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Effects of shoulder-assist exoskeletons on muscle activity and balance during a wire pulling task on a simulated scissor lift

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ABSTRACT

Construction workers, especially electricians, frequently perform overhead tasks on elevated platforms, increasing their risk of musculoskeletal disorders (MSDs) and falls. This study evaluated the effects of three passive upper extremity exoskeletons (PUEEs) on shoulder muscle activity and postural balance during a simulated wire pulling task on a motion platform replicating scissor lift dynamics. Nine male participants completed tasks at two force levels (65 N and 130 N), with and without exoskeletons. Electromyography, motion capture, and force plate data were used to assess shoulder muscle activation, joint kinematics, and postural stability. The tested PUEEs significantly reduced peak activity in key shoulder muscles—including upper trapezius (−17 % to −38 %) and much of deltoid (−1 % to −49 %)—without increasing load in the back or lower limbs. Postural stability improved with the tested PUEEs (5 %–25 %), particularly with the heavy ones, though distinct kinematic changes were observed across models. These results suggest that PUEEs may reduce biomechanical strain and improve balance during static or quasi-static overhead work, but task-specific demands and device characteristics should be carefully considered.

1. Introduction

Construction workers face significant risks when using elevated work platforms such as scissor lifts. Many fall-related deaths occur annually from such activities (Burkart et al., 2004; McCann, 2003). According to the Bureau of Labor Statistics (BLS), falls are the leading cause of death in the construction industry, accounting for over a third of all fatalities (2019–2022 BLS data). In a study using Census of Fatal Occupational Injuries (CFOI) data from 1992 to 1999, it was found that nearly 44 % of vertical lift-related fatalities involved falls from scissor lifts, with another 30 % being attributed to scissor lift tip-overs (McCann, 2003). Another study found that from 1992 to 2003, 70 % of fatal incidents involving scissor lifts were from a fall or lift height of ten feet or higher (Pan et al., 2007). Additionally, tip-overs are more likely to occur when a worker on a scissor lift is performing forceful actions or continuous periodic movement (Dong et al., 2012) due to their inherent instability at elevated heights (Pan et al., 2012). The fall and tip-over hazards while working at height in scissor lifts pose a clear and significant danger to construction workers, including electricians.

In addition to the risk of falls, construction workers also have an elevated risk of musculoskeletal disorders (MSDs) due to the physically demanding nature of their jobs. Their daily tasks often require high force exertion and repetitive motions (Wang et al., 2021), which can lead to overexertion, causing strains, sprains, and MSDs involving upper extremities, the neck and shoulders, and the lower back. Specifically, electricians are at significant risk of MSD injuries from labor-intensive work that includes material handling, like cable and wire pulling, and over the shoulder tasks, such as installing fixtures and electrical components (Rogerson et al., 2024). They are also required to perform bending, twisting, and repetitive motions for over half of their time at work, which increases the likelihood of MSDs (CPWR–The Center for Construction Research and Training, 2018). Lifetime risk of overexertion injuries like MSDs in construction is about 21 %, meaning that about 1 in 5 construction workers are expected to have an overexertion injury during their career (Dong et al., 2014). In 2015, over exertions from material handling accounted for 67 % of all work-related MSDs in construction (CPWR–The Center for Construction Research and Training, 2018). The high prevalence of these injuries has resulted in loss of productivity (Inyang et al., 2012), significant medical costs, diminished quality of life (Beaudart et al., 2018), shortened careers, and an increased risk of premature workforce exit accompanied by economic hardship (Sharpe et al., 2022; Welch et al., 2010). Furthermore, multiple

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studies have found a strong correlation between MSDs and prescription opioid use among construction workers (Dong et al., 2020, 2022). Compared to other physically demanding occupations such as agriculture, manufacturing, and transportation, the construction industry has the highest incidence of opioid overdose deaths (Morano, 2018).

To address these concerns for reducing MSDs, previous research has explored the effectiveness of employing exoskeleton devices. Use of such devices has gained significant attention and popularity in recent years. Exoskeletons are wearable devices that can support users' joints and muscles during the performance of prolonged physically demanding tasks. They are categorized as either active or passive. To function, active models use actuated/motorized components and passive models use simple mechanical systems. Previous research has shown promising results regarding the benefits of exoskeletons to reduce injury risks (De Looze et al., 2016; Zhu et al., 2021). Studies have reported that users of exoskeletons have experienced decreases in muscle fatigue (De Bock et al., 2020) and biomechanical loadings, as well as improvements in posture (Vallée, 2024). The benefits received from using exoskeletons could help reduce the risk of MSDs in the regions of the body where the exoskeletons are used (Kim et al., 2018a; Picchiotti et al., 2019a). These findings suggest that exoskeletons could be a valuable tool for improving the safety and well-being of construction workers.

Passive upper extremity exoskeletons (PUEEs) are a type of exoskeleton designed to reduce biomechanical loading on the upper extremities without the use of motorized components. Past laboratory studies of PUEEs have explored their effects on muscular stress and postural stability while lifting and carrying loads (Theurel et al., 2018; Tounekti et al., 2024), performing overhead tasks (Huysamen et al., 2018; Hyun et al., 2019; Kim et al., 2018a; Maurice et al., 2019; Schmalz et al., 2019; Wang et al., 2021), and more (Musso et al., 2024). Field studies involving use of PUEEs for overhead work have also been performed in industrial manufacturing settings such as boat sanding and painting (Moyon et al., 2018) and automotive assembly line labor (Iranzo et al., 2020). While each of these studies affirms the potential of PUEEs for reducing the risk of MSDs, other studies have also reported a significant reduction in anteroposterior stability in static positions (Kim et al., 2018b) and while walking (Tounekti et al., 2024). Another study noted increases in postural strains and upper limb kinematics while using a PUEE to lift, carry, and stack loads (Theurel et al., 2018). Iranzo et al. documented various significant differences in posture due to restrictions imposed by the PUEE they studied (2018). These secondary effects, which were all observed when the PUEE was used at ground level on stable surfaces, could have a direct impact on a user's risk of falling when working at heights on an unstable platform. No research has yet looked at the implications of these secondary effects when wearing and working with PUEEs at height on less stable standing surfaces, such as scissor lifts. The aim of this study is twofold: first, to assess the effectiveness of PUEEs in reducing the risk of MSDs among electricians working at height on a scissor lift; and secondly, to observe the effect of PUEEs on postural stability under the same conditions.

2. Methods

2.1. Participants

Nine healthy male subjects over 18 years old were recruited via email solicitation. All subjects claimed no history of musculoskeletal disorders and were free from on-going musculoskeletal pains at least seven days prior to data collection. They were also free of visual or vestibular deficits that may impact normal balance control. The sample size of the subjects was based on a previous study involving construction workers on scissor lifts (Pan et al., 2017) and the demographics of worker in the construction industry (Gallagher, 2022). A priori power analysis using SAS software indicated that eight participants would be sufficient to detect meaningful differences among different exoskeletons at $\alpha = 0.05$ with power = .9; therefore, nine male participants were recruited to ensure adequate power. The purpose of the experiment and the procedures and risks associated with the required tasks were explained to the subjects before testing began. Subjects' written consents were collected along with their age, gender, race and body mass, height, upper arm length, forearm length, hand length, and hand dominance. The mean (standard deviation) age, weight, and height of participants were 28.9 (3.9) years, 82.7 (11.6) kg, and 174.9 (7.1) cm respectively. This study was reviewed and approved by the Oregon State University Institutional Review Board. All the participants consented to participate in the study.

2.2. Simulated workstation design and development

Five tri-axial accelerometers (Kionix, Model KXRB5, Ithaca, NY) embedded in protective housing were used to measure the dynamic motions imitated by the subject on the scissors' lift platform (Fig. 1) while simulating the task of pulling wires through conduit. The x-y-z orientations of each accelerometer were aligned with the platform coordinate system, as shown in Figs. 1 and 2. The accelerometers were secured using glue and tape to the four corners of the floor frame and one longer side of the platform (Fig. 2).

Movement data collected on the dynamic motion of the NIOSH scissor lift was input into a 6-degree-of-freedom high-fidelity motion platform (MB-E−6DOF/24/1800 KG; Moog Inc.; East Aurora; NY) that was used to simulate the dynamic motions of a scissor lift within a laboratory setting. Sinusoidal motions in the direction of pulling on the motion platform were set to have 2-inch displacement. Some examples of typical dynamic motions of the scissor lift were described in detail in a previously published article (Dong et al., 2012).

2.3. Apparatus and experimental setup

Bipolar surface electromyography (EMG) electrodes (Trigno Avanti;

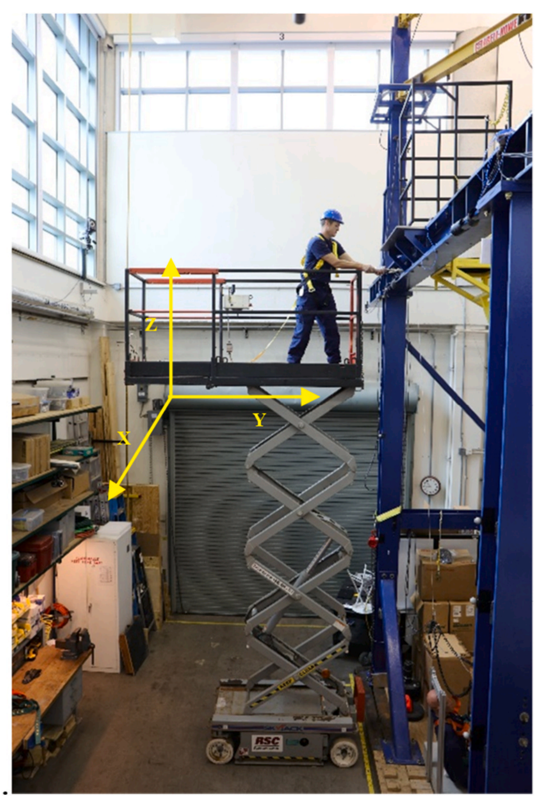

Fig. 1. Dynamic motion data of a scissor lift were collected in the high bay lab of NIOSH.

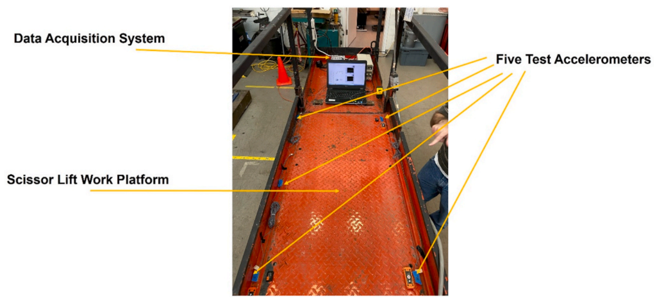

Fig. 2. Five tri-axial accelerometers were placed in the scissor lift main platform.

Delsys; Natick, MA) were used to collect muscle activation data from both the left and right side of the following muscles: upper trapezius, middle deltoid, anterior deltoid, biceps brachii, erector spinae, rectus femoris, biceps femoris, and tibialis anterior. The EMG sampling frequency was 1000 Hz. Kinematics data were collected using an eleven-camera optical motion capturing system (Flex 13; Optitrack; Natural Point, OR) at a sampling rate of 100 frames per second. Forty-three reflective markers were placed on the participant's head, upper and lower arms, hand, trunk, pelvis, upper and lower legs, and feet (Motive 2.0; Optitrack; Natural Point, OR). When direct placement of the markers was not possible due to the presence of exoskeletons, the markers were positioned in proximity to the exoskeletons.

To evaluate postural stability, two force platforms (AMTI BMS464508-2K-SYS, Watertown, MA, USA) were used to measure tri-axial ground reaction forces and moments at a sampling rate of 1000 Hz. The two force platforms were mounted side-by-side on the center of the motion platform and participants would place one foot on each platform (Fig. 3).

For the experimental task, a 6/3 electrical wire was attached to a wireless digital force gauge (ergoFET; Hoggan Scientific, LLC.; Salt Lake City, UT, USA) as shown in Fig. 3. The force participants were exerting for the task was measured and displayed on a wall-mounted monitor using the gauge's software (FET Data Collection; Hoggan Scientific, LLC.; Salt Lake City, UT, USA).

In a repeated-measures laboratory study, we evaluated three passive upper extremity exoskeletons. Each participant performed simulated wire pulling tasks with and without the exoskeletons while simulating the dynamic motions of a scissor lift in a laboratory setting. During the tasks, shoulder muscle activity, posture (shoulder flexion, abduction, and elbow flexion), and postural balance were continuously measured.

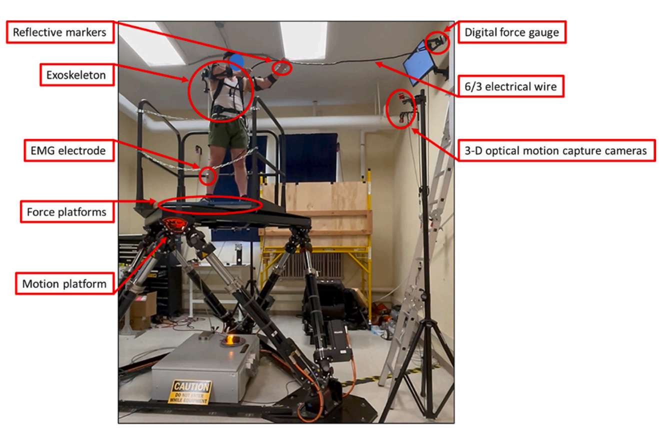

Fig. 3. Experimental setup showing a participant performing the experimental task while standing on two force platforms mounted on the motion platform.

2.4. Independent variables

Three independent variables were considered in the current study. The first independent variable was the type of PUEE exoskeleton worn. It had four levels: No PUEE, PUEE1, PUEE2, and PUEE3. The second independent variable was pulling force level (FORCE), it had two levels 65 N and 130 N. Pulling force was defined as the required force level to be reached while performing a wiring task. The third independent variable was task performance (TASK), it had two levels: pre-task performance and post-task performance, defined as immediately before and after the performance of any required wiring task. The wiring task is defined in greater detail in the experimental protocol section.

2.5. Experimental procedure

After a short warm-up period, EMG electrodes were attached to test participants for collection of maximum voluntary contraction (MVCs) data (Boettcher et al., 2008; Bussey et al., 2018; Roman-Liu and Bartuzi, 2018; Siddiqi et al., 2015; Szpala et al., 2011). Three MVCs were collected for each muscle. Each contraction lasted for 3 s with a 2-min break between contractions (Soderberg and Knutson, 2000). Afterwards, one of the three PUEE models, (Fig. 4), was fitted and adjusted on each participant according to their anthropometric measurements. Each participant wore each of the three PUEE models in a randomized order. These PUEEs are designed with mechanical springs to provide postural support and reduce biomechanical load in the shoulders and upper limbs.

Data were collected from 11-optical motion capture cameras set up around the laboratory. While wearing one of the exoskeleton conditions, 43 reflective markers, and 16 electromyography (EMG) electrodes, participants pull on the 6/3 electrical wire at eye-level height. The force exerted was measured by the force gauge attached to the wire and displayed on the wall-mounted monitor.

Once the exoskeletons were fitted, reflective markers and EMG electrodes were placed on participants, and they were given sufficient practice time to become familiarized with the experimental task and setup. This practice session lasted until subjects were able to perform the task correctly and provide verbal confirmation of their ability and familiarity with the experimental procedures.

After the MVC trials, participants were asked to perform a simulated electrical wiring task on the motion platform (Fig. 1). The 20-s wire pulling task involves pulling an electrical wire five times in sync with the vibration profile (i.e., participants would pull when the motion platform moves "in reaction" to the wire pulling). The height of the cable was adjusted to each participant's eye height to ensure they would be pulling the cable at their eye-height level. Participants were asked to pull with either 65N or 130N of force and perform the task two times for each force. Participants were provided a 5-min break between the 65N and 130N force conditions to minimize the potential effects of residual fatigue. The order of exoskeleton conditions was randomized to minimize the effects of testing bias.

2.6. Dependent variables

Three categories of dependent variables were evaluated: normalized EMG (NEMG) data, kinematics measures, and postural stability measures. The NEMG data was determined for the left and right upper trapezius, middle deltoid, anterior deltoid, biceps brachii, erector spinae, rectus femoris, biceps femoris, and tibialis anterior muscles. Kinematics measures included shoulder flexion and abduction and elbow flexion angles. Postural stability measures included mean velocity of center of pressure (COP), root mean square distance in both the medial-lateral direction as well as the anterior-posterior direction and the sway areas of COP.

(a) PUEE1 (4.15 kg) (b) PUEE2 (1.7 kg) (c) PUEE3 (5.95 kg)

Fig. 4. The three commercially available exoskeletons used in the study: (a) PUEE1, (b) PUEE2, and (c) PUEE3.

2.7. Data processing

The collected EMG data were filtered using a band pass filter of 20–400 Hz, rectified, and averaged by root mean square (RMS) using a 125-ms moving window (EMGworks; Delsys; Natick, MA). For normalizing muscle activity, the highest RMS signal over a 1-s period of the MVC contractions was used for normalizing the data as a percentage of the MVC (%MVC). The normalized data were then summarized by the 10th (static), 50th (central tendency), and 90th percentile (peak) muscle activities based on the Amplitude Probability Density Function (APDF) (Jonsson, 1978).

Kinematic data were filtered by a 4th order, zero-phase-lag, Butterworth filter with a cutoff frequency of 6 Hz (Motive 2.0; Optitrack; Natural Point, OR). The filtered kinematic data were then used to calculate shoulder flexion and abduction as well as elbow flexion angles through a biomechanics analysis software (Visual3D; C-Motion Inc., Germantown, MD) (Kia et al., 2023a,b). Shoulder flexion and abduction and elbow flexion angles were summarized as 5th, 50th, and 95th percentile values.

Ground reaction forces and moments data to measure postural stability were filtered using a low-pass 4th order, zero-phase-lag, Butterworth filter with a 10 Hz cut-off frequency and then transformed to obtain COP values (Davidson et al., 2004). Sway measures of mean velocity, RMS distance in both anterior-posterior and medial-lateral orientations, and elliptical sway area were derived from the COP trajectories (Lin et al., 2008; Prieto et al., 1996). The anterior-posterior and medial-lateral orientations of the postural sway measures, collected from the force platforms, are shown in Fig. 5. Data were collected from the force platforms used in postural stability assessments. These data included the anterior-posterior (AP) directions falling along the point of ingress/egress while the medial-lateral (ML) directions fall along the direction of the wire pulling.

2.8. Statistical analyses

Generalized linear mixed models (GLMM) were used to determine the effects of EXOSKELETON on all four categories of tested dependent variables. EXOSKELETON was the fixed effect with random intercepts introduced to account for within-subject correlations. All dependent variables followed normal distributions except for NEMG data, which were highly skewed, and consequently log-transformed. For determining statistical significance, a Type I error of .05 was used and any significant results were followed up with Tukey's HSD post-hoc tests. The statistical analyses were performed using R programming language

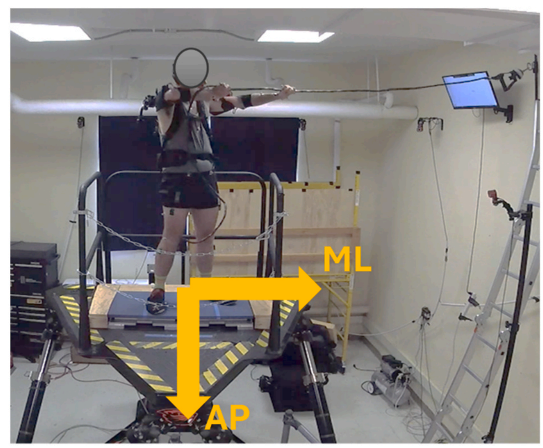

Fig. 5. Orientation of the experimental setup.

(R 4.3.1, R Core Team; Vienna, Austria).

3. Results

A total of nine male participants completed the study. Statistical analyses indicated that the exoskeleton model had a significant effect on muscle activity, kinematic measures, and postural stability.

3.1. Muscle activity

Significantly smaller peak muscle activation levels were observed among upper trapezius and deltoid muscles from both force pulling levels using exoskeletons (Fig. 6). Compared with the no-PUEE status, the tested PUEEs significantly reduced peak activity in both left and right upper trapezius muscles (average: 26 %, range: 17 % to −38 %; $p < 0.001$) and much of the deltoid (average: 20 %, range: 1 % to −49 %; $p < 0.001$), except for PUEE2 on anterior deltoid at 65 N and PUEE1 on middle deltoid at 130 N. This impact was less pronounced in the biceps brachii and no significant impact was observed on the back muscles. Some reduction of peak muscle activation levels was observed among the right biceps femoris and the right tibialis anterior muscles when using the exoskeleton for wire pulling at 130N. Higher peak muscle activation levels were observed on the right rectus femoris under similar conditions (Table 1). The majority of significant differences were observed between using the PUEE1, PUEE2, or PUEE3 exoskeletons

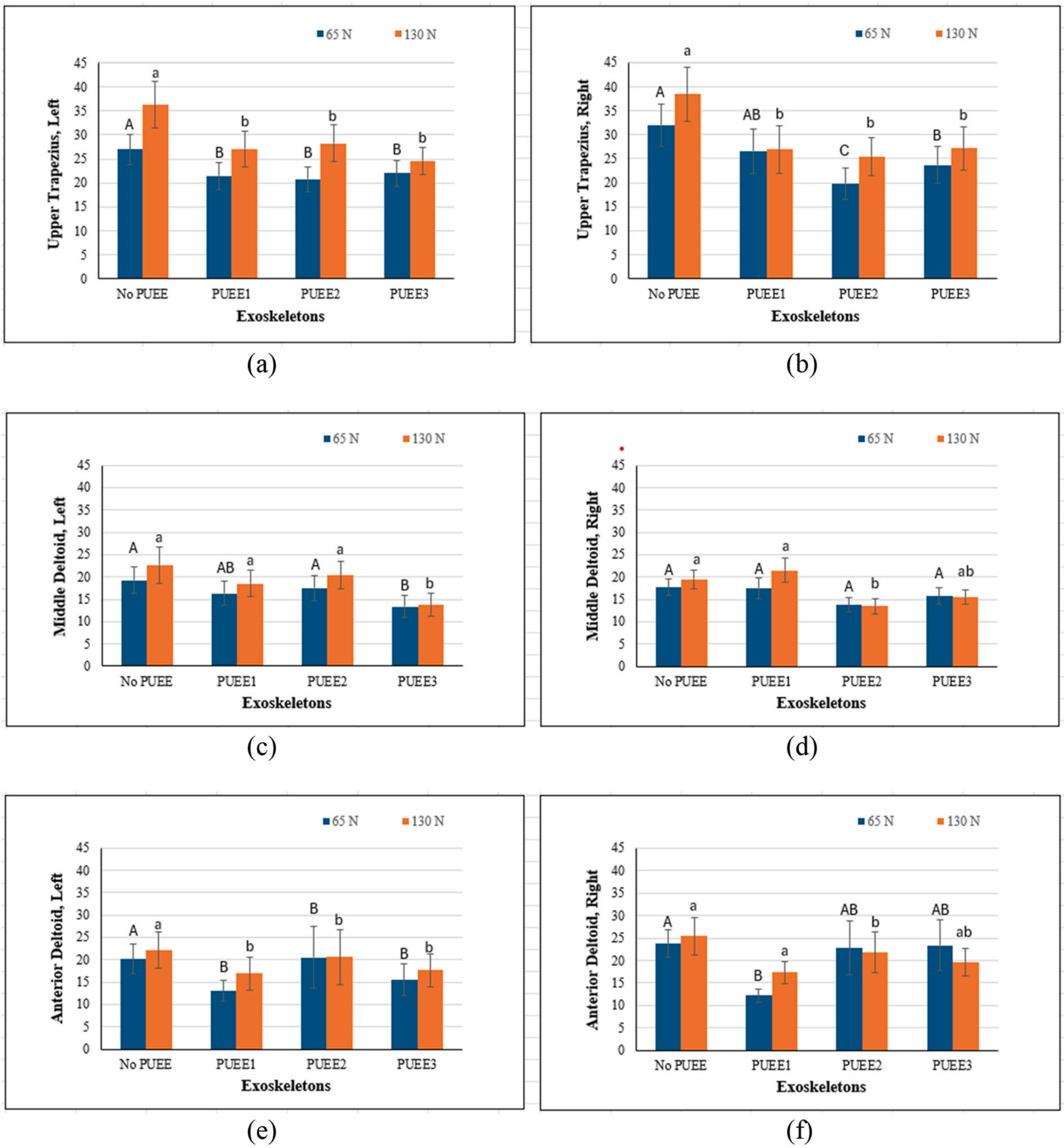

Fig. 6. The peak (90th percentile) muscle activity in (a) Upper Trapezius-Left, (b) Upper Trapezius-Right, (c) Middle Deltoid-Left, (d) Middle Deltoid-Right, (e) Anterior Deltoid-Left, (f) Anterior Deltoid-Right. **Note:** At the force level of 65 N, different upper-case letters indicate statistically significant differences based on Tukey HSD post-hoc tests ($p < 0.05$). At the force level of 130 N, different lower-case letters indicate statistically significant differences based on Tukey HSD post-hoc tests ($p < 0.05$).

versus not using an exoskeleton (No PUEE) (Fig. 6). Differences between exoskeleton models were mostly not significant except in a few conditions (Table 1).

3.2. Angle

Both left and right shoulder flexions were significantly affected by the model of exoskeleton worn ($p < 0.001$). Significantly smaller flexion angles were observed from the left shoulder while wearing PUEE3 (64.9° and 62.7° for the pulling force of 65 and 130 N, respectively), and larger flexion angles observed among right shoulders while wearing PUEE1 (120.4° and 118.3° for the pulling force of 65 and 130 N, respectively). Model of exoskeleton also had significant impacts on shoulder abduction and elbow flexions (Table 2). Kinematics results showed that compared to the No PUEE condition, PUEE1 generated significantly larger flexion among right shoulders (+35.8 %, $p < 0.001$) and smaller flexion among left elbows (−27.4 %, $p < 0.001$) when handling the 130N pulling force. PUEE3 produced significantly smaller flexion among left shoulders (−27.8 %, $p < 0.001$) and larger flexion among right elbows (+22.5 %, $p < 0.001$) when handling the 130N pulling force. Meanwhile, PUEE2 generated no significant kinematic difference as compared to No PUEE conditions (Table 2).

3.3. Postural stability

Wearing the exoskeleton models used in this study resulted in

Table 1
Median (50th percentile) [10th,90th percentile] of the muscle activity in biceps brachii, left and right erector spinae, rectus femoris, biceps femoris, and tibialis anterior during wire pulling at two different force levels (65N and 130N) across four different exoskeleton conditions [N = 9].

Muscle		Force (N)	Exoskeleton Condition				P-value
			No PUEE	PUEE1	PUEE2	PUEE3	
Biceps Brachii	Left	65	16.5 [13.0,22.4]	18.7 [13.2,27.6]	13.6 [10.2,19.5]	18.3 [9.9,22.9]	.087
		130	29.5 [14.0,37.0]	30.9 [13.3,39.9]	27.7 [13.3,40.2]	27.3 [16.6,41.8]	.801
	Right	65	11.4^{A} [3.6,25.6]	6.5^{B} [2.3,12.3]	9.8^{AB} [4.0,18.2]	9.3^{B} [3.3,17.5]	**.001**
		130	17.8 [5.4,28.0]	12.2 [4.2,28.4]	14.9 [5.3,22.2]	14.5 [5.9,25.9]	.351
Erector Spinae	Left	65	4.1 [3.4,8.9]	4.0 [3.5,7.7]	4.3 [3.2,9.4]	4.3 [3.5,9.7]	.467
		130	5.2 [3.8,13.3]	5.8 [3.8,18.2]	6.4 [3.6,13.2]	6.2 [3.6,21.0]	.857
	Right	65	13.4 [10.0,18.5]	13.7 [10.2,18.6]	14.2 [9.2,16.4]	12.3 [8.6,17.0]	.541
		130	17.9 [13.4,22.9]	16.4 [13.0,25.0]	18.2 [11.3,22.6]	16.1 [9.5,26.5]	.375
Rectus Femoris	Left	65	6.1 [4.6,11.8]	6.8 [4.6,9.6]	7.4 [5.5,14.1]	6.9 [5.9,11.4]	.322
		130	9.4 [7.0,14.8]	10.7 [7.3,16.7]	11.0 [7.1,15.2]	13.7 [7.9,18.8]	.377
	Right	65	5.5 [3.9,6.5]	6.1 [5.0,8.4]	6.6 [4.6,8.2]	8.2 [6.1,10.6]	.095
		130	6.5^{A} [5.2,8.9]	8.2^{AB} [5.5,11.9]	8.9^{B} [6.1,12.9]	8.6^{B} [6.3,17.3]	**.027**
Biceps Femoris	Left	65	13.9 [9.6,20.9]	10.0 [9.0,14.2]	11.7 [9.7,14.1]	10.3 [9.5,12.9]	.425
		130	21.2 [12.9,27.4]	14.6 [12.5,22.6]	16.7 [14.9,20.5]	15.3 [10.6,19.6]	.184
	Right	65	5.6 [4.2,22.6]	5.6 [3.1,11.8]	10.0 [4.6,20.9]	7.1 [3.8,20.7]	.230
		130	8.5^{AB} [6.0,26.5]	8.8^{AB} [4.0,26.4]	15.0^{A} [8.3,27.8]	7.7^{B} [4.8,28.4]	**.040**
Tibialis Anterior	Left	65	4.9 [3.3,13.0]	4.2 [3.0,6.3]	3.7 [2.6,9.5]	4.9 [3.9,12.2]	.740
		130	17.3 [5.7,23.0]	16.4 [6.2,22.7]	16.2 [4.9,23.5]	16.1 [4.6,22.1]	.376
	Right	65	10.5 [4.7,14.8]	8.5 [3.8,14.1]	8.9 [4.0,13.8]	6.9 [3.7,10.2]	.373
		130	18.6^{A} [17.0,32.4]	19.2^{AB} [15.4,24.1]	17.7^{AB} [11.4,21.4]	17.8^{B} [7.7,21.8]	**.016**

The p-values represent the statistical significance of the main effect of the exoskeleton condition on muscle activity. Different superscript letters (A and B) indicate statistically significant differences across banger bar conditions based on Tukey HSD post-hoc tests ($p < 0.05$).

Table 2
Mean (standard error) of peak (95th percentile) left and right shoulders and elbows angles during wire pulling at two different force levels (65N and 130N) across four different exoskeleton conditions [N = 9].

Angle		Force (N)	Exoskeleton Condition				P-value
			No PUEE	PUEE1	PUEE2	PUEE3	
Shoulder Flexion	Left	65	83.0^{AB} (9.5)	101.7^{A} (10.1)	79.6^{B} (13.3)	64.9^{B} (9.3)	**<.001**
		130	86.9^{A} (9.8)	105.1^{A} (9.9)	87.4^{A} (11.9)	62.7^{B} (10.4)	**<.001**
	Right	65	94.3^{A} (11.9)	120.4^{B} (8.9)	101.1^{A} (9.0)	100.7^{A} (9.9)	**<.001**
		130	87.1^{A} (10.7)	118.3^{B} (8.6)	99.1^{A} (9.6)	92.7^{A} (9.0)	**<.001**
Shoulder Abduction	Left	65	61.6 (5.3)	59.7 (5.0)	60.0 (3.7)	59.2 (4.2)	.151
		130	62.0 (4.7)	60.2 (4.9)	61.4 (3.4)	61.1 (3.8)	.447
	Right	65	54.3 (4.1)	56.5 (4.0)	54.1 (4.1)	58.1 (3.6)	.389
		130	57.5^{AB} (3.8)	56.8^{AB} (4.0)	50.8^{A} (3.7)	64.3^{B} (3.0)	**.001**
Elbow Flexion	Left	65	123.3 (16.1)	110.4 (13.0)	125.3 (9.0)	116.6 (13.3)	.497
		130	131.6^{A} (16.7)	95.6^{B} (13.1)	109.8^{AB} (14.1)	115.5^{AB} (12.0)	**.025**
	Right	65	112.6^{AB} (12.9)	108.0^{A} (13.5)	119.2^{AB} (11.7)	133.9^{B} (10.1)	**.019**
		130	110.7^{A} (13.4)	106.1^{A} (13.3)	119.6^{AB} (11.9)	135.6^{B} (11.5)	**.011**

The p-values represent the statistical significance of the main effect of the exoskeleton condition on the angles. Different superscript letters (A and B) indicate statistically significant differences based on Tukey HSD post-hoc tests ($p < 0.05$).

significantly reduced COP mean velocity, RMS displacement and sway area for almost all conditions except for RMS displacement using both pull force levels. This reduction of postural stability measures is an indicator of improved postural stability. This effect was most pronounced when wearing PUEE3 (Table 3).

Table 3
Mean (standard error) of center of pressure (COP) sway measures during wire pulling at two different force levels (65N and 130N) across four different exoskeleton conditions [N = 9].

Parameter	Direction	Force (N)	Exoskeleton Condition				P-value
			No PUEE	PUEE1	PUEE2	PUEE3	
Mean Velocity (mm/s)	Medial-Lateral	65	174.8^{A} (9.37)	144.07^{B} (11.4)	145.9^{B} (8.49)	137.14^{B} (11.72)	**.008**
		130	245.05^{A} (11.54)	214.73^{B} (10.33)	215.35^{B} (10.49)	197.58^{B} (9.00)	**<.001**
	Anterior-Posterior	65	42.03^{A} (3.11)	33.65^{B} (2.08)	32.66^{B} (2.65)	31.61^{B} (2.31)	**.002**
		130	54.76^{A} (4.26)	47.19^{AB} (3.27)	46.87^{AB} (3.46)	44.24^{B} (3.07)	**.028**
RMS Displacement (mm)	Medial-Lateral	65	100.25^{A} (8.98)	90.61^{AB} (7.43)	107.28^{A} (10.88)	78.29^{B} (9.54)	**.016**
		130	142.52^{A} (12.55)	135.13^{A} (9.27)	144.01^{A} (12.86)	108.91^{B} (9.63)	**.003**
	Anterior-Posterior	65	68.47 (4.86)	55.86 (8.70)	63.85 (9.03)	47.05 (5.12)	.096
		130	51.92 (8.10)	50.66 (7.36)	59.66 (6.52)	45.15 (7.26)	.381
Sway Area (mm^2)		65	11682.95^{A} (1104.11)	9322.92^{AB} (838.44)	9412.72^{AB} (905.08)	8955.56^{B} (1051.52)	**.037**
		130	19750.15^{A} (2134.06)	18273.68^{AB} (1825.02)	17387.83^{AB} (1031.24)	16726.11^{B} (1394.23)	**.051**

The p-values represent the statistical significance of the main effect of the exoskeleton condition on the sway measures. Different superscript letters (A and B) indicate statistically significant differences based on Tukey HSD post-hoc tests ($p < 0.05$).

4. Discussion

This study evaluated the effectiveness of passive upper extremity exoskeletons (PUEEs) for reducing the risk of falls and MSDs among electricians performing a wire pulling task on scissor lifts. Wearing PUEEs lowered peak activation in the upper trapezius and deltoid muscles by up to 49 %, indicating substantial reductions in shoulder loading and delayed onset of fatigue. The current results are also consistent with findings of previous investigations regarding the impact of using an upper extremity exoskeleton while performing overhead activities (Claramunt Molet et al., 2019; Kim et al., 2018a; Kong et al., 2023).

On the other hand, back and lower-limb muscle activity remained largely unchanged, likely because the task required little trunk bending or leg motion. Although the tested exoskeletons added about 6 kg to the torso, only slight increases were observed in the right rectus femoris and biceps femoris at the highest pulling force (130 N). The assistance provided to the arms appeared to offset any additional trunk co-contraction. Earlier studies report mixed effects of exoskeletons on low-back and leg muscles (Harith et al., 2021; Huysamen et al., 2018; Kim and Nussbaum, 2019; Picchiotti et al., 2019a; Rashedi et al., 2014; Theurel et al., 2018), likely reflecting differences in task dynamics and device design. Shoulder and elbow kinematics also varied among models, suggesting that exoskeleton configuration influences movement patterns rather than offering a single “best” option.

Current results also demonstrated that using an exoskeleton significantly improved postural stability (Lin et al., 2008), particularly with PUEE3. Improved postural stability likely resulted from reduced shoulder and upper extremity activity, lowering overall stabilization demands (Kong et al., 2023). This effect was reflected in a ~5 % decrease in tibialis anterior activity with the PUEE3 model, suggesting less effort was required to maintain balance on the scissor lift (Lin et al., 2009; Lu et al., 2015; Yaggie and McGregor, 2002). However, previous studies have reported reduced postural stability with added external weight (Qu and Nussbaum, 2009; Kim et al., 2018b), so exoskeleton use should be approached cautiously, especially given the high rate of slips, trips, and falls on scissor lifts (Pan et al., 2007).

Passive upper-extremity exoskeletons reduced upper extremity MSD risk and postural sway during quasi-static wire-pulling on a scissor lift. These devices appear best suited for static or quasi-static overhead tasks common in manufacturing and assembly (De Bock et al., 2020; Gillette and Stephenson, 2018; Gillette et al., 2022; Pacifico et al., 2020; Spada et al., 2017, 2019). In contrast, our prior work with dynamic blocklaying tasks on a mast climbing work platform, which required dynamic, fast-paced trunk and upper-extremity motions for material handling, found limited benefits (Zheng et al., 2024), highlighting the task-specific nature of exoskeleton performance. Therefore, adoption in construction should carefully account for the dynamic demands of work tasks to ensure meaningful improvements in productivity, safety, and worker health.

A key strength of this study is the use of a high-fidelity motion platform to replicate the dynamic movements of a scissor lift, which allowed us to assess balance and muscle activity under controlled but realistic task conditions. Another strength is the use of multiple objective measures—including EMG, motion capture, and force plate data—that provided a comprehensive evaluation of both biomechanical loading and postural stability. Additionally, the randomized crossover design minimized potential order and subject bias, and the inclusion of three different commercially available passive upper extremity exoskeletons provided broader insight into this class of devices.

At the same time, several limitations should be noted. Because of federal restrictions on naming or endorsing commercial products, the specific exoskeleton brands used in this study are not identified. As such, the results should be interpreted as representative of PUEEs more generally rather than of individual models. The tasks tested were relatively short in duration; future studies should investigate longer task periods to better capture fatigue and usability effects. Only male participants were recruited, reflecting construction workforce demographics, but sex-related differences in exoskeleton applicability were not examined. Finally, while the motion platform provided a novel way to mimic unstable elevated surfaces, it may not fully replicate real-world scissor lift environments. These limitations should be considered when interpreting the findings.

Beyond the observed benefits, this study points to broader considerations for research and practice. Passive upper extremity exoskeletons should be positioned as part of an integrated construction safety strategy, complementing training, task design, and administrative controls. Their effectiveness may depend on how well specific devices are matched to task demands, worker characteristics, and work environments. Future research should extend beyond laboratory simulations to field-based studies, examine prolonged use to capture fatigue, comfort, and usability outcomes, and include more diverse worker populations to evaluate generalizability. Investigations into long-term adoption, productivity effects, and integration with other safety interventions would provide critical insight into how exoskeletons can be effectively and sustainably deployed in construction and related industries.

5. Conclusions

This study showed that using a passive upper extremity exoskeleton for a quasi-static electrical wire pulling task on scissor lifts can be effective in reducing biomechanical loads in the upper extremities and improving postural stability, without increasing the loads in the low back and lower extremities. Therefore, a passive upper extremity exoskeleton has the potential to serve as an effective intervention for constructions workers who are at risk of musculoskeletal and fall-related injuries associated with working on scissor lifts. This finding contrasts with findings from our previous study using simulated blocklaying tasks on a MCWP. Those tasks required dynamic and fast-paced motions to accomplish the lifting and positioning tasks. Therefore, especially in the construction industry, it is important to consider the dynamic nature of each work task when selecting and adopting passive upper extremity exoskeletons as personal protective equipment or an intervention technique.

CRediT authorship contribution statement

Liying Zheng: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Christopher Pan:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Kiana Kia:** Methodology, Investigation. **Allen Chan:** Methodology, Investigation. **Mina Salehi:** Methodology, Investigation. **Andrew Moorehead:** Methodology. **Jeong Ho Kim:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Conceptualization.

Disclaimers

The findings and conclusions in this review are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC). Mention of any company or product does not constitute endorsement by NIOSH/CDC.

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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