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Assessing the influence of a passive, upper extremity exoskeletal vest for tasks requiring arm elevation: Part I – "Expected" effects on discomfort, shoulder muscle activity, and work task performance

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ABSTRACT

Use of exoskeletal vests (designed to support overhead work) can be an effective intervention approach for tasks involving arm elevation, yet little is known on the potential beneficial impacts of their use on physical demands and task performance. This laboratory study ($n = 12$) evaluated the effects of a prototype exoskeletal vest during simulated repetitive overhead drilling and light assembly tasks. Anticipated or expected benefits were assessed, in terms of perceived discomfort, shoulder muscle activity, and task performance. Using the exoskeletal vest did not substantially influence perceived discomfort, but did decrease normalized shoulder muscle activity levels (e.g., ≤ 45% reduction in peak activity). Drilling task completion time decreased by nearly 20% with the vest, but the number of errors increased. Overall, exoskeletal vest use has the potential to be a new intervention for work requiring arm elevation; however, additional investigations are needed regarding potential unexpected or adverse influences (see Part II).

1. Introduction

Work with elevated arms or overhead work – any work performed at or above the acromion level (Bjelle et al., 1981) – is a well-documented risk factor for shoulder musculoskeletal disorders (MSDs) (Nordander et al., 2016; Svendsen, 2004; van Rijn et al., 2010). Shoulder MSDs are a particular health concern in the workplace, as they can require a lengthy recuperation period. For example, shoulder injuries in the U.S. resulted in a median of 23 lost workdays, while the back or all types of injuries respectively entailed a median of 7 days or 9 days (BLS, 2016). Nonetheless, overhead work is still required in some jobs (e.g., when installing/repairing components on the underside of a structure, in construction, etc.), and which may not be easily eliminated from the workplace due to costs and the nature of a job.

Arm elevation and overhead work impose complex physiological (e.g., increased intramuscular pressure, muscle fatigue) and biomechanical demands (e.g., higher tissue loading) on the shoulder complex (Grieve and Dickerson, 2008). Intervention approaches to control such demands include engineering controls such as tilting car assembly lines (Kadefors et al., 1996), task-specific tool design such as custom overhead drilling device (Rempel et al., 2007, 2010), workplace exercise programs (Lowe and Dick, 2015), and administrative controls such as guidelines for duty cycles (Garg et al., 2006; Nussbaum et al., 2001). Recently, de Looze et al. (2015) discussed the growing interest in exoskeletons as an alternative to control physical demands, particularly related to manual material handling (e.g., lifting and carrying). An exoskeleton is a wearable system, designed to augment the wearer by providing assistive moments to body joints or structural support, and which has been more actively considered to date in military and clinical medicine/rehabilitation applications (Bogue, 2009; Yan et al., 2015; Yang et al., 2008).

Specific to occupational tasks involving arm elevation or overhead work, however, there are a few reports of studies that investigated the efficacy of exoskeleton use in manufacturing tasks (e.g., Gillette and Stephenson, 2017; Rashedi et al., 2014; Sylla et al., 2014). For example, Rashedi et al. (2014) examined the use of commercial exoskeletal vest (involving vertical rods that connect the shoulder and pelvis parts) and gravity balancing mechanical arm (connected to the vertical rod) as an

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intervention for overhead tasks. Using such a system resulted in reduced levels of shoulder muscle activity (up to 56%) and discomfort, particularly with a heavier tool, and which interestingly coincided with a marginal increase in low back demands. A commercial upper extremity exoskeletal vest with passive moment generator around the shoulder (Levitate Airframe™, www.levitatetech.com) was piloted tested on actual workers when being trained on painting and welding simulators (Butler, 2016). The author reported increased productivity (up to 86%) and reduced levels of shoulder discomfort, and also emphasized that safety professionals need to understand the potential benefits and safety challenges of exoskeletons prior to introducing them into the workplace. Overall, these and related studies (de Looze et al., 2015) support the potential of exoskeletons as an effective ergonomic intervention, but also suggest the need for more systematic research regarding the impact of exoskeleton use on worker safety and health, to promote the safe adoption of this technology.

Thus, the current study aimed to evaluate the potential protective value of a new passive upper extremity exoskeletal vest (EksoVest™ prototype, www.eksobionics.com) in terms of the impacts on worker safety and health, and task performance. Note that this vest is conceptually similar to the noted Levitate Airframe™, but has different moment generation and hinge mechanisms around the shoulder. Specifically, the EksoVest™ has a moment generation mechanism that is connected to an upper arm cuff, and provides a gradually-increasing support moment as the arm elevates; the support moment can be easily turned off by the user if needed. The vest includes both neck (similar to a U-shape neck pillow) and back pads, as well as adjustability in trunk length. After consulting manufacturing industry experts, we selected and developed a set of evaluation tests to assess the potential benefits and likelihood of unexpected side effects of using the exoskeletal vest (i.e., EksoVest™). Because of the broad range of outcome measures obtained in the study, the results are presented in two parts. This paper reports on an evaluation of expected consequences, or those that were intended through the design of the device (i.e., comfort, reduced shoulder demands, maintained or enhanced task performance). The study was done using simulated occupational tasks that were considered representative of potential applications of such an upper-extremity support device, specifically repetitive drilling and light assembly. A companion manuscript reports on an evaluation of potential unexpected effects (e.g., shoulder range of motion, physical demands on the low back, and postural balance).

2. Methods

2.1. Participants

A convenience sample of 12 gender-balanced participants completed the study, and were recruited from the local university and community. Respective mean (SD) age, stature, and body mass were 32.5 (11.8) yrs, 172.3 (4.6) cm, and 72.6 (9.1) kg for males; and 22.5 (1.5) yrs, 169.7 (5.2) cm, and 63.8 (6.2) kg for females. No participants had any self-reported musculoskeletal injuries or disorders in the past 12 months. All participants provided informed consent, following procedures approved by Virginia Tech Institutional Review Board.

2.2. Work simulation – repetitive drilling and light assembly

A repetitive drilling task and a light assembly (i.e., connecting wires) task were each simulated at two different work heights using a height-adjustable workpiece (See Fig. 1). The two work heights were set to individual shoulder height and an overhead work height. The latter was derived using two anthropometric measures – hand height with the shoulder and elbow flexed at 90° (A) and hand height with the upper arm in full extension (B). Overhead work height was set at A + 0.4(B – A), as described in Sood et al. (2007), and was intended to impose substantial arm elevation but avoid the end range-of-motion of the upper extremity.

Simulated drilling task: We simulated a repetitive, precision task modeled on that presented by Alabdulkarim et al. (2017). An aluminum rung (5.08 × 5.08 cm hollow rectangular stock, 121.9 cm long) was attached to the vertical structure of the workpiece (Fig. 1) and had six evenly spaced holes, each 1.3 cm in diameter. Simulated drilling was performed with a pneumatic drill attached with a custom-built drill bit (or "probe"). The probe had sequential portions of steel and nylon, with respective lengths of 3.3 cm and 2.5 cm, and the diameter was 1 cm. The probe base was connected to a load cell (Interface, SML-100, Scottsdale, AZ) that was "chucked" into the drill. Note that the hole size in the rung and the diameter of the probe were determined to induce the quality requirement specification of a large aircraft manufacturer for drilling fuselage fastener holes – an angularity tolerance of < 2° from normal to the surface. The drill mass was 3.63 kg (8 lb), and this was also increased to 5.9 kg (13 lb) using an additional mass (Fig. 2).

Completing a drilling action required participants to first insert the probe into a hole, push the probe to exert a sufficient normal force (i.e. ≥ 111.2 N), exceed this force for a cumulative total of 2.5 s, and then remove the probe. Whenever the exerted force exceeded the threshold, and until the drilling action was completed, any contact between the probe and the rung (i.e., beyond the angularity tolerance) was counted as an error. Note that during the drilling action, computer-generated drilling, completion, and error sounds were provided as relevant. Each trial of the drilling task required completing four drilling actions – alternating two times between two holes located directly in front of (i.e., shoulder work height) or above participants (i.e., overhead work height), as quickly as possible while minimizing errors.

Simulated light assembly (wiring) task: For this task, a Styrofoam block (mimicking an electrical junction box) was attached on top of the rung (Fig. 1), and from which five pairs of color-coded wires were left loose (Fig. 1). Completing the light assembly task involved connecting all five pairs of wires according to their colors.

2.3. Experimental design and procedures

Participants completed two sessions. In the first session, they were introduced to and properly fitted with the exoskeletal vest, then asked to practice the drilling and light assembly tasks at the overhead and shoulder heights, both with and without the exoskeletal vest (total mass = 6.5 kg). For each experimental condition, participants were encouraged to find their preferred working posture. This practice lasted ~40 min. Participants were also asked to complete a "wall sit" and give ratings of perceived discomfort (RPD) of the thigh during this, using the Borg CR10 scale (Borg, 2004). This procedure was used to ensure that they understood and practiced using the rating scale (Sood et al., 2007).

The second session was used to assess the effects of the exoskeletal vest on shoulder physical demands and work performance during the simulated work tasks. Three simulated *Work Task* levels were included: drilling ($\text{Drilling}_{\text{LIGHT}}$), drilling with additional mass ($\text{Drilling}_{\text{HEAVY}}$) and wiring. Participants performed each work task in four configurations, including all combinations of two levels of *Intervention* (with vs. without the exoskeletal vest) and two levels of *Work Height* (shoulder vs. overhead). The presentation order of *Work Task* conditions was counter-balanced using 3 × 3 Latin squares, and within a given work task condition the presentation orders of *Intervention* and *Work Height* conditions were alternated between participants. Participants completed two trials of a given condition (i.e., specific combination of *Work Task*, *Intervention*, and *Work Height*) before moving to the next one, and were instructed to perform each task as quickly and accurately as possible. After completing the two trials, RPD scores were obtained for select body parts: neck, shoulder, upper arm, forearm, upper back, low back, and leg. For bilateral body parts, participants were asked to provide a rating for the side experiencing a higher level of discomfort. Three minute or longer periods of rest were given between experimental conditions. This second session lasted ~2.5 h, and upon

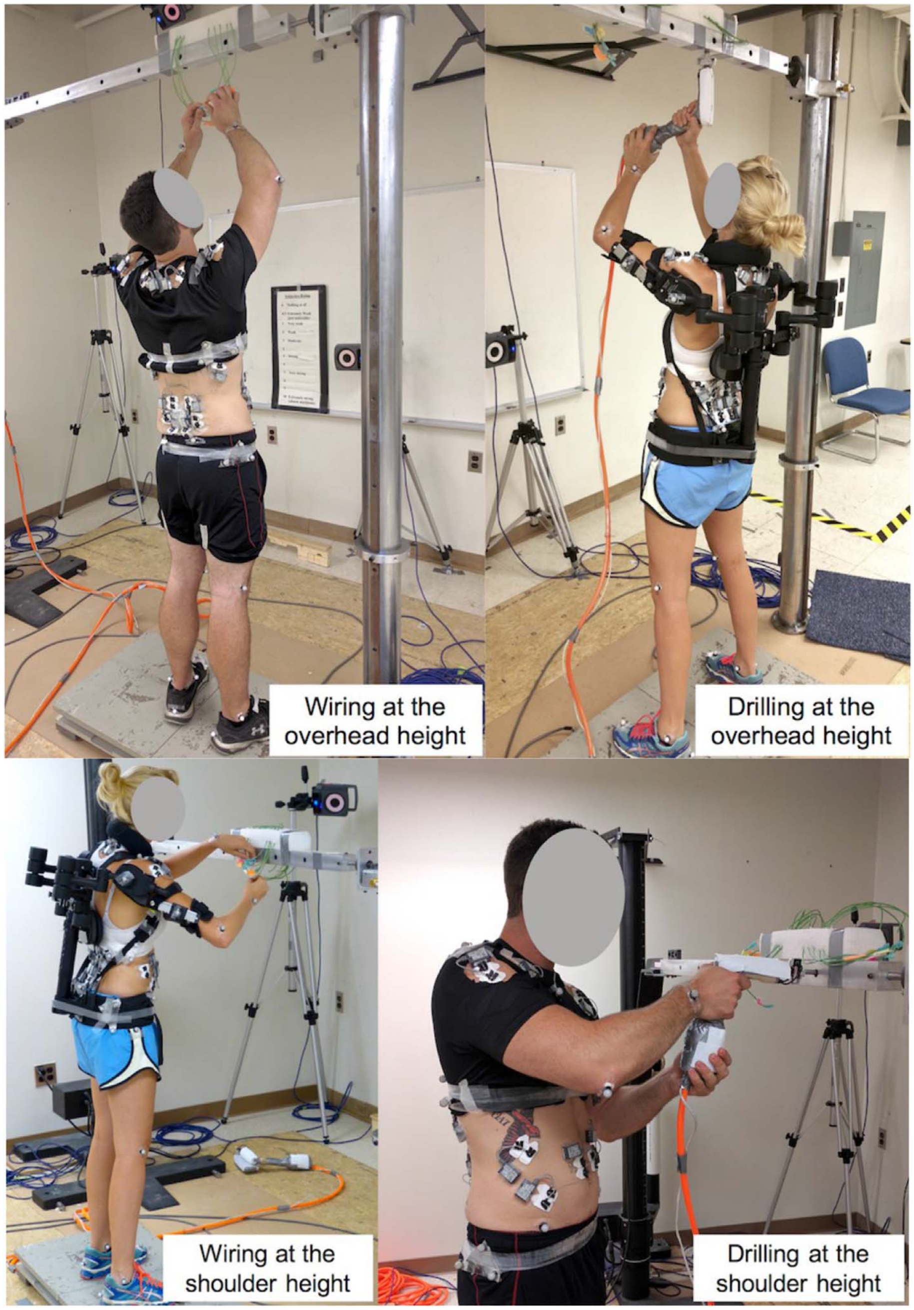

Fig. 1. Height adjustable workpiece and example of drilling and wiring tasks at two different work heights (i.e., shoulder and overhead).

Fig. 2. A pneumatic drill connected with a load cell and the simulated drill bit (Left), with 2.27 kg additional mass (Right).

completing it participants were asked to provide their thoughts on the use of the exoskeletal vest.

2.4. Instrumentation and data processing

During the work simulations, muscle activity was monitored using surface electromyography (EMG). Pairs of pre-gelled, bipolar, Ag/AgCl electrodes with a 2.5 cm inter-electrode spacing were placed bilaterally over three accessible shoulder muscles, the anterior and middle deltoid, and the descending trapezius, similar to Rashedi et al. (2014). To normalize EMG signals, isometric maximal voluntary contractions (MVCs) were performed bilaterally to isolate each shoulder muscle. Participants were asked to raise their arm as hard as possible, while the arm was held at ~45° shoulder flexion and both ~90° and ~130° shoulder abduction, with resistance provided by an investigator. This was repeated three times, and during which non-threatening verbal encouragement was provided. After completing MVC trials, five minute or longer periods of rest were given. Raw EMG signals were sampled at 1 kHz using a telemetered system (TeleMyo Desktop DTS, Noraxon, AZ, USA), and signals were subsequently band-pass filtered (20–500 Hz, 4th-order Butterworth, bidirectional).

For each experimental trial, shoulder EMG signals were low-pass filtered (3 Hz cut-off, 4th order Butterworth, bidirectional) to create linear envelopes. Normalized EMG (nEMG) values were then obtained using corresponding maximum values obtained during MVCs. Specific to the drilling task (i.e., Drilling$_{LIGHT}$ and Drilling$_{HEAVY}$), both the total number of errors and the completion time were obtained as measures of performance, similar to Alabdulkarim et al. (2017).

2.5. Statistical analysis

All statistical analyses were performed using JMP Pro 11 (SAS, Cary, NC), and summary data are reported as means (SDs) unless stated otherwise. Outcome measures common to both the drilling and light assembly task were: RPD scores, the peak (95%-ile) and median (50%-ile) values of total normalized shoulder muscle activity [i.e., the sum of nEMG values across all shoulder muscle groups (Chopp et al., 2010)], peak and median nEMGs for each muscle group monitored, and task completion time. Three-way, repeated-measures analyses of variance (ANOVAs) were performed separately for each outcome measures to determine the effects of *Intervention*, *Work Task*, and *Work Height*. Errors were only quantified for the drilling task, and for this a generalized regression with the Poisson distribution was used. Significant effects were followed by *post hoc* pairwise comparisons (Tukey's HSD tests or Student's *t* tests), and significant interaction effects were further examined using simple effects analysis. The order of exoskeletal vest presentation was initially included as a blocking variable in the ANOVAs; no significant order effects were found in any analyses, so this effect was not considered in final ANOVAs. Statistical significance was determined at $p < 0.05$, and effect sizes are reported using eta squared (η^2). Reliability of each outcome measure was quantified using intraclass correlation coefficients (Kim, 2013), and these were interpreted as follows: 0.00–0.39 poor, 0.40–0.59 fair, 0.60–0.74 good and 0.75–1.00 excellent (Cicchetti and Sparrow, 1981). The subsequent presentation of the results and the discussion emphasize the main and interactive effects of *Intervention*, given the aim of the current study.

3. Results

Reliability of EMG measures varied depending on experimental conditions. Across work heights and tasks, the median and peak nEMG for each muscle, and the total shoulder muscle activity, had ICC values that ranged from 0.66 (good) to 0.99 (excellent) without the vest and from 0.59 (fair) to 0.99 (excellent) with the vest. Mean (SD) ICC values for the median and peak nEMG were, respectively, 0.94 (0.06) and 0.91 (0.08) without the vest, and 0.85 (0.12) and 0.85 (0.09) with the vest. In the case of drilling performance, across work heights and tasks completion time had ICC values [mean (SD) = 0.78 (0.19)] from 0.52 (fair) to 0.96 (excellent) without the vest, and ICC values [0.89 (0.09)] from 0.76 (excellent) to 0.98 (excellent) with the vest. The number of errors had ICC values [0.89 (0.08)] from 0.75 (excellent) to 0.97 (excellent) without the vest; and ICC values [0.76 (0.15)] from 0.55 (fair) to 0.91 (excellent) with the vest.

Table 1 summarizes the ANOVA results for RPD scores. *Intervention*-related effects were found to be significant only on forearm RPD, which included the main effect of *Intervention* and the *Intervention* × *Work Task* interaction. While use of the vest reduced forearm discomfort overall, this reduction was most substantial (and statistically significant) for Drilling$_{HEAVY}$, the most demanding condition (Fig. 3). Forearm RPD was also significantly affected by main and interaction effects of *Work Height* and *Work Tasks*; forearm RPD significantly increased when tasks were done at the overhead (vs. shoulder) height, but only in the Drilling$_{HEAVY}$ condition. There were also significant main effects of *Work Height* on neck and shoulder RPDs, which were higher at the overhead level [neck = 1.7 (1.7), shoulder = 2.4 (2.1)] vs. shoulder level [neck = 0.4 (0.7), shoulder = 1.3 (1.3)]. The main effect of *Work Task* was significant on all RPDs, being highest during Drilling$_{HEAVY}$ and lowest during Wiring.

Summaries of ANOVA results for peak and median nEMG values are given in Tables 2 and 3, respectively. In general, *Intervention*, *Work Height*, and *Work Task* had significant main effects on both peak and median nEMG values for most of the shoulder muscle groups monitored and the total across these muscles. Furthermore, the *Intervention* × *Work Height* interaction significantly affected peak nEMG values for right and left middle deltoid (RMD and LMD), and the left descending trapezius (LTR); this interaction effect also approached significance for the peak total shoulder muscle activity. The *Intervention* × *Work Height* interaction also significantly affected the median nEMG values for all except right anterior deltoid (RAD). Using the exoskeletal vest reduced peak and median nEMG values to the greatest extent at the overhead work height (e.g., Figs. 4 and 5). Specifically, peak nEMG reductions were 38.4% for RMD, 24.5% for LMD, 44.7% for LTR, and 30.3% for the total shoulder muscle activity. Reductions in median nEMG were 48.5% for RMD, 34.8% for right descending trapezius (RTR), 24.0% for left anterior deltoid (LAD), 49.6% for LMD, 24.2% for LTR, and 33.5% for the total shoulder muscle activity. Significant *Intervention* × *Work Task* interaction effects were found on the peak nEMG for RMD and RTR, and the median nEMG for LAD (Fig. 6); peak values for RMD and RTR were more substantially reduced, by ~30–41%, during the drilling tasks, while the median reduction for LAD was 59.5% during the wiring task. Significant *Work Height* × *Work Task* interaction effects were found for all shoulder muscle groups except RTR. The levels of normalized muscle activity (i.e., peak and median values) were generally higher when tasks were done at the overhead (vs. shoulder) work height and during the drilling (vs. wiring) task.

Regarding drilling performance, completion time was significantly affected only by the main effect of *Intervention* [with the exoskeletal vest = 14.6 (3.0) sec.; without = 18.0 (5.1) sec.]. The number of errors was significantly affected by a main effect of *Work Task* and the *Intervention* × *Work Task* interaction. At the overhead work height, using the exoskeletal vest led to an increase in the number of errors (Fig. 7).

4. Discussion

This study aimed to examine the "expected" or intended consequences of a passive upper extremity exoskeletal vest, in terms of worker safety and health as well as work performance. Overall, our results indicated that wearing the current prototype vest did not alter the level of perceived discomfort for the body parts considered during different work simulations. An exception to this was the forearm, where use of the vest decreased discomfort. In contrast, the exoskeletal vest reduced the peak and median muscle activity of several shoulder muscle groups by up to ~45% and ~50%, respectively, depending on work height and/or work task. With respect to task performance, using the prototype vest caused an increase in the number of errors made during the intermittent repetitive drilling task, but only when working at the overhead height, yet it reduced completion time by nearly 20%.

Perceived discomfort observed here was comparable for all the body parts considered both with and without the prototype vest, except, as noted, for the forearm especially during drilling with the heavy tool (Fig. 3). The lack of an effect on other body parts here is inconsistent with earlier work (Butler, 2016; Liu et al., 2017; Rashedi et al., 2014), which reported substantially reduced pain/discomfort levels for the upper arm, shoulder, and/or neck areas with an exoskeleton. For example, Rashedi et al. (2014) found a reduction of upper arm and shoulder RPDs by up to ~50% during a simulated, intermittent

Table 1
Summary [*F* value (*p* value, η^2)] of ANOVA results regarding the main and interaction effects of *Intervention*, *Work Height*, and *Work Task* on RPD scores. Note that significant effects are highlighted using bold font.

	Intervention (I)	Work Height (H)	Work Task (T)	I x H	I x T	H x T	I x H x T
Neck	0.059 (0.81, 0.0004)	**18.43 (0.001, 0.20)**	**5.50 (0.011, 0.027)**	0.0005 (0.98, 0.00001)	2.52 (0.10, 0.007)	0.62 (0.55, 0.003)	0.15 (0.86, 0.0006)
Shoulder	0.03 (0.87, 0.0002)	**12.14 (0.0045, 0.09)**	**17.20 (< 0.0001, 0.17)**	0.95 (0.35, 0.002)	0.35 (0.71, 0.001)	2.77 (0.08, 0.007)	0.22 (0.81, 0.0009)
Upper Arm	0.44 (0.52, 0.002)	4.52 (0.055, 0.04)	**23.94 (< 0.0001, 0.18)**	0.006 (0.94, 0.00001)	0.28 (0.76, 0.0007)	0.04 (0.96, 0.0001)	0.73 (0.49, 0.003)
Forearm	**6.48 (0.0256, 0.03)**	**7.25 (0.0196, 0.05)**	**16.45 (< 0.0001, 0.15)**	0.16 (0.70, 0.0004)	**5.20 (0.013, 0.013)**	**4.71 (0.019, 0.015)**	0.78 (0.47, 0.002)
Upper Back	0.03 (0.87, 0.0005)	3.35 (0.09, 0.027)	**10.38 (0.0006, 0.054)**	0.27 (0.61, 0.0006)	0.94 (0.40, 0.002)	0.91 (0.42, 0.003)	0.82 (0.45, 0.003)
Low Back	0.017 (0.90, 0.0003)	3.97 (0.069, 0.032)	**11.65 (0.0003, 0.05)**	0.50 (0.49, 0.0007)	0.05 (0.95, 0.00001)	1.38 (0.27, 0.003)	0.71 (0.50, 0.0025)
Leg	2.71 (0.13, 0.009)	0.83 (0.38, 0.01)	**9.81 (0.0008, 0.05)**	0.50 (0.49, 0.002)	0.43 (0.65, 0.001)	2.16 (0.14, 0.009)	2.34 (0.12, 0.01)

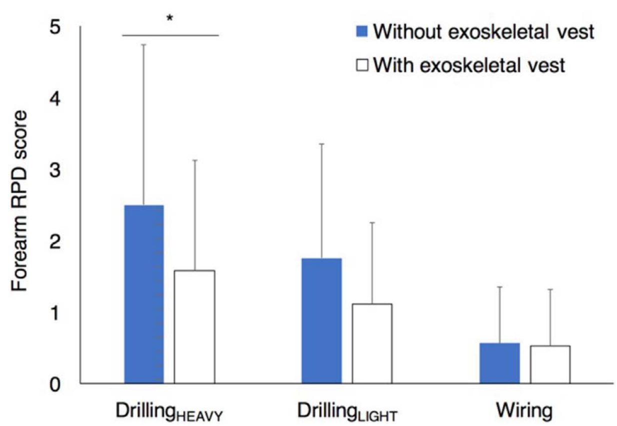

Fig. 3. *Intervention* × *Work Task* interaction effects on forearm RPD. Note that the symbol * indicates a significant difference ($p < 0.05$) between the levels of *Intervention*, and error bars indicate standard deviations.

overhead task. Though we did not observe such a reduction here, reduced forearm RPD scores might be associated with reduced shoulder muscle activity levels (e.g., Figs. 4 and 5). Given that the biceps and triceps are bi-articular muscles spanning the shoulder and elbow joints, the activity level of these might have decreased, leading to reduced RPD scores for the forearm. In addition, participants might have adopted different wrist postures with vest use, leading to reduced forearm RPD scores. Further investigation is required, however, to determine if the absence of noticeable decrease in perceived discomfort in the current study was due to differences in experimental conditions (e.g., tasks of interest, physical demands involved) and/or exoskeletal design approaches (e.g., use of an articulated arm, different moment generation and hinge mechanisms).

Use of the prototype vest reduced peak and median shoulder muscle activity levels especially at the overhead work height (Tables 2 and 3, and Figs. 4 and 5). A reduction in peak muscle activity was more pronounced during the drilling task, while a reduction in median muscle activity (specifically, LAD) was evident during the wiring task (Fig. 6). While there were several significant *Intervention*-related interactions on peak nEMG values, their associated effect sizes were rather small ($\eta^2 \leq 0.01$), except for the *Intervention* × *Work Height* interaction effect on LMD ($\eta^2 = 0.04$). Note that $\eta^2 = 0.01$ and 0.06 are often considered small and medium effect sizes, respectively (Miles and Shevlin, 2001). Across work heights and tasks, peak nEMG of the RAD, RMD, and RTR, and the peak total shoulder activity, decreased with use of the prototype vest by mean levels of roughly 28%, 38%, 32% and 30%, respectively. Peak activities of the RMD and LMD were reduced respectively by ~48% and ~45% only at the overhead work height (e.g., Fig. 4). In the case of median nEMG, the reduction with vest use was contingent on work height, in that ~24–50% reductions in the considered shoulder muscles (except RAD) were observed only at the overhead work height. Overall, these results regarding the effect of a

Table 2
Summary [*F* value (*p* value, η^2)] of ANOVA results for peak nEMG values, in terms of main and interaction effects of *Intervention*, *Work Height*, and *Work Task*. Note that significant effects are highlighted using bold font.

	Intervention (I)	Work Height (H)	Work Task (T)	I x H	I x T	H x T	I x H x T
Total	**6.02 (0.032, 0.05)**	**60.91 (< 0.0001, 0.32)**	**42.84 (< 0.0001, 0.16)**	4.75 (0.052, 0.01)	0.40 (0.68, 0.0003)	**31.85 (< 0.0001, 0.04)**	0.38 (0.69, 0.0003)
RAD	**6.08 (0.031, 0.04)**	**28.22 (0.0002, 0.25)**	**36.10 (< 0.0001, 0.17)**	1.40 (0.26, 0.003)	0.019 (0.98, 0.00001)	**28.14 (< 0.0001, 0.07)**	1.25 (0.31, 0.002)
RMD	**6.82 (0.024, 0.05)**	**32.19 (0.0001, 0.23)**	**16.80 (< 0.0001, 0.09)**	**5.02 (0.047, 0.01)**	**3.72 (0.041, 0.005)**	**13.46 (0.002, 0.023)**	0.047 (0.95, 0.0001)
RTR	**8.08 (0.016, 0.08)**	**12.27 (0.005, 0.06)**	**62.21 (< 0.0001, 0.34)**	1.01 (0.34, 0.001)	**5.53 (0.011, 0.008)**	0.16 (0.85, 0.0005)	3.32 (0.055, 0.005)
LAD	2.89 (0.12, 0.02)	**29.19 (0.0002, 0.31)**	**19.93 (< 0.0001, 0.07)**	1.61 (0.23, 0.004)	1.79 (0.19, 0.002)	**32.64 (< 0.0001, 0.09)**	0.52 (0.60, 0.0006)
LMD	**5.94 (0.033, 0.05)**	**57,02 (< 0.0001, 0.33)**	**17.73 (< 0.0001, 0.04)**	**6.64 (0.026, 0.04)**	0.027 (0.97, 0.00001)	**22.43 (< 0.0001, 0.05)**	0.80 (0.46, 0.001)
LTR	2.05 (0.18, 0.02)	**76.71 (< 0.0001, 0.32)**	**39.35 (< 0.0001, 0.15)**	**5.29 (0.042, 0.01)**	0.32 (0.73, 0.0004)	**25.79 (< 0.0001, 0.03)**	0.31 (0.74, 0.0004)

§ Total = sum of nEMG across all muscle groups monitored, RAD/LAD = Right/Left anterior deltoid, RMD/LMD = Right/Left middle deltoid, and RTR/LTR = Right/Left descending trapezius.

Table 3
Summary [*F* value (*p* value, η^2)] of ANOVA results for median nEMG values, in terms of main and interaction effects of *Intervention*, *Work Height*, and *Work Task*. Note that significant effects are highlighted using bold font.

	Intervention (I)	Work Height (H)	Work Task (T)	I x H	I x T	H x T	I x H x T
Total	**7.22 (0.021, 0.07)**	**62.89 (< 0.0001,0.28)**	**72.71 (< 0.0001, 0.21)**	**7.09 (0.022, 0.02)**	0.16 (0.85, 0.0003)	**51.94 (< 0.0001, 0.05)**	0.97 (0.39, 0.001)
RAD	**6.80 (0.024, 0.05)**	**26.55 (0.0003, 0.22)**	**40.61 (< 0.0001, 0.18)**	1.00 (0.34, 0.003)	2.01 (0.16, 0.003)	**40.61 (< 0.0001, 0.07)**	2.13 (0.14, 0.003)
RMD	**8.34 (0.015, 0.08)**	**26.54 (0.0003, 0.18)**	**23.48 (< 0.0001, 0.09)**	**7.57 (0.019, 0.03)**	0.82 (0.45, 0.001)	**15.74 (< 0.0001, 0.02)**	0.05 (0.95, 0.0001)
RTR	**8.27 (0.015, 0.08)**	**11.69 (0.0057, 0.04)**	**62.59 (< 0.0001, 0.36)**	**5.55 (0.038, 0.005)**	2.83 (0.08, 0.005)	0.53 (0.60, 0.002)	3.15 (0.06, 0.006)
LAD	**5.65 (0.037, 0.03)**	**30.05 (0.0002, 0.26)**	2.04 (0.18, 0.005)	**28.39 (< 0.0001, 0.12)**	**6.59 (0.006, 0.008)**	**27.17 (< 0.0001, 0.09)**	0.47 (0.63, 0.0006)
LMD	**7.94 (0.017, 0.05)**	**54.65 (< 0.0001,0.30)**	**29.95 (< 0.0001, 0.07)**	**8.69 (0.013, 0.05)**	0.22 (0.81, 0.0006)	**28.59 (< 0.0001, 0.06)**	0.89 (0.43, 0.002)
LTR	2.59 (0.14, 0.03)	**83.93 (< 0.0001, 0.34)**	**9.28 (0.011, 0.01)**	**57.99 (< 0.0001, 0.19)**	0.23 (0.79, 0.0004)	**27.65 (< 0.0001, 0.04)**	0.89 (0.42, 0.001)

§ Total = sum of nEMG across all muscle groups monitored, RAD/LAD = Right/Left anterior deltoid, RMD/LMD = Right/Left middle deltoid, and RTR/LTR = Right/Left descending trapezius.

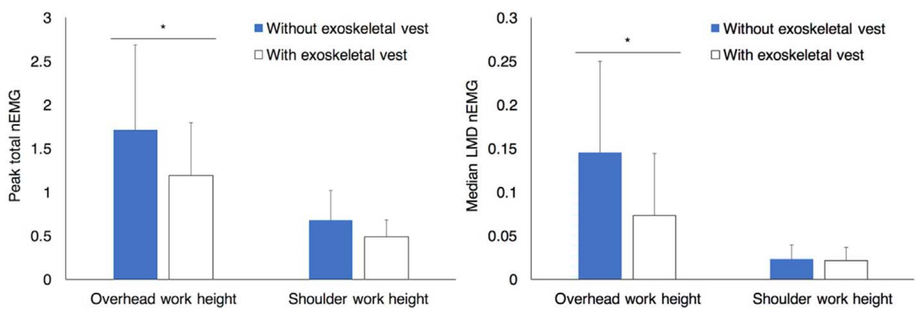

Fig. 4. *Intervention* × *Work Height* interaction effects on the peak total nEMG (Left) and peak nEMG for the left middle deltoid (LMD). Note that the symbol * indicates a significant difference ($p < 0.05$) between the levels of *Intervention*. Error bars indicate standard deviations.

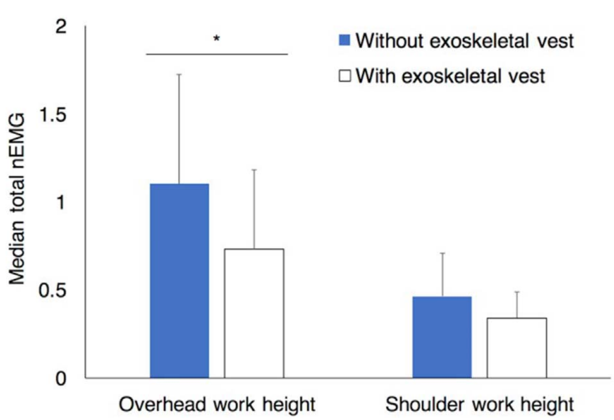

Fig. 5. *Intervention* × *Work Height* interaction effects on the median total nEMG (Left) and median nEMG for the left middle deltoid (LMD). Note that the symbol * indicates a significant difference between the levels of *Intervention*. Error bars indicate standard deviations.

upper-extremity exoskeleton are consistent with the earlier work of Rashedi et al. (2014), though they reported reductions mainly in RAD activity levels of ~25–50%, suggesting that a specific exoskeleton may benefit different shoulder muscle groups.

These results regarding discomfort and muscle activity in the upper extremity thus appear somewhat contradictory. Specifically, use of the current exoskeleton reduced upper-extremity muscle activity, yet perceived discomfort was unchanged other than at the forearm. One potential explanation for this discrepancy is that the tasks were not of sufficient duration to cause measurable discomfort (i.e., due to muscle fatigue). Measures of perceived exertion, not obtained here, may have provided subjective results that were consistent with those reflecting muscle activation levels. And, longer-term testing might have identified more consistent results for discomfort and muscle activity.

Use of the prototype exoskeletal vest appeared to have mixed impacts on drilling performance. From one perspective, task completion time was reduced by 3.4 s (18.9%) with the device. This agrees with earlier studies on the use of the Levitate Airframe™. Specifically, Butler (2016) reported 53% and 86% increases in "productivity", respectively during painting and welding operations. Spada et al. (2017) reported a 34% performance gain (increase in the number of completed tasks) during a simulated overhead sealing operation (i.e., line tracing with a pen). In contrast, we found that the number of errors significantly increased when using the prototype exoskeletal vest (Fig. 7). While the overall magnitude of this increase was rather small, it was both significant and substantial when working at the overhead height. Though further investigation is needed, we believe that this increase may have resulted because: 1) participants were able to work faster with the prototype vest (i.e., speed-accuracy tradeoff), 2) vest use may have affected upper extremity proprioception, and/or 3) participants may have needed a longer training period to develop and adopt an optimal work strategy specific to vest use.

Limitations in the study should be mentioned. First, participants did not span the full range of the working population, being relatively young and healthy. Caution thus should be taken in generalizing the current results for older, injured, and/or obese workers. Second, participants were novices for the work tasks considered here. The drilling and wiring tasks examined here can be viewed as generic tasks that an individual may infrequently or occasionally need to perform in their life, and all participants reported being competent in performing the experimental tasks after training. While involvement of novices may

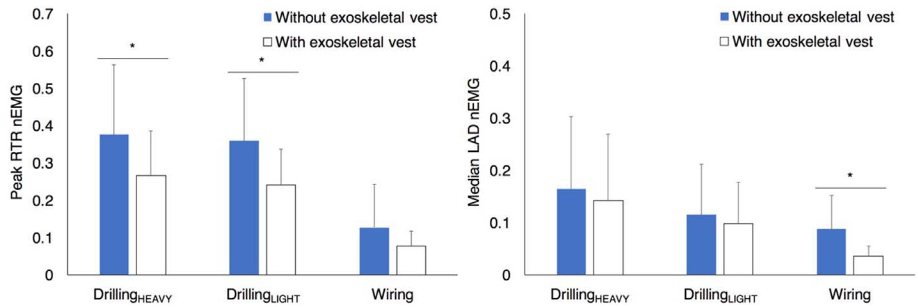

Fig. 6. *Intervention* × *Work Task* interaction effects on peak nEMG for the right descending trapezius (RTR; Left) and the median nEMG for the left anterior deltoid (LAD; Right). Note that the symbol * indicates significant differences ($p < 0.05$) between *Intervention* conditions. Error bars indicate standard deviations.

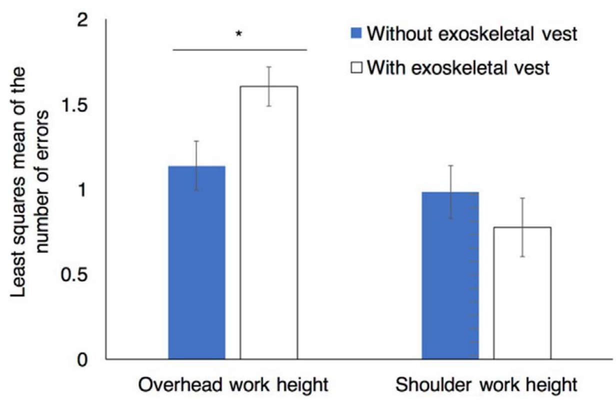

Fig. 7. *Intervention* × *Work Task* interaction effect on the number of errors made during the simulated drilling task. Note that the symbol * indicates a significant difference ($p < 0.05$) between *Intervention* levels, and error bars are 95% confidence intervals.

not be an important limitation, it remains possible that the effects of an exoskeletal vest may be different for experienced workers. Third, work tasks were performed in a controlled laboratory environment. Spada et al. (2017) noted that participants raised a concern about physical interference with their surroundings (e.g., contacting an automotive frame). Such a case, or suboptimal work environments in general (e.g., the presence of multiple workers, restricted working space), may influence the effects of an exoskeletal device. Fourth, upper extremity kinematics were not examined, so it is unclear if using the exoskeletal vest affected such kinematics when performing a task. Lastly, the current study focused on short-term effects of the exoskeletal vest. Future work is clearly needed to examine longer-term influences of using such an intervention. For example, while somewhat debatable, long-term use of trunk orthoses could cause trunk muscle weakness (Azadinia et al., 2017), and a similar effect could occur with upper extremity exoskeletons. Use of an exoskeletal vest could pose other threats to worker safety and health, and several such unexpected or unanticipated outcomes are reported in the companion manuscript.

In summary, occupational tasks involving arm elevation (e.g., overhead work) may not be entirely eliminable in the workplace, though controlling physical demands during overhead work can be of great practical importance given the injury risk imposed by such work. The current study assessed the effects of a prototype exoskeletal vest on physical demands and task performance during work task simulations, and demonstrated that using the device had limited effects on body part discomfort, reduced shoulder muscle activity, had mixed effects on drilling task performance. Overall, these results suggest that use of an upper-extremity exoskeletal vest has the potential to be an effective intervention for overhead work, yet as discussed above, future work is needed to assess the longer-term consequences (e.g., benefits, side effects, changes in work strategies) of such an intervention with diverse populations and more generally to better understand on-site health and safety issues that may occur with such technology.

Conflicts of interest

None.

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