Subjective Evaluation of Passive Back-Support Wearable Robot for Simulated Rebar Work

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Abstract -

Work-related musculoskeletal disorders continue to be a severe problem in the construction industry. Rebar workers are exposed to ergonomic risks such as repetitive stooping and forward bending resulting in low back injuries. Wearable systems such as back support exoskeletons are emerging as potential solution to reducing the risk of low back injuries. User acceptance of exoskeletons is necessary to facilitate adoption of the technology in the construction industry. Exoskeletons could have unintended consequences such as discomfort and interference with work. This paper presents an assessment of a commercially available back-support exoskeleton for rebar work in terms of usability and perceived discomfort. Ten student participants performed rebar tasks with and without the back-support exoskeleton. Participants completed usability (ease of use, learning, and comfort) and level of perceived discomfort questionnaires after the task. Findings indicate that the back-support exoskeleton is easy to learn and use but reduced the participant's comfort. Although, the exoskeleton triggered increased discomfort, there was a reduction in the level of perceived discomfort at the lower back and lower leg. This study contributes to existing discourse on the influence of perceived usability and level of discomfort when using exoskeleton on user acceptance.

Keywords -

Wearable robot; Rebar work; Usability; Discomfort

1 Introduction

Work-related musculoskeletal disorders have emerged as one of the top causes of non-fatal occupational injuries, as well as a critical health and safety factor in the U.S. construction industry [1]. Workrelated musculoskeletal disorders (WMSDs) is a severe and widespread problem in the construction industry, with an incidence rate of 1.7 times the overall industry average [2]. A variety of construction operations involve a high level of physical exertion of the body. Most WMSD injuries are caused by overexertion efforts, including repetitive physical motion, excessive force, and unusual postures [3]. Moreover, construction tasks often require extended standing, bending, and stooping postures, which directly impose varying stresses on the worker's musculoskeletal system [4] and have been identified as some of the primary triggers of WMSDs [5].

The number of cases of WMSD-related injuries among reinforcing iron and rebar workers have alarmingly risen by a staggering 400% in the last two years [6]. This might be considerably higher, given that research estimates that approximately one-fourth (27%) of construction injury cases go unreported due to lack of proper reporting [7]. Compared to other occupations, construction employees who undertake rebar-related tasks are more likely to be subjected to stressful and physically demanding work conditions [8]. Rebar work typically entails placing and tying rebars prior to concrete pouring. These tasks are typically performed by assuming non-neutral trunk postures for extended periods [9]. Rebar workers spend approximately 40-48% in the forward trunk bending position [10], exposing them to a heightened risk of low-back disorders compared with other construction trades[11]. One of the implications of back disorder is increased absenteeism amongst workers and in severe cases, premature disability [12]. Furthermore, construction project profitability can be significantly hampered as a result of WMSDs. WMSDs can also lead to a surge in early retirement [13] resulting in labour shortage in the industry. In addition to the direct expenses of WMSDs, organizations may also incur various indirect expenditures (e.g., absent wage, cost of lost time, and reduced productivity) [12].

In recent years, wearable robots or exoskeletons are increasingly being explored as a potential solution to WMSDs in the construction industry [14]. An exoskeleton is a wearable device that can augment a wearer's physical abilities, thereby reducing the load and risk of WMSDs on the supported body part [15]. Among the types of exoskeletons (i.e., active and passive exoskeletons), passive back-support exoskeletons are increasingly attracting industry interest because they are cheaper and lighter than active exoskeletons and do not require external power source [5].

Commercially available exoskeletons are designed for rehabilitation purposes, where the technologies are intended to support disabled people. Some exoskeletons have also been developed for healthcare and military applications. Given the benefits of reduced muscular activity and improved productivity experienced from the use of exoskeletons in these industry sectors[16], it is important to explore the applicability of exoskeletons in construction.

To support the uptake of exoskeletons in the construction industry, it is important to investigate its usability for construction work. Usability is a key intervention concept that can be used to decide whether a technological solution can be successful in the workplace. However, there are scarce studies exploring the usability of exoskeletons for trade-specific applications in construction. The integration of passive back-support exoskeleton could introduce unintended consequences, such as deviated working posture and discomfort [17]. Since construction tasks may have different physiological exposures, it is also crucial to understand the level of discomfort from the use exoskeletons. Endusers (such as rebar workers) will be reluctant to utilize the technology if it lacks acceptable usability or if there is an elevated level of discomfort, leading to a counterproductive intervention.

Therefore, the objective of this study is to assess the usability and level of discomfort of a passive back-support exoskeleton for rebar work.

2 Background

Studies have showcased the potential of passive backsupport exoskeletons to reduce physical demands on the back [1]. Laevo, BackX, FLx ErgoSkeleton and SPEXOR are some of the passive back-support exoskeletons being explored in different industry sectors such as healthcare and automobile industries. The adoption of the exoskeletons depends on user acceptance of the device.

Researchers have conducted usability studies to assess user acceptance by employing structured questionnaires addressing ease of use, donning and doffing, comfort and perceived discomfort [3]. FLx ErgoSkeleton was assessed for patient transfer tasks wherein participants showcased a good level (76.2/100) of usability [5]. Another study tested SPEXOR for twelve different functional tasks where participants reported a reduced low back discomfort [5].

Of all these exoskeletons, Laevo was identified as one of the most promising back support devices due to its ability to allow axial rotation of the upper body [7]. Usability studies on Laevo showcased moderate to good levels of user acceptance and reduced discomfort. For example, participants identified lower discomfort at the waist and moderate usability during material handling task, while using Laevo compared to the BackX exoskeleton [2]. Lee, Yang [3] explored Laevo for industrial and functional tasks and reported a good level of usability (75.4/100). Ogunseiju, Gonsalves [5] evaluated Laevo for flooring tasks and identified reduction in perceived discomfort of the back (28%). Alemi, Madinei [18] reported moderate level of usability for Laevo during repetitive lifting tasks. The tasks performed in above studies involved forward bending and twisting actions which are similar risks that rebar workers are exposed to during placing and tying tasks. Thus, one can envision similar exoskeleton being useful for rebar tasks. Despite the high occurrences of WMSDs amongst rebar workers, scarce studies have explored the suitability of back support exoskeleton for rebar work. Thus, this study evaluates a commercially available passive back support exoskeleton for the rebar work in terms of usability and perceived discomfort.

3 Methodology

This section presents the approach employed in this study (Figure 1), including an overview of the backsupport exoskeleton, participants involved, simulated rebar task, study design, and data collection and analysis.



Figure 1. Overview of the methodology

3.1 Participants

The study employed a convenience sample size of 10 male student participants. The subjects signed the informed consent form approved by the Institutional Review Board at Virginia Tech prior to commencing the experiment. None of the participants reported any musculoskeletal injuries affecting their ability to perform physical tasks. The mean and standard deviation of the demographics of the participants was: age = 23yrs ± 1.99, weight = 155.70 lbs. ± 22.51 and height = 173.40 cm ± 4.97.

3.2 Exoskeleton

A commercially available passive back-support exoskeleton called Laevo V2.56 was employed in this study which weighs 2.8 kgs. Laevo is a rigid wearable device which is designed to provide support to users' back muscles while they perform forward bending tasks. The exoskeleton (shown in Figure 2) consists of a chest pad, thigh pads, adjustable hip pad, metal torso, smart joint and comes with three torso sizes (i.e., small, medium and large) to fit different body types. Once switched on, the energy-storing spring system in the smart joint is activated and generates the torque, which provides support to workers when they assume stooping postures through the chest pad, thereby relieving stress from the back muscle and transferring the load to the legs via the thigh pad.



Figure 2. Laevo exoskeleton

3.3 Experimental Task

The participants of the study performed rebar task (Figure 3) consisting of placing and tying subtasks which were simulated using metal bars in the form of prefabricated gates. Each participant performed a total of four cycles for each experimental condition (i.e., with and without the exoskeleton). The subjects placed the prefabricated gates, comprising of #11 bars at 2" centre to centre in both directions, on the floor and used a plier to tie six of the joints with pre-cut ties. Combination of placing and tying subtasks was considered as one cycle.

3.4 Study Design

The participants signed the informed consent form after which they were introduced to the rebar task. The participants were allocated 20 minutes to practice the rebar task until they were comfortable. Thereafter, the participants performed the rebar tasks without the exoskeleton. Following that, the students were allowed to rest for 15 mins. to avoid fatigue and were asked to complete a level of perceived discomfort questionnaire (section 3.5). Subsequently, the functioning of the exoskeleton was explained to the subjects. Once they were confident with the exoskeleton, the participants were asked to don the exoskeleton during which they were timed. Afterwards, the students performed the rebar task with the exoskeleton. After completing the task, the participants were timed while doffing the exoskeleton. After both experimental conditions (with and without exoskeleton) were completed, the participants were asked to fill the usability and level of perceived discomfort questionnaire (section 3.5).



Figure 3. Participant performing rebar task

3.5 Data Collection and Analysis

The usability and level of perceived (LOD) were measured using structured questionnaires. The questionnaire, designed for assessing the usability of back-support exoskeleton, consisted of 16 questions addressing three criteria (i.e., ease of use, ease of learning and comfort). The ease of use the responses from the participants were recorded using a 5-point Likert's scale (varying from 1- Strongly Disagree to 5 - Strongly The LOD questionnaire presented the Agree). participants with eight different body parts (i.e., hand/wrist, upper arm, shoulder, lower back, thigh, lower leg, neck and chest). Using the Borg CR 10 scale, varying from 0 - 'Nothing at all' to 10 - 'Maximal', the participants provided the level of discomfort experienced at each body part.

The usability data, and donning and doffing timings were analysed using descriptive statistics such as mean and standard deviation. Two-way Analysis of Variance (ANOVA) was used to analyse the collected LOD data. The dependent variable was the participants' ratings whereas the body parts and experimental conditions were the independent variables. Separate bar charts were plotted for the results of the usability and LOD to understand the trends of the data.

4 Results

Usability 4.1

The usability questionnaire covered three aspects which included, ease of use (Figure 4), ease of learning (Figure 6) and comfort (Figure 7) of the exoskeleton. Furthermore, the durations of the donning and doffing were recorded for each participant (Figure 5).

4.2 Ease of Use

The participants provided an average rating of moderate to high (3.5 ± 0.29) for the overall ease of use of the exoskeleton. The average time registered by the participants to don and doff the Laevo was less than a minute (Figure 4) whereas moderate to high rating (3.7 ± 0.30) for donning and doffing the exoskeleton was recorded. When asked about 'ease of adjustment', the participants provided an above average rating of 3.8 ± 1.17 . The ability of the exoskeleton to help the participants in task accomplishment, as well as meeting user requirements received moderate rating. The participants' preference to use the Laevo for rebar tasks received the lowest rating of 3.1 ± 1.04 whereas the participants' ability to use the exoskeleton without assistance attracted the highest rating of 3.9 ± 1.22 .



Figure 4. Ease of use



Figure 5. Donning and Doffing

4.3 **Ease of Learning**

The ease of learning questionnaire included one negative question (i.e., on prior knowledge - Figure 6) and five positive questions. A low rating of 1.8 ± 1.17 for a negative question suggests that the participants did not require any previous knowledge to effectively learn the exoskeleton's functioning. Overall, for the positive questions, the subjects provided a high rating of 4.2 \pm 0.21 suggesting good ease of learning. When asked whether the participants' could assemble, adjust and check the fit, a high rating was recorded. The ability of the participants to remember the procedure was high as well (4.3 ± 1.01) . Similar to ease of use, the highest rating (4.5 ± 0.69) was recorded for the participants' ability to use the exoskeleton without assistance.



Figure 6. Ease of learning

4.4 Comfort

The participants were asked whether the exoskeleton restricted their movement (2.6 ± 1.43) as well as if the exoskeleton interfered with the work environment (2.2 \pm 0.87). Both negative questions received a low to moderate rating, inferring that the exoskeleton posed minimal interference with the rebar task. The participants'





Figure 7. Comfort

4.5 **Overall Usability**

The overall usability included positive and negative questions. The rating for positive questions (Figure 8) was highest for ease of learning (4.2 ± 0.21) , followed by ease of use (3.5 ± 0.29) , and comfort (3.2 ± 1.32) . Overall, moderate to high rating was registered across all the three positive questions. The negative questions (Figure 9) received a low to moderate rating. The higher rating for positive questions and lower ratings for negative questions suggest good usability of the exoskeleton for rebar work.



Figure 8. Overall rating for positive questions



Figure 9. Overall rating for negative questions

4.6 Level of Perceived Discomfort

Table 1 presents the summary of the ANOVA (Mean, F-Value, P-Value, and effect sizes $(\eta 2)$) performed across the different body parts and exoskeleton conditions (see table 1). P-values with '*' have a confidence level < 0.05.

Table 1. Perceived level of discomfort of participants with and without the exoskeleton during rebar task

Outcome		Body	Experimental	B x E
Measure		Parts	conditions	
	Mean	3.85	0	1.48
	F-	11.8	0	3.01
LOD	value			
	P-	2.08E-	1	0.007
	value	09*		9*
	η2	0.246	0	0.037
Note: $E = Experimental Condition, B = Body parts$				

The ANOVA results (Table 1) suggest a significant difference (p < 0.05) was observed in the perceived discomfort across different body parts as well as body parts and experimental conditions with an effect size of 0.246 and 0.037 respectively. Discomfort level increased in the neck (22.73%), chest (90.91%) and thighs (45.45%) while using the exoskeleton. The perceived discomfort decreased for the low back (118.18%) and lower legs (54.55%) while performing the rebar tasks with the exoskeleton. The upper arm, shoulder and hand/wrist did not have a significant impact between the two experimental conditions.



Figure 10. Level of Perceived Discomfort

5 Discussion and Conclusion

The need to improve construction health and safety and reduce work-related musculoskeletal disorders has ushered the adoption of exoskeletons into the construction industry. With the growing interest in exoskeletons and its potential to mitigate at least 60% of construction WMSDs [1], there is a need to assess the usability of exoskeleton for construction activities. This study investigates the potentials of Laevo back-support exoskeleton for mitigating WMSDs by assessing users' perceptions of the ease of use, ease of learning, comfort, and perceived level of discomfort during simulated rebar tasks.

Overall, the study revealed that the exoskeleton was easy to use. Participants could don and doff the exoskeleton without assistance in less than a minute and could easily adjust it to their desired comfort level. This may suggest a low impact of the exoskeleton on increasing rebar task completion time.

However, the participants were moderately satisfied with the ability of the exoskeleton to support rebar tasks and moderately preferred to work with the exoskeleton. This may be influenced by their moderate ratings of the exoskeleton to meet their demands during rebar tasks which can impact the willingness to adopt the exoskeleton.

The assessment of ease-of-learning reveals that it is easy to learn the use of Laevo exoskeleton for rebar tasks. The functionality of the exoskeleton was not complicated, and easy to remember. This may suggest that it can appeal to the construction industry with workers of different ethnicity and educational levels.

Despite the prospects of the exoskeleton, assessing the comfort of users is important for usability. The exoskeleton did not restrict participants' movement and did not interfere with the work environment. This is important as construction activities are dynamic and requires workers to assume awkward postures while working under aggressive environmental conditions. The comfort of working with the exoskeleton was further investigated by assessing users' perceived level of discomfort across different body parts. The findings revealed that the exoskeleton reduced discomfort felt in the lower back and lower leg. This supports similar studies [2, 3] where the use of exoskeletons reduced discomfort at the back and suggests the potential of the exoskeleton for reducing low back injuries during rebar tasks. However, unintended consequences such as increase in the discomfort in the neck, thigh and shoulder and a significant increase in the discomfort at the chest were reported in this study. This may imply the need for improvements to the design of the exoskeleton to suit the dynamic nature of construction activities.

There are some limitations of this study that may impact the generalizability of the results. The study was a laboratory simulation where participants were students and not construction workers and interaction of the exoskeleton with real site conditions is unknown. Hence, the usability assessment of the exoskeleton with experienced construction rebar workers will be explored in future studies. In addition, a high variability across the perceived discomfort levels was reported which shows that these results are highly subjective. Hence, objective measures such as measuring the muscle activity using electromyography sensors, identifying unsafe postures using inertial measurement unit, and assessing discomfort across different body parts are required to further validate these findings.

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