et al., 2018; Kim et al., 2018a; Maurice et al., 2020). When maintaining static overhead postures, utilizing an ASE reduced mean upper trapezius muscle activity, though the ASE increased lower trapezius muscle activity (de Vries et al., 2021). Using an ASE has also been found to reduce perceived exertion and workload (de Vries et al., 2021; Huysamen et al., 2018; Maurice et al., 2019).

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Despite increasing evidence of the effects of ASE use, there are relatively few comparative studies of different ASE designs, and even fewer that have included diverse task demands. Specifically, current evidence is limited with respect to three important issues. First, whether the benefits of a given ASE are dependent on the design of that ASE. From a field study of the effects of two ASEs on perceived local and whole body strain, Hefferle et al. (2020) found that only one device reduced perceived bilateral shoulder strain. During an overhead task that required force exertion in the upward direction at different heights, use of three ASEs led to different physiological reactions in shoulder muscles, suggesting that some of the ASEs were not beneficial for the task (Weston et al., 2022). Moreover, Alabdulkarim and Nussbaum (2019) showed that physical demands during a simulated drilling task differed between three ASEs. Second, whether the beneficial effects of ASEs during overhead work are substantially task dependent. For example, ratings of perceived exertion decreased with ASE use during plastering activities, though these ratings increased when applying gypsum on a wall (de Vries et al., 2021). De Bock et al. (2020) tested two ASEs and found that one decreased but the other increased upper body discomfort. Yet, most existing work has focused on assessing ASE effects in fairly specific scenarios. Force exertion direction and target height, in particular, place distinct physical demands on muscles in the shoulder and other regions (Maciukiewicz et al., 2016). Third, whether ASE use affects working postures or strategies, for instance because using an ASE can limit shoulder range of motion (Ferreira et al., 2020; Kim et al., 2018b). There is no available information, to our knowledge, regarding ASE influences on working postures during overhead tasks.

To help address these limitations, we examined the effects of three commercially available ASE designs during simulated overhead tasks that were performed in a range of task conditions, which differed in target height and force direction. We included several outcome measures, including muscle activity and working postures, and supplemented these with several subjective assessments. Here, results are presented for pseudo-static working conditions, whereas results for more dynamic simulated tasks will be presented separately. Based on earlier results, we expected that using any of the three ASEs during pseudo-static overhead tasks would reduce shoulder muscle activation, decrease perceived exertion, and modify working postures. Importantly, we also anticipated that the magnitudes of these effects would depend substantially on both the specific ASE used and the specific task demands.

2. Methods

2.1. Participants

A convenience sample of 18 young, gender-balanced participants completed the study and were recruited from the university and local community. Respective means (SD) of age, body mass, stature, and body mass index were 23.8 (4.0) years, 75.1 (10.8) kg, 178.9 (5.1) cm, and 23.6 (3.8) kg/m^2 for males; and 23.6 (3.5) years, 62.9 (7.7) kg, 164.6 (5.6) cm, and 23.3 (3.7) kg/m^2 for females. All participants self-reported being right-handed and having no current or recent (past 12 months) musculoskeletal disorders or injuries. The research reported herein complied with the tenets of the Declaration of Helsinki and the study protocol was approved by the Institutional Review Board at Virginia Tech. Informed consent was obtained from all participants prior to any data collection.

2.2. Task simulations

A pseudo-static overhead task was completed in several task conditions in a laboratory environment. These conditions, and other aspects of the study, were designed to simulate common aspects and requirements during final assembly automotive manufacturing tasks performed under the vehicle body. Participants were asked to use both hands to hold a pneumatic right-angle nutrunner (mass ~2.3 kg) and to exert forces on work targets using the tool end effector. Triaxial load cells (AMTI MCA3a-6, Watertown, MA, USA) were used as the work targets and to monitor the forces exerted by the participants. Completing the tasks required participants to exert normal forces on the work targets within a range of 13–20 N, for a cumulative total of 30 s. Different computer-generated auditory tones were used to provide feedback that the exerted force was within the specified range, that the tool was "running," and that the task was completed.

The simulated assembly task was completed in a total of 24 experimental situations, involving all combinations of four Interventions (see below) and six task conditions. The latter included all combinations of three levels of work *Height*, and two levels of *Force Direction* (Fig. 1). The three *Height* conditions were low, medium, and high, and these were defined from two anthropometric measures using methods adapted from Sood et al. (2007) – hand height with the shoulder flexed at 60° and forearm upright (*A*), and hand height with the upper arm in full extension (*B*). Using these measures, the low, medium, high heights were set at A, $A + 0.53(B - A)$, and $A + 0.7(B - A)$, respectively. The two *Direction* conditions were forward and upward, representing the external force applied on the work targets. In each of the six conditions, participants were instructed to locate themselves at a self-selected, comfortable distance from the work target and to hold the tool in their preferred way to perform the task (determined during initial practice in each condition as described below).

Three commercially available ASEs were included: EVO (EV; Ekso-Bionics, eksobionics.com/ekso-evo), shoulderX™ V3 (SX; suitX, www.suitx.com/shoulderx), and Paexo Shoulder V1 (PX; Ottobock, paexo.com/paexo-shoulders). These three were selected to represent diverse design characteristics (see Table A.1). Existing studies have demonstrated the efficacy of these ASEs (either current or older versions) in reducing physical demands during simulated overhead tasks (e.g., Kim, Nussbaum, Esfahani et al., 2018; Maurice et al., 2019; Van Engelhoven et al., 2019).

2.3. Experimental procedures

Participants completed an initial training session (~3 h) and two subsequent experimental sessions (~3 h each), all on separate days. In the training session, participants were introduced to the overhead task and were fitted with each of the three ASEs following manufacturer recommendations. Participants then practiced the overhead task in each of the six task conditions, both without an ASE and with each of three ASEs. The latter was intended to provide familiarization with ASE functionality and the different support settings provided by each device. Participants selected preferred support levels for each ASE in each experimental condition (summarized in Appendix A1). To familiarize participants with the Borg CR-10 scale (Borg, 1998) that was used during the experimental sessions, they were asked to do a "wall sit" to the maximum of their endurance while providing intermittent ratings of perceived exertion (RPEs) at the thighs using this scale.

In each experimental session, participants completed multiple trials of the static overhead task, one trial in each of the six task conditions in two of the four *Intervention* levels (i.e., EV, SX, PX, and No Device = baseline). This approach was used because completing all four levels of *Intervention* in a single session was found to be too lengthy and likely to increase the development of localized fatigue. The presentation order of *Intervention* levels was counterbalanced using multiple 4 × 4 balanced Latin Squares. Within a given *Intervention* level, the presentation order of *Height* was counterbalanced using 3 × 3 Latin Squares, and the presentation order of *Direction* was alternated across participants. A minimum of 2 min of rest of was given between each condition.

2.4. Instrumentation, data collection, and data processing

At the start of each experimental session, and following appropriate

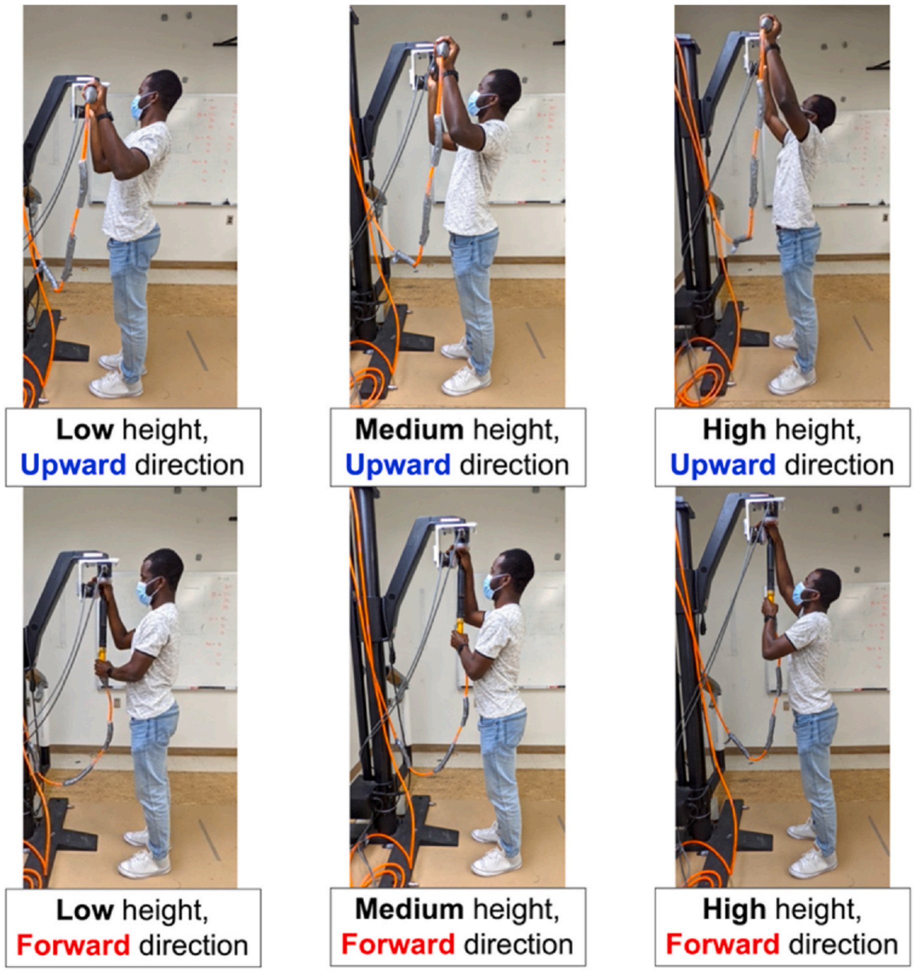

Fig. 1. Illustrations of the simulated overhead task in each of the six task conditions (three work heights and two force directions).

skin preparation, pairs of pre-gelled, bipolar, electromyography (EMG) electrodes (Ag/AgCl, with a 2.5 cm inter-electrode spacing) were placed bilaterally following methods described in earlier work (Criswell, 2010; Nordander et al., 2004). Electrodes were placed over seven muscle groups crossing the shoulder of the dominant arm, and bilaterally over one neck flexor muscle group and one low back extensor muscle group. The specific shoulder muscle groups monitored were the upper trapezius (TRP); anterior, middle, and posterior deltoid (AD, MD, and PD, respectively); pectoralis major (PM); infraspinatus (IF); and serratus anterior (SA). The specific neck and back muscle groups were the sternocleidomastoid (SCM) and erector spinae (ES), respectively. These muscles were selected based on relevance to the simulated overhead task and accessibility across the ASEs used (e.g., lumbar support locations and different contact areas with the body).

Subsequently, participants performed a series of maximum voluntary isometric contractions (MVICs) for each muscle group. For the shoulder muscles, participants were asked to raise their arms as hard as possible, while the arm was held at ~60° shoulder flexion and ~60°, ~90°, and ~120° shoulder abduction, with resistance provided from a floor-mounted chain connected to a handle and an investigator. For the SCM, participants were seated on a chair and were asked to flex their heads forward as hard as possible against resistance provided by an investigator on the forehead (Clark et al., 1993). For the ES, participants were positioned in a Roman Chair for back extension and were asked to extend their trunk against external manual resistance. MVICs for a given muscle were replicated twice, during which non-threatening verbal encouragement was provided. At least 60 s of rest were provided between MVIC trials.

During the MVICs and experimental trials, raw EMG signals were recorded at 1.5 kHz using a telemetered system (TeleMyo Desktop DTS, Noraxon, AZ, USA). These signals were band-pass filtered (20–450 Hz, 4th-order Butterworth, bidirectional), and root-mean-square values were then obtained with a sliding window of 300 ms to create linear envelopes. Processed EMG signals were extracted from the 30 s of each trial during which exerted forces were within the target, then were normalized to the corresponding maximum values collected during the MVICs. Median (50th-ile) normalized EMG (nEMG) levels were obtained as outcome measures, since the experimental task mainly involved static upper extremity postures and exertions.

Whole-body kinematics were monitored at 15 Hz using two Azure Kinect™ systems (Microsoft Corporation, Seattle WA, USA). These systems were positioned orthogonally about 2.5 m from the participants, an arrangement that was determined to be effective during pilot testing. Three-dimensional joint locations were extracted using a custom C# script and then low-pass filtered (5 Hz, 4th-order Butterworth, bidirectional). Several metrics were subsequently derived to describe working postures in each trial. *Work distance* was defined as the smallest horizontal distance between the right ankle and the right wrist (Fig. 2A). Shoulder posture was described using *elevation angle* and *horizontal rotation angle,* which were derived from the locations of the elbow, shoulder, neck, and umbilicus. Shoulder elevation was obtained as the angle between a vector projected from the shoulder to the elbow and the global horizontal plane (Fig. 2B). Shoulder horizontal rotation was obtained by projecting the same vector onto the global horizontal plane, then determining the angle between this projection and the sagittal plane (Fig. 2C). The latter was defined using locations of the shoulder,

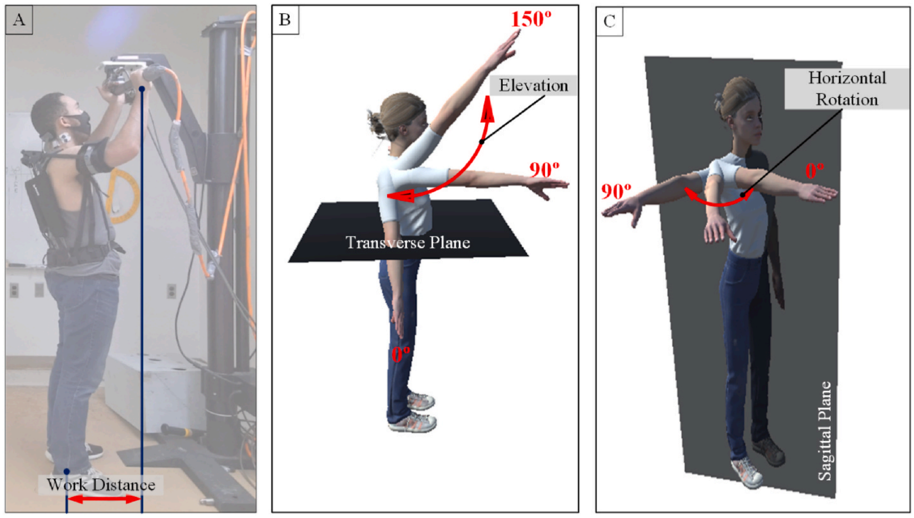

Fig. 2. Illustrations of the derivation of working posture metrics: A = work distance; B = shoulder elevation angle; and C = shoulder horizontal rotation angle. Note that shoulder elevation angle = 0° when the upper arm is at the side of the body, and shoulder horizontal rotation angle = 0° when the upper arm is parallel to the sagittal plane.

neck, and umbilicus. Mean values of these three measures of working posture in a given trial served as outcome measures.

After completing each trial, participants provided ratings of perceived exertion (RPEs) using the Borg CR-10 scale, separately for the neck, shoulder, elbow, wrist/hand, upper back, low back, and hip. Fractional scores were encouraged, and ratings were obtained on the dominant side for bilateral body parts.

2.5. Statistical analyses

Separate three-way, repeated measures analyses of variance (ANOVAs) were used to assess the effects of *Intervention, Direction,* and *Height* on each of the outcome measures – median nEMG, mean measures of working posture, and RPEs. *Gender* was included as a blocking effect. The presentation orders of *Intervention* and *Height* were also included as blocking effects (note that order effects were significant in only a few cases and no consistent patterns were evident). To meet parametric model assumptions, nEMG and working posture measures were log-transformed to achieve normally-distributed model residuals; summary results were back-transformed to the original units for the purpose of presentation. Significant main and interaction effects were followed by *post-hoc* pairwise comparisons (Tukey's HSD test). EMG and kinematic data for one experimental trial were missing for each of three participants, due to errors during data collection.

All statistical analyses were performed with JMP Pro 15 (SAS, Cary, NC) using the restricted maximum likelihood (REML) method. Statistical significance was concluded when $p < 0.05$, though interesting effects approaching significance are highlighted. Partial eta squared (η_p^2) was used to quantify effect sizes. Summary data are reported as least-square means (with 95% confidence intervals) from statistical model fits. Given the study aims, the subsequent presentation of results emphasizes only the main and interactive effects of *Intervention*.

3. Results

3.1. Median normalized muscle activation (nEMG)

ANOVA results are summarized in Table B1 of Appendix B. Main or interactive effects of Intervention were not significant for the PD, PM, IF, SA, or left ES muscles. Detailed results are provided separately below for the remaining muscle groups.

3.1.1. Sternocleidomastoid (SCM)

Intervention main effects and/or *Intervention* × *Height* interaction effects were significant for the bilateral SCM (Fig. 3). The SX significantly reduced median activation of the left SCM in the medium height condition (by 43%), and the PX reduced median activation of the left SCM by 43% in the high height. Although not significant, the PX reduced median activation of the right SCM by 36% at the high height, while the SX caused a reduction of 32% at the medium height.

3.1.2. Trapezius (TRP)

Median TRP nEMG was significantly affected by *Intervention* as well as the *Intervention* × *Height* (Fig. 4); additionally, the *Intervention* × *Direction* interaction effect approached significance. Across work heights, using the EV and SX led to larger reductions in TRP activation (EV = ~19–33%, SX = ~28–39%) vs. using the PX (~12–20%). Using any of the ASEs caused greater reductions in median TRP activation when forces were exerted forward (EV = ~34%, PX = ~26, SX = ~53%) than when exerted upward (EV = ~22%, PX = ~10, SX = ~27%). Of note, only the SX only caused statistically significant reductions when forces were in the forward direction.

3.1.3. Deltoid muscles

Median nEMG of the AD was significantly affected by the *Intervention* × *Gender, Intervention* × *Height,* and *Intervention* × *Direction* interactions (Fig. 5). For a given gender there were no significant differences between the No Device and ASE conditions. However, among males, nEMGs decreased by ~25–40% depending on the specific ASE used. In contrast, median AD values increased among females, respectively by 17% and 51% with the EV and PX, but decreased by ~28% with the SX. Although, *Intervention* × *Height* interaction effects were significant, there were no significant paired differences between the No Device and ASE conditions for a given *Height.* Yet, median AD nEMG values decreased ~19–33%, 17–38%, and 10–16% in the low, medium, and high work height conditions, respectively, depending on the ASE used. Similarly for the *Intervention* × *Direction* interaction effect, no significant paired differences were found between the No Device and ASE conditions for a given *Direction.* Yet, depending on the ASE used, median AD nEMG values decreased ~24–46% and ~2–17% in the forward and upward force direction conditions, respectively.

The EV significantly reduced median activation of the MD in the low and medium height conditions, by ~51% in both cases (Fig. 6). Although not statistically significant, use of the EV and PX led to

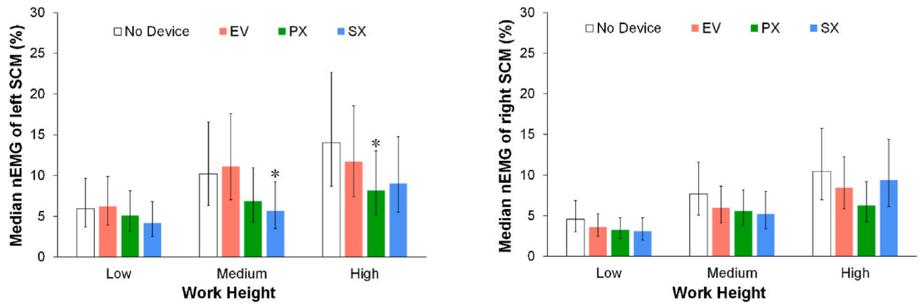

Fig. 3. *Intervention* × *Height* interaction effects on median nEMG of the left and right sternocleidomastoid (SCM). Note that * (here and below) indicates a significant difference between results using a given ASE vs. the baseline condition (i.e., No Device) at a given work height. Error bars (here and below) indicate 95% confidence intervals.

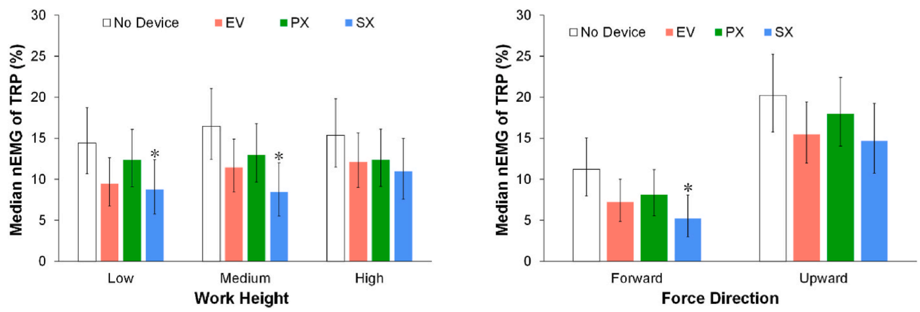

Fig. 4. *Intervention* × *Height* (left) and *Intervention* × *Direction* (right) interaction effects on median nEMG of the upper trapezius (TRP).

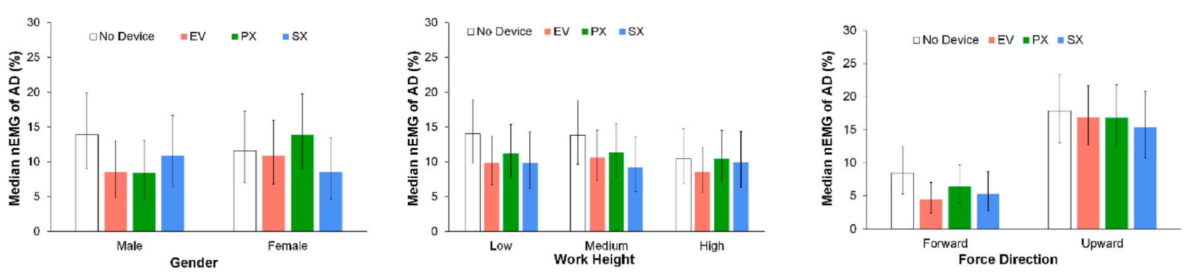

Fig. 5. *Intervention* × *Gender* (left), *Intervention* × *Height* (middle), and *Intervention* × *Direction* (right) interaction effects on anterior deltoid (AD) activation.

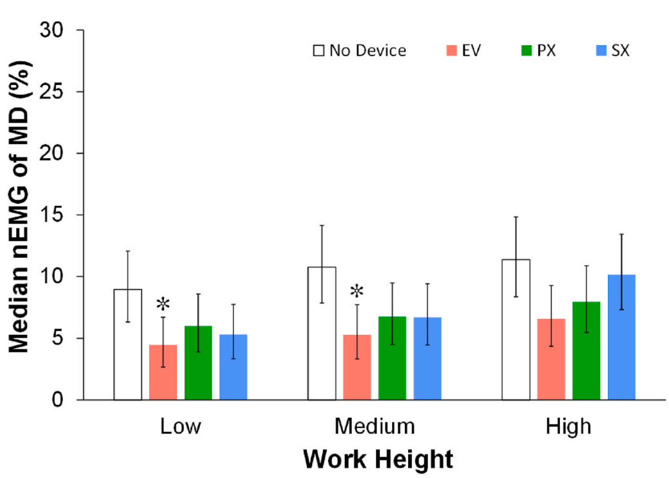

Fig. 6. *Intervention* × *Height* interaction effect on middle deltoid (MD) activation.

~30–42% reductions in MD activation at the high work height. There were no significant main or interactive effects of *Intervention* on median nEMG of the posterior deltoid.

3.1.4. *Infraspinatus (IF)*

IF activation was significantly affected by the *Intervention* × *Height* × *Direction* and *Intervention* × *Gender* interactions. Using the PX increased median nEMG values in the low (46–51%), medium (19–41%) and high (29–39%) work heights, though not significantly. Of note, the magnitude of such increases was dependent on *Force Direction* (Fig. 7). Regarding the *Intervention* × *Gender* interaction, use of EV and SX reduced median IF values by 4–20% among males, though not statistically significant. Among females, in contrast, use of PX significantly increased median IF values (99%).

3.1.5. *Erector spinae (ES)*

RES activation was significantly affected by the *Intervention* × *Height* × *Direction* interaction. Using any of the ASEs led to a greater reduction in median nEMG values in the low (23–36%) and high (26–47%) height conditions vs. at the medium height (2–30%). Further, the magnitude of such reductions differed between ASEs and *Force Directions* (Fig. 8). However, activation of the RES was quite low overall. There were no significant main or interactive effects of *Intervention* on the LES.

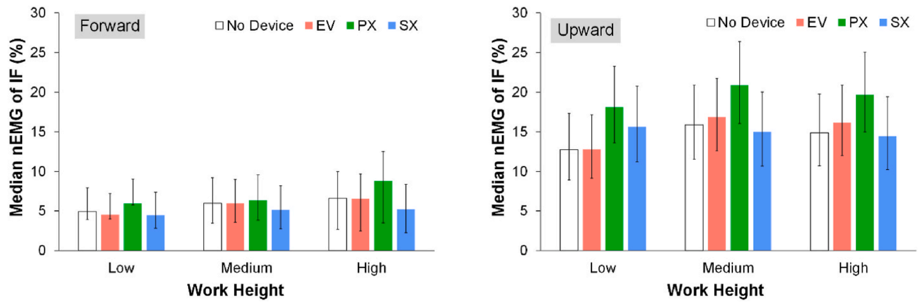

Fig. 7. *Intervention* × *Height* × *Direction* interaction effect on Infraspinatus (IF) activation.

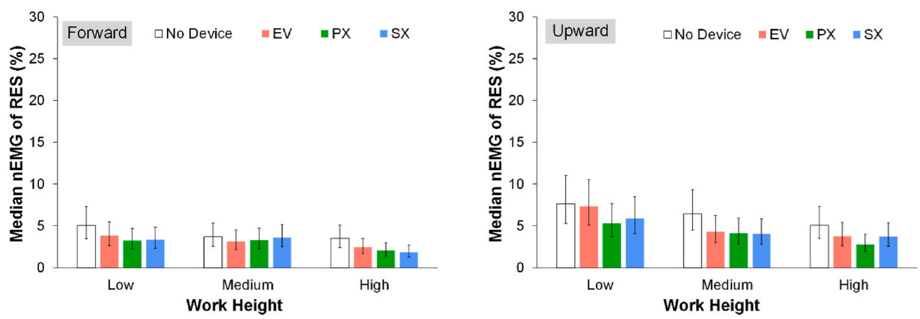

Fig. 8. *Intervention* × *Height* × *Direction* interaction effect on right erector spinae (RES) activation.

3.2. Working postures

ANOVA results for working postures are summarized in Table B.2 of Appendix B. *Intervention* had a significant main effect on work distance (Fig. 9). Participants stood approximately 50% (~6 cm) further away from the work target when using the SX vs. with no ASE.

Horizontal shoulder rotation was significantly affected by *Intervention*, and the *Intervention* × *Gender* interaction effect approached significance. Compared to the No Device condition, female participants used larger horizontal rotation angles regardless of the ASE used: EV [28% (3.4°)]; SX [40% (5.5°)]; and PX [49% (7.7°)]. Compared to the No Device condition, males used larger horizontal rotation angles with the EV [20% (4.2°)] and SX [24% (5.4°)], yet had comparable angles when using the PX (Figure B2 of Appendix B).

Shoulder elevation was significantly affected by the *Intervention* × *Height* interaction. At the low height, elevation angle increased by ~13% when using both the EV and SX (~14°), and by 19% with the PX (~21°).

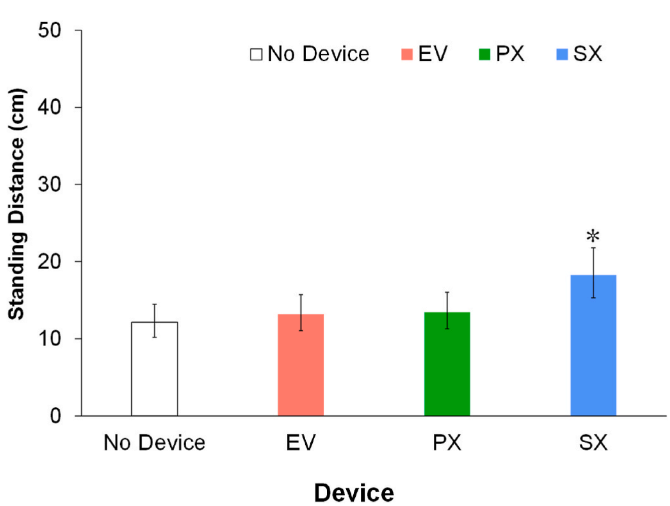

Fig. 9. *Intervention* main effect on horizontal work distance.

At the medium height, using the EV or PX resulted in a ~10% increase compared to using No Device (12°). At the high height, using the SX caused a significant decrease of 12% (16.6°). The *Intervention* × *Gender* interaction effect approached significance (p = 0.070) for shoulder elevation angle (Figure B1 of Appendix B). While joint angles were similar between males and females in the ND, PX, and SX conditions, females used more shoulder elevation with the EV than males (132° vs. 122°). Additionally, while EV use caused a 9% increase in elevation angle among females, PX used led to an 8% increase for males. Conversely, SX use led to elevation angles similar to when using No Device for both genders.

3.3. Ratings of perceived exertion (RPEs)

ANOVA results for RPE values are provided in Table B.3 of Appendix B. *Intervention* main effects were significant on RPEs at the neck, shoulder, elbow, and upper back. Using the EV reduced RPEs in the shoulder (29%), elbow (27%), and upper back (29%) compared to the No Device condition. Neck RPE values were also significantly affected by the *Intervention* × *Height* interaction (Figure B4 of Appendix B). Specifically, RPEs were similar across *Intervention* levels at the low height, and PX and SX led to non-significant decreases at the medium height (38% and 36%, respectively). At the high height, in contrast, there was a significant decrease (37%) in neck RPE when using the PX.

Intervention effects approached significance (p = 0.07) for the wrist, and RPEs were lower overall in the EV (15%) and SX (13%) conditions. The *Intervention* × *Direction* interaction also approached significance (p = 0.07) for the low back. RPEs in the low back when using the ND and EV were slightly higher in the upward vs. forward *Direction* (17% and 33%, respectively), whereas RPEs using the PX and SX were similar to the No Device condition in both force directions (Figure B5 of Appendix B).

4. Discussion

We investigated the effects of three different ASEs during a pseudo-static overhead task that was simulated over a range of work conditions (i.e., varying work heights and force directions). Our results partially confirmed our first hypothesis, that using ASEs during overhead tasks would reduce muscle activation of the shoulder muscles, decrease perceived exertion, and modify working postures. Specifically, using the three ASEs reduced bilateral SCM, TRP, and AD activity by up to 42, 57, and 51%, respectively, compared to the baseline (i.e., No Device), though the pairwise comparison was not statistically significant. Using an ASE also influenced work postures, with greater work distances and horizontal angles observed, though the latter were not statistically significant. Perceived exertion was either reduced or comparable to using no device at the shoulder, elbow, and upper back regions. The following discussion addresses these effects in more detail, including the differential effects of the three ASE designs and task-dependency in effects.

4.1. Effects of ASEs on muscle activity

When an ASE was used, SCM activity was mostly reduced, independent of work height and force direction (Fig. 3). The PX had an add-on neck support, and using that particular ASE reduced median left SCM activity up to 42%. A recent study by Garosi et al. (2022) examined the use of a neck-support exoskeleton during an overhead task (fastening/unfastening nuts), finding that it reduced SCM activities by up to 53%. They also found, however, that using the neck exoskeleton caused up to a 49% increase in TRP activity. They suggested that this increase potentially arises from exoskeleton design (i.e., mass and straps) and force re-distribution, and that there may be a need for additional support to mitigate increased TRP activity. This adverse effect was not observed with the PX here, suggesting that a neck-support exoskeleton might be more effective when used together with an ASE. Interestingly, although the SX did not have a neck support, using this ASE decreased bilateral SCM activities (left SCM by ~29–43%; right SCM by ~11–32%), though it led to a smaller reduction in left SCM activity in the high height condition. SX could have reduced SCM activity without an add-on neck support because of their designs. Specifically, as shown in Table A1 of Appendix A, the SX may have had similar reduction compared to PX because it has a back support mesh which provides more structural rigidity and support for the participant. Further, this reduction in SCM activity may indicate that external moments from an ASE effectively lower demands on muscles in the shoulder complex, since the SCM originates at the sternoclavicular joint. These results confirm the results of Schmalz et al. (2022), who predicted reduced SCM muscle forces based on computational musculoskeletal modeling when using the PX (without an add-on neck support) during a simulated construction-related overhead task.

Across the current simulated work conditions (i.e., height and force direction), using an ASE reduced median TRP activity (by 10–53%; Fig. 4). The magnitude of these reductions was conditional on the specific ASE and work conditions, with a larger reduction of TRP activity generally observed when forces were generated forward vs. upward (53% vs. 10%). This difference is likely due to the upward force exertions requiring larger upper extremity muscle activity, especially when the force target is located further away from the body (Chopp et al., 2010; Maciukiewicz et al., 2016). Reduced TRP activity with ASE use, as found here, is consistent with earlier studies, such as a 18–46% reduction during simulated overhead drilling and wiring (Kim et al., 2018a), static and dynamic overhead drilling (Van Engelhoven et al., 2019), and different static overhead arm postures (de Vries et al., 2019). However, it should be noted that some earlier studies found that using an ASE had no or minimal effects on TRP activity. During a simulated aircraft riveting task, Jorgensen et al. (2022) reported that using an ASE generally had no effect on TRP activity in four different work height conditions, except that left TRP activity significantly decreased by 7–8% at the two highest work height conditions (roughly involving both hands above shoulder level). A minimal beneficial effect of using an ASE on TRP activity was reported for automotive assembly tasks performed in actual facilities by Gillette and Stephenson (2019). Thus, it appears that the beneficial effect of ASE use may be dependent on task conditions, both in the lab and the field.

While a prior review reported rather consistent, beneficial effects of using an ASE on the AD muscle (McFarland and Fischer, 2019), our results showed mixed effects of different ASEs on median AD activity and that these effects varied between genders, work heights, and force directions (Fig. 5). For a given gender or force direction, we found no statistically significant differences between the baseline and any of the ASE conditions. Male participants consistently had decreased median AD activities using any of the ASEs (compared to the baseline), whereas females exhibited increased median AD activities only with the PX. The source of these gender- and ASE-specific differences are frankly unclear to us. One potential explanation is that males and females have different decision rules in selecting a support setting. For example, females may have selected less “optimal” support settings for a given task demand, perhaps due to the fit and comfort of a given ASE. Madinei et al. (2020) reported that male and female participants selected similar support settings for back-support exoskeletons during quasi-static manual assembly tasks, and that females often exhibited larger reductions in back muscle activities. In contrast, females here tended to select lower support settings than males (Appendix B.1). Thus, females may have experienced lower levels of *relative* shoulder supporting torques, especially when using the EV and the PX. Further study is recommended to help understand how different users select preferred support settings/levels for a given task and a given exoskeleton, and to determine if such a selection is associated with (in)adequacy of exoskeleton design approaches to accommodate user anthropometric differences.

Use of ASEs here mostly increased IF activity (by 3–99%), and these effects were similar between genders and work heights (Fig. 7). Participants changed their arm postures when wearing an ASE. Maciukiewicz et al. (2016) reported that muscular demands on the shoulder (including IF activity) were lower in a closer working posture (i.e., smaller distance to a work target) when force was applied upward, and higher in a closer working posture when force was applied forward. Thus, the changes we found in IF activity may be related to changes in shoulder posture with ASE use. Yet, we found that participants tended to stand further away from the work target (Fig. 9). Considering that a major function of IF is to stabilize the glenohumeral joint by pressing the humeral head into the glenoid fossa (Steele et al., 2013), our results may suggest that the external torques provided by an ASE adversely affect the glenohumeral joint stability. Further investigation is warranted to understand how individuals adapt to these external torques, especially when an ASE is used frequently or over a longer period.

ASEs reduced RES activity (Fig. 6), by 10–47% depending on work height and force direction. Although effects were statistically significant, the magnitude of changes in mean RES activity when using an ASE were somewhat small. These results are qualitatively consistent with the report of Kim et al. (2018b), which indicated that an earlier version of the EV decreased lower-spine loads. Their study, and more recent ones (Desbrosses et al., 2021; Yin et al., 2020), suggest no adverse effects of ASE use on back muscle activation.

4.2. Effects of ASEs on working posture

Participants adopted different shoulder postures when using an ASE. Depending on the specific ASE, participants used more shoulder abduction (by 3.4–7.7° for females, and by ~°–5.4° for males), more shoulder elevation at the low work height (by 14–21°), and less shoulder flexion at the high work height (by 16°). Maurice et al. (2020) similarly observed increased shoulder abduction when using an ASE during an overhead drilling task, and they suggested that such a posture modification might have occurred because their participants had less need to actively support their arm mass. Here, shoulder postures were found to be modified differently depending on gender, work heights, and specific ASEs. Given that the ASEs we examined have different torque profiles (i.e., supportive torques as a function of shoulder flexion angles), our results may suggest that participants adopted shoulder postures to counterbalance the external torque of an ASE to the extent possible, while considering individual factors (e.g., shoulder strength) and a given work condition. Furthermore, participants overall stood further away from the work target when using an ASE, especially with SX use (Fig. 7). These work posture modifications may be viewed as a natural adaptation to the supportive (external) torque of an ASE, yet it is unclear what these modifications might mean in terms of long-term musculoskeletal health (e.g., changes in shoulder joint stability as noted above). Although we did not directly measure neck angles, we speculate that the greater work distance may result from leveraging ASE support to achieve reduced neck extension.

4.3. Effects of ASEs on perceived exertion

Ratings of perceived exertion at the shoulder, elbow, and upper back region were typically either comparable or significantly decreased when using any of the three ASEs (Figure B.4 – B.5). RPE reductions in shoulder region were anticipated, given that ASEs are designed to offset external moments on this joint by providing counterbalancing moments. Moreover, use of PX significantly decreased neck RPE at the high height, suggesting that the add-on neck support provided some relief to the participants, consistent with results regarding SCM activity. Use of the EV led to larger reductions in RPEs at the shoulder, elbow, and upper back (Figure B3), even though this ASE did not consistently lead to the largest reductions in muscle activity. EV does have distinct design features (Table A1 of Appendix A), which could have influenced participants' perceptions. However, we are unsure as to what specific causes may have been present.

4.4. Limitations

A few limitations of this study should be mentioned. First, participants in this study were all relatively young (i.e., 18–35 years old), and thus do not represent the full age range of the working population (in automobile assembly or otherwise). For example, the mean age of full-time operators at Ford Motor Co. is 51 years (Ford Motor Company, 2019). As such, caution should be taken in generalizing the results, especially older workers. Second, although participants were familiarized with the ASEs during an initial training session, it remains unknown whether the duration of the training was sufficient. Third, the duration of the simulated task was fairly brief, and it is unclear regarding the extent to which the current results can be generalized to more prolonged ASE use, especially regarding subjective responses. Fourth, the task demands simulated here, although representative of common situations in automotive assembly, were low to moderate overall (e.g., normalized muscle activations of ~2.3–17% and RPEs = 0.3–1.7). Further work is needed to assess the effects of ASEs over a wider range of task demands. Finally, the current study was simulated in a laboratory environment and did not include several aspects that could influence the results, such as confined spaces, tool vibrations and torque reactions, and environmental conditions. Each of the potential influences warrants further investigation, especially given recent evidence that lab-based results may not always be comparable to those obtain in the field (De Bock et al., 2020).

5. Conclusions

Overhead tasks are a major risk factor for shoulder WMSDs, yet it is impractical to modify or eliminate all of them. Thus, alternative intervention approaches such as ASEs are of growing interest. We evaluated the effects of three commercially-available ASEs during pseudo-static simulated overhead tasks, in terms of median muscle activity, working postures, and perceived exertion in multiple body regions. Using these ASEs could reduce median activity of the SCM, TRP, AD, MD, and RES muscles, by up to 51%. Participants also changed their working postures when using an ASE (e.g., moved farther away from the work target and maintained higher shoulder elevation angles). In most of the tested conditions, ASE use decreased rating of perceived exertion in the shoulder, elbow, neck, and upper back regions, **by up to 38%**. Overall, our results suggest that the beneficial effects of an ASE are somewhat task specific and depended on the design of the ASE. Therefore, caution is suggested before generalizing ASE results across different designs and task demands.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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