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Assessing the influence of a passive, upper extremity exoskeletal vest for tasks requiring arm elevation: Part II – "Unexpected" effects on shoulder motion, balance, and spine loading

Sunwook Kim[a], Maury A. Nussbaum[a,b,*], Mohammad Iman Mokhlespour Esfahani[a], Mohammad Mehdi Alemi[c], Bochen Jia[d], Ehsan Rashedi[e]

[a] Department of Industrial and Systems Engineering, USA
[b] School of Biomedical Engineering and Sciences, USA
[c] Department of Mechanical Engineering, Virginia Tech, Blacksburg, VA 24061, USA
[d] Department of Industrial and Manufacturing Systems Engineering, University of Michigan-Dearborn, 4901 Evergreen Rd., Dearborn, MI 48126, USA
[e] Department of Industrial and Systems Engineering, Rochester Institute of Technology, Rochester, NY 14623, USA

A R T I C L E   I N F O

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A B S T R A C T

Adopting a new technology (exoskeletal vest designed to support overhead work) in the workplace can be challenging since the technology may pose unexpected safety and health consequences. A prototype exoskeletal vest was evaluated for potential unexpected consequences with a set of evaluation tests for: usability (especially, donning & doffing), shoulder range of motion (ROM), postural control, slip & trip risks, and spine loading during overhead work simulations. Donning/doffing the vest was easily done by a wearer alone. The vest reduced the max. shoulder abduction ROM by ~10%, and increased the mean center of pressure velocity in the antero-posterior direction by ~12%. However, vest use had minimal influences on trip-/slip-related fall risks during level walking, and significantly reduced spine loadings (up to ~30%) especially during the drilling task. Use of an exoskeletal vest can be beneficial, yet the current evaluation tests should be expanded for more comprehensiveness, to enable the safe adoption of the technology.

1. Introduction

An exoskeleton is a wearable, external structure that enhances/assists the muscular strength and performance of the wearer by providing assistive joint moments and/or structural support (Bogue, 2009; Lee et al., 2012; Yang et al., 2008). While exoskeletons have been actively considered to date for military, clinical, and rehabilitation applications, there is growing interest in potential occupational applications to reduce musculoskeletal demands and associated injury risks (de Looze et al., 2015). One such an application is the use of an exoskeletal vest for tasks with elevated arms or overhead work, given that such occupational activity is a major risk factor for work-related musculoskeletal disorders (WMSDs) of the shoulder (Nordander et al., 2016; Svendsen, 2004). Shoulder WMSDs may be more severe than other injuries and illnesses; in the U.S., a median of 23 lost workdays was reported for shoulder injuries and illnesses in 2016 (BLS, 2016), compared to a median of 8 days for all lost workday cases.

Existing reports, however, are rather limited regarding exoskeleton use during overhead work. Rashedi et al. (2014), in one example, showed that the use of a commercial exoskeletal vest and a mechanical arm (connected to the vest) can reduce shoulder muscle activity (up to 56%) and discomfort during a simulated, repetitive overhead activity. Another commercial, upper extremity exoskeletal vest, which includes passive moment generation around the shoulder (Levitate Airframe™, www.levitatetech.com), was assessed recently for painting and welding tasks (Butler, 2016), several simulated tasks (Spada et al., 2017), and laparoscopic surgery (Liu et al., 2017). These authors reported reduced levels of neck and shoulder discomfort/pain with the vest, and also improved productivity. In our companion paper (Kim et al., 2018), we reported that a prototype upper extremity exoskeletal vest, conceptually similar to the Levitate Airframe™, can reduce shoulder muscle activity (e.g., up to 45% reduction in peak muscle activity) during simulated drilling and light assembly tasks. Drilling task completion time was also reduced, though with a slight increase in the number of errors in some testing conditions. Overall, such evidence suggests that the use of an exoskeletal vest has potential as a beneficial intervention for controlling physical demands during overhead work, as well as to enhance work performance in some cases.

* Corresponding author. Department of Industrial and Systems Engineering, Virginia Tech, 250 Durham Hall (0118), Blacksburg, VA 24061, USA.
E-mail address: nussbaum@vt.edu (M.A. Nussbaum).

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Exoskeletal use in the workplace, however, may introduce unexpected or unintended health and safety challenges, though to our knowledge there are no formal reports to date that have investigated this issue. One such challenge is related to balance, and the associated risk of slips, trips and falls. A wide body of related research exists on this topic, which indicates that wearing an exoskeleton might increases the risk of such hazards. For example, earlier work (Lee and Lee, 2003; Qu and Nussbaum, 2009; Rugelj and Sevšek, 2011) demonstrated that carrying an external load (i.e., analogous to wearing an exoskeletal vest) can adversely affect postural balance performance, and that the magnitude of such an effect depends on load configuration (e.g., size, shape, and location). Furthermore, the rigid structure of an exoskeletal vest might constrain the natural kinematics of the trunk or upper extremities, and which thereby could influence gait performance. Trunk kinematics are particularly relevant, since it is associated with step width control to ensure frontal place stability (Arvin et al., 2016; Hurt et al., 2010). Additionally, some exoskeletal vests include a portion connecting the vest with the upper arms to provide an external moment about the shoulder. Such a configuration might interfere with natural arm reactions in response to slips and trips, potentially influencing balance recovery ability, including reaching for an external support (King et al., 2011; McIlroy and Maki, 1995), counterbalancing inertial/gravitational forces (Marigold, 2002; Pijnappels et al., 2010; Roos et al., 2008), and/or preparing for impact with the ground (McIlroy and Maki, 1995; Roos et al., 2008). Unintended physical demands imposed by an exoskeleton are another potential challenge of this technology. Spada et al. (2017) noted that using an exoskeletal vest can increase physical demands to maintain balance in some situations. Rashedi et al. (2014) and Theurel et al. (2018) reported that, when using a different exoskeletal vest design (which included an articulated arm), an increase in low back demands, heart rate, and/or antagonist muscle activity occurred along with a reduction in shoulder demands. An exoskeleton should, ideally, not alter or change the natural kinematics of a body joint, as this could increase discomfort and injury risks (Nichols et al., 2006; Schiele and van der Helm, 2009). However, when an exoskeleton is worn, segmental motions of a wearer may be constrained due to the additional mass, or the joint mechanism(s) and fastening straps of an exoskeleton.

The goal of the current study was to evaluate the potential benefits and challenges associated with 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. We selected and developed a set of evaluation tests, including work task simulations, after consulting manufacturing industry experts and considering the potential unintended safety challenges noted above. Simulated tasks were chosen to be representative of potential applications of such an upper-extremity support device, specifically repetitive drilling and light assembly. While an evaluation of expected consequences is reported in the companion paper (Kim et al., 2018), this paper reports on an evaluation of potential unexpected or unintended effects (i.e., donning/doffing times, shoulder range of motion, postural control, slip/trip risks, and spine loads).

2. Methods

2.1. Participants

A convenience sample of 27 participants (14 males and 13 females) completed one or more evaluation tests and were recruited from the local university and community. Table 1 summarizes the characteristics of participants in each test. 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. Overview of experimental design

Participants completed any of the following depending on their availability, which were completed on separate days: preliminary session, work simulations, slip & trip risk assessment. The preliminary session served to introduce the exoskeletal vest to participants, and in this session they also completed donning & doffing, shoulder ROM, and/or postural control tests. These tests (described in Section 2.3), except for the former, were performed both with and without the exoskeletal vest (total mass = 6.5 kg), the presentation of which was alternated between participants. Participants also practiced the simulated tasks at both overhead and shoulder work heights, both with and without the exoskeletal vest. Note that the companion paper provides a more detailed description of the simulated tasks (i.e., repetitive drilling and light assembly), task setup, and work simulation session (S. Kim et al., 2018).

In the work simulation test session, a full factorial design was used to examine the effect of the exoskeletal on physical demands and performance with respect to work tasks and work heights. Three independent variables were manipulated: *Work Task* [drilling ($\text{Drilling}_{\text{LIGHT}}$), drilling with additional mass ($\text{Drilling}_{\text{HEAVY}}$), and wiring], *Work Height* (shoulder vs. overhead work height), and *Intervention* (with vs. without the exoskeletal vest). Participants completed two trials in each of the 12 combinations of these independent variables, and were instructed to perform each task as quickly and accurately as possible. In the slip & trip risk assessment session, participants were first familiarized with a linear walking track by walking across the track several times both with and without the exoskeletal vest. Subsequently, they completed several trials of level walking on the track, at their self-selected comfortable gait speed, with and without the exoskeletal vest. The presentation order of with/without the vest was alternated between participants.

2.3. Evaluation tests

The prototype vest has a moment generation mechanism that is connected to an upper arm cuff, and provides a gradually-increasing support moment as the arm elevates. This support moment can be easily turned off by the user if needed, and was turned off during all of the current evaluation tests except for the work simulations.

2.3.1. Donning & doffing the exoskeletal vest

To understand one aspects of usability of the exoskeletal vest, the times needed to don and doff the vest were measured. Such measures were included because a worker may need to transition back and forth between using and not using the vest, or need to take off the vest in the event of an emergency. We first demonstrated how to don and doff the exoskeletal vest, with step-by-step instructions (provided by the manufacturer), and then let participants practice donning and doffing a minimum of four times or until they felt comfortable and competent. The vest was initially placed on a chair. Participants were asked to explore different strategies to don/doff the vest efficiently and comfortably (e.g., wearing the shoulder straps while sitting or standing, trying different orders to fasten straps and the waist belt, etc.). All participants chose to begin donning while sitting on the chair. Times to don and doff the vest were measured separately three times, again with the vest initially placed on a chair. Upon completing doffing, participants placed the vest back on the chair.

2.3.2. Shoulder range of motion (ROM)

To determine the extent to which the exoskeletal vest affects the natural shoulder ROM, both shoulder flexion and abduction were performed over the maximum voluntary ROM while keeping the trunk upright, maintaining the shoulders parallel to the ground, and minimizing externally/internally rotating the arm. ROM tests were completed using the dominant arm. Participants were instructed to stand

Table 1
Anthropometric and demographic characteristics of participants in each evaluation test – mean (SD) age, body mass (BM), stature, and body mass index (BMI).

Evaluation test	Total (*n*)	Male					Female				
		n	Age (Yrs)	BM (Kg)	Stature (cm)	BMI (kg/m^2)	*n*	Age (Yrs)	BM (Kg)	Stature (cm)	BMI (kg/m^2)
Donning & doffing	27	14	30.4 (9.6)	76.9 (14.1)	174.4 (4.3)	24.4 (2.9)	13	24.9 (8.4)	66.2 (9.2)	163.9 (8.1)	24.8 (3.9)
Shoulder range of motion (ROM)	17	10	27.1 (5.3)	72.6 (6.2)	173.8 (4.9)	24.1 (1.9)	7	22.4 (1.4)	64.7 (6.2)	169.9 (4.7)	22.4 (1.8)
Postural control	20	10	30.6 (9.9)	73.7 (10.2)	174.5 (4.7)	24.2 (3.1)	10	22.5 (1.7)	65.1 (10.0)	166.0 (8.9)	23.7 (4.0)
Slip & trip risk	20	10	29.3 (9.4)	73.7 (8.1)	169.6 (5.5)	25.6 (2.2)	10	25.4 (3.9)	64.8 (10.5)	163.0 (4.6)	24.5 (4.3)
3D spine loads	12	6	32.5 (11.8)	72.6 (9.1)	172.3 (4.6)	24.5 (2.8)	6	22.5 (1.5)	63.8 (6.2)	169.7 (5.2)	22.1 (1.8)

with their arm by their side and thumb pointing forward, and to perform two cycles of shoulder flexion and abduction in a slow, comfortable, and smooth manner.

2.3.3. Postural control in quiet, upright stance

Trials of quiet, upright stance were used to assess postural control performance. During a given trial, participants were asked to stand on a force platform (AMTI OR6-7-1000; AMTI, Watertown, MA, USA) for 70 s, and were instructed to stand as still as possible with their feet together, eyes closed, and arms at their sides. Participants completed two such trials, and a minimum of 30 s rest was provided between each.

2.3.4. Slip & trip risks

Slip and trip risks were assessed during level walking across a linear track (1.5 m × 15.5 m). The track was instrumented with two force platforms (AMTI OR6-7-1000; AMTI, Watertown, MA, USA45) near the middle of its length. For a given exoskeletal vest condition, participants completed 10 walking trials at their preferred walking speed while wearing standardized footwear.

2.3.5. Work simulation – repetitive drilling and light assembly

Both repetitive drilling and light assembly (i.e., connecting wires) tasks were simulated at two different work heights (i.e., individual shoulder and an overhead work height) using a height-adjustable workpiece. For the repetitive drilling task, participants completed four drilling actions on an aluminum rung connected to the workpiece using an instrumented pneumatic drill. The total drill mass was 3.63 kg (8 lb) or 5.9 kg (13 lb), with the latter obtained by attaching an additional mass. For the light assembly task, a Styrofoam block (mimicking an electrical junction box) was attached on top of the rung, and from which five pairs of color-coded wires were left loose. Participants were asked to connect all five pairs of wires by matching colors.

2.4. Instrumentation, data processing, and outcome measures

During the shoulder ROM, slip & trip risk, and work simulation tests, segmental body kinematics were monitored at 100 Hz using an 8-camera optical motion capture system (Vicon Vero, Vicon, Denver, CO, USA), and subsequently low-pass filtered (9 Hz cut-off; 4th-order Butterworth; bidirectional). For the shoulder ROM tests, reflective markers were attached unilaterally or in the mid-sagittal plane over select anatomical landmarks: the spinous processes of the seventh cervical (C7) vertebrae; incisura jugularis (IJ); xiphoid process (XP), acromial process (AC), lateral humeral epicondyle (LHE), and the midpoint between AC and LHE. For the slip & trip risk and work simulation tests, reflective markers were attached similar to the method described by Kim et al. (2011). Specifically, markers were placed bilaterally or in the mid-sagittal plane over: calcaneus; second metatarsal head; lateral and medial malleoli, lateral and medial tibial epicondyles, great trochanters, ACs, lateral and medial humeral epicondyles, midpoint between radialis and ulnar styloid processes, C7, IJ, XP, and the anterior and posterior superior iliac spines (ASIS and PSIS). When the exoskeletal vest was used, reflective markers were placed over the device's waist belt at the ASIS and PSIS levels. In addition, and specific to the work simulation session, clusters of three markers were placed over the thorax and over the pelvis.

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 eight accessible muscles crossing the lower lumbar region as in our previous work (Jia et al., 2011). Prior to completing the simulations, procedures were completed to individually calibrate an EMG-based model for estimating spine loads; the model was developed to estimate muscle forces and spine loads under various dynamic tasks, and additional model details are provided in Jia et al. (2011). Raw EMG signals were sampled at 1 kHz using a telemetered system (TeleMyo Desktop DTS, Noraxon, AZ, USA), and these were subsequently band-pass filtered (20–500 Hz, 4th-order Butterworth, bidirectional). Using the noted model, 3D spine forces were estimated at the lumbosacral level, specifically anteroposterior shear (F_{AP}), lateral shear (F_{LAT}), and compression (F_{COMP}). During the postural control test, tri-axial ground reaction forces and moments were collected at 1 kHz from the force platforms, and these were subsequently low-pass filtered (20 Hz cut-off; 4th-order Butterworth; bidirectional).

From data collected during each trial of the evaluation tests, specific outcome measures were obtained. For the shoulder ROM tests, maximum shoulder joint abduction and flexion angles were obtained with respect to trunk orientation, based on Wu et al. (2005). For the postural control test, force platform data were transformed to obtain center of pressure (COP) time series in the anteroposterior (AP) and the mediolateral (ML) direction, with the initial 5 s and last 5 s removed to avoid initial transients and anticipation effects, respectively. Following Prieto et al. (1996), mean COP velocity (MV) was obtained in the AP and ML direction. To assess trip and slip risk, the minimum foot clearance (MFC) and required coefficient of friction (RCOF) were obtained, respectively. MFC was determined as the minimum vertical distance between the 2nd metatarsal head and the ground during the swing phase of gait, and this was obtained for each foot when participants walked across the two force platforms embedded in the gait track. Note that this MFC definition does not represent the actual MFC, but permits a comparison between experimental conditions (Loverro et al., 2013). RCOF was calculated for each foot, as the largest instantaneous ratio of the horizontal (resultant force in the AP and ML directions) to vertical ground reaction force obtained 50–200 m s after heel contact (Perkins, 1978). From the work simulations, peak (95%-ile) and median (50%-ile) values of 3D lumbosacral forces were determined.

2.5. Statistical analysis

All statistical analyses were performed using JMP Pro 11 (SAS, Cary, NC), and summary data are reported as means (SDs) in original units unless stated otherwise. For the donning & doffing test, we observed that the donning and doffing times were different between males and females, and which was thus formally tested using one-way repeated measures analyses of variance (ANOVAs). For the shoulder ROM, postural control, and slip & trip tests, one-way, repeated measures ANOVAs were performed separately for each of relevant outcome measures (i.e., max. shoulder flexion and abduction angles, MV_{AP}, MV_{ML}, MFC, and max. RCOF) to determine the effect of *Intervention*. For the work simulations, separate three-way, repeated measures ANOVAs were performed to assess the influences of *Work Task*, *Work Height*, and *Intervention* on peak and median values of 3D spine forces. To meet parametric model assumptions, all measures of postural control and 3D spine forces were log transformed. Significant effects were followed by *post hoc* pairwise comparisons (Tukey's HSD tests), and significant interaction effects were further examined using simple effects analysis. 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 (ICC, 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 results and the discussion emphasizes the main and interactive effects of *Intervention*, given the aim of the current study.

3. Results

3.1. Donning & doffing, shoulder ROM, postural control, and slip & trip risk tests

Reliability of measures related to donning & doffing, shoulder ROM, postural control, and slip & slip risks were generally excellent, with ICC values of 0.93–0.98 with the vest and 0.79–0.97 without the vest. Overall donning and doffing times were 67.1 (18.1) sec. and 17.4 (4.3) sec., respectively. Donning time was significantly ($p = 0.04$) faster for female [59.5 (9.4) sec.] than male participants [72.5 (20.7) sec.], though doffing time was comparable ($p = 0.38$) between females [16.5 (3.3) sec.] and males [18.0 (4.9) sec.]. Table 2 summarizes the results from shoulder ROM, postural control, and slip & trip tests between *Intervention* conditions and the associated statistical results. *Intervention* significantly reduced maximum shoulder flexion and abduction angles, and significantly increased MV_{AP}. When the exoskeletal vest was worn, maximum shoulder flexion and abduction angles were reduced by roughly 2.6% and 10%, respectively, while MV_{AP} increased by ~12%.

3.2. Work simulation test – 3D spine forces

Reliability of 3D spine force measures varied between experimental conditions. Across work heights and tasks, ICCs for median and peak spine forces ranged from 0.46 (fair) to 0.98 (excellent) without the vest, and from 0.45 (fair) to 0.99 (excellent) with the vest. Mean (SD) ICC values for mean and median F_{AP}, F_{COMP}, and F_{LAT} were, respectively, 0.80 (0.14), 0.82 (0.13), and 0.70 (0.22) with the vest; and 0.89 (0.07), 0.85 (0.09), and 0.78 (0.17) without the vest.

A summary of ANOVA results for peak and median values of 3D spine forces is presented in Table 3. *Intervention* had main effects only on the median F_{LAT}, with least squares mean (95% Confidence Interval) = 74.4 (52.6, 105.1) N with the exoskeletal vest, and 41.1 (29.1, 58.1) N without the vest. *Work Height* had significant main effects on peak anteroposterior shear (F_{AP}), peak F_{LAT}, and median F_{LAT}. *Work Task* had significant main effects on peak and median values of all three spine forces. The *Intervention* × *Work Height* interaction significantly affected peak F_{AP} and peak F_{COMP}. Specific to the shoulder work height, wearing the exoskeletal vest reduced peak F_{AP} and F_{COMP}, respectively by 29.5% and 19.3% (Fig. 1). Significant *Intervention* × *Work Task* interaction effects were also found on peak F_{COMP} and F_{LAT}, and median F_{COMP} (Fig. 2). When using the exoskeletal vest, peak and median F_{COMP} decreased by 15.8–21.6% during the drilling task, whereas peak F_{LAT} increased by 87.9% during the wiring task.

Interaction effects of *Work Height* × *Work Task* were significant on all spine force measures except median F_{COMP}. Particular to the drilling task, peak and median F_{AP} and F_{LAT} were comparable or larger at the shoulder *versus* overhead work height, while peak F_{COMP} was comparable at both work heights (Table 4). For the wiring task, all three spine force measures had similar values between the two work heights.

4. Discussion

Adopting exoskeleton technologies in the workplace may introduce unexpected or unintended worker safety challenges. The current study examined several such potential outcomes for a prototype upper extremity exoskeletal vest. This was done using several evaluation tests, specifically for donning & doffing the exoskeletal vest, shoulder ROM, postural control (during upright, quiet stance), slip & trip risk, and work simulations to assess physical demands on the low back. The latter was included since this body region is commonly affected by WMSDs (Bureau of Labor Statistics, 2016), though it is not the primary design focus of an upper extremity exoskeletal vest. Our results showed that donning/doffing the exoskeletal vest appeared to be rather straightforward and not time-consuming, supporting that vest use may be easily incorporated into an existing work process even where the vest would be used intermittently. Wearing the prototype vest reduced maximum voluntary shoulder ROM and increased COP MV_{AP} during upright, quiet

Table 2
Mean (SD) of outcomes measures for shoulder range of motion (ROM), postural control, and slip & trip risk tests, with *F* values (*p* value, η^2) for the effects of *Intervention* (vest use) on each measure. Significant effects are highlighted using bold font.

Evaluation test		Intervention	Mean (SD)	*F* value (*p* value, η^2)
Shoulder ROM	Max. flexion (°)	With	157.3 (19.9)	**23.87 (0.0002, 0.01)**
		Without	161.6 (18.6)	
	Max. abduction (°)	With	145.2 (17.3)	**4.91 (0.04, 0.18)**
		Without	161.4 (17.2)	
Postural control	MV_{AP} (mm/s)	With	13.1 (6.2)	**36.21 (< 0.0001, 0.01)**
		Without	11.7 (4.8)	
	MV_{ML} (mm/s)	With	12.2 (6.0)	3.32 (0.08, 0.005)
		Without	11.6 (6.5)	
Slip & trip risk	MFC (mm)	With	62.8 (8.0)	2.43 (0.14, 0.004)
		Without	63.8 (8.3)	
	Max. RCOF	With	0.21 (0.04)	0.88 (0.36, 0.001)
		Without	0.20 (0.04)	

MV_{AP} and MV_{ML} = mean COP velocity in the anteroposterior and mediolateral directions, MFC = minimum foot clearance, and RCOF = required coefficient of friction.

Table 3
Summary [*F* value (*p* value, η^2)] of ANOVA results regarding the main and interaction effects of *Intervention*, *Work Height*, and *Work Task* on peak and median values of 3D spine forces. 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
Peak F_{AP}	1.81 (0.21, 0.006)	**5.52 (0.038, 0.04)**	**105.42 (< 0.0001, 0.24)**	**7.15 (0.022, 0.013)**	0.08 (0.93, 0.0003)	**8.92 (0.001, 0.026)**	0.95 (0.40, 0.001)
Peak F_{COMP}	2.92 (0.12, 0.007)	1.28 (0.28, 0.004)	**61.28 (< 0.0001, 0.17)**	**7.56 (0.019, 0.007)**	**5.82 (0.01, 0.008)**	**3.77 (0.039, 0.008)**	0.63 (0.54, 0.0007)
Peak F_{LAT}	2.08 (0.18, 0.01)	**86.64 (< 0.0001, 0.09)**	**75.23 (< 0.0001, 0.28)**	3.89 (0.07, 0.01)	**4.66 (0.02, 0.028)**	**20.89 (< 0.0001, 0.03)**	0.98 (0.39, 0.004)
Median F_{AP}	1.47 (0.25, 0.01)	3.69 (0.08, 0.029)	**43.80 (< 0.0001, 0.11)**	3.92 (0.07, 0.01)	0.68 (0.52, 0.002)	**3.67 (0.042, 0.015)**	1.33 (0.29, 0.002)
Median F_{COMP}	3.99 (0.07, 0.008)	4.23 (0.06, 0.005)	**30.00 (< 0.0001, 0.06)**	3.31 (0.10, 0.003)	**5.45 (0.012, 0.007)**	3.18 (0.06, 0.005)	0.76 (0.48, 0.0005)
Median F_{LAT}	**7.43 (0.02, 0.07)**	**43.33 (< 0.0001, 0.10)**	**33.74 (< 0.0001, 0.17)**	2.62 (0.13, 0.009)	1.78 (0.19, 0.009)	**10.55 (0.0006, 0.02)**	1.19 (0.32, 0.006)

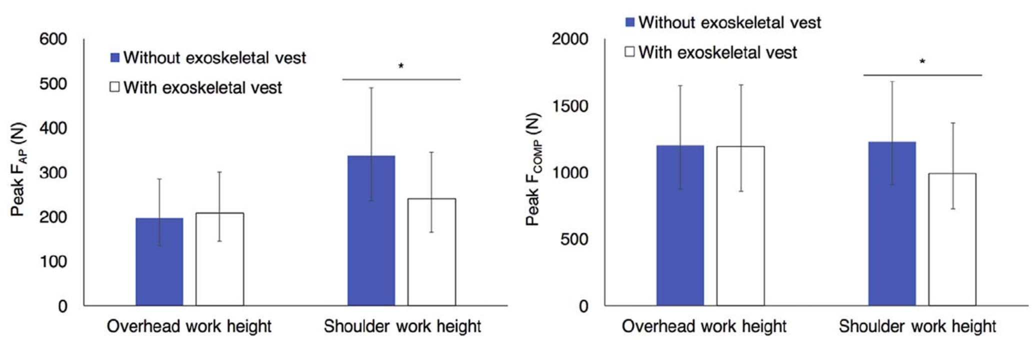

Fig. 1. *Intervention* × *Work Height* interaction effects on peak anteroposterior shear (F_{AP}) and peak compressive (F_{COMP}) forces at the lumbosacral joint. Note that the symbol * indicates a significant difference ($p < 0.05$) between the levels of *Intervention* (i.e., with vs. without the exoskeleton). Values reported are least squares means ± 95% confidence intervals (CIs).

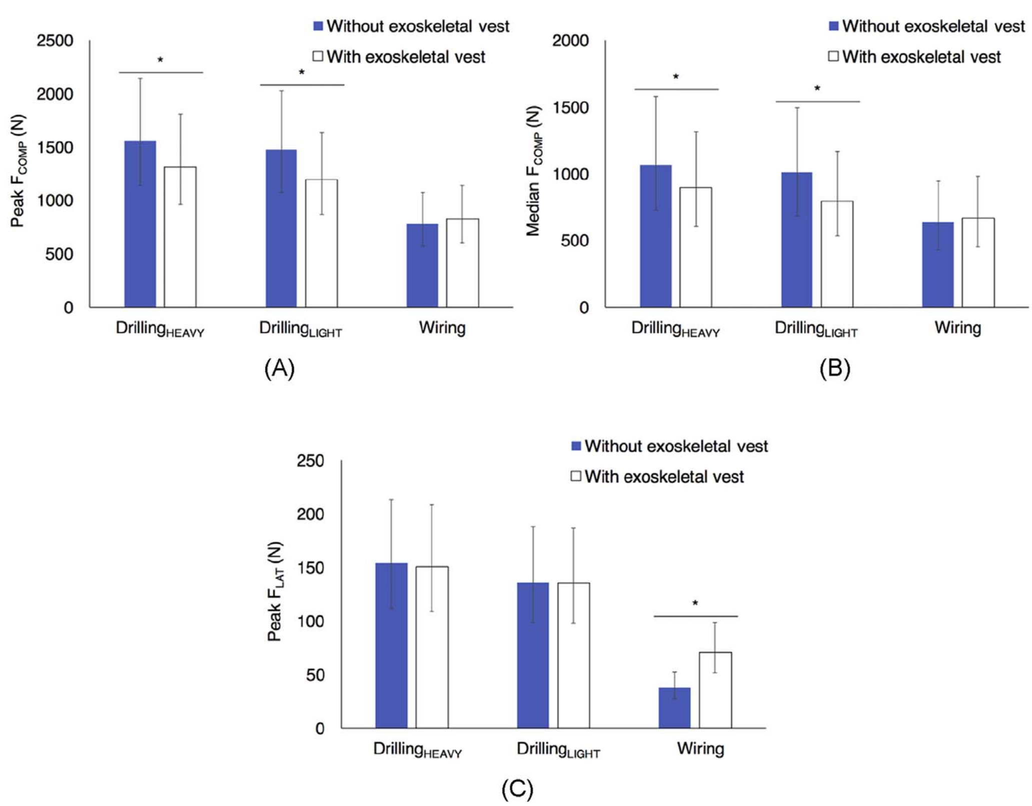

Fig. 2. *Intervention* × *Work Task* interaction effects on: (A) peak and (B) median compressive (F_{COMP}) forces, and (C) peak lateral shear force (F_{LAT}) at the lumbosacral joint. Note that the symbol * indicates a significant difference ($p < 0.05$) between the levels of *Intervention*. Values reported are least squares means ± 95% CIs.

Table 4
Least squares mean (95% CI) of peak and median anteroposterior and lateral shear forces (F_{AP} and F_{LAT}) and peak compressive forces (F_{COMP}) at the lumbosacral joint during the drilling task.

Spinal force (N)	$Drilling_{HEAVY}$		$Drilling_{LIGHT}$	
	Shoulder height	Overhead height	Shoulder height	Overhead height
Peak F_{AP}	405.0 (280.2, 585.6)	275.1 (190, 397)	445.9 (308.3, 644.9)	225.2 (155.8, 325.6)
Peak F_{COMP}	1314.3 (952.5, 1813.7)	1555.8 (1127.2, 2147.2)	1386.6 (1004.7, 1913.9)	1262.5 (914.9, 1742.3)
Peak F_{LAT}	214.2 (161.8, 283.5)	108.1 (81.6, 143.1)	208.3 (157.3, 275.9)	87.9 (66.4, 116.4)
Median F_{AP}	203.3 (133.0, 310.5)	147.8 (96.7, 225.8)	225.1 (147.3, 344.0)	121.1 (79.3, 184.9)
Median F_{LAT}	128.3 (91.2, 180.3)	52.7 (37.4, 74.1)	118.7 (84.3, 167.1)	42.8 (30.4, 60.2)

stance. Further, there was no evidence of changes in MFC or maximum RCOF values, and use of the vest appeared to be beneficial to the low back, given that lumbosacral forces were reduced in most cases.

Maximum voluntary shoulder ROM was reduced with the prototype vest on. Observed reductions were 4.3° (2.6%) in flexion and 16.2° (10%) in abduction. These outcomes are consistent with informal feedback provided by several participants, who noted that they felt somewhat restricted at the end ROM and that the shoulder pads got in the way when their arm was fully raised. Though not directly comparable to the current study, LaFiandra et al. (2003) reported that wearing a backpack can also restrict the range of shoulder flexion/extension, even during walking, depending on the amount of shoulder padding. Thus, the reduction in maximum voluntary shoulder ROM observed here appears largely due to the shoulder pad/strap design (e.g., width, thickness) and material (e.g., stiffness). As such, future exoskeleton designs may benefit from additional attention to these aspects. Yet, these reductions may not represent a practically meaningful influence, since it is unclear if such exoskeletons will be used (or useful) near the limits of shoulder ROM.

Wearing the prototype vest resulted in a potentially compromised postural control strategy during quiet stance, but no evident change in trip- and slip-related fall risks during level walking. Values of COP MV_{AP} increased by ~12% with (vs. without) the vest, and this increase is qualitatively consistent with earlier studies of load carriage (Qu and Nussbaum, 2009; Rugelj and Sevšek, 2011). During upright, quiet stance, the postural control system is suggested to adopt a strategy relying on information about the whole-body center of body mass (COM) velocity (Masani et al., 2003). It may be thus anticipated that the mass of an exoskeletal vest would cause difficulty in controlling COM velocity, and indeed a significant increase in the AP direction was found, and an increase in the ML direction that approached significance. In contrast, the use of exoskeletal vest had no effects on MFC or maximum RCOF values during level walking, and which generally agrees with existing work. Specifically, carrying a load ≤10% of body mass was found to have minimal impact on slip propensity (S. Kim and Lockhart, 2008); the mass of the prototype vest here was 6.5 kg, and it was on average near or below 10% of participants' body mass. In other work, effects of carrying a load on lower extremity joint kinematics have been inconsistent, depending on many factors such as the magnitude, distribution, and/or position of a mass (Holt et al., 2003; James et al., 2015; Majumdar et al., 2010; Silder et al., 2013). Note, though, that the external mass considered in these and related studies was typically greater than 6.5 kg. Overall, the current results suggest some additional postural control challenge while wearing the prototype vest, but that such a challenge, or changes to gait kinematics, were not reflected as any increased slip or trip risks measured during natural gait. However, the latter conclusion may be limited to the relatively simple gait task that we investigated.

Use of the prototype vest appears to be beneficial in reducing spine loading at the lumbosacral joint, particularly at the shoulder work height (Fig. 1) and during the drilling task (Fig. 2), though vest use did increase peak lateral shear force (F_{LAT}) during the wiring task. Specifically, at the shoulder work height, using the vest reduced peak AP shear and compressive forces by 29.5% and 19.3%, respectively. Vest use further reduced peak and median compressive forces during the drilling task, respectively by 18.5%–19.1% and 16.5%–21.6%. In contrast, peak F_{LAT} increased by 87.9% with the vest, although the magnitude of F_{LAT} was generally quite small overall (Fig. 2). The results as a whole, though, suggest that the beneficial effects of the current vest may be task-specific. Further, these beneficial effects on spinal loading (generally during the drilling task at the shoulder height) are rather unexpected, since the current vest was designed primarily to support the upper extremities and to reduce loading on the shoulders.

Contrary to our findings, a recent study by Weston et al. (2018) reported that using an exoskeletal vest with a mechanical arm increased spine loads during simulated drilling tasks at the eye and waist levels. Earlier evidence by Rashedi et al. (2014) during simulated overhead work tasks, using a similar exoskeleton, also indirectly suggested an increase in spine loads, in that there was an increase in paraspinal muscle activity with vest use. Weston et al. (2018) suggested that the increase in spine loads may have resulted from the device weight and a larger moment about the low back caused by the mechanical arm. Since the current prototype vest did not have a mechanical arm, participants could likely maintain their preferred horizontal working distance from the workpiece, and the rigid structure of the vest may have assisted them in maintaining better trunk posture and spinal stability. Such benefits could have helped participants to exert and maintain the required drilling force more easily, resulting in the observed reductions in spine loads. A secondary analysis of trunk kinematics indeed indicated that vest use resulted in more neutral (upright) trunk postures when drilling at the shoulder height. For example, peak trunk flexion, lateral bending, and axial rotation angles with respect to the pelvis were 2.8° (4.1°), 5.7° (4.3°) and 8.8° (11.5°) when using the exoskeletal vest; and 1.5° (4.2°), 8.7° (4.9°) and 16.9° (10.5°) without the vest. Note that peak trunk flexion increased slightly when using the vest, and which might be of assistance in generating a trunk flexion moment with the weight of the vest.

The current study shares the same limitations reported in our companion paper (S. Kim et al., 2018), such as the inclusion of rather healthy and young individuals with no work experience for the tasks considered, and a focus on the short-term effects of the exoskeletal vest use. Specific to the current study, as noted earlier the slip & trip risk test only considered linear, level walking. When turning a corner, frictional demands at the shoe-floor interface can be more substantial, exceeding those during descending ramps, walking straight, and descending (Fino and Lockhart, 2014). Additionally, fall recovery was not considered, though wearing this or other exoskeletal vest might interfere with fall recovery strategies (King et al., 2011; McIlroy and Maki, 1995; Roos et al., 2008). Thus, further investigation is needed to understand more fully the effects of an exoskeletal vest on slip, trip, and fall risks.

In summary, we examined several potential adverse (or unexpected) effects of a prototype upper extremity exoskeletal vest, using a set of evaluation tests to capture the effect of the exoskeletal vest use on worker safety. Overall, they suggested that donning/doffing the vest can be easily done by a wearer alone, and that vest use can decrease maximum voluntary shoulder ROM and increase the challenge of static postural control. Vest use, however, appeared to have minimal influences on trip- and slip-related fall risks during level walking, and moreover reduced spine loadings especially during the drilling task. Though the latter can be considered a beneficial outcome, it should still be emphasized that future efforts are still needed to understand more completely how an exoskeleton affects physical demands on body parts that are not the primary design focus of the technology. Concerns have been raised earlier about increased physical demands on such "other" body parts with an exoskeletal vest that supports a tool for overhead work (Rashedi et al., 2014) and with a passive exoskeleton that distributes low back demands to the chest and legs during manual lifting (Bosch et al., 2016). It remains unclear if any unexpected health benefits (or concerns) are due to differences in exoskeleton design approaches and/or the characteristics of work tasks considered (e.g., static *versus* dynamics, different work heights). Therefore, future work is needed to extend the current evaluation tests to more comprehensively assess exoskeletons in the workplace with additional tests, such as fall recovery analyses (Madigan and Lloyd, 2005) and pressure mapping to examine the interaction between an exoskeleton and the human body (Reid et al., 2014).

Conflicts of interest

None.

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