Industry Perspectives of the Potential of Wearable Robot for Pipe Installation Work

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Abstract –

The physically demanding nature of construction work exposes workers to ergonomic risks resulting back-related musculoskeletal disorders. Back injuries amongst pipe installers increased by 2.3 times in the last year. Back support exoskeletons are emerging as a potential intervention to address back injuries. Without willingness of construction workers to use back-support exoskeletons, the intervention will not be successful in the construction industry. This paper presents the perception of pipe installers regarding the suitability of a commercially available back-support exoskeleton for pipe installation work. Fourteen pipe installers performed their regular work task with a passive exoskeleton during which they provided their experience with the wearable technology. The results indicate that the benefits of the exoskeleton, barriers to the use of the exoskeleton and modifications to the design of the exoskeleton. Participants perceived health benefits in terms of reduced back stress and recommended employing the exoskeleton for outdoor manual labor activities. There were concerns about the use of the exoskeleton in confined spaces and the compatibility of the exoskeleton with on-site safety provisions. Integration of safety harness with the wearable robot was identified to be an essential modification. The findings showcase willingness amongst the pipe installers to adopt exoskeletons. This study contributes to the existing literature on the suitability of passive back-support exoskeleton in construction.

Keywords –

Wearable robot; User assessment; Pipe installation; Exoskeletons

1 Introduction

The construction industry is a labour-intensive sector with high risk of injuries. Each year, federal agencies such as the United States Department of Labor record non-fatal injuries in the construction industry. Non-fatal injuries are sometimes triggered by the physically demanding nature of construction work [1], which exposes workers to awkward work postures (e.g., twisting, reaching, pulling, lifting and bending) resulting in work-related musculoskeletal disorders (WMSDs) [2].

WMSDs account for 33% of all workplace injuries [1]. In 2020, the United States Bureau of Labor and Statistics [3] reported a WMSD incidence rate of 40.6 musculoskeletal disorders (MSD) per 10,000 full time workers (FTE) which is approximately 1.7 times higher than the average of all the industries. This condition is more severe amongst pipe layers and fitters whose WMSD incident rate is 1.4 times the rate of other construction trades [4]. In fact, the rate of WMSDs amongst pipe layers tripled between 2018 and 2019 [4]. Pipe layers spend a significant amount of time in back-bending postures, when performing pipe installation tasks, that can impact the muscles, nerves, discs, and ligaments in the back. This causes injuries or disorders in the back, which accounts for 43% of all the affected body parts in the construction industry [5]. Evidence suggests that back injuries could cause permanent impairment leading to early retirement of the workforce[6]. Besides the health risks, WMSDs have significant financial consequences and has resulted in work absenteeism in the construction industry [7]. Moreover, WMSDs are one of the leading causes of lost productivity among construction workers [8]. Thus, the health and safety performance of the workforce has a direct impact on the profitability of construction projects [9].

Wearable robots, also referred to as exoskeletons, are increasingly being recognized as a promising ergonomic solution for preventing WMSDs. Wearable robots are designed to reinforce the wearer's performance by augmenting key body parts (e.g., back and shoulder) or the full body. Wearable robots or exoskeletons can be classified as 'active' or 'passive'. An active exoskeleton uses actuators to support the wearer's effort and stimulates the joints, while passive exoskeletons use springs to store energy from the wearer's motion to provide ergonomic support [10]. Unlike active exoskeletons, passive exoskeletons are lighter and more cost-effective. Considering that the back is the body part that is most affected by WMSDs during pipe installation, back-support exoskeletons could be a potential solution to reduce the physical demands and fatigue experienced by pipe workers, thus improving their safety, health, and performance [11].

As evidence continues to evolve regarding the suitability of back-support exoskeletons in the construction industry [12], there is a need to evaluate user acceptance amongst construction workers. Lack of user acceptance has long been an impediment to the successful deployment of technology in the workplace [13]. Perspectives of end-users could help identify workers' willingness to use the technology, task-specific applications, and facilitators and barriers to advancing back-support exoskeletons in the construction industry.

Existing studies [14, 15] on exoskeletons are mostly laboratory-based studies, which do not reflect the nature of interactions between exoskeletons and the work environment. Construction sites are often characterized as harsh environments with somewhat unsuitable conditions such as dusty and muddy surroundings, hot and cold weather conditions, and confined spaces [16]. Under these conditions, the use of back-support exoskeletons could have unintended consequences such as discomfort to the body parts, device failure and incompatibility with personal protective equipment [5]. Insights into how commercially available exoskeletons can be deployed in such environments could be beneficial for designers to adapt designs of existing exoskeletons to suit construction work. This is significant, as the commercially available exoskeletons are not designed specifically for use in the construction industry [5].

Therefore, the study aims to understand the perceptions of potential beneficiaries of exoskeleton (e.g., pipe layers) regarding the suitability of a commercially available back support exoskeleton for construction work. User perception is captured in terms of the benefits of back-support exoskeletons, barriers to the use of back-support exoskeleton for pipe installation work, and modifications necessary to adapt back-support exoskeletons to pipe installation work.

2 Background

Over the years, there has been several attempts to address the issue of WMSDs in the construction industry. These efforts have ranged from proactive to more reactive measures (e.g., using exoskeletons). The reactive approach includes educating workers about the risk associated with their work so that they can self-manage or control their exposure. For example, developed training manuals and programs to educate workers on how to perform manual material handling tasks in safe postures. To provide workers with opportunities to practice safe work procedures, immersive training environments (e.g., virtual reality) have been proposed [16]. Yan, Li [17] also developed a framework that uses sensing technologies (e.g. inertial measurement units) to track workers movements while on the job and alerts them on unsafe work habits so that they can control their exposures. The alerts could serve as a distraction and affect workers' productivity.

Commercially available passive back-support exoskeletons, such as BackX and Laevo, are being recognized as a preventive approach to WMSDs. BackX has been demonstrated, via laboratory studies, as being more suitable for work involving back bending and repetitive lifting [18-20]. Till date, there is scarce evidence on how back-support exoskeletons (e.g., BackX) can benefit construction workers. In particular, little is known of how exoskeletons would benefit potential end-users such as pipe layers. It is possible that existing design configurations would need to be modified to suit construction work. However, these can only be determined by deploying the exoskeleton in the field and obtaining feedback from construction workers.

3 Methodology

3.1 Participants

Fourteen pipe layers, installing sewage and water pipelines in Northern Virginia in the United States, volunteered to participate in this study. All the participants signed the informed consent form approved by the Virginia Tech Information Review Board (#IRB 19-1180). None of the workers reported any muscle related injuries, which could influence their ability to carry out daily tasks or could potentially affect their perception of the exoskeleton. The demographics of the participants are as shown in Table 1.

Table 1. Participant's demographics

Demographic Parameters	Mean	SD	Max.	Min.
Age (yrs.)	37.63	10.19	55	22
Height (ft.)	5' 7"	3.95"	6' 11"	5'
Weight (kgs.)	84.12	10.97	108.86	63.5
BMI (kg/m2)	27.96	3.95	38.7	20.7
Exp. (yrs.)	12.92	7.37	35	2
Note: SD = Standard Deviation, Exp. = Experience, yrs. = years, Max. = Maximum, Min. = Minimum.				

3.2 Wearable Robot

BackX™ S, a commercially available passive back-support exoskeleton was used in this study. The choice of BackX™ S for this study was guided by the benefits documented in Kazerooni, Tung [21]. The exoskeleton is designed to reduce back strain when performing activities that require bending, stooping, or reaching. BackX™ S weighs 3.4kg and can sustain a load of up to 13kg. BackX™ S, shown in Figure 1, comprises of a frame and a harness. The frame houses a torque generator (i.e., the activation point), a chest-plate, and thigh and leg straps. The harness is made up of a chest pad, a hip belt, and shoulder straps, which are all attached to the body via the frame. The exoskeleton has numerous fixture configurations that may be customized to fit the user's body structure.

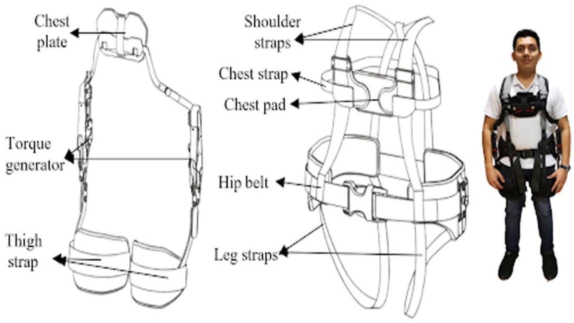

Figure 1. BackX exoskeleton (a) frame (left), (b) harness (middle) and (c) complete exoskeleton (right)

3.3 Experimental Design

Prior to commencing the study, the study procedure was explained to the participants. Subsequently, each participant signed the informed consent form. Thereafter, the back-support exoskeleton was fitted on the participants (Figure 2) considering their height, chest width and waist size as per the guidelines provided by the manufacturers. The functioning of the exoskeleton was explained to the participants and they had the opportunity to explore its operations until they were confident to deploy it. Subsequently, the participants performed their regular pipe installation tasks while wearing the exoskeleton. The tasks were performed for four hours. The tasks involved climbing, squatting, kneeling, bending, cutting pipe, carrying heavy tools, working in trench boxes and confined spaces, working with fall protection, pouring inverts, levelling and shovelling. While performing the tasks, the participants were prompted to provide verbal feedback regarding their experience (e.g., body discomfort and interference with work) with the back-support exoskeleton. At the end of the task, the participants completed a questionnaire designed to capture their perceptions regarding the usability of the exoskeleton, their comfort with the exoskeleton, impact on their performance when using the exoskeleton and how safe they were while using the exoskeleton. The questionnaire also contained open-ended questions aimed at further capturing the participants' subjective feedback regarding the pros and cons of the back-support exoskeleton, context for the use of the exoskeleton in construction and any modifications that could be made to the design of the exoskeleton to make it more suitable for construction work. Given the length restrictions of this paper, only the subjective feedback to the open-ended questions are reported in this paper.

Figure 2. Pipe layer wearing BackX

3.4 Data Analysis

The participants' responses to the probing questions (obtained while performing work) and the open-ended questions (obtained after the task) were recorded by the investigators. Transcripts of the responses were imported into NVivo 11, and analysed using Thematic analysis [22]. NVivo is a qualitative analysis software which is commonly used by researchers to analyse qualitative data from interviews, surveys, and focus groups [23]. The data were coded using various themes that emerged from the responses. Thereafter, using the inductive coding process, similar or related codes were clustered to form meaningful themes which were identified as categories as shown in Figure 3 and presented in the next section. To confirm the validity and reliability of the findings, an inter-coder reliability testing was conducted using Cohen-kappa coefficient. Cohen-kappa is a commonly used method to measure the level of agreement between coders, where the value of the coefficient ranges from 0 to 1, with 0 being no agreement and 1 being perfect agreement [24]. The assessment showed a percentage agreement of 78% between two coders. A Cohen-kappa coefficient of 0.62 was obtained, showing substantial agreement.

4 Results

Three categories of the themes were extracted from the responses (Figure 3). These include benefits of the back-support exoskeletons, barriers to implementation of back-support exoskeletons on construction projects, and modifications to the design of the back-support exoskeleton.

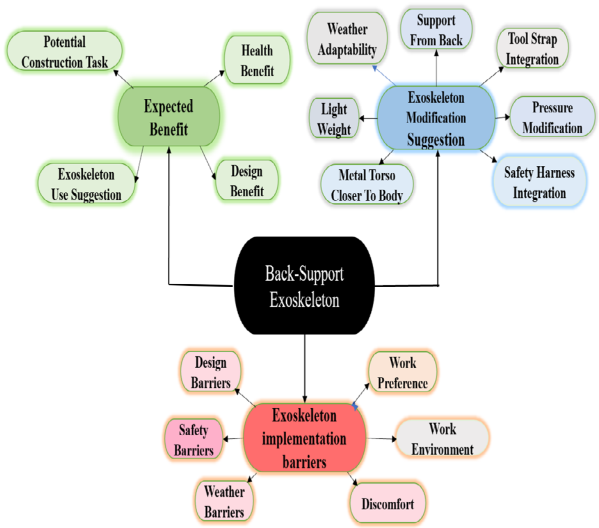

Figure 3. Categories and sub-categories from participants' responses

4.1 Benefits of Exoskeletons

85% of the participants perceived the exoskeleton to be beneficial for construction related tasks and described specific tasks where the exoskeleton could be most useful. The participants suggested tasks such as shovelling, levelling, working in inverts, forward bending, walking on uneven surfaces, working outdoors and applying lubricant for pipe joints: *"While shovelling and applying the pipe lubricant, it was helpful", "I would use it for invert", "While walking on an uneven surface, on a pile of dirt, I did not have any problems and no imbalances out of the ordinary. Also, while walking uphill the exoskeleton helped me. While picking loads straight up, it is useful".* About two-thirds of the responders perceived health benefits as a major outcome of using a back-support exoskeleton. According to one of the respondents: *"good device for people with back injuries as it provides good support."* Another participant reported, *"Very beneficial as it provides support to the thighs and chest which helps me reduce the stress from the back".* One of the participants felt like the exoskeleton helps in keeping the back straight while working: *"felt like the exoskeleton also helps in keeping the back straight which is very useful.........What I like most is the ability to feel no strain on back and knees while working".* The participants also emphasized some general benefits of the design of the back-support exoskeleton e.g., lightweight, comfortable chest and thigh support: *"it is not heavy, rather lighter than the fall protection that we use", "I like the chest and the thigh support".* Furthermore, the participants also provided some suggestions for the use of exoskeletons *"the exoskeleton can be very helpful when we use it in an outdoor environment".* Some participants also felt *"While using the ladder it is better to switch the support system to off".* Of all the participants who perceived the back-support exoskeleton to be beneficial, 38% suggested potential construction tasks where the use of exoskeletons would be beneficial, 35% suggested health benefits of the exoskeleton, 15% suggested ways by which the exoskeleton can be operated for effective and 12% suggested design benefits (Figure 4).

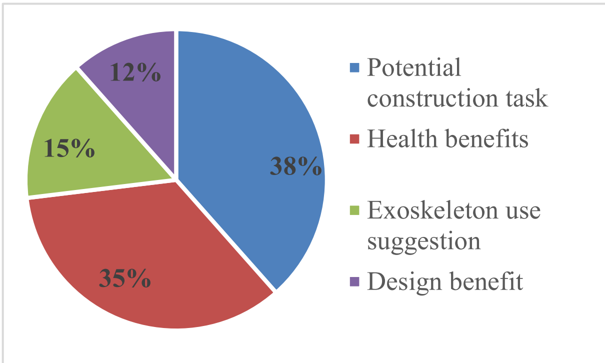

Figure 4. Benefits of back-support exoskeleton

4.2 Barriers to Implementation of Exoskeletons

Overall, 75% of the participants identified potential barriers for the implementation of back support exoskeletons. Some of these respondents had concerns about the design of the exoskeleton and perceived these as barriers to implementing the technology for pipe-laying tasks. A participant mentioned, *"the metal rods caused problems for my under arms."* Another participant reported, *"the chest pad makes it very hard to go down".* Similarly, some of the participants expressed concerns about the discomfort from the device: "*With the exoskeleton, it is not easy to bend and work…The exoskeleton puts pressure on my body parts especially chest and hips…it causes discomfort to my hips.*" The participants also concluded that wearing an exoskeleton with a safety harness would be challenging: "*it does not work with the fall protection harness and I sweat much more while working."* Some of the participants were also concerned about pressure imposed on their chests by the pads, which caused their heartbeats to race and made them feel exhausted: "*When working hard, due to the pressure my heart pumps faster which makes me tired.*" On the other hand, trenches and manholes are the most common areas that pipe layers work, and the participants reported that their mobility was restricted while working in such tight spaces: "*I do not think it is suitable for pipe work as we work in tight spaces*". With a variety of exemplary benefits, the exoskeleton also introduces several safety issues: "*if anyone falls while wearing the exoskeleton, it can hurt them because of the metal parts*". From these implementation barriers, design barriers (27%) and discomfort (27%) were identified as the most significant, followed by work environment (20%), safety (17%), work preference (7%), and weather barriers (3%) (Figure 5).

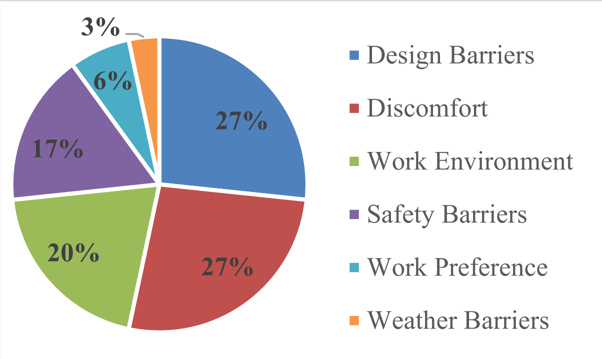

Figure 5. Implementation barriers

4.3 Suggestions to Modification of Exoskeleton

Although the exoskeleton is expected to provide considerable support to workers during pipe installation work, numerous modifications were suggested to make the device more suitable for construction related tasks.

71% of the participants suggested modifications to the exoskeleton. For example, some participants suggested the integration of the safety harness with the back-support exoskeleton: *"If there was a design with in-built fall protection, it would be great."* Another important add-on feature for the exoskeleton was suggested by a participant: *"If the harness had any spots to carry my tools it would be very useful… have straps for my tape and communication device etc."*, One of the interviewees recommended a weather adaptability function for the device: *"If we can change the colour to white then maybe it would be much better"*. Another suggestion is, *"If the torso was closer to the body and not coming out, it would be better"*. One participant felt that having pressure points on the back body part would be beneficial: *"It would have been better if the pressure was on the back"*. Accordingly, the integration of the safety harness with the back-support exoskeleton was the most suggested modification (40%), followed by reducing the pressure from the chest pad (10%), repositioning of the metal torso (10%), and back support (10%) (Figure 6).

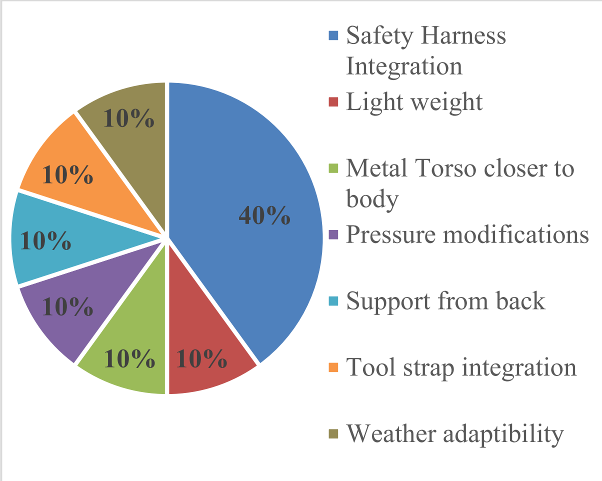

Figure 6. Modifications to back-support exoskeletons

5 Discussion

This study presents a user-assessment of a commercially available back support wearable robot for pipe installation. The result of the assessment includes the benefits of back-support exoskeleton, barriers to the use of back-support exoskeleton and modifications that could be made to back-support exoskeletons to improve their suitability for construction work. The back-support exoskeleton can provide health benefits such as reduction of stress on the back muscles, which is consistent with previous studies [18, 25]. The workers found value in using the back-support exoskeleton for forward bending tasks such as shovelling, levelling and pouring storm-water inverts. This is contrary to Bosch, van Eck [26] where there was an increase in discomfort in the chest when the participants performed work in similar postures. The discomfort was due to pressure from the chest and thigh pad which some participants in this study found beneficial. Also, the workers felt that wearing the back-support exoskeleton could help them work for longer hours which would increase their productivity. This is consistent with the study of Kim, Moore [27] where the authors found that using back support exoskeleton would help workers perform work faster and for longer durations.

Despite the benefits of using a back-support exoskeleton, some barriers were also noticed which should be taken into consideration. Pressure exerted by the metal torso to the chest caused discomfort to the chest while wearing a back-support exoskeleton. This, on the other hand, does not correlate with the findings of Antwi-Afari, Li [28] which showed that the use of a back support exoskeleton significantly reduced discomfort on the chest. This disparity could be due to the first-time effect of wearing the back-support exoskeleton, and may not suffice after prolonged use.

The workers felt that using both the exoskeleton and tool belt would impact their productivity and ability to work in confined spaces. A key modification suggested to the design of the back-support exoskeleton includes integrating the exoskeleton with workers' tool belt. This could reduce the time to don and doff the exoskeleton. A similar attempt was made by Salvietti, Franco [29] who integrated a passive exoskeleton with a robotic supernumerary finger to improve grasp compensation in Chronic stroke patients. Furthermore, Kim, Moore [27] identified cost as a critical factor for adoption of exoskeleton in construction industry. The integration of tool belt and safety harness with the exoskeleton as suggested by the pipe workers could increase the cost of the device, which could be a potential barrier for adoption of exoskeleton.

6 Conclusion

This study focused on understanding construction workers' perception of the suitability of a commercially available back-support exoskeleton for construction work. The back-support exoskeleton was found to be beneficial for construction tasks and having significant health benefits of reducing back stress. While there were some discomfort experienced from the use of the exoskeleton, most of the participants found it beneficial to supporting the body during pipe installation. Workers could be more willing to adopt the exoskeleton if design can be improved to accommodate existing work wearables such as tool belts and personal protective equipment (e.g., safety vests and harness).

Furthermore, a small sample size was adopted in this study, which is not sufficient to generalize the findings to the entire construction industry. Future work will involve a larger sample size with demographics representative of the construction industry. In addition, the exoskeleton was tested for pipe work, thus the findings might not be adaptable to other types of construction work. In order to promote widespread adoption of exoskeleton to mitigate occurrences of WMSDs, similar studies will need to be carried out to identify suitability of the exoskeleton for supporting other construction trades. Furthermore, this is a short-term field study where the participants used the exoskeleton for four hours. To understand the willingness of construction workers to adopt exoskeletons and evaluate the impact of prolonged use of exoskeletons for construction work, a long-term field study is necessary.

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