ASSESSMENT OF A PASSIVE WEARABLE ROBOT FOR REDUCING LOW BACK DISORDERS DURING REBAR WORK

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SUMMARY: Low back disorder continues to be prevalent amongst construction workers, especially the rebar workers who are often engaged in repetitive stooping postures. Wearable robots, exoskeletons, are recent ergonomic interventions currently explored in the construction industry that have potentials of reducing the risks of low back pain by augmenting users' body parts and reducing demands on the back. This paper presents the assessment of a commercially available passive wearable robot, BackX, designed for reducing low back disorder amongst rebar workers. The study evaluated the exoskeleton in terms of task performance and physiological conditions. Outcome measures such as completion time were employed to evaluate the effect of the exoskeleton on task performance, while activations of Erector Spinae and Latissimus Dorsi muscles, and perceived discomfort across body parts were employed to assess the physiological effects of the exoskeleton. The results indicated mixed effects of the exoskeleton on muscle activations. Although the results revealed that the exoskeleton can reduce muscle activations across the Latissimus Dorsi, mixed effects were observed for the Erector Spinae especially during the forward bending tasks. The exoskeleton reduced completion time by 50% during the rebar tasks. There was also a 100% reduction in perceived discomfort on the back, but discomfort was tripled at the chest region when the exoskeleton was worn. This study reveals the potentials of the exoskeleton for reducing low back disorder and improving productivity amongst the rebar workers. However, the unintended consequences such as increased discomfort at the chest region and activations of the muscles highlight the need for improving existing exoskeleton designs for construction work.

KEYWORDS: Low back disorders, Wearable robots, Exoskeleton, Rebar work, Electromyography, Muscle activity, Discomfort

1 INTRODUCTION

Work-related musculoskeletal disorders (WMSDs) make up about 37% of non-fatal injuries and illnesses experienced by construction workers (Statistics, 2016). Construction workers are constantly exposed to awkward work postures which are repetitive and physically demanding in nature leading to WMSDs. According to the United States Bureau of Labor and Statistics (BLS), 18,070 construction trades (44.6 per 100,000 full-time workers (FTE)) sustained WMSDs in 2019 (BLS, 2020). This rate is about 60% higher than the rate of 27.8 per 10,000 FTE for all industries (BLS, 2020). Rebar workers are one of the construction trades with the highest rates of non-fatal injuries and illnesses (Umer et al., 2017, Yan et al., 2018). Rebar work involves tying and placing reinforcing bars in formworks prior to filling the formworks with concrete. A National Institute for Occupational Safety and Health (NIOSH) evaluation of iron workers' exposures found that rebar workers are prone to a high risk of low back disorders. This is because rebar workers spend approximately 40–48% of their working time in prolonged non-neutral trunk working posture (Forde and Buchholz, 2004).

Low back disorders or injuries are the most prevalent of all musculoskeletal disorders (Wang et al., 2017a). These disorders were responsible for approximately 40% of WMSD cases and resulted in an average of 7 lost workdays in 2019 (BLS, 2019). Back disorders have been known to trigger worker ill-health, reduced productivity, and financial loss. For example, according to a 2019 report by Liberty Insurance (Mutual, 2019), workers' compensation costs due to musculoskeletal disorders amounted to about $5.99 billion annually. There were reports of severe back disorders resulting in permanent disability and premature exits from the workforce (Wang et al., 2015). In 2018, lost work days due to back disorders among rebar workers was about 4 times more compared to the average of 14 days for all construction trades (BLS, 2020). One of the leading causes of back injuries is overexertion. Rebar workers are constantly exposed to well-documented risk factors of overexertion such as awkward postures and repetitive motions (Everett, 1999, Wang et al., 2015, Wang et al., 2017b, Ray and Teizer, 2012).

Exoskeletons are increasingly being recognized as prospective innovative ergonomic interventions to control physical demands on body parts. Exoskeletons are wearable robots designed to augment the wearer's body to reinforce or boost their performance. Although exoskeletons have shown promises for rehabilitation, medical and military applications, recently, there has been increasing interest in their potential for reducing WMSDs for occupational applications (De Looze et al., 2016). Exoskeletons are classified as 'active' or 'passive'. Active exoskeletons comprise of actuators that use external power source (e.g., electrical motors) to augment body parts, whereas passive exoskeletons use springs or dampers to store and release energy from the wearer's movements for augmenting the body parts (De Looze et al., 2016, Matthew et al., 2015). Although active exoskeletons can provide more augmentation, they are heavier and more expensive than passive exoskeletons. These make passive exoskeleton a more attractive intervention for reducing WMSD in the construction industry.

Exoskeletons are categorized according to the body parts they are designed to augment, e.g. back support, shoulder-support or full-body exoskeletons (Pillai et al., 2020). In rebar work, back-support exoskeleton can assist in reducing the physical demands on the wearer's back by providing assistive moments about the hip or lower spine to support the back muscles (Zhang and Huang, 2018). In addition to the intended design effect, studies (Kim et al., 2018, Kim et al., 2020) have shown that back-support exoskeletons may trigger unintended consequences such as health and safety challenges. Till date, there is little evidence regarding the extent to which back-support exoskeletons can reduce physical demands of construction work. Thus, the objective of this study is to investigate the effect of BackX exoskeleton during rebar work, in terms of task completion time and physical demands. Physical demands will be assessed in terms of muscle activations in the back and participant's ratings of discomfort on the back, chest, shoulder, thigh and upper arm.

2 BACKGROUND

2.1 Interventions to address WMSDs in the construction industry

Over the years, efforts to reduce WMSDs have been largely focused on educating and training construction workers on how to perform work safely, tracking workers' performance and alerting them of unsafe postures, and using wearable robots such as exoskeletons to reduce ergonomic risks during work performance (Akanmu et al., 2020, Gillen, 2010, Antwi-Afari et al., 2019). Safety and health organizations such as the Occupational Safety and Health Administration (OSHA) and NIOSH published guidelines for addressing general ergonomic and postural

issues experienced during general material handling tasks. Moore et al. (2011) and Albers and Estill (2007) provided graphical ergonomic guidelines for executing construction tasks with alternative tools and equipment such as a power tier. Albers and Hudock (2007) suggested that the use of power tier could allow workers to have one hand free, which can help to support their trunk and consequently increase their productivity. Unfortunately, such technological interventions are merely used as a tool to increase productivity with little attention on addressing WMSDs. However, advances in virtual technology have triggered developments of immersive and interactive work training environments. For example, Akanmu et al. (2020) developed and assessed a virtual reality (VR) based environment where workers can practice work in safe postures and get feedback based on their performance. Dias Barkokebas and Li (2020) also proposed a VR environment for assessing ergonomic risks associated with performance of industrialized construction tasks. Training with manuals and within the VR environments occur before or after workers' actual workday, thus the linkage between the actual performance of the worker and learning for continuous improvement is not established. In contrast, on-the-job interventions have also been investigated. Yan et al. (2018) proposed a wearable inertial measurement units-based personal protective equipment for tracking and alerting rebar workers about the risks associated with their trunks. While this effort has potential for reducing ergonomic risks of construction work, alert system used could be a distraction which could affect workers' productivity. Furthermore, compliance with the feedback is at the discretion of the workers as they might choose to neglect the alert, thereby disrupting the sole purpose of this intervention. Thus, a wearable system independent of the workers feedback to mitigate WMSDs has inspired the assessment of wearable robots such as exoskeletons.

2.2   Exoskeleton for WMSD Prevention

With recent advances in technology, there has been a shift from ergonomics training and adaptions of workforce behavior and work environment towards wearable robotic devices. Various back-support exoskeletons [e.g. Laevo, Personal lift-assistive device (PLAD), BackX, and SPEXOR] have been explored for a few occupational applications. Literature has identified the following factors as significant for evaluating back-support exoskeleton use: Muscle activity, discomfort, and task completion time (Kermavnar et al., 2020). Using the PLAD, Abdoli-E et al. (2006) reported a reduction of 14-28% in loading of the erector spinae muscles. Abdoli-e and Stevenson (2008) identified a reduction of 23-35% in the lumbar erector spinae, thoracic erector spinae, and the contralateral external oblique muscles when the PLAD was employed for lifting and static holding tasks. Koopman et al. (2020) evaluated SPEXOR exoskeleton for static bending and lifting tasks, and reported that the back muscle activity was successfully reduced by 20–27%. Bosch et al. (2016) and Koopman et al. (2019) explored Laevo for static back bending and holding tasks, respectively. The authors showed that Laevo exoskeleton can reduce activity in the trunk extensor muscles by 34-38% for the static back bending and 11-57% for the holding tasks. Wearing the exoskeleton resulted in reduced discomfort in the low back. A decrease in activities of the trapezius pars ascendens and erector spinae muscles between 0.8 and 3.8% was observed when the Laevo exoskeleton was used for industrial tasks (Cardoso et al., 2020). The exoskeleton was also found to interfere with the execution of the task by limiting movement and causing discomfort in the neck, shoulders, chest, hips, and thighs. A study comparing BackX and Laevo exoskeletons found more reduction in the back muscle activity with the BackX than the Laevo exoskeleton (i.e. 37.9% vs. ≤ 23.9% reduction) (Madinei et al., 2019, Madinei et al., 2020). Both exoskeletons minimally impacted the perceived discomfort and the task completion time. These evidence highlight the benefits of back-support exoskeleton in reducing muscle activity and task completion time and the unintended consequence of discomfort on user body parts.

However, most of the tasks performed in the above studies mainly involved static and forward bending back postures in other industries, wherein the participants were restricted to specific body movement and unfree to assume desired postures. In contrast, construction tasks are physically demanding comprising of diverse subtasks, each of which requires different postures. Also, construction activities being physically-demanding often pose serious ergonomic risks to different body parts of workers (Inyang et al., 2012). For example, construction rebar work involves persistent awkward postures during heavy manual material lifting, carrying, and manual rebar tying during a regular workday (Schneider and Susi, 1994). However, despite the potentials of adopted ergonomic interventions such as workers trainings and ergonomics tools, work-related injuries remains high. Sinyai and Choi (2020) explained that in 2017, compared to other industry sectors, 971 construction workers died from work-related injuries, while 80,000 construction workers suffered from work-related nonfatal injuries.

Extant studies (Kim et al., 2019, Zhu et al., 2021) have investigated the needs and benefits of exoskeleton in the construction industry, hence highlighting the exigency for its adoption in the construction industry. For example, Kim et al. (2019) presented the practical values and influencing factors to the adoption of exoskeleton in the construction industry. The authors posit that the adoption of exoskeletons can improve productivity, increase financial gains, and improve work retention. Zhu et al. (2021) assessed the potentials of exoskeleton and proposed the need for further investigation in the benefits of exoskeleton for improved productivity and work quality. However, limited studies have explored the physiological effects and consequences of exoskeleton on construction workers. Also, evaluating exoskeletons in the context of the different subtasks inherent in each task is essential to facilitating user acceptance in the construction industry. Therefore, this study assessed the effects of a back-support exoskeleton (BackX) for rebar tasks in terms of task completion time, muscle activations and perceived level of discomfort. In this study, participants were free to assume any posture they find fit to achieve the task, thus, dynamic body movement was encouraged. It is proposed that findings from this study will provide insights on design issues of existing back-support exoskeleton, significant for improving their designs and possibly enhancing their usability for construction tasks such as rebar work.

2.3 Research Gap

Despite the above-mentioned benefits of exoskeletons, there are limited studies on the impact of BSEs in the construction industry. Considering that almost 33% of all cases of occupational injuries and illness requiring days away from work are attributed to WMSDs wherein back disorder accounts for 43% of these cases (Kim et al., 2019, Umer et al., 2017), it is imperative to explore the suitability of emerging technologies such as BSEs for construction work. BackX exoskeleton is designed for use in different maneuvers such as squatting, cycling, walking, and climbing ladders (Kazerooni et al., 2019), which are in line with the range of maneuvers assumed by the construction workers. But there are scarce studies assessing the implications of BSEs (like BackX) for construction-related tasks (e.g., rebar, flooring, and finishing). Existing studies on BSEs showcasing benefits, such as reduction in back stress and level of discomfort, focus majorly on static holding and forward bending tasks (Koopman et al., 2019, Alemi et al., 2020, Kazerooni et al., 2019) and do not consider dynamic body movements which is the nature of construction work. This paper aims to sets the path towards addressing these gaps. Thus, this study addresses these gaps by assessing a commercially available back support exoskeleton (BackX) for construction work in terms of completion time, muscle activity, and level of perceived discomfort.

3 METHODOLOGY

This section presents the approach employed in the assessment of the exoskeleton (Fig. 1), including an overview of the back-support exoskeleton, participants involved, simulated rebar task, experimental procedure, data collection, and analysis.
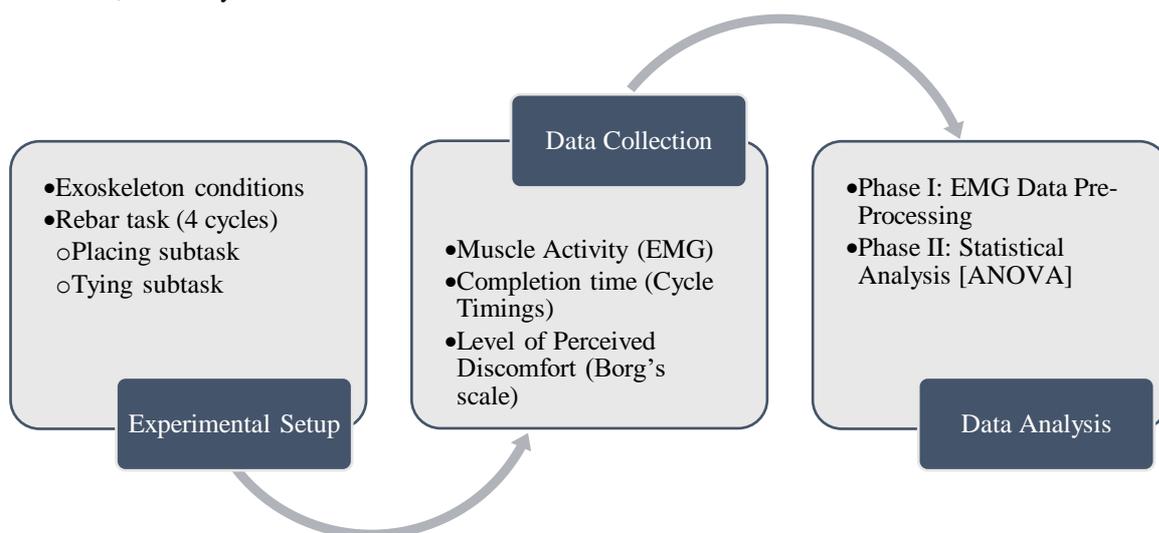

FIG. 1: Overview of Methodology

3.1 Exoskeleton

The passive exoskeleton, BackX™ S (https://www.suitx.com/backX), used in this study is shown in Fig. 2. BackX™S is intended to reduce the load on a wearer's lower back while performing work that involves bending, stooping, or reaching. BackX™ S weighs 3.4kg and is designed to provide 13.6kg of support to the lower back. The exoskeleton consists of a frame and a harness. The frame comprises of a torque generator, chest-plate and thigh straps. The torque generator serves as the activation point for the exoskeleton. The chest-plate and thigh straps are connected on both sides of the body with metal frames. The harness consists of a chest pad, hip belt, and straps (for the shoulder, chest, and legs), all of which are secured to the frame to the body. The frame is overlaid on the harness.
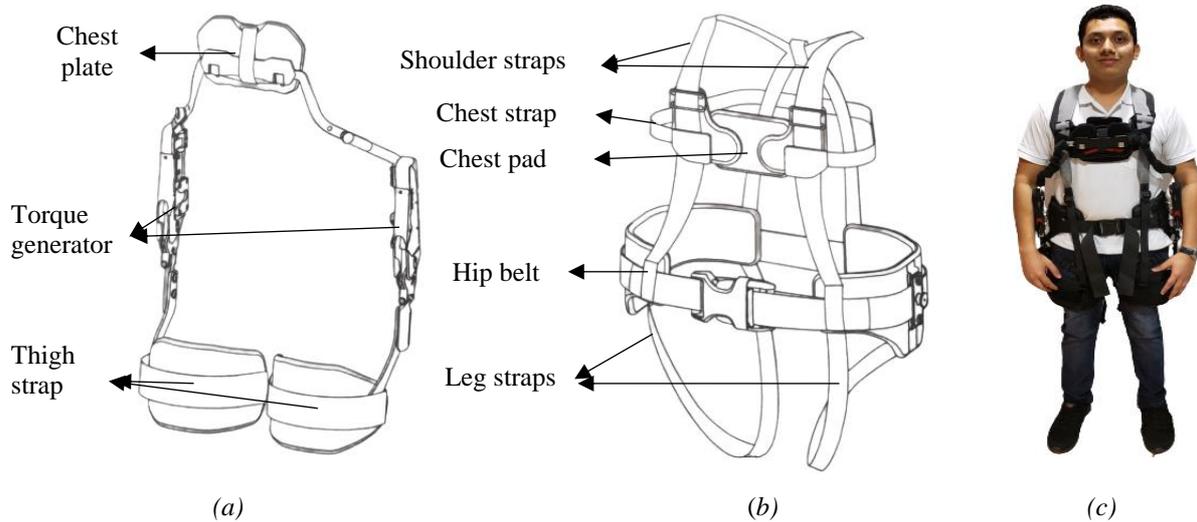

(a)　　　　　　　　　　　　　　　*(b)*　　　　　　*(c)*

FIG. 2: BackX exoskeleton (a) frame (left), (b) harness (middle) and (c) complete exoskeleton (right)

3.2 Participants

Ten individuals were recruited from the Virginia Polytechnic Institute and State University to participate in the study. The participants signed a consent form after being informed about procedures of the experiment. The consent form was approved by the Virginia Tech Institutional Review Board (IRB-19-796). All the participants reported having no current or prior musculoskeletal issues that affect their ability to stand, walk, bend, and lift. The participants were male with the demographic information presented in Table 1.

Table 1: Participants' demographics

Demographic Characteristic	Mean	SD	Min.	Max.
Age (years)	23	2	21	25
Weight (Kg)	75.14	8.74	56.6	86
Height (cm)	175.95	4.70	167.74	185.42
BMI (Kg/m2)	24.36	3	18.5	28.1
Note: SD = Standard Deviation, Min. = Minimum, Max. = Maximum				

3.3 Procedure

This was a within subject experimental study where participants performed four cycles of rebar task in a laboratory, with and without wearing the exoskeleton. The experiment was performed in two conditions (with and without exoskeleton) within the tasks and systematically varied across subjects. The participants were allowed to rest after each task to avoid fatigue. To ensure that the participants were familiar with the procedure, a training session was provided prior to commencing the task. Participants were recorded while performing the rebar task using a time-stamped camera. The video recording served as ground truth during data analysis.

3.4 Task Description – Simulated Rebar Work

The simulated rebar task (see Fig. 3) involved repetitive placing and tying (subtasks) of four prefabricated gates. Each gate has a cross-sectional area of 600mm by 400mm, with #6 rebars placed at 127mm on center (both ways). Participants were asked to place each prefabricated gate on the ground and tie the joints with pre-cut ties using a plier. To replicate the repetitive nature of rebar tasks, the participants placed the gate and tied 6 joints which represented as one cycle. Each participant completed four cycles without and with the exoskeleton.

FIG. 3: Participant performing simulated rebar task.

3.5 Data collection

Three types of data (completion time, muscle activity, and perceived discomfort) were collected as follows:

3.5.1 Completion time

The participants' performance of the rebar tasks was captured using a time-stamped camera. The camera was positioned in such a way that the work area and each participant's movement could be captured.

3.5.2 Muscle activity

Muscle activity was measured using Somaxis Cricket surface electromyography sensor (sEMG). The sEMG sensors were placed bilaterally over the left and right erector spinae (ES) and latissimus dorsi (LD) muscles using the placement procedure in earlier studies (Florimond, 2009). Erector spinae muscle group is one of the major muscles activated during forward bending which occurs during rebar work (Umer et al., 2017, Bosch et al., 2016, Huysamen et al., 2018). Latissimus dorsi is also activated during lateral movement (or axial rotation) of the trunk (Umer et al., 2017, Weston et al., 2018, Picchiotti et al., 2019). In addition to the sensor placement, medical tapes were used to secure the sensors on the muscles. Before commencing the rebar task, the participants were asked to perform a series of isometric maximum voluntary contraction (MVC) tasks. These tasks were aimed at isolating specific muscles so that the peak muscle activity can be determined for further electromyography (EMG) normalization. The MVC has been identified as one of the most effective methods for physiologic interpretation in healthy individuals (Sousa and Tavares, 2012). The MVC allows comparison of the task demands between subjects and normalization of EMG data for each subject. The EMG amplitudes were normalized using three 10 secs MVCs at 30°, 45°, and 90°. Each MVC was followed by a rest period. During the experiments, EMG amplitudes were collected at a sampling rate of 500 Hz.

3.5.3 Discomfort

Participants' discomfort in the back, chest, shoulder, thigh and upper arm were measured using the Borg's 10-point scale (Borg, 2004). Pictorial representations of facial expressions of discomfort at each scale were presented to the participants. Post task performance the participants were asked to rate their discomfort in each of the body parts (i.e. the back, chest, shoulder, thigh and upper arm) based on a 10-point scale (i.e., 0 = no discomfort to 10 = extreme discomfort) at the end of each condition, with and without the exoskeleton.

3.6 Data Analysis

The completion time, EMG and discomfort data were analyzed in two stages: pre-processing and statistical analysis.

3.6.1 Pre-processing

From the recorded videos, the subtasks involved in the rebar task, their timings and cycles were extracted for all participants and stored in a spreadsheet. The raw EMG data was bandpass filtered at 20-500 Hz. Root mean square values were then calculated using a 100ms sliding window. Subsequently, the EMG data were normalized to the MVCs (Mirka, 1991). These were used to compute the peak (90 percentile), median (50 percentile), and static (10 percentile) values. The perceived discomfort for all participants across the measured body parts with and without the exoskeleton was structured in a spreadsheet. All data processing was conducted using MATLAB 2020Ra and Microsoft Office Excel 2020.

3.6.2 Statistical analysis

All statistical analysis for the study was performed using R studio (Version 1.2.5042). Repeated measures analysis of variance (ANOVA) was utilized to make comparisons between the exoskeleton conditions (i.e., the Exoskeleton and No Exoskeleton) for the tasks completion time and muscle activations. Three separate three-way repeated measure ANOVA tests were conducted on the two dependent variables, which were the completion time of the subtasks and EMG data for the examined muscles and ratings. For the completion time, the independent variables were the exoskeleton conditions, cycles, and subtasks. While exoskeleton conditions were selected to understand any statistical significance between the two experiment conditions, cycles were selected to examine the effects of the exoskeleton on productivity, and subtasks were selected to evaluate the impact of the exoskeleton during each subtask (placing and tying). For EMG data, independent variables were exoskeleton conditions, subtasks, and muscle groups. Similar to completion time, exoskeleton conditions and subtasks were selected as an independent variable to understand the statistical impacts of the exoskeleton on muscle activations and subtasks, while muscle groups was selected to examine the statistical relationships between left and right side of each muscle group. Cycles were not considered as an independent variable for EMG data as the focus here was to evaluate the overall significance between each experimental task and not between cycles.

A two-way ANOVA was performed on the perceived level of discomfort (LPD) across the measured body parts as the LPD data was collected after the end of each task and not after each cycle. The independent variables for LPD were body parts to account for discomfort between each body parts, and exoskeleton conditions to compare the discomfort levels between the two experimental tasks. For all analysis, significant effects were reported at 95% confidence level, and post hoc were performed on all observed significant effects between variables using Tukey's Honest Significant Difference (HSD).

4 RESULTS

The experimental results of each outcome measures are discussed as follows:

4.1 Task Completion Time

Table 2 presents the summary of the ANOVA (F-Value, P-Value and effect sizes (η^2)) and Post Hoc tests performed for completion time, across the subtasks, cycles, and exoskeleton condition. P-values with '*' have a confidence level < 0.05.

Table 2: Completion time of participants with and without BackX exoskeleton during rebar tasks.

	F-value	P-Value	η^2	Post Hoc
Exo	6.033	**0.034***	0.006	Noexo > BackX
Subtasks	51.01	**3.13e-05***	0.65	Tying > Placing
Cycles	4.293	**0.012***	0.004	
Exo X Subtask	4.258	0.066	0.004	
Exo X Cycles	7.486	**0.0007***	0.005	
Subtask X Cycles	5.913	**0.003***	0.005	Tying (1) > Tying (4)
Exo X Subtask X Cycles	7.814	**0.0005***	0.005	Noexo Tying (1) > BackX Tying (1, 2, 3, 4) Noexo Tying > BackX Tying

Note: Exo = Exoskeleton Condition

Fig. 4 shows the overall mean completion time for the exoskeleton conditions across four cycles during placing (Fig. 4a) and tying (Fig. 4b) subtasks, and the error bars indicate the standard deviation of the mean as a measure of variations across all participants. Overall, the effect of the exoskeleton reduced rebar task completion time ($p = 0.034$). During the placing subtask, the use of the exoskeleton reduced the completion by at least 20% for the first, second, and third cycles (Fig. 4a). However, the exoskeleton reduced task completion time by only 15% at the fourth cycle. The results revealed that the completion time of the tying subtask was significantly higher than the placing subtask ($p = 3.13e-05$). Hence, the effect of the exoskeleton was revealed differently across these subtasks. For the tying subtasks, there was a significantly lower completion time at the first cycle ($p = 0.0005$). When tying subtasks was performed with the exoskeleton, the task completion time was reduced by 50% for the first cycle (Fig. 4b). The effects of the exoskeleton on completion time during cycle 1 was significantly higher than the other cycles, although, for subsequent cycles, the task completion time was reduced by at least 7%.

(a)   (b)
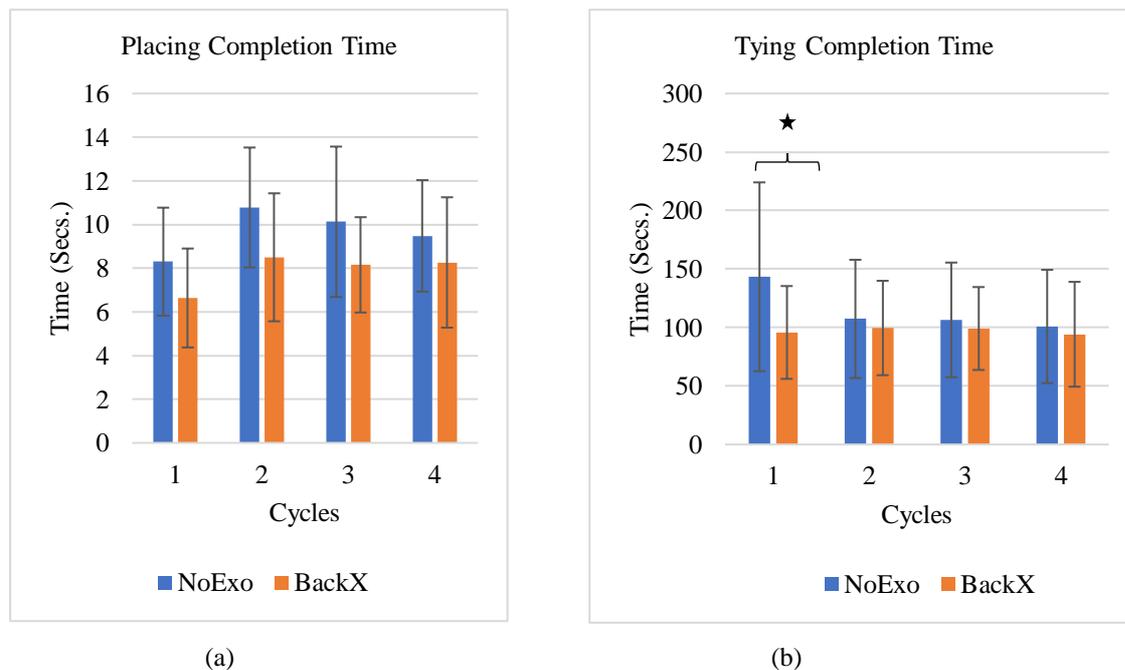
FIG. 4: Completion time across cycles with and without exoskeleton conditions for (a) placing subtasks (left) and (b) tying subtasks (right). Note: The error bars represent standard deviations and '' indicates a significant difference, and blue and orange bars represent NoExo and Exo (BackX) conditions respectively.*

4.2 Muscle Activity

Tables 3, 4 and 5 presents summary of the ANOVA (F-Value, P-Value and effect sizes (η^2)) and post Hoc tests performed for the EMG data, across the subtasks, cycles, and exoskeleton condition. P-values with '*' have a confidence level < 0.05.

During the rebar task, no statistical effects of the exoskeleton was observed on the muscle activations. Results show some increase in the Erector spinae (ES) and Latissimus dorsi (LD) muscle activations. Static muscle activations were significantly higher during placing subtask than during tying subtask for ES ($p = 1.22e-05$) and LD ($p = 0.049$). There was a correspondingly large effect size for both muscles (Table 3). Significant statistical difference was observed in latissimus dorsi muscle ($p = 0.041$), with left latissimus dorsi being higher than right latissimus dorsi. The median muscle activations of the left ES was higher than the right ES during placing subtask ($p = 0.047$) [Table 4]. For erector spinae muscle, placing subtask was higher than tying subtask for median ($p = 3.84e-05*$) [Table 4] and peak ($p = 0.00048$) [Table 5] muscle activations.

Table 3: ES and LD Muscle activations of participants with and without BackX exoskeleton during rebar tasks for static muscle activation level.

Static (ES, LD)				
	F-value	P-Value	η^2	Post Hoc
Exo	0.803, 0.560	0.394, 0.472	0.082, 0.053	N/A
Subtasks	74.18, 5.017	**1.22e-05*, 0.049***	0.892, 0.334	Placing >Tying, Placing >Tying,
Muscle sides	4.94, 5.50	0.053, **0.041***	0.354, 0.355	LLD> RLD
Exo X Subtask	0.042, 0.185	0.842, 0.676	0.005, 0.018	N/A
Exo X Muscle sides	0.344, 0.573	0.572, 0.467	0.037, 0.054	N/A
Subtask X Muscle sides	4.004, 1.889	0.076, 0.199	0.308, 0.159	N/A
Exo X Subtask X Muscle sides	0.440, 0.723	0.524, 0.415	0.047, 0.067	N/A

Note: Exo = Exoskeleton Condition, LLD = Left latissimus dorsi, RLD = Right latissimus dorsi, ES = Erector spinae, LD = Latissimus dorsi, LES = Left erector spinae and RES = Right erector spinae.

Table 4: ES and LD Muscle activations of participants with and without BackX exoskeleton during rebar tasks for median muscle activation level

Median (ES, LD)				
	F-value	P-Value	η^2	Post Hoc
Exo	0.436, 1.336	0.526, 0.275	0.046, 0.118	N/A
Subtasks	55.700, 3.077	**3.84e-05***, 0.110	0.861, 0.235	Placing >Tying
Muscle sides	3.907, 3.368.	0.079, 0.096	0.303, 0.252	N/A
Exo X Subtask	0.067, 0.094	0.801, 0.765	0.007, 0.009	N/A
Exo X Muscle sides	0.060, 0.373	0.812, 0.555	0.007, 0.036	N/A
Subtask X Muscle sides	5.295, 1.361	**0.047***, 0.270	0.370, 0.120	Placing RES, LES >Tying RES, LES. Placing LES> Placing RES
Exo X Subtask X Muscle sides	1.699, 0.250	0.225, 0.628	0.159, 0.024	N/A

Note: Exo = Exoskeleton Condition, LLD = Left latissimus dorsi, RLD = Right latissimus dorsi, ES = Erector spinae, LD = Latissimus dorsi, LES = Left erector spinae and RES = Right erector spinae.
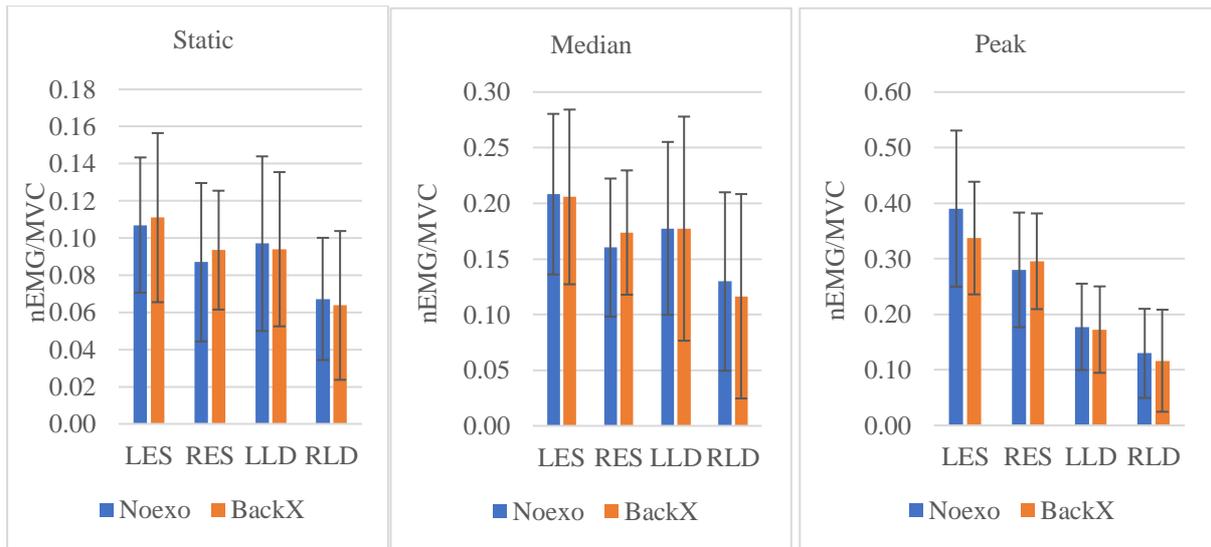
Table 5: ES and LD Muscle activations of participants with and without BackX exoskeleton during rebar tasks for peak muscle activation level.

| | **Peak (ES, LD)** | | | |
	F-value	P-Value	η^2	Post Hoc
Exo	0.089, 0.862	0.773, 0.375	0.010, 0.079	N/A
Subtasks	28.320, 3.133	**0.00048***, 0.107	0.759, 0.239	Placing> Tying
Muscle sides	5.069, 1.841	0.051, 0.205	0.360, 0.155	N/A
Exo X Subtask	0.053, 1.380	0.823, 0.267	0.006, 0.121	N/A
Exo X Muscle sides	0.353, 0.524	0.567, 0.486	0.038, 0.050	N/A
Subtask X Muscle sides	4.626, 1.605	0.060, 0.234	0.339, 0.138	N/A
Exo X Subtask X Muscle sides	0.500, 1.206	0.497, 0.298	0.053, 0.108	N/A

Note: Exo = Exoskeleton Condition, LLD = Left latissimus dorsi, RLD = Right latissimus dorsi, ES = Erector spinae, LD = Latissimus dorsi, LES = Left erector spinae and RES = Right erector spinae.

Fig. 5 shows the overall mean static (Fig. 5a), medium (Fig. 5b), and peak (Fig. 5c) muscular efforts for the exoskeleton conditions during placing subtasks, and the error bars indicate standard deviation of the mean as a measure of variations across all participants. For the placing subtasks, the effects of the exoskeleton did not substantially influence the muscle activities. Static muscle activations for the left and right ES during placing subtasks were increased by 4% and 7% respectively (Fig. 5a) and reduced by 3% and 5% for the left and right LD, respectively. The median EMG was reduced by 1% for left ES and increased by 8% for right ES. There was no observed change in the left LD, but an 11% reduction was observed for the right LD (Fig. 5b). However, the effects of the exoskeleton were more prominent on the peak EMG, muscle activations were reduced by 16% for left ES, and increased by 5% for right ES, while the muscle activity levels reduced by 3% and 11% for the left and right LD muscles respectively (Fig. 5c).

Likewise, Fig. 6 shows the overall mean static (Fig. 6a), medium (Fig. 6b), and peak (Fig. 6c) muscular efforts for the exoskeleton conditions during tying subtasks, and the error bars indicate standard deviation of the mean as a measure of variations across all participants. During tying subtasks, there was a 2% increase in static muscle activations for both left and right ES, but the use of the exoskeleton reduced muscle activities by 7% and 4% at the left and right LD respectively (Fig. 6a). The median EMG for the right ES increased by 13%, but the exoskeleton showed no effects on muscle activation in the left ES (Fig. 6b). The left and right LD peak muscle activities were reduced by 6% and 10% respectively. Although there was an increase in the left ES (3%), and right (10%) peak ES muscle activities, the effect of the exoskeleton was prominent at the LD, as results revealed a 6%, and 10% decrease in left and right peak muscles activations, respectively (Fig. 6c).
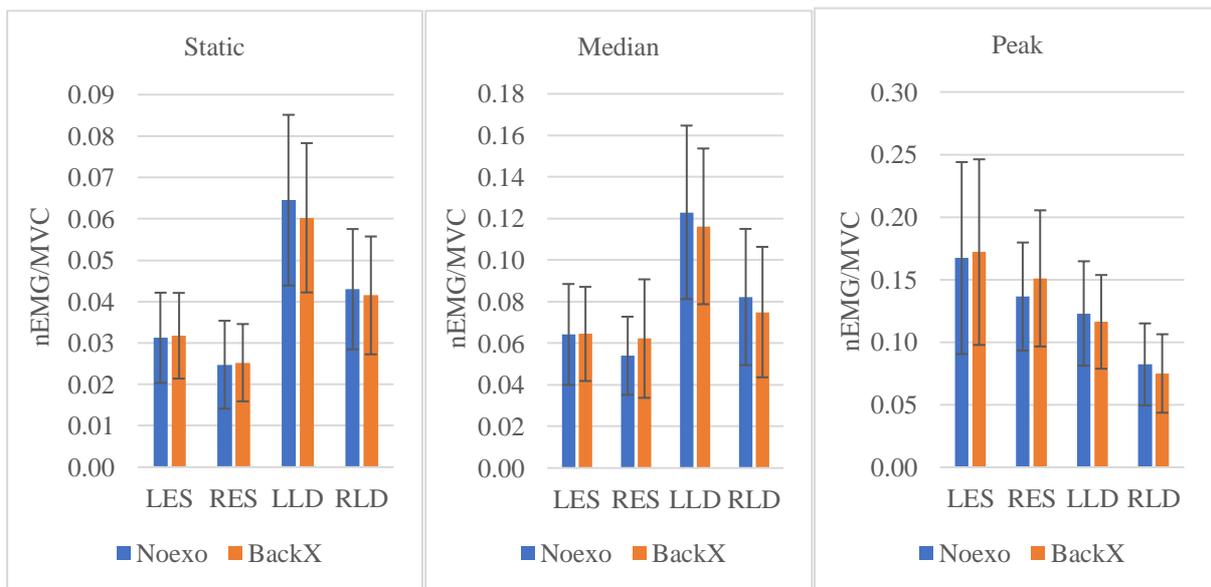
FIG. 5: (a) Static (left), (b) median (middle) and (c) peak (right) mean EMG values across different muscle groups for placing subtasks. Error bars represents standard deviations and blue and orange bars represent NoExo and Exo (BackX) conditions respectively.

Fig. 6: (a) Static (left), (b) median (middle) and (c) peak (right) mean EMG values across different muscle groups for tying subtasks. Error bars represents standard deviations and blue and orange bars represent NoExo and Exo (BackX) conditions respectively.

4.3   Discomfort

Table 6 presents summary of (F-Value, P-Value and effect sizes (η^2)) the ANOVA and Post Hoc tests performed for level of discomfort, across the different body parts and Exoskeleton condition. P-values with '*' have a confidence level < 0.05.

Table 6: Perceived level of discomfort of participants with and without BackX exoskeleton during rebar tasks.

	F-value	P-Value	η^2	Post Hoc
Body parts	10.440	**6.67e-09***	0.223	(C, LB, T, LL) > (N, UA, S, H)
Exo	0.003	0.957	0	N/A
Body parts X Exo	7.745	**6.50e-07***	0.080	BackX (C) > Noexo (C)

Note: Exo = Exoskeleton Condition, and B = Body parts, where H – Hand/wrist, UA – Upper arm, S – Shoulder, LB – Lower back, T – Thigh, N – Neck, LL – Lower leg, and C – Chest.

The perceived discomfort significantly varied across different body parts (Table 6). With the highest discomfort felt in the chest, perceived discomfort in the chest, lower back, thigh, and lower leg was significantly higher than the neck, upper arm, shoulder, and hand (p = 6.67e-09). Fig. 7 shows the overall mean perceived discomfort across different body parts (hand/wrist, upper arm, shoulder, low back, thigh, neck, chest, and lower leg/ foot) for the exoskeleton conditions, and the error bars indicate the standard deviation of the mean as a measure of variations in the perceived discomfort across all participants. Results also revealed substantial effects of the exoskeleton in the form of reduced discomfort across the lower back and leg (Fig. 7), and no effects were observed across the shoulder, upper arm, and wrists. However, results showed a significantly higher discomfort (383%) in the chest (p = 6.50e-07) when the exoskeleton was used to perform the tasks. Conversely, participants experienced over 100% reduction in discomfort at their lower back when the tasks were performed with the exoskeleton (Fig. 7).
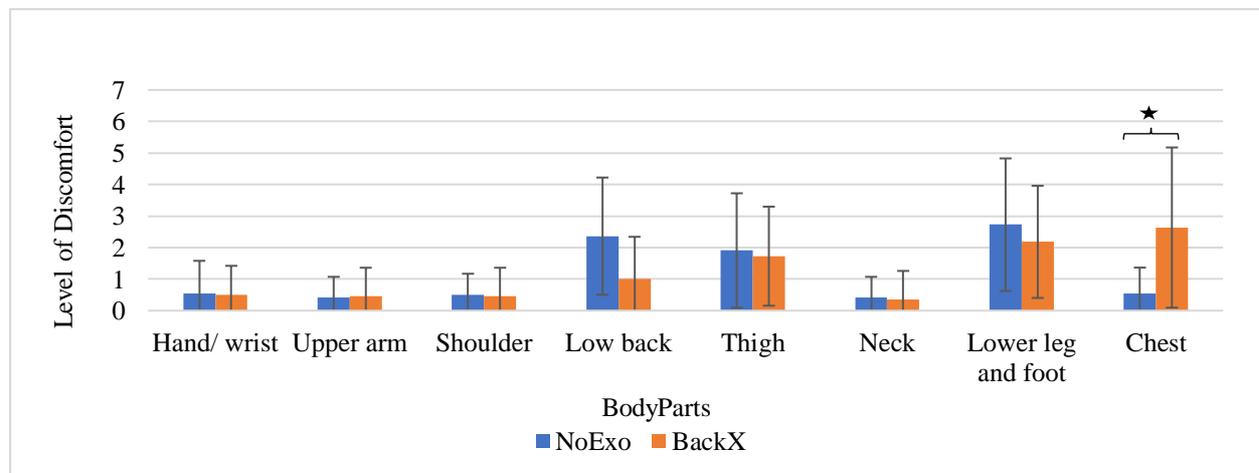

FIG. 7: Mean perceived discomfort across different body parts Note: The error bars represent standard deviations and '' indicate a significant difference, and blue and orange bars represent NoExo and Exo (BackX) conditions respectively.*

5   DISCUSSION

This study presents the evaluation of a back support exoskeleton (BackX) for rebar work. The study assessed the exoskeleton in terms of task performance and participants' physiological conditions. The outcome measures such as completion time was employed to evaluate the effect of the exoskeleton on task performance, while the muscle activations and perceived level of discomfort across body parts was used to assess the physiological effects of the exoskeleton on participants.

The use of the exoskeleton significantly reduced the time to complete the rebar tasks, although the effect sizes were rather small (η^2=0.006). As explained by Fritz et al. (2012), effect sizes describe the magnitude of the significant effects irrespective of impacts of the sample sizes and are often measured as ($\eta2 = 0.01$) small, ($\eta2 = 0.06$) medium, and ($\eta2 = 0.14$) large. The placing subtask being a shorter duration activity showed more reduction in completion time when compared to tying subtask. However, with a 50% reduction in completion time for the first cycle and a 7% reduction for subsequent cycles, it can be inferred that participants got adjusted to the exoskeleton during the first cycle. Therefore, it can be inferred from this study that the use of the exoskeleton can reduce task completion time, and consequently improve the productivity of rebar tasks. These results are consistent with the findings of Butler and Wisner (2017) where an upper-body exoskeleton resulted in 73% reduced completion time and 86% more welds.

The study revealed significant effects of the exoskeleton on reducing discomfort on different body parts of the users during rebar tasks. The chest, lower back, thigh, and lower leg are the body parts mostly impacted by the exoskeleton. While discomfort was significantly reduced in the lowe r back, an unintended discomfort was consequently imposed at the chest region when the exoskeleton was worn ($\eta2 = 0.08$). Similarly, Bosch et al. (2016) and Alemi et al. (2020), reported high discomfort in the chest and low discomfort in the lower back when a passive exoskeleton (Laevo and BackX respectively) was used for forward bending tasks. Perceived discomfort in lower leg which is a potentially affected body part during bending and lifting tasks was also reduced when the exoskeleton was worn. From Fig. 7, it can be inferred that the use of BackX has minimal effects on the discomfort of the wrists, upper arms, shoulder, and neck.

Overall, the use of the exoskeleton reduced muscle activities (3% - 11%) in the LD for both placing and tying subtasks. This is consistent with the findings of Madinei et al. (2020) who reported reduced back muscle activations (6% – 13% of MVIC) for asymmetric lifting when BackX was used. This differed for the muscle activities in the ES for both subtasks. Although there was an increase in the muscle activities for tying subtasks, mixed effects of the exoskeleton were observed in the ES during the placing subtask. The effects of the exoskeleton for reducing muscle activations in the ES were more pronounced during the placing subtask (p = 0.0469). The exoskeleton consistently increased the static, median, and peak muscle activation in the right ES, and reduced the medium and peak muscle activities at the left ES. While the medium activity levels at the left ES was reduced by 1%, the peak muscle activations were reduced by 16%. This may be because the placing subtask requires forward bending often requiring activation of the ES. During the tying subtasks, the exoskeleton consistently reduced the static, median, and peak muscle activations at the LD, but triggered an increase in the static and peak ES muscle activity levels. Moreover, the exoskeleton had no impact on the medium muscle activations for the left ES. The overall ES muscle group results are not in accordance with other studies conducted on BackX by Alemi et al. (2020) and Kazerooni et al. (2019) which reported a consistent reduction in back muscle activity up to 2% and 75% respectively.

The disparity in the effects of the exoskeleton across the muscles and subtasks can be explained by the location of these muscles, and the required postures for both subtasks. The LD is attached to the spine but actions are perceived from the shoulder during lateral bends and axial twists (Gerling and Brown, 2013) while the ES is closer to the spine. Therefore, the effects of the exoskeleton in reducing muscle activations were more prominent in the LD than in the ES during tying subtasks because tying involves more arm actions, and twists, while placing involves a forward bending posture. It is also important to state that although tying subtask requires significantly more completion time than placing subtasks (Table 2), the effects of the exoskeleton on reducing muscle activations did not substantially increase while the participants performed the tying subtask. This may be because the muscle activities during placing subtasks was significantly more than during tying subtasks. This can suggest that the duration of use of the exoskeleton may not substantially increase the effect of the exoskeleton on reducing the muscle activities.

6 CONCLUSION

This study assessed the effects of a wearable robot (BackX) during rebar works, by exploring the impact of the exoskeleton on task completion time, perceived discomfort, and muscle activity. The exoskeleton reduced the task completion time, and thus improved the performance of rebar task. With more impact observed for the shorter duration activity (placing subtask), it is imperative to state that the effect of BackX on task performance may be prominent for activities involving shorter durations. The reduced task completion time could imply an increase in

productivity of workers once they become comfortable with the use of the exoskeleton. This is an interesting finding because exoskeletons are often perceived as an invasive ergonomic innovation that may restrict movement of construction workers during task performance. However, findings from this study indicate increased task performance, which can possibly inform the decisions of construction stakeholders on investing in exoskeletons.

Although the use of the exoskeleton increased task performance, the exoskeleton had mixed effects on the muscle activities and perceived discomfort across different body parts of the users. While perceived discomfort was significantly reduced in the lower back, unintended discomfort was consequently felt at the chest region while using the exoskeleton. That is, despite the potentials of BackX to reduce the prevalent lower back pain in the industry, the increased discomfort at the chest region may restrict the wide acceptance of exoskeletons in the construction industry.

Similarly, the exoskeleton reduced muscle activations in the LD during the rebar task, but induced more muscle activations in the ES, especially during the tying subtasks. This suggests that the postures assumed, and the actions involved in different tasks are critical to selecting an appropriate and suitable exoskeleton. Therefore, it is imperative that construction companies critically evaluate the appropriateness and suitability of BackX for each trade as it is pertinent that workers are protected against extensive muscle activations and discomfort while using the exoskeleton. Furthermore, reduction in muscle activity suggests less stress on the workers' back muscle groups, which can help reduce the occurrences of back disorders in the construction industry. The reduced stress and perceived discomfort in the lower back would result in less fatigue, which could in turn help to increase the productivity of the workers. The managerial implication of the increased productivity could suggest a reduction in project timeline thereby achieving earlier project completion leading to cost benefits. The improved health of the workforce would mean fewer lost workdays and higher retention of skilled labor thereby helping to mitigate the problem of labor shortage. Also, reduced occurrences of WMSDs would result in financial savings from workers' compensation.

This study contributes to existing body of knowledge on the use of passive back support exoskeletons for the construction industry. The findings of this study showcased that the use of the back support exoskeleton could potentially be a successful intervention for back muscle injuries particularly for the rebar work. The results provide preliminary data on the effect of the passive back support exoskeletons on muscle activation, body parts and workers productivity. This study sets precedence for future research in wearable robots for the construction industry and suggests potential design modifications for future exoskeletons tailored for construction trades. Also, the findings of this study should only be considered for BackX exoskeleton and not for other available passive back support exoskeletons.

There are some limitations in this study which are potential considerations for future research work. The participants of this study were students who are naïve, and not professional rebar workers in the construction industry. Hence, the process of executing the rebar tasks and postures assumed during these tasks may not be representative of the real jobsite. Also, the exoskeleton was used for a short period of time, in a controlled laboratory, and not the regular working hours of construction workers. Hence, the impact of prolonged use of the exoskeleton on a typical jobsite was not acknowledged in this study. Besides, the demographics such as age of participants may not represent the ages of experienced workers in the construction industry. Workers may be well advanced in age, and their BMI may vary dramatically compared with the sample size. This in turn may influence task completion, muscle activities and perceived discomfort across the different body parts. Therefore, future works will involve simulating this study with experienced rebar workers on the jobsite for an extended period.

Additionally, the sample size for this study involved only 10 participants, which may impact generalizability of the findings. It is recommended that future studies involve a larger sample size and varying demographics. Furthermore, the Level of Perceived Discomfort (LPD) was not measured after each cycle. As the tasks are repeated, the LPD may vary across cycles. In addition, this study only involved two muscle groups (latissimus dorsi and erector spinae), but considering the results of LPD, the stress levels in the muscle groups of different body parts such as thigh, chest, abdomen will be assessed in the future studies. Lastly, the effects of the exoskeleton on other physiological factors such as kinematics, and users' heart rate will be explored in future studies.

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