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Shoulder-assist exoskeleton effects on balance and muscle activity during a block-laying task on a simulated mast climber

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ABSTRACT

Interest in utilizing exoskeletons to mitigate the risks of musculoskeletal disorders (MSDs) among construction workers is growing, spurred by encouraging results in other industries. However, it is crucial to carefully examine their impact on workers' stability and balance before implementation. In this study, seven male participants lifted a 35-lb cinder block from a production table to a simulated wall at two heights—elbow and shoulder levels—using three different exoskeleton models on an unstable platform, where their balance and shoulder muscle activity were assessed. Balance-related parameters, included mean distance (MDIST), total excursion (EXCUR), and mean velocity (VEL) of the center of pressure, were derived from force plate data. Muscle activity in six shoulder and upper arm muscles was estimated using electromyography (EMG) data. The results indicated that wearing two of the exoskeletons significantly increased both total and medio-lateral (ML) MDIST compared to not wearing an exoskeleton. Wearing one of the exoskeletons significantly increased total and ML VEL and ML EXCUR. Although lifting level did not have a significant impact on the balance parameters, it did affect the muscle activity in most of the measured muscles. Moreover, only one exoskeleton significantly reduced the activity in a particular shoulder muscle compared to no exoskeleton use. In conclusion, the evaluated shoulder-assist exoskeletons showed limited benefits for preventing upper extremity MSDs and may negatively affect whole-body balance during a block-laying task on an unstable platform. These findings underscore the importance of comprehensive evaluations of balance and effectiveness prior to adopting exoskeletons in construction.

1. Introduction

Due to overexertion, construction workers are often at high risk of work-related Musculoskeletal Disorders (MSDs). In the United States, lifetime risk of overexertion injuries in construction is about 21%, which means more than 1 in 5 construction workers might be expected to have an overexertion injury during their career (Dong et al., 2014). The average annual cost of occupational injuries and work-related diseases in the construction industry has been estimated at almost $13 billion USD, with construction injuries representing 15% of all private industry injury costs (Waehrer et al., 2007). Work-related MSDs are recognized as a leading cause of nonfatal injuries in construction and have been studied globally (Antwi-Afari et al., 2023). They not only result in days away from work, but they also can shorten careers and impact retirement (Sharpe et al., 2022; Welch et al., 2010). Many construction workers retire in their mid-50s due to MSDs. MSDs also contribute to the pain epidemic (Carnide et al., 2019), from the overuse and misuse of prescription and illicit drugs including opioids (Ahrnsbrak et al., 2017). Notably, construction workers have the highest incidence of prescription opioid-related overdose deaths when compared to their counterparts in other industries, where work-related pain, such as that from repetitive motion, has been speculated to contribute to opioid initiation or usage (Harduar et al., 2018). To proactively prevent the initial and potentially more severe consequences of MSDs in the construction industry, it is crucial to embrace innovative and emerging intervention technologies.

As an emerging technology, an exoskeleton is a device that is worn externally on the body to provide support and assistance to the wearer's

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musculoskeletal system. Exoskeletons have been successfully used in military, rehabilitation, automotive and other industries (Gillette and Stephenson, 2019; Proud et al., 2022; Spada et al., 2017; Terrazas-Rodas et al., 2022). Exoskeletons are increasingly being explored in various occupational activities, primarily to mitigate work-related MSD risks (Xia et al., 2024; Zheng et al., 2022, 2024). Positive results using exoskeletons were shown during overhead work and material handling tasks in logistics and manufacturing industries (de Looze et al., 2016; Iranzo et al., 2020; Maurice et al., 2019; Schmalz et al., 2019). A comprehensive review study conducted by de Looze et al. (2016), which analyzed 40 papers covering 26 distinct exoskeletons, highlighted a significant decrease in back muscle activity when individuals wore exoskeletons while engaging in lifting tasks. Additionally, Bär et al. using a systematic review and meta-analysis, reported statistically significant effects of using back, upper-limb, or lower-limb exoskeletons. Effects included reduced muscle activity, joint moments, and perceived strain in the supported body areas (Bär et al., 2021). Specifically, shoulder-assist exoskeletons have demonstrated promising results in overhead occupational activities within realistic or simulated industrial environments. These positive outcomes have been observed in environments such as automotive assembly lines (Iranzo et al., 2020), finishing tasks like sanding and painting in boat manufacturing (Moyon et al., 2018), and agricultural activities in fruit orchards (Wang et al., 2021).

Given promising outcomes observed across diverse industries, there has been growing interest in the construction trades to leverage exoskeleton technology as a means to mitigate the risks of MSD among workers (Kim et al., 2019; Mahmud et al., 2022; Zhu et al., 2021). Exoskeletons are seen as a potential avenue to alleviate the physical demands and fatigue experienced by construction workers and help improve worker safety, health, and performance (Kim et al., 2019). In contrast to tasks in certain other industries where arm positions tend to remain relatively stable, such as overhead assembly, construction work often entails a wide range of movements and postures. Within the construction sector, shoulder-assist exoskeletons have been assessed in activities like plastering and bricklaying (de Vries et al., 2021; Musso et al., 2024). These tasks entail a diverse range of arm movements in various directions, some of which may oppose the intended support provided by the exoskeletons. As anticipated, the exoskeletons were expected to offer assistance for only part of these multifaceted tasks. Nevertheless, research conducted by de Vires (de Vries et al., 2021) demonstrated significant reductions in shoulder muscle activity during the exoskeleton-supported part of the tasks, while no significant increase in the muscle activity was observed in other part of the tasks. In some instances, the tested shoulder-assist exoskeleton was even able to decrease shoulder muscle activity when task motions were performed below the optimal exoskeleton-operating range (Musso et al., 2024). These encouraging results demonstrate the practical applications of shoulder-assist exoskeletons in similar tasks within construction trades.

More specifically, several stakeholders in the construction sector have shown particular interest in investigating the feasibility of using shoulder-assist exoskeletons in masonry work. As a sub-specialty of the construction industry, masonry work consists of brick and block-laying tasks. Masonry work can be physically demanding. A concrete block can weigh between 9 and 27 kg. The rate of overexertion among masonry workers was 33.4 per 10,000 FTEs compared to the average rate of 21.5 per 10,000 FTEs in all industries (CPWR, 2018). Work-related MSD pain and discomfort was even prevalent in young masonry apprentices (Anton et al., 2020). Shoulder disorders are the second most common MSD disorder after back injuries, with approximately 50% of bricklayers and blocklayers complaining of shoulder symptoms (Cook et al., 1996; Hess et al., 2012). It's important to highlight a distinctive working environment that masonry workers commonly operate in, which involves daily tasks performed on an unstable elevated work platform, such as a mast climbing work platform. Research indicates that workers' postural sway length increases significantly with greater elevations (Bhattacharya et al., 2002). These platforms pose challenges to balance and stability due to their inherent instability at elevated heights, compared with solid ground surfaces (Pan et al., 2012; Wimer et al., 2017). Consequently, working on an unstable work platform at elevation can increase the risks of slips, trips and falls on the same level, and falls to a lower level. From 1990 to 2017, there were a total of 35 recorded fatalities associated with the use of mast climbers. Of the 35 fatalities, 13 were masonry workers (OSHA, 2019; Pan et al., 2021). Additionally, working on a mast climbing work platform can create awkward working postures due to the confined nature of the workspace. Nonetheless, shoulder-assist exoskeletons represent an attractive possibility for mitigating MSD risks among masonry workers. Therefore, it is crucial to ensure that these exoskeletons do not compromise workers' stability and balance when working at elevated heights, an important use factor that has not been previously investigated.

Research has shown that center of pressure (COP) measurements estimated from force-plate data are linked to balance and the risk of falling. For instance, increased COP movements and velocities can indicate balance challenges and are associated with a higher risk of falling in older adults (Mirka, 1991; Piirtola and Era, 2006). The primary objective of this study was to evaluate the effects of three selected models of passive shoulder-assist exoskeletons on balance and shoulder muscle activity during a masonry task on a simulated mast climber described in previous work (Pan et al., 2021). The balance-related parameters and shoulder muscle activities were compared when using or not using the exoskeletons.

2. Method

2.1. Participants

The study's inclusion criteria required male participants aged 21–50 years with at least three months of construction work experience (including professional and temporary roles). Exclusion criteria eliminated individuals with musculoskeletal abnormalities, a history of elbow or shoulder disorders, injuries, surgeries, or visual/vestibular deficits that could impact balance control. Further, we used SAS statistical software to estimate the sample sized required prior to this study. With repeated measures design, the results showed that eight participants were sufficient to detect meaningful differences at the significance level of 0.05, and power of 0.9. Based on these criteria and sample size calculation, eight male participants were recruited initially in this study. Each participant met the construction work experience requirement. All subjects claimed no history of musculoskeletal disorders and were free from ongoing musculoskeletal pains at least seven days prior to the data collection. The experimental protocol was approved by the Texas Tech University Institutional Review Board, and all the participants consented to participate in the study.

One participant was excluded from the final analysis because of missing force-plate data due to a technical error. The data from a total of seven male participants (age: 32 $\pm$ 8 years old; height: 181.1 $\pm$ 5.3 cm; weight: 89.1 $\pm$ 13.3 kg) were used for further analysis. The hip height is defined as the vertical distance from the standing surface to the greater trochanter. The elbow height is defined as the vertical distance from the standing surface to the depression at the elbow between the humerus and the radius. The shoulder height is defined as the vertical distance from the standing surface to the most lateral point of the acromial process of the scapula. The mean and standard deviation of the hip, elbow, and shoulder heights for the seven participants in the study were 106.6 $\pm$ 3.9 cm, 116.5 $\pm$ 4.9 cm, and 151.4 $\pm$ 5.2 cm, respectively.

2.2. Simulated unstable work platform

A customized workstation was built to simulate a typical working setup for masonry workers on an unstable work platform (Fig. 1a). The workstation has an adjustable simulated wall, an adjustable production

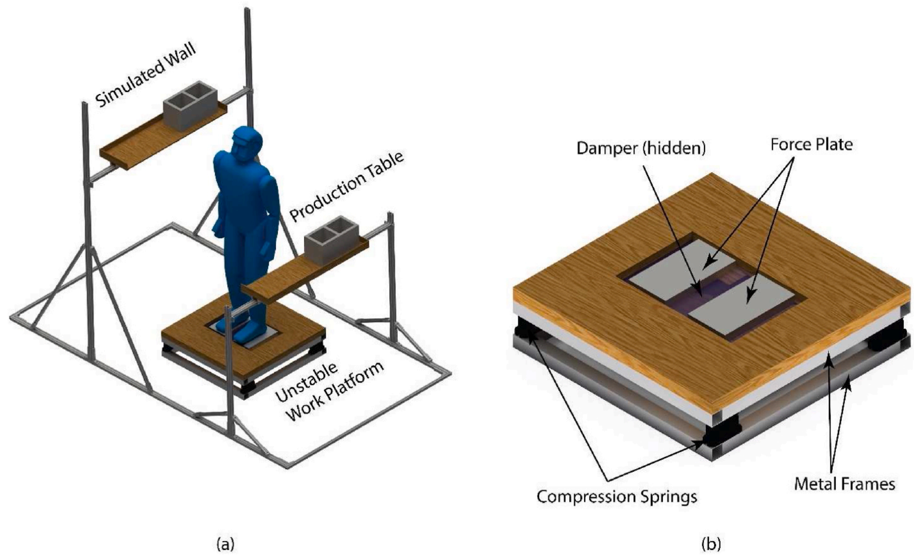

Fig. 1. (a) A customized workstation which simulates a typical working setup for masonry workers on an unstable mast climber work platform. (b) A close-up illustration of the unstable work platform.

table, and an unstable work platform. The unstable surface conditions simulated those experienced by masonry workers working on elevated mast climbers. Detailed features of the unstable work platform are presented in a previous study (Pan et al., 2021). Briefly, the unstable work platform (Fig. 1b) consisted of four 1785.8 kg/m (100 lb/in) springs and one 2678.7 kg/m (150 lb/in) damper. The vertical displacement of the platform was about 1.91–2.54 cm (0.75–1 inch) during the block-laying activities.

The masonry worker was expected to lift a concrete block from the production table and place it onto the simulated wall. The production table was set at the worker's hip height, and the simulated wall was set at two different levels—the subject's elbow height and their shoulder height. The height of the production table and the simulated wall were based on the hip, elbow, and shoulder heights of each subject.

2.3. Shoulder-assist exoskeletons

Three passive shoulder-assist exoskeletons were tested in this study (Exo1, Exo2, and Exo3; Fig. 2a). These three exoskeletons are readily available in the United States and are among the most frequently utilized models in private industry (Weston et al., 2022). In general, passive shoulder-assist exoskeletons are designed to reduce the load on the user's shoulder joint from using arms and tools/objects, especially at or above shoulder height, by transferring it to the wearer's hip joints. The three exoskeletons share a common 'vest' design, comprising both hardware and soft components. The hardware typically consists of a shoulder structure with adjustable arm support and a waist structure, connected by an adjustable spine structure. Meanwhile, the soft components often include arm cuffs, chest straps, back pads, and hip pads, covering areas where the exoskeletons make contact with the users. These three exoskeletons also employ springs as actuators to support the arms, with slight variations in their support mechanisms: Exo1 offers four support levels at three "activation zones" to assist users in performing in-front and/or overhead work; Exo2 features five cassettes with varying support levels, providing adjustable assistance based on the user's arm angle; and Exo3 is equipped with adjustment knobs that allow for continuously control over support levels, along with different angle-of-support settings to accommodate tasks at overhead, eye level and chest level. More detailed comparisons of the supportive torques in these exoskeletons were provided in a previous study (Watterworth et al., 2023). The level of support provided by each of the exoskeletons was set to a 'medium' level and remained consistent across all subjects and sessions. The exoskeletons were fit and adjusted for each subject, according to the manufacturer's guidelines. Each subject also participated in a training session to became familiarized with using the exoskeleton.

2.4. Experimental tasks

The subjects were asked to lift a concrete block (35 lb/15.9 kg; 8 × 8 × 16 in) from the production table located on their left side and then turn to place it on the simulated wall located on their right side (Fig. 2b). The participants were explicitly instructed to maintain a consistent foot placement during the task. The production table height was set at the subject's hip height. The simulated wall height was set at two different levels, the subject's elbow height and the shoulder height. Subjects repeated each task twice at each of the two simulated wall heights without wearing an exoskeleton (NoExo), wearing Exo1, wearing Exo2, and wearing Exo3. Each subject performed a total of 16 trials (2 × 4 × 2). Two repetitions were chosen to provide reliable data with practical constraints of participant endurance and study duration. Prior to data collection, participants practiced the masonry tasks on the unstable work platform with and without exoskeletons at least three times, or until they felt comfortable, to minimize learning effects and ensure they were comfortable with the platform and the tasks. The testing order of participant's wearing three exoskeletons (Exo1, Exo2, and Exo3) and a control condition of not wearing an exoskeleton (NoExo), and two lifting levels were balanced to reduce carryover effects. To balance for these effects, the testing order was established using the concept of Latin square designs to assure that each treatment follows each of the others the same number of times. The participants were then randomly assigned to a specified testing order.

2.5. Measurements and data processing

Balance. The K-Force plates (KINVENT Biomechanique SAS, Montpellier, France) were equipped with electronic force transducers to record the subject's ground reaction forces. Ground reaction forces were measured at a sample frequency of 75 Hz while performing the block-laying tasks. To evaluate the subject's stability and balance, three balance-related parameters were calculated using the coordinates of COP recorded by the force plates: (1) the mean distance (MDIST), (2) the total excursion (EXCUR), and (3) the mean velocity of the movement (VEL). To calculate MDIST, the resultant distance (RD), which is the

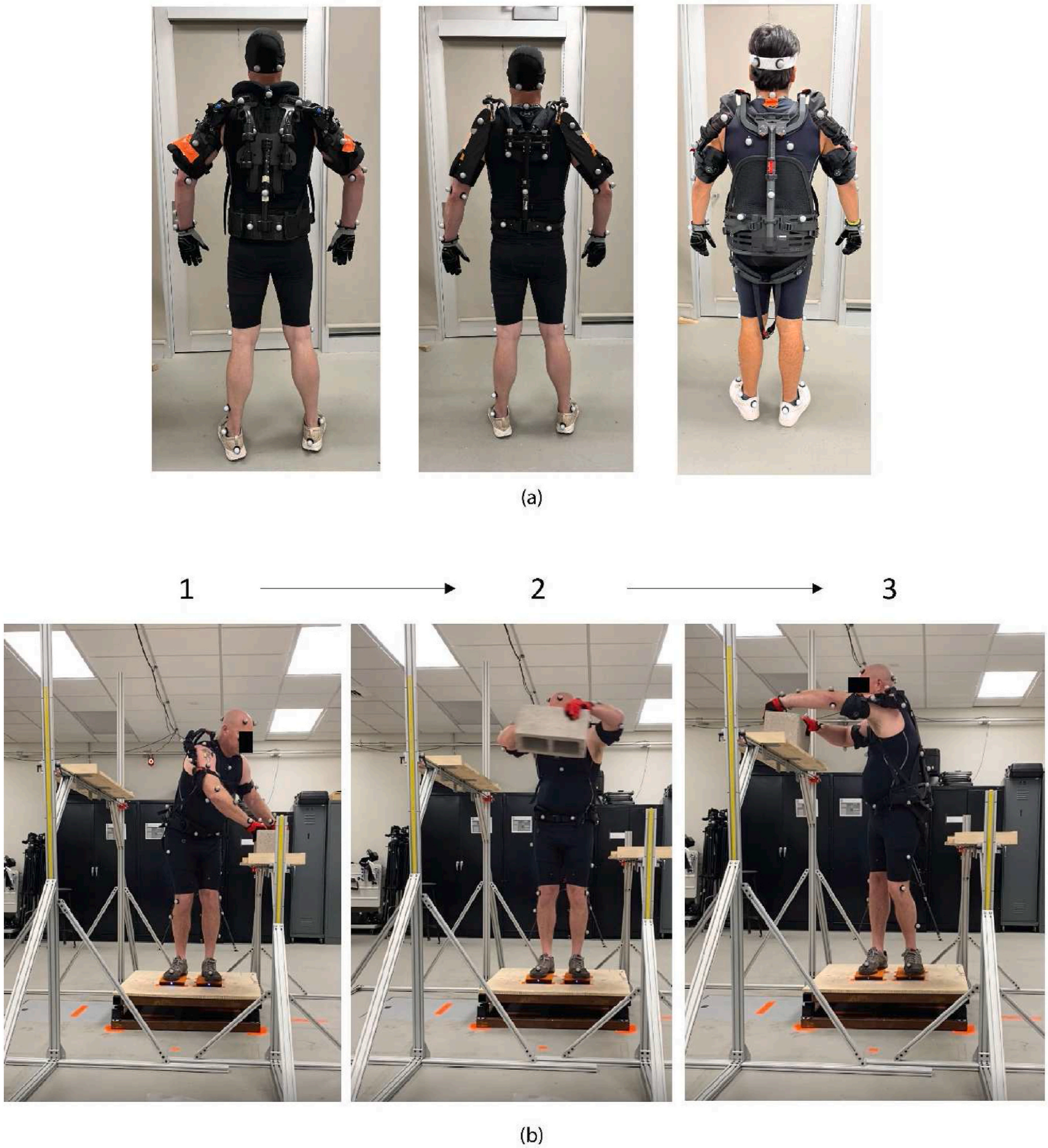

Fig. 2. (a) Three passive shoulder-assist exoskeletons tested in this study from left to right: Exo1, Exo2 and Exo3; (b) The simulated concrete block-laying activity of lifting a cinder block from the production table, turning, and placing it on the simulated wall (step 1 to step 3).

vector distance from the mean COP location to each point in the antero-posterior (AP) and medio-lateral (ML) directions was first obtained. The mean value of all RDs recorded during a movement becomes the MDIST. MDIST represents the average distance from the COP of any given motion during the movement to the mean COP location of the entire movement. The EXCUR represents the total COP distance travelled during the movement. Finally, the VEL is defined as the average COP travelling velocity which is calculated by dividing the EXCUR by the total time of the movement. The MDIST, EXCUR and VEL were calculated in both the AP and ML directions.

Muscle activity. Surface electromyography (EMG) data were collected from six shoulder and upper arm muscles from each participant's dominant side: upper trapezius (UppTrapezius), anterior deltoid (AntDeltoid), medial deltoid (MedDeltoid), posterior deltoid (PostDeltoid), biceps and triceps (Fig. 3). The placements of the surface EMG electrodes were guided by the recommendations outlined in the EMG manual, "The ABC of EMG" (Konrad, 2005). Before the placements of EMG electrodes, the skin underneath the anatomical locations was shaved and cleaned with isopropyl alcohol. Prior to fitting the exoskeleton, we securely wrapped the sensors with medical tape to prevent potential motion artifact. The EMG data of the arm muscles was recorded using the Delsys Quattro sensors and the EMG data from the shoulder muscles was recorded using the Delsys Avanti sensors (Delsys Inc., Natick, MA, USA). The EMG signals were sampled at 2000 Hz.

The raw EMG data were filtered by applying a 4th order Butterworth band-pass filter with lower and upper cut-off frequencies of 20 Hz and 450 Hz. After applying the filter, the signal was rectified by taking the absolute value. The rectified EMG signal was then smoothed by the Root Mean Square (RMS) envelope with a 50-ms moving window. Consistent with previous studies (Ricard et al., 2005; Suydam et al., 2017), the

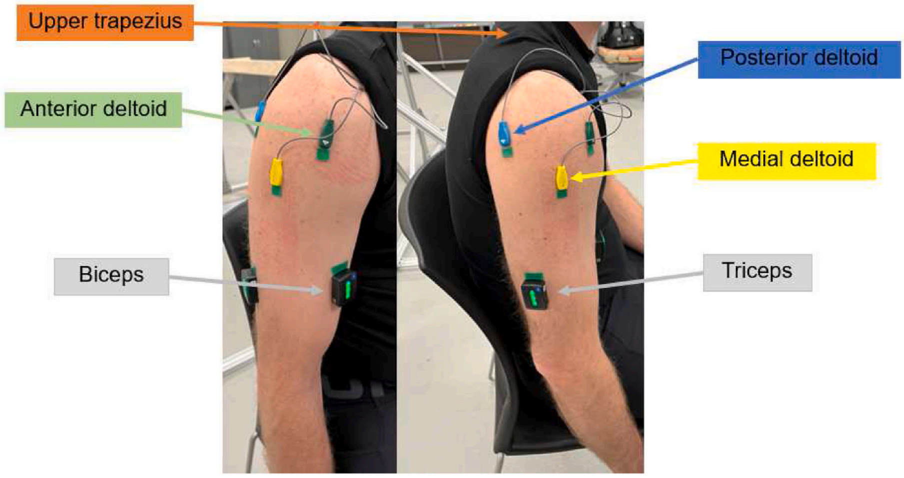

Fig. 3. Placement of EMG electrodes on the subject's dominant side, targeting six shoulder and upper arm muscles: upper trapezius, anterior deltoid, medial deltoid, posterior deltoid, biceps, and triceps.

dynamic movements in our tasks showed greater muscle activation than maximum voluntary isometric contractions. Therefore, for each recorded muscle, we used the maximum EMG values across all the dynamic trials (MaxD) for the same subject as the reference for normalization (Besomi et al., 2020; Burden, 2010; Maddox et al., 2022). The EMG data of each trial was collected from the neutral starting position to the neutral ending position. It was then filtered, rectified, and normalized. The mean and peak normalized EMG data were calculated for each trial. The data from replicate trials were averaged for the same conditions.

2.6. Statistical analysis

The Repeated Measures Analysis of Variance (ANOVA) was performed on the balance and muscle activity data using a mixed model. In this mixed model, the fixed effects included the four exoskeleton conditions (NoExo, Exo1, Exo2, and Exo3) and the two wall heights defined by elbow and shoulder height. The random effect included the participant effect. The interaction between exoskeleton device and lifting level was also included in the model.

Prior to any statistical testing, the normality assumption of the dependent variables was examined using a normal probability plot. For dependent variables that were highly skewed, log transformations were performed first. To control the error rate in the post-hoc multiple comparisons, the Bonferroni adjustment was used to determine significant differences among different experimental conditions. The analyses were performed using the Statistical Analysis System (SAS) software (SAS Institute Inc., Cary, NC, USA). Significance level (α) for hypothesis testing was set at 0.05.

3. Results

3.1. Balance

Exoskeleton devices had significant effects on the MDIST-ML ($p < 0.001$), MDIST ($p < 0.001$), Vel-ML ($p < 0.01$), Vel ($p < 0.05$), and EXCUR-ML ($p < 0.05$) (Table 1). Lifting to elbow or shoulder height had no significant effects on the balance-related parameters, however there was a significant interaction effect between exoskeleton device and lifting height in EXCUR-AP ($p < 0.05$) and EXCUR ($p < 0.05$) (Table 1).

The post-hoc analysis found that the MDIST in the ML direction was significantly larger while wearing exoskeletons Exo2 and Exo3 as compared to not wearing an exoskeleton (Exo2 vs. NoExo: $p < 0.001$; Exo3 vs. NoExo: $p < 0.01$; Fig. 4a). The MDIST was significantly larger when wearing exoskeletons Exo1, Exo2 and Exo3 as compared to not wearing an exoskeleton (Exo1 vs. NoExo: $p < 0.05$; Exo2 vs. NoExo: $p < 0.001$; Exo3 vs. NoExo: $p < 0.01$; Fig. 4b). The VEL-ML and VEL values were larger when wearing exoskeleton Exo3 than those when not wearing an exoskeleton or wearing exoskeletons Exo1 and Exo2 (all $p < 0.05$; Fig. 4c and d). The EXCUR in the ML direction was significantly larger when wearing the exoskeleton Exo3 as compared to not wearing an exoskeleton or wearing exoskeleton Exo1 (both $p < 0.05$; Fig. 4e).

Table 1
Repeated measures ANOVA results (p values) of balance-related parameters (* indicates statistically significant effects. ***: p-value <0.001, **: p-value <0.01, *: p-value <0.05).

	Device (NoExo, Exo1, Exo2, Exo3)	Lifting Level (Elbow, Shoulder)	Interaction (Device × Lifting Level)
MDIST-ML (mm)	**0.0002** ***	0.1919	0.7209
MDIST-AP (mm)	0.1974	0.9681	0.4619
MDIST (mm)	**0.0006** ***	0.1960	0.5038
Vel-ML (mm/s)	**0.0056** **	0.5249	0.1026
Vel-AP (mm/s)	0.1088	0.9662	0.0535
Vel (mm/s)	**0.0166** *	0.6854	0.0757
EXCUR-ML (mm)	**0.0150** *	0.1018	0.0727
EXCUR-AP (mm)	0.3511	0.3585	**0.0196** *
EXCUR (mm)	0.0540	0.1565	**0.0312** *

3.2. Muscle activity

Lifting level had significant effects on the mean and peak EMG values of all the shoulder and upper arm muscles, except for biceps (all $p < 0.01$). Lifting the concrete block to shoulder level required significantly larger muscle activity as compared to lifting it to elbow level (Table 2).

The exoskeleton device also had significant effects on the PostDeltoid, MedDeltoid, and UppTrapezius muscle activities (Fig. 5; $p < 0.05$). The mean EMG value of the MedDeltoid muscle was significantly lower when wearing exoskeletons Exo2 or Exo3 as compared to wearing exoskeleton Exo1 (both $p < 0.01$; Fig. 5c). The mean EMG value of the UppTrapezius was significantly lower when wearing exoskeleton Exo2 as compared to not wearing an exoskeleton or wearing exoskeleton Exo3 (both $p < 0.05$; Fig. 5d).

There were significant interactions between lifting levels and

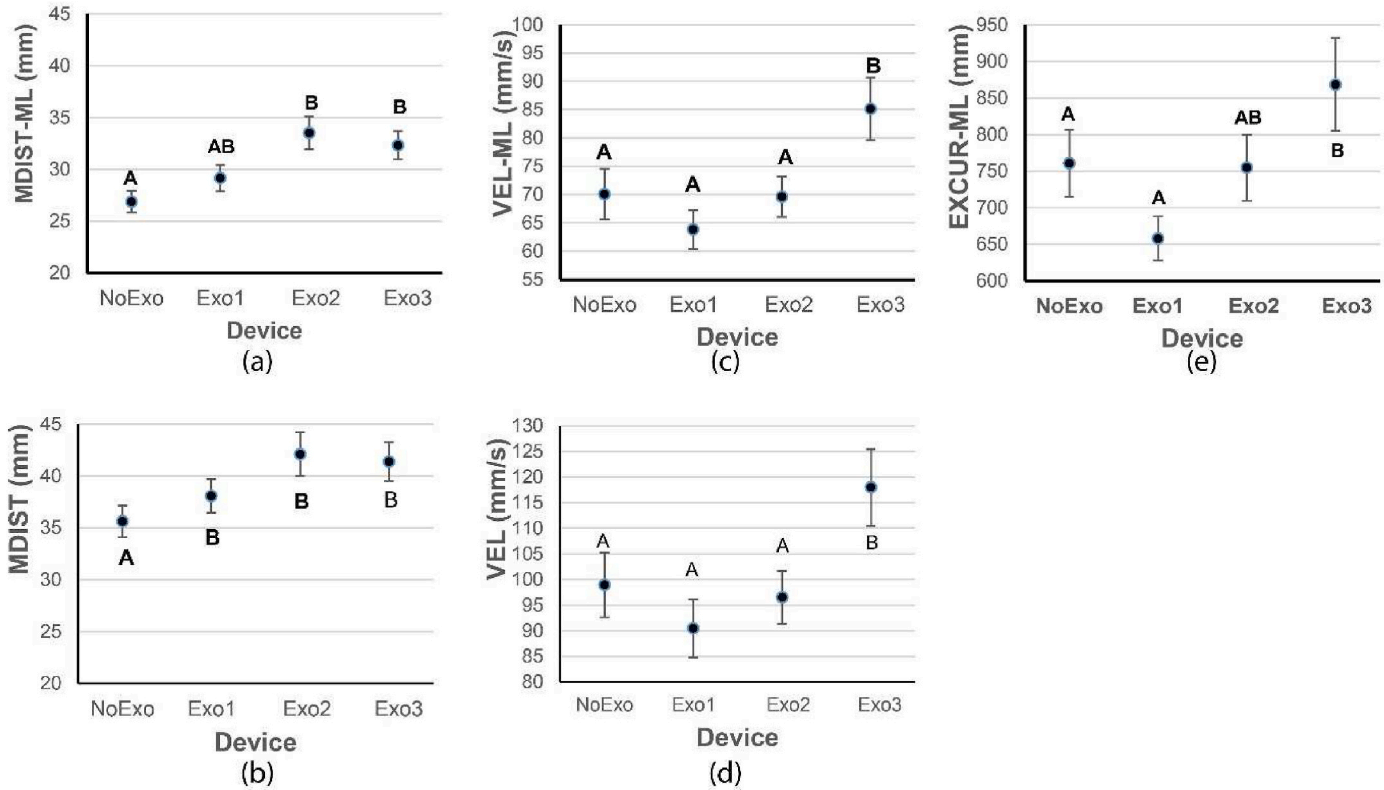

Fig. 4. Mean values and standard errors of balance-related parameters that were significantly affected by the exoskeleton device; MDIST-ML (a), MDIST (b), VEL-ML (c), VEL (d) and EXCUR-ML (e). Different letters denote values that are significantly different from one another.

Table 2
The mean and peak values of the normalized EMG data for five muscles (% of MaxD; mean ± standard errors) while lifting the concrete block to the shoulder and elbow heights.

Muscles	Shoulder Height (% of MaxD)		Elbow Height (% of MaxD)	
	Mean	Peak	Mean	Peak
Triceps	11 ± 1	62 ± 5	5 ± 1	22 ± 3
PostDeltoid	15 ± 1	64 ± 4	10 ± 1	46 ± 4
MedDeltoid	16 ± 1	68 ± 3	9 ± 1	39 ± 3
AntDeltoid	13 ± 1	62 ± 4	7 ± 1	32 ± 3
UppTrapezius	22 ± 1	78 ± 2	17 ± 1	59 ± 3

exoskeleton devices for PostDeltoid mean ($p < 0.001$) and peak ($p < 0.01$) values. When not wearing an exoskeleton, the mean ($p < 0.001$) and peak ($p < 0.01$) PostDeltoid EMG values were significantly higher for lifting to shoulder height versus lifting to elbow height. However, differences between lifting levels diminished when wearing exoskeleton devices (Fig. 5a and b). When lifting the block to shoulder height, there was no significant difference in the mean and peak EMG values for the PostDeltoid among the four exoskeleton devices conditions ($p > 0.05$). When lifting the concrete block to elbow height, it is worth noting that the peak EMG values of the PostDeltoid muscle were larger when wearing exoskeleton Exo2 as compared to not wearing an exoskeleton ($p = 0.01$, Fig. 5b).

Finally, wearing or not wearing an exoskeleton did not significantly affect the mean and peak EMG values of the biceps, triceps and AntDeltoid muscles, or the peak EMG values of the MedDeltoid and UppTrapezius muscles ($p > 0.05$).

4. Discussion

The present study evaluated three selected passive shoulder-assist exoskeletons during a common masonry activity of lifting a concrete block from hip height to elbow height or shoulder height on a simulated unstable work platform. Compared to not wearing an exoskeleton, the three tested exoskeleton devices did not reduce activity in most of the shoulder muscles, indicating that these exoskeletons may provide limited benefit for reducing MSD risks. Increased muscle activity, particularly if sustained or repetitive, may contribute to muscle fatigue, and strain, which could eventually lead to work-related MSDs. Research has shown that excessive muscle activation and poor biomechanical practices can play a role in the development of work-related MSDs (Armstrong et al., 1993; Brandt et al., 2024; Kumar, 2001; Nordander et al., 2016). Based on the balance results, wearing exoskeletons may introduce more whole-body balance-related hazards than not wearing an exoskeleton. Although specific thresholds for increased fall risk can vary, comparable differences in COP-based measurements, such as COP movements and velocities, have been observed between healthy young and elderly adults at the millimeter and millimeters-per-second scale (Prieto et al., 1996) and between fallers and non-fallers at the centimeter and centimeters-per-second scale (Melzer et al., 2004). This implies that the COP-based differences found in the present study could be associated with balance challenges and an increased risk of falling. Similar effects on postural control were found during an overhead task while wearing one of the shoulder-assist exoskeletons tested in the present study (Kim et al., 2018), where the exoskeleton use significantly increased the mean center of pressure velocity in the AP direction by 1.4 mm/s as compared to not wearing an exoskeleton. Since the masonry lifting task in the present study was lifting the block from the left side to the right side (i.e., from the production table to the simulated wall), it was not surprising that the postural control was significantly affected in the ML direction instead of in the AP direction. On the contrary, using a lighter weight shoulder-assist exoskeleton with a more flexible structure was found to reduce both center of pressure displacement and velocity during an overhead task (Maurice et al., 2020). These results suggest that the

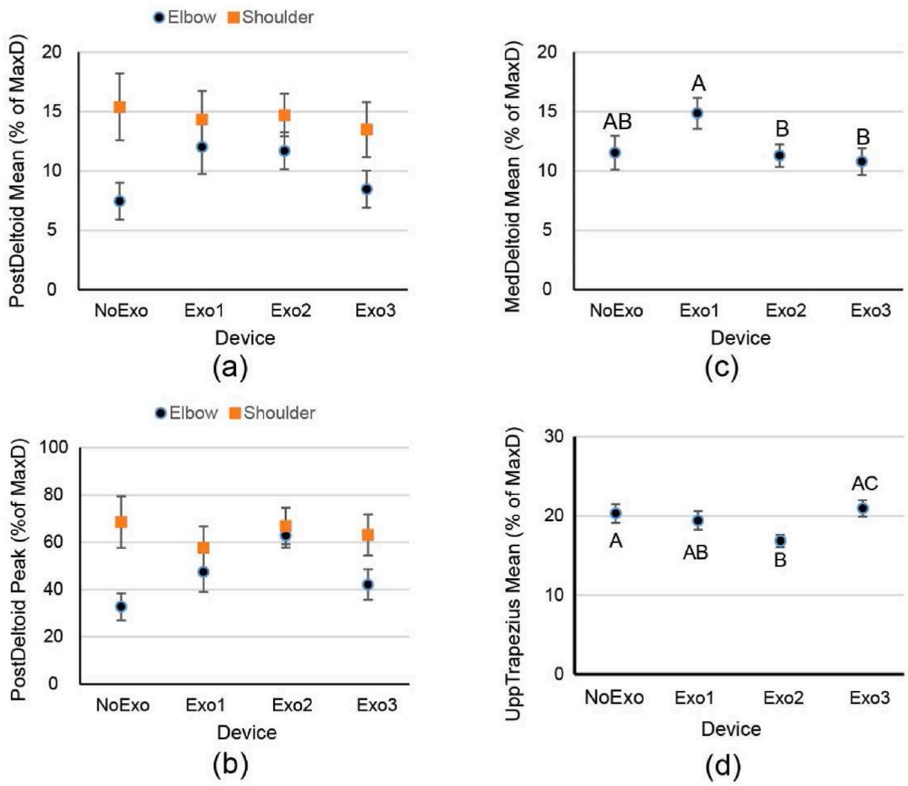

Fig. 5. The mean and standard error of EMG values (% of MaxD) that were significantly affected by exoskeleton device and/or the interaction between lifting height and exoskeleton device; PostDeltoid Mean (a), PostDeltoid Peak (b), MedDeltoid Mean (c), and UppTrapezius Mean (d). Different letters denote values that are significantly different from one another.

design and weight of the exoskeleton may play an important role in postural control during different tasks.

As expected, the block-laying task lifting from hip height to shoulder height demanded higher muscle activity than lifting to elbow height, with or without wearing an exoskeleton (Table 2). However, wearing exoskeletons tended to diminish the mean and peak EMG values of the PostDeltoid muscle between these two lifting heights (Fig. 5a & b). As expected, exoskeleton effects on muscle activity in the present study were found to be different than those in overhead tasks, especially during static or quasi-static tasks with prolonged upper arm elevation (McFarland and Fischer, 2019; Schmalz et al., 2019). During this dynamic lifting masonry task, the arm and shoulder were constantly at lower positions, which are often not the most favorable positions for which shoulder-assist exoskeletons are designed. The design disadvantage appeared more pronounced when the concrete block was lifted from hip height to elbow height (Fig. 5a and b), where most of the mean and peak EMG values in the PostDeltoid muscle tended to be higher when wearing an exoskeleton than when not wearing an exoskeleton, however this difference was not significant. In this study, effects on observed muscle activity were not as promising as those reported for “dynamic” construction tasks (de Vries et al., 2021; Musso et al., 2024). This difference may lie in the task selection. With the dynamic plastering activities used by de Vries, the study noted that, although the task involved various movements and postures, lowering the arm had a shorter duration compared to raising the arm, as subjects primarily worked on the ceiling. In the bricklaying tasks used by Musso et al. (2024), participants were tasked with transferring ten 2-kg bricks from one table to another, whereas in our study, participants handled a 35-lb (15.9 kg) concrete block. These differences in task requirements might have led to distinct muscle activation patterns, especially when controlling the downward speed while carrying the heavy block. The use of the shoulder exoskeletons tested in this study did not seem to provide a benefit for moving relatively heavy objects, particularly at elbow height. Based on the muscle activity results, little and inconsistent beneficial effects of wearing the tested shoulder-assist exoskeletons were found during a common masonry lifting task. Although different measurements were used in another exoskeleton evaluation study (Weston et al., 2022), a similar conclusion was reached that little to no physiological benefit was offered by similar types of upper-extremity exoskeletons during a simulated overhead occupational task of exerting a vertical force against a hand transducer.

There are several limitations in this study. With only seven subjects (all male and of similar age, which aligns with the representative population of construction workers), we were able to observe significant differences in the parameters of interest, indicating a strong and consistent impact of the interventions across participants. While our findings suggest that the exoskeleton did not reduce muscle activity in most of the shoulder muscles, it is important to interpret these results with caution. The small sample size used in this study could limit the generalization of our findings. This limitation may have prevented the detection of smaller, yet meaningful, changes in muscle activation. Future studies with larger sample sizes are warranted to confirm these findings and further explore the effects of exoskeletons on muscle activity as well as examining potential sex and age differences, which could influence the exoskeletons’ effects. Additionally, the participants in the present study had limited construction experience in masonry tasks, which could also impact the results. Future studies with larger and more diverse participant groups are needed to fully understand the impact of these variables and to confirm and generalize our findings. Furthermore, while we did not extensively investigate the design differences between the shoulder exoskeletons, we acknowledge that these differences could contribute to the variations in our results. Factors such as range of motion, support mechanisms, and weight distribution may influence muscle activation and user performance. Future research should explore the impact of specific design features in more detail. Additionally, other factors such as the effects of heat, added load, and pressure points caused by wearing exoskeletons are worth investigating in future studies (Howard et al., 2020; Rykaczewski, 2023). Last but not least, OSHA regulations require fall protection when construction workers are at elevations greater than 6 feet (OSHA, 2015). This includes the use of personal fall arrest systems, guardrails, and safety nets. Therefore, extensive research is needed to ensure that exoskeletons can be safely and effectively used in conjunction with fall protection systems and within confined working areas.

While opinions seem to be divided on whether an exoskeleton offers benefits for certain types of tasks, it is generally accepted that most exoskeleton use is highly task specific. As an emerging technology, there is optimism that future exoskeletons will undergo rapid advancements to better align with the specific needs and requirements of various tasks. Nevertheless, it's crucial to underscore the necessity for heightened attention to the potential risk and hazard related to the user's balance while wearing an exoskeleton, even when the exoskeleton can deliver the anticipated assistance. Despite often being taken for granted, maintaining balance while performing daily life and work tasks can be inherently challenging due to the erect bipedal posture of the human body. This challenge becomes notably more significant when workers are assigned tasks involving the handling of heavy objects on an unstable and confined elevated workspace such as a mast climber. Another limitation of this study is that participants were explicitly instructed to maintain a consistent foot placement during the task. This instruction may accentuate the constrained conditions experienced working on a mast climber, although, in real-world scenarios, workers often naturally restrict their movements on such platforms. Moreover, wearing an exoskeleton might introduce sensory conflicts by altering feedback from the vestibular system, proprioceptors, or other sensory systems, potentially disrupting balance control and spatial awareness. Although each subject participated in a training session to familiarize themselves with the exoskeletons, it's important to recognize that a more extended adaptation period might be essential. Users often need extra time to refine their balance control and spatial awareness, which can be affected by wearing exoskeletons. Additionally, it is important to recognize that the adverse effects of exoskeletons on balance may not be noticeable during static or quasi-static movements, but they may become more pronounced during many dynamic tasks. Exoskeletons have the potential to alter the user's center of mass, joint stiffness, or range of motion, all of which can present challenges in maintaining balance during dynamic tasks. Conversely, recent studies have explored the use of a powered lower-limb exoskeleton to enhance user's balance by reacting more quickly than the body's physiological responses (Beck et al., 2023). While it is not yet suitable for industrial use, studying similar concepts and designs can provide valuable insights for the development of next-generation ergonomic interventions that can assist workers in physically demanding tasks and enhance balance simultaneously.

5. Conclusion

Based on EMG results, the passive shoulder-assist exoskeletons evaluate in this study appeared to offer minimal and inconsistent benefits for reducing upper extremity musculoskeletal risk during a block-laying task on a simulated, unstable, elevated mast climbing work platform. Additionally, the center of pressure data suggested that these tested exoskeletons may have negative effects on workers' whole-body balance while working on an unstable work platform.

In the future, ergonomic devices, such as exoskeletons designed to reduce MSD risks during elevated construction tasks should place particular emphasis on the balance component. Therefore, a comprehensive evaluation of both balance and effectiveness should be carried out to ensure its safety and efficacy.

Disclaimer

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

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Liying Zheng: Writing – original draft, Investigation, Formal analysis, Conceptualization. **Christopher Pan:** Writing – review & editing, Supervision, Funding acquisition, Formal analysis, Conceptualization. **Leonardo Wei:** Investigation. **Hossein Bahreinizad:** Investigation. **Suman Chowdhury:** Writing – review & editing, Methodology, Investigation. **Xiaopeng Ning:** Validation, Formal analysis. **Felipe Santos:** Investigation.

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.

Data availability

Data will be made available on request.

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