Industry Perception of the Suitability of Wearable Robot for Construction Work

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Abstract: Work-related musculoskeletal disorders is a serious problem affecting the construction workforce. Pipe workers are subjected to forward bending tasks that cause back injuries. Recent advancements in wearable robotic technologies have led to a growing interest in the use of back-support exoskeletons as a potential solution to reduce the occurrences of back injuries. However, without the willingness of workers to use exoskeletons, the intervention will not be successful in the industry. This study conducted a user assessment of a commercially available passive back-support exoskeleton for pipework in terms of usability, level of perceived discomfort, and subjective perception of the benefits, barriers to adoption, and design modifications. Fourteen pipe workers performed their regular work tasks using a passive back-support exoskeleton and provided feedback on their experience with the device. The results indicate that the exoskeleton is easy to use (4.13 ± 0.34) and did not affect workers' productivity (2.07 ± 1.22). Participants reported willingness to use the exoskeleton but raised concerns about the compatibility of the exoskeleton with the safety harness. Reduced perceived discomfort was observed in the lower back. However, there was an increase in discomfort at the chest (20%), thigh (73%), and shoulder (250%). There was a strong correlation ($p < 0.05$) between discomfort at the chest, thigh, shoulder, and upper arm and workers' perception of usability of the exoskeleton. Health benefits such as reduction in stress in the back muscle were reported. Discomfort was experienced while using the exoskeleton in confined spaces. Design modifications, such as the integration of the safety harness and the tool strap with the exoskeleton, were identified. The findings are expected to inspire studies in the area of human-wearable robot interaction and task-specific applications of exoskeletons for construction work. **DOI: 10.1061/JCEMD4.COENG-12762.** *© 2023 American Society of Civil Engineers.*

Author keywords: Work-related musculoskeletal disorders; Back injury; Wearable robot; Pipe workers; User perception.

Introduction

The construction industry is a labor-intensive sector. Construction workers are often subjected to physically demanding work tasks, which involve bending, stooping, lifting heavy materials, twisting, maintaining awkward postures for prolonged hours, vibrations due to the use of tools and machinery, and environmental factors such as humidity and varying temperature (Choi et al. 2016). These physical and environmental factors impose stress on workers' musculoskeletal systems such as muscles, joints, tendons, ligaments, and nerves, resulting in work-related musculoskeletal disorders (WMSDs).

WMSDs are work-related injuries that cause mild to severe pain to different body parts (Frymoyer and Cats-Baril 1991). According to the US Bureau of Labor Statistics (BLS), cases of WMSDs in the construction industry are among the highest in the United States (BLS 2022). In 2020, cases of WMSDs among construction workers were approximately 1.6 times higher than cases on all other industries combined (BLS 2022). Pipe workers are one of the most affected construction trades. Pipe layers, pipefitters, plumbers, and steamfitters are all characterized under pipe workers (Rosecrance et al. 1996). Although the type of work performed by these trades differs, the job activities are very similar. These workers perform a variety of material handling tasks such as lifting, carrying, and replacing heavy materials, exposing them to musculoskeletal disorders. The rate of WMSDs per 10,000 full-time employees (FTE) among pipe workers is 1.5 times the average of all workers in the construction industry (BLS 2022). Cases of WMSDs among pipe layers tripled between 2018 and 2019 (BLS 2022). Pipe workers perform work that involves overexertion or forward bending, imposing stress on the back muscles (Rosecrance et al. 1996). Overexertion of the back over prolonged periods causes back injuries (Kim et al. 2019). The rate of back injuries per 10,000 FTE, among pipe layers is twice the average of all workers in the construction industry (BLS 2022). Back injuries have resulted in an average of 29 lost workdays among pipe layers. In severe cases, back injuries have been known to cause permanent disabilities (Frymoyer and Cats-Baril 1991). This leads to early retirements of skilled labor, which is a major cause of labor shortage in the construction industry (Ayodele et al. 2020). Occurrences of WMSDs have financial implications in terms of direct workers' compensation as well as an indirect economic burden such as loss in tax and personal loss to household services (Marcum and Adams 2017). It is estimated that

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Note. This manuscript was submitted on June 6, 2022; approved on December 5, 2022; published online on February 16, 2023. Discussion period open until July 16, 2023; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Construction Engineering and Management***, © ASCE, ISSN 0733-9364.

the construction industry in the United States loses approximately $54 billion annually due to WMSDs, which account for 40% of all the compensable cases (Marcum and Adams 2017).

Wearable robots, such as back-support exoskeletons (BSEs), are emerging as ergonomic solutions to reduce the overexertion or physical demands of the body (Madinei et al. 2020). Back-support exoskeletons are external wearables that assist in reducing physical demands on the back by providing assistive moments about the hip or lower spine to support the muscles (Zhang and Huang 2018). Other industrial sectors such as automobile, manufacturing, shipbuilding, and healthcare have found value in the use of back-support exoskeletons in terms of reduced trunk muscle activity, range of motion decreased, and increased endurance time (Bosch et al. 2016; Kim et al. 2020). As a result, in recent years researchers have been exploring the suitability of exoskeletons for construction work. For example, Cho et al. (2018) designed and evaluated a back-support exoskeleton for brickwork and observed a reduction in flexion of the waist. Gonsalves et al. (2021) reported a decrease in the activity of the erector spinae muscles and perceived discomfort at the lower back when using back-support exoskeleton for manual repetitive handling and rebar work, respectively. Although the aforementioned studies provide evidence of the efficacy of exoskeletons for reducing physical demands of work, their use on construction sites might have some unintended consequences such as being caught around wires, affecting work postures, and physical discomfort, which could impact usability, self-efficacy, and safety (Baltrusch et al. 2021). These could affect the willingness of construction workers to use wearable device. User experience (Karahanoğlu and Erbuğ 2011), perceived discomfort (Bosch et al. 2016), and usability in terms of ease of use, task performance, and worker safety (Kim et al. 2019) have been identified as critical factors that could impact end users' intention to use exoskeletons. Without the willingness of construction workers to use exoskeletons, the intended health benefits (i.e., reduced fatigue and body disorders) may not be realized, thereby leading to failure in adoption (Siedl and Mara 2021). This necessitates a user-centered approach for evaluating exoskeleton devices to improve usability and acceptability among the end users.

Thus, the objective of this study is to assess a commercially available back-support exoskeleton for pipework in terms of user perception, level of perceived discomfort (LOD), and usability. The "Background" section describes efforts to mitigate WMSDs in the construction industry, the potential of the exoskeleton for construction work, and the theoretical underpinning for this research. The "Methodology" section describes the exoskeleton employed in this study, the demographics of the recruited participants, and the experimental design. The "Results" section describes the inputs provided by the participants for all the aforementioned outcome measures based on which the discussion and conclusion are presented.

Background

Mitigating WMSDs in the Construction Industry

Efforts to reduce WMSDs have been largely focused on training workers to perform work safely (Cheung 2007), modifying existing tools and equipment to make construction sites ergonomically safe (Vi 2006), alerting workers of unsafe postures while they are performing work (Yan et al. 2017), and the use of wearable robots such as exoskeletons (Bosch et al. 2016; de Looze et al. 2016) to reduce on-site ergonomic risks.

Organizations such as the National Institute for Occupational Safety and Health (NIOSH) and Occupational Safety and Health Administration (OSHA) have developed training manuals for addressing general ergonomic and postural issues experienced during manual material handling tasks (Cheung 2007). Vi (2006) evaluated the potential of a rebar-tying machine for reducing WMSDs typically experienced by rebar workers while using pliers for tying rebar and concluded that the machine reduced the frequency and duration of exposure to awkward posture. It was identified that the machine could affect the quality of rebar ties and may be more suitable for specific mesh configurations. To reduce discomfort experienced by rebar workers when tying rebar in a squatting posture, Umer et al. (2017) assessed a low-height stool attached to workers' pants to enable them to perform work in a sitting posture. No significant difference was observed in the muscle activity of the back and fatigue between the normal and stool-based rebar-tying postures. A wearable inertial measurement unit attached to the personal protective equipment (PPE) was proposed by Yan et al. (2018) for tracking and informing rebar workers of the ergonomic risks associated with their work. While this effort has the potential for reducing ergonomic risks of construction work, the feedback from the proposed system could be disruptive to work performance, and compliance with the feedback is at the discretion of the workers. Technological advances have promoted the use of immersive and interactive virtual environments for workforce training. For example, Akanmu et al. (2020) developed a virtual reality–based environment for workers to practice safe work postures and receive feedback based on their performance. Trainings using manuals and virtual environments are conducted before or after working hours. This does not create a link between workers' learning and their work performance.

In recent times, advancements in technology have led to a shift in WMSD mitigation efforts from ergonomics training and workplace adjustment to the use of wearable robotic devices (Okpala et al. 2022; Zhu et al. 2021). Wearable robots such as exoskeletons have showcased benefits for rehabilitation, medical, and military applications. As such, there has been a growing interest in their potential of reducing WMSDs for other occupational applications (Bosch et al. 2016; de Looze et al. 2016). Broadly, exoskeletons are classified as active and passive systems. Active exoskeletons use actuators that employ external power sources (such as electric motors) to enhance body parts, whereas passive exoskeletons have springs or dampers that store and release energy from the wearer's movements (Bosch et al. 2016). While active exoskeletons provide more ergonomic support than passive exoskeletons, they are heavier and more expensive. As a result, passive exoskeleton is becoming a more appealing intervention for reducing WMSDs in the construction industry.

Potential of Exoskeletons in the Construction Industry

Researchers (Alemi et al. 2019; Bosch et al. 2016; Cho et al. 2018) have assessed different commercially available passive back-support exoskeletons, such as Laevo, BackX, SPEXOR, and PLAD, for different work tasks. Reduced muscle activity, range of motion, and exertion, and increased endurance time have been associated with the aforementioned exoskeletons. However, for such wearable devices to be accepted and potentially utilized by end users, they need to attain some level of usability and positive user feedback (Meyer et al. 2021). Specifically, the devices need to be comfortable and easy to learn and use, and should not affect worker performance and safety. The devices need to have reduced unintended consequences such as discomfort to other body parts (Kuber and Rashedi 2020; de Looze et al. 2016). Thus, the literature has identified usability, subjective feedback, and discomfort as significant to assess user acceptance of exoskeletons (Kermavnar et al. 2021).

In recent years, there have been a few laboratory-based studies aimed at assessing the usability of commercially available exoskeletons for industry sectors such as healthcare, automobile, agriculture, industrial, and logistics. For example, Graham et al. (2009) tested the PLAD exoskeleton on 10 participants performing automotive assembly tasks and assessed the exoskeleton using a user acceptability survey and subjective feedback. The results indicate positive subjective opinion with an average score of 4.2 out of 5 on the user acceptability scale and 80% of the participants indicated willingness to adopt the exoskeleton. All the participants reported reduction in perceived discomfort at the lower back, but suggested some modifications to the exoskeleton (e.g., better shoulder support and materials) for improved comfort and low back support. Baltrusch et al. (2018) assessed the Laevo V2.56 exoskeleton for 12 functional tasks such as lower lifting, carrying load, walking, and climbing stairs and ladder in terms of user impression and local discomfort. The results indicate an increase in discomfort at the chest and thigh, but the participants ($n = 18$) reported a significant reduction in discomfort of the low back. Kim et al. (2020) observed a moderate to high level of usability for the Laevo and BackX passive exoskeletons when both exoskeletons were deployed for simulated assembly tasks performed by 18 participants. Alemi et al. (2020) also evaluated both exoskeletons for repetitive symmetric and asymmetric lifting tasks in standing and kneeling postures and identified slight (30/100) to very helpful (70/100) usability in terms of usefulness of using the exoskeleton for the given tasks. However, the participants ($n = 18$) reported increased discomfort at the chest, waist, and thigh. Although the aforementioned studies demonstrated acceptable usability of a back-support exoskeleton, the studies were laboratory based and the participants were not end users. Perspectives of end users are needed in the design and evaluation of wearable technologies, because this is critical to improving the acceptability of the technologies among targeted users (Angelini et al. 2013).

There have also been usability studies conducted in actual field environments involving end users. Hensel and Keil (2019) assessed the suitability of the Laevo exoskeleton for automotive work (i.e., assembling car parts and disassembling press tools) among 30 workers with regards to user acceptance (i.e., donning and doffing, intention to use, and task performance) and physical discomfort using a 7-point Likert scale. Results indicate a reduction in discomfort at the lower back and a significant increase in discomfort at the chest region. A high user rating for donning and doffing and task performance was reported by the participants, whereas the intention to use decreased significantly throughout the test period. Marino (2019) evaluated BackX for stocking and tire installation tasks in terms of ease of use, comfort, work performance, and perceived usefulness. The workers ($n = 10$) reported willingness to use the exoskeleton and provided a high rating (4 out of 5) for comfort, device usefulness, ease of work, and donning and doffing.

The tasks performed in the aforementioned studies involve forward bending and repetitive movements, which are also the nature of the construction work. Considering the positive feedback obtained from the usability studies, one can envision construction workers benefiting from the use of back-support exoskeletons on construction sites. However, the field conditions and the range of activities that construction workers are exposed to differ from other industry sectors. This makes it necessary to evaluate a back-support exoskeleton for construction work.

Research Gap

Despite the high occurrences of WMSDs in the construction sector (Wang et al. 2017) and the benefits of using exoskeletons (Alemi et al. 2019; Bosch et al. 2016; Cho et al. 2018), there are few studies on the use of BSEs for construction work. Recently, some researchers (Antwi-Afari et al. 2021; Cho et al. 2018; Gonsalves et al. 2021) have investigated the use of BSEs for construction work. However, these studies mainly focused on objective measures such as muscle activity and range of motion and did not consider users' perception of using BSEs for construction work. Although studies conducted by Ogunseiju et al. (2021) and Gonsalves et al. (2022) measured the usability of BSEs for flooring and rebar work, respectively, these are laboratory studies, and the participants were students and not actual construction workers. To understand the performance and usability of BSEs, it is necessary to evaluate exoskeletons in real-world conditions (i.e., construction workers using an exoskeleton on construction sites). Thus, this study aims to address this gap by involving construction workers for assessing user acceptance of BSEs.

Theoretical Underpinning

User acceptance of new technology is crucial for driving the adoption of technologies in industry sectors. User acceptance can be determined by capturing potential users' perceptions (Davis 1989). User perception comprises feelings toward technologies, which usually generates from experience with technology. Such experiences provide insights that could enable designers to design technologies that are more adaptable to conditions of workplaces, align with users' expectations, and reduce negative attitudes toward technology (Rohcraher 2010). Understanding how construction workers perceive wearables, such as exoskeletons, is crucial to the design of work-, environmental-, and anthropometric-friendly devices. Such perceptions, also characterized as human factors, have been identified as a key consideration for the successful implementation of technologies in industries (Cho 2009). In recent years, researchers have developed human factors principles that should be considered when designing and adopting technologies for workplaces. For example, Motti and Caine (2014) provided a set of 20 human factors principles necessary for designing wearable devices. These include aesthetics, affordance, comfort, contextual awareness, customization, ease of use, ergonomics, intuitiveness, obstructiveness, resistance, responsiveness, satisfaction, simplicity, user friendliness, and wearability. Building on these principles, Kuber and Rashedi (2020) identified the following as being suitable for evaluating exoskeleton designs: adjustability, applicability, usability, ease of use and performance, comfort, wearability, and satisfaction. The purpose of passive exoskeletons is to protect workers from ergonomically risky work tasks by reducing overexertion of body parts. Despite these benefits, exoskeletons may cause unintended consequences such as restricting movement (Wege and Zimmermann 2007), adversely affecting work postures while reducing overexertion (Frost et al. 2009), and physical discomfort (de Looze et al. 2016). These may affect usability (Young-Corbett et al. 2010), productivity (Kim et al. 2018), and safety (Rugelj and Sevšek 2011). Construction workers such as pipe workers are exposed to harsh working conditions such as working in confined spaces where there is limited room for movement. This may require the workers to maintain diverse postures in order to access their workspaces. An exoskeleton is an additional wearable layer, which may induce some discomfort such as restricting free body movement. Pipe workers will need to don (wear) the exoskeletons to perform daily work tasks. If the use of exoskeletons makes workers uncomfortable, this may affect their work performance and they may be unwilling to use the exoskeleton. To this end, this study aims to answer the following questions:

1. What impact would the use of exoskeletons have on the different body parts?
2. What are pipe workers' perceived usability of exoskeletons?
3. What is the perception of pipe workers regarding the use of an exoskeleton?

Methodology

This section describes the methodology adopted in this study. The key elements include the wearable robot, participants, study design, data collection, and analysis. Fig. 1 provides a graphical overview of the adopted methodology.

Wearable Robot

The wearable robot employed in this study is a commercially available back-support exoskeleton called the BackX (version 2) from SuitX (Emeryville, California) (BackX 2022). BackX, which weighs 3.4 kg, consists of a metal torso and a harness. The metal torso, shown in Fig. 2(a), consists of the chest plate, thigh pads, and the torque generator. The chest and thigh pads support the chest and thigh when both body parts are at inclined positions. The torque generator can generate a force of 9–13 kg to support a worker's lower back during forward bending tasks. The torque generator has two modes: the instant and standard modes, which facilitate support at 30° and 45°, respectively. The harness that supports the metal torso, shown in Fig. 2(b), consists of a shoulder strap, leg strap, chest strap, chest pad, hip belt, and hip pads.

Participants

Construction workers performing pipe laying work participated in this study. The workers included a pipe layer (connects new pipe to existing pipe), tail man (supports the pipe layer and checks alignment of the pipe), and top man (supports both the pipe layer and tail man by delivering pipe and tools). Lewis (1994) and Tullis and Stetson (2014) showed that the likelihood of detecting usability problems is higher using small sample sizes. Virzi (1992) claimed that 80% of the usability problems could be detected with four or five participants. Furthermore, most of the studies that evaluated the usability of exoskeletons adopted sample sizes between 8 and 20, as evident in the section "Potential of Exoskeletons in the Construction Industry" and literature reviews conducted by Kermavnar et al. (2021) and Zhu et al. (2021). Thus, this study adopted a convenience sample size of 14 pipe workers. All the participants were men, with two participants aged less than 30 years, three between 30 and 40 years, six between 41 and 50 years, and three in their 50s. Eight of these participants have 5–15 years of experience and the rest have experience greater than 15 years. The participants did not report any muscle injuries or health problems affecting their ability to perform their daily tasks. Before commencing the study, the

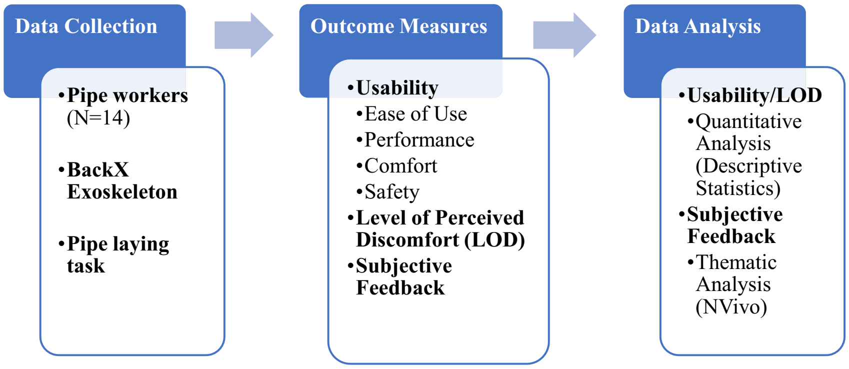
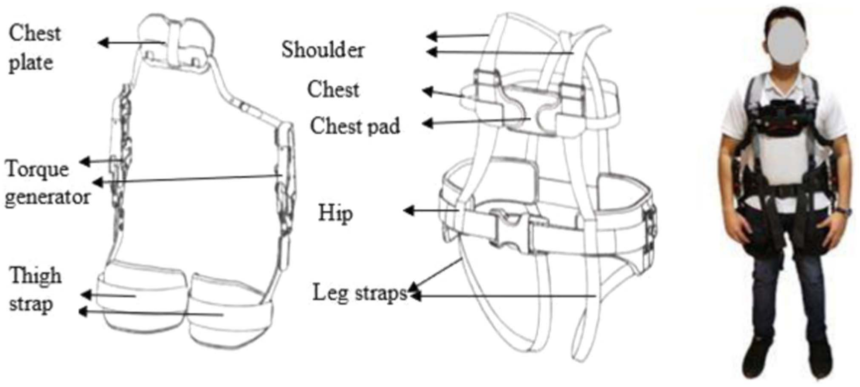


Fig. 1. Overview of methodology.



(a) (b) (c)

Fig. 2. BackX exoskeleton: (a) metal torso; (b) harness; and (c) exoskeleton worn by a user. [Images (a and b) courtesy of SuitX; Image (c) by Abiola Akanmu.]

participants signed the informed consent (IRB-19-1180) form approved by the Institutional Review Board at Virginia Tech.

Study Design

Prior to commencing the study, the participants signed the informed consent form. Thereafter, the participants were provided in-person instruction on the functioning of the back-support exoskeleton on site, which included the process of donning (i.e., putting on), fitting, adjusting, activating, and doffing (i.e., taking off). When the participants were comfortable with the exoskeleton, they performed their daily work duties for a period of approximately 4 h. Some ($n = 4$) of the participants used the exoskeleton in conjunction with the safety harness (for fall protection) to meet their work requirements. The participants' daily work duties included lifting and carrying heavy equipment (such as a tripod stand and metal chains and hooks), shoveling, grading, laying pipe, and cutting pipe. Although all the participants performed most of the tasks mentioned, the tasks performed during the experiment varied depending on the role of the participants (i.e., pipe layers, tail man, or top man). For instance, the pipe layer and tail man would typically be in a trench box and perform tasks like shoveling, grading, and laying pipe, whereas the top man would be involved in carrying heavy equipment and cutting pipes. The participants bend, squat, and climb ladders while performing the tasks. While performing work, the participants were prompted to provide verbal feedback regarding their experience with the use of the exoskeleton, which revolved around two questions: (1) How are you feeling while using the exoskeleton for your work? and (2) What are your thoughts or what do you think about using the exoskeleton for your work? Based on the responses provided by the participants, they were further probed to provide more details, which were written by the investigators. Verbal feedback is often employed by researchers to engage participants in a conversation so they can freely express their perception (Ogunseiju et al. 2022; Olmsted-Hawala et al. 2010). Participants' feedback was also registered through a structured questionnaire that included level of discomfort on the body parts (i.e., the hand/wrist, upper arm, shoulder, lower back, thigh, lower leg, neck, and chest) and the usability of the exoskeleton. The LOD was evaluated twice: (1) halfway through the study session, and (2) at the end of the study session. The usability data were recorded at the end of the study session using a structured questionnaire. The participants' experiences with the use of the exoskeleton were collected through a descriptive questionnaire and verbal feedback, which were obtained at the end of the session and through prompts during the session, respectively.

Data Collection and Analysis

Level of Perceived Discomfort

Research Question 1 was answered using the LOD. Data on the LOD were collected using the 10-point Borg scale as adopted by Bosch et al. (2016). The participants rated their body parts from 0 to 10, with 0 being no discomfort and 10 being very severe discomfort. Two LOD readings were obtained to account for the impact of discomfort over time, i.e., midway into the study session and at the end of the study session. Because the data were collected using a scale, Wilcoxon signed rank test, a commonly used nonparametric method, was employed to understand the change in initial and final LOD reading (Hensel and Keil 2019; Kluth and Hefferle 2022; Siedl and Mara 2021). The test for the LOD data was conducted using RStudio (version 1.2.5042).

Usability

In response to Research Question 2 (section "Theoretical Underpinning"), data on the usability of the exoskeleton were collected using a structured questionnaire that included positive and negative statements. Structured questionnaires are commonly adopted to evaluate the usability of exoskeletons (Kim et al. 2019). The participants rated 20 usability questions on a 5-point Likert scale (i.e., 1 = strongly disagree to 5 = strongly agree) depending on their level of agreement with each question. The usability questionnaire was based on four criteria: ease of use, comfort, performance, and safety. Cronbach's α, a commonly adopted method (La Bara et al. 2021; Schmidtler et al. 2017) for measuring the internal consistency of questionnaire, was employed to test the internal reliability of the usability questionnaire. The results indicate very high reliability ($\alpha > 0.9$) of the developed questionnaire. The collected usability data were analyzed using descriptive statistics such as mean and standard deviation using Microsoft Excel. Furthermore, to check if there is any correlation between LOD and usability, Spearman's rank correlation analysis, which is a widely employed method for nonparametric data (Hensel and Keil 2019), was conducted using RStudio.

Subjective Feedback

The participants' perception of the back-support exoskeleton was employed to answer Research Question 3 (section "Research Gap"), which was captured via four descriptive questions that were developed to elicit feedback on the benefits of the exoskeleton, barriers to the adoption of the exoskeleton, and potential modifications that should be made to the exoskeleton to make the device suitable for pipe laying work. Further verbal feedback was obtained during the session through prompts aimed at understanding the user experience with the exoskeleton. Qualitative analysis was conducted on the data to understand the participants' perspectives. The investigators analyzed the collected data based on a codebook that was developed with NVivo, a qualitative analysis software (Welsh 2002). An inductive coding approach was adopted whereby codes of similar meanings were clustered together and emerging categories were identified. Thereafter, to check the validity of the coding, Cohen's kappa coefficient was adopted, a commonly used statistical measure for checking the inter-rater reliability of qualitative data (Hallgren 2012). The coefficient ranges from 0 to 1, where 0 is considered as no agreement and 1 is considered complete agreement. A substantial agreement with a Cohen's kappa coefficient of 0.62 was attained and a strong percentage agreement of 78% was observed between the coders.

Results

Level of Perceived Discomfort

Fig. 3 represents the mean perceived discomfort across the different body parts. The error bars indicate the standard deviation across all the participants. As shown in Fig. 3, the participants reported the highest discomfort in the chest, thigh, and shoulder compared with the hand, upper arm, low back, neck, and lower leg. Because p-value was more than 0.05 for all the body parts, the results of the Wilcoxon signed rank test did not indicate any significant changes in the level of perceived discomfort between the conditions (i.e., midway into the session and at the end of the session). However, as shown in Fig. 3, an increase in the mean perceived discomfort between the conditions was observed in the chest (20%), thigh (73%), shoulder (250%), and upper arm (100%).

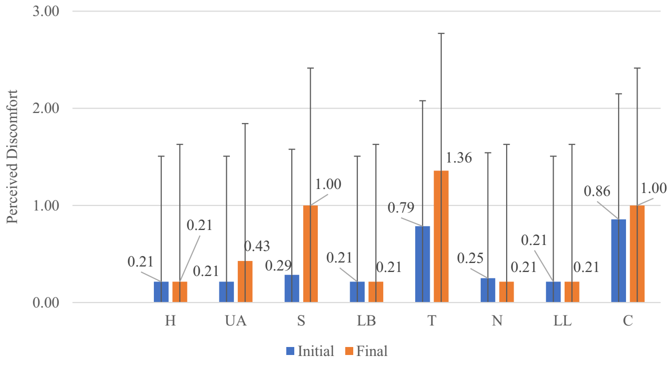


Fig. 3. Level of perceived discomfort (H = hand/wrist; UA = upper arm; S = shoulder; LB = lower back; T = thigh; N = neck; LL = lower leg and foot; and C = chest).

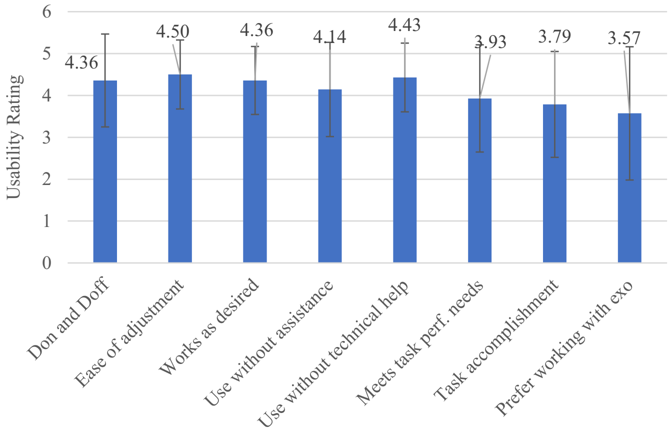


Fig. 4. Ease of use.

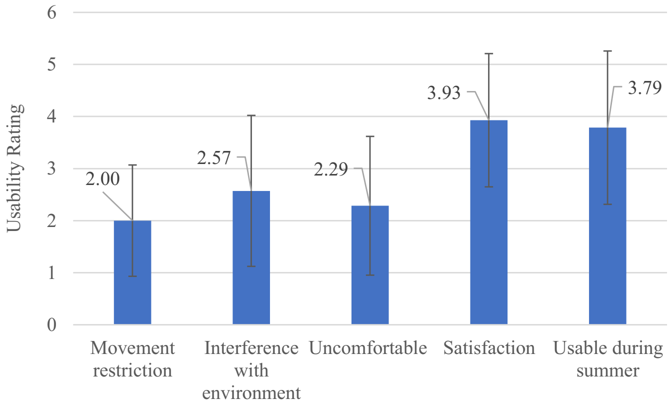


Fig. 5. Comfort with using the exoskeleton.

Usability (Questionnaire)

The overall usability assessment of the back-support exoskeleton was conducted based on four factors: ease of use (Fig. 4), comfort (Fig. 5), performance (Fig. 6), and safety (Fig. 7). Furthermore, the impact of LOD on usability was investigated using correlation analysis. Tables 1–4 provide the correlation coefficients between LOD and usability.

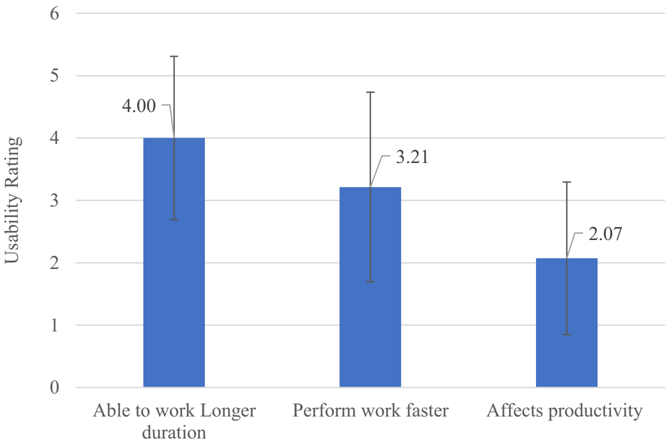


Fig. 6. Performance using the exoskeleton.

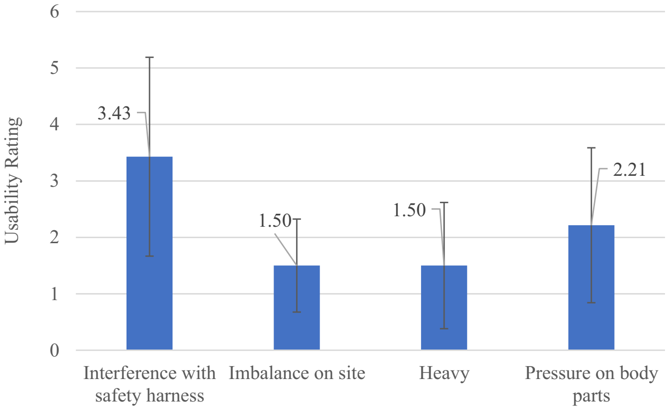


Fig. 7. Impact on worker's safety.

Ease of Use

The ease of use included eight questions to which participants provided an overall high rating (4.13 ± 0.34). The participants found the donning and doffing of the exoskeleton to be easy and provided a high rating (4.36 ± 1.11). The ease of adjusting the exoskeleton received a high to very high rating (4.50 ± 0.82). The participants felt that the exoskeleton was working as they desired and provided a high rating of 4.14 ± 1.12. However, when asked if the exoskeleton meets task performance requirements and helps accomplish the task, the participants provided moderate to high ratings, i.e., 3.93 ± 1.28 and 3.79 ± 1.26, respectively. The participants were highly confident to use the exoskeleton without any assistance and technical help. Which is evident through the high ratings of 4.14 ± 1.12 and 4.43 ± 0.82, respectively. Although the participants gave a high rating for ease of use, they moderately (3.57 ± 1.59) preferred working with the exoskeleton. Several correlations were observed between ease of use and LOD as shown in Table 1. A strong ($p < 0.05$) negative correlation was observed between the perceived discomfort at the shoulder (−0.59) and thigh (−0.59) and workers' preference to use the exoskeleton. Similar correlation was also observed between the perceived discomfort at the shoulder (−0.55) and thigh (−0.65) and workers' perceived task accomplishment. Discomfort at the thigh negatively affected workers' perception of the exoskeleton meeting performance needs (−0.68) and working as desired (−0.58). Participants further perceived lesser ease of adjustment with an increase in discomfort at the hand (−0.48) and upper arm (−0.57).

Table 1. Correlation analysis results for ease of use criteria

Criteria	C	S	T	H	LL	N	UA	LB
Don and doff	−0.51	−0.40	−0.27	−0.38	−0.38	−0.38	**−0.66**	−0.38
Ease of adjustment	−0.46	−0.33	−0.23	**−0.48**	−048	−0.48	**−0.57**	−0.48
Work as desired	−0.53	−0.19	**−0.58**	−0.42	−0.42	−0.42	−0.45	−0.42
Use without assistance	−0.18	**−0.60**	−0.26	−0.37	−0.37	−0.37	−0.63	−0.37
Use without technical help	−0.36	−0.25	−0.42	−0.44	−0.44	−0.44	−0.50	−0.44
Meets task performance needs	−0.53	−0.37	**−0.68**	−0.48	−0.48	−0.48	−0.40	−0.48
Task accomplishment	−0.43	**−0.55**	**−0.65**	−0.47	−0.47	−0.47	−0.50	−0.47
Prefer working with exoskeleton	−0.51	**−0.59**	**−0.59**	−0.44	−0.44	−0.44	−0.51	−0.44

Note: H = hand/wrist; UA = upper arm; S = shoulder; LB = lower back; T = thigh; N = neck; LL = lower leg and foot; and C = chest. The significant correlations (i.e., $p < 0.05$) are shown in bold.

Table 2. Correlation analysis results for comfort criteria

Criteria	C	S	T	H	LL	N	UA	LB
Movement restriction	0.31	0.52	0.46	0.26	0.26	0.26	0.22	0.26
Interference with environment	0.19	0.37	0.37	0.03	0.03	0.03	0.05	0.03
Uncomfortable	0.27	0.44	0.44	0.18	0.18	0.18	0.39	0.18
Satisfaction	**−0.6**	−0.48	**−0.74**	−0.48	−0.48	−0.48	**−0.54**	−0.48
Usable during summer	**−0.57**	−0.35	**−0.69**	−0.44	−0.44	−0.44	−0.37	−0.44

Note: H = hand/wrist; UA = upper arm; S = shoulder; LB = lower back; T = thigh; N = neck; LL = lower leg and foot; and C = chest. The significant correlations (i.e., $p < 0.05$) are shown in bold.

Table 3. Correlation analysis results for performance criteria

Criteria	C	S	T	H	LL	N	UA	LB
Able to work for longer duration	**−0.64**	−0.27	**−0.65**	−0.49	−0.49	−0.49	**−0.56**	−0.49
Perform work faster	**−0.51**	−0.37	**−0.58**	−0.43	−0.43	−0.43	−0.47	−0.43
Affects productivity	−0.19	0.49	0	0.26	0.26	0.26	0.38	0.26

Note: H = hand/wrist; UA = upper arm; S = shoulder; LB = lower back; T = thigh; N = neck; LL = lower leg and foot; and C = chest. The significant correlations (i.e., $p < 0.05$) are shown in bold.

Table 4. Correlation analysis results for safety criteria

Criteria	C	S	T	H	LL	N	UA	LB
Interference with safety harness	0.22	0.27	0.12	−0.11	−0.11	−0.11	0.10	−0.11
Imbalance on site	**0.64**	0.05	**0.49**	0.47	0.47	0.47	0.22	0.47
Heavy	0.37	0.06	0.14	0.43	0.43	0.43	0.211	0.43
Pressure on body parts	**0.83**	0.34	**0.61**	0.18	0.18	0.18	0.40	0.18

Note: H = hand/wrist; UA = upper arm; S = shoulder; LB = lower back; T = thigh; N = neck; LL = lower leg and foot; and C = chest. The significant correlations (i.e., $p < 0.05$) are shown in bold.

Comfort

Five questions, of which three were negative and two were positive, were used to assess the comfort of using the exoskeleton. Participants' experience with the exoskeleton restricting their free movement and interfering with their work environment received low to moderate ratings, i.e., 2.00 ± 1.07 and 2.57 ± 1.45, respectively. When asked whether it was uncomfortable to perform the task with the exoskeleton, the participants provided low to moderate agreement of 2.29 ± 1.33. The workers seemed to be satisfied using the exoskeleton because they gave a high rating of 3.93 ± 1.28. Moderate to high agreement of 3.79 ± 1.47 was expressed for how usable the exoskeleton is during the summer season. Table 2 gives the correlations between LOD and comfort. Perceived discomfort at the chest (−0.6) and thigh (−0.74) negatively impacted workers' satisfaction with the exoskeleton. Workers' perception of using the exoskeleton during the summer was also impacted negatively by the discomfort at the chest (−0.57) and thigh (−0.69). Furthermore, a strong ($p < 0.05$) negative correlation was observed between discomfort in the upper arm (−0.54) and workers' satisfaction with using the exoskeleton.

Performance

Two positive and one negative question were asked to assess the participants' performance while using the exoskeleton. The question of whether the participants feel like they can use the exoskeleton for longer durations provided a high level of agreement (4.00 ± 1.31). The participants did not feel like the exoskeleton negatively affected their productivity as indicated by the low to

Table 5. Categories, subcategories, and frequency of user feedback

Category	Subcategory	Frequency of feedback	Outcome measures
Benefits	Health	Thigh pad support (9); stress reduction (9)	Safety
	Design	Light weight (1); chest and thigh support (2)	Ease of use
	Application	Shoveling, stormwater invert, applying pipe lubricant, and leveling (4)	Performance
Adoption barriers	Design barriers	Discomfort due to metal torso (3); heavy (1); bulky (2)	Performance
	Work environment	Working in confined spaces (6)	
	Work preference	Prefer not to use (2)	
	Weather barriers	Discomfort during summer (1)	
	Comfort	Straps getting in the way (1); pressure on chest and thigh (3); use of exoskeleton with harness and tool strap (4)	Comfort
	Safety barriers	Incompatibility with safety harness (4); metal parts could cause damage (1)	Safety
Design suggestions	Safety harness	Integrating safety harness (4)	Ease of use
	Light weight	Reducing weight of exoskeleton (1)	
	Metal torso	Torso closer to body (1)	
	Pressure modifications	Chest pressure modifications (1)	
	Back support	Pressure at the back body part (1)	Perceived discomfort
	Tool strap	Integrating tool strap (1)	Performance
	Weather adaptability	Change color to white (1)	

moderate rating of 2.07 ± 1.22. However, the participants provided a moderate to high rating of 3.21 ± 1.52 when asked if they performed work faster with the exoskeleton. Increase in discomfort at the chest (−0.51) and thigh (−0.58) negatively impacted workers' perception of working faster while using the exoskeleton. A strong ($p < 0.05$) negative impact on workers' perception of working for a longer duration when using the exoskeleton due to the discomfort at the chest (−0.64) and thigh (−0.65) was observed. However, there was no significant impact on workers' productivity due to LOD (i.e., $p > 0.05$). Correlations between performance and LOD are presented in Table 3.

Safety

The safety questionnaire included four negative questions aimed at identifying the impact of the use of the exoskeleton on worker's safety. The participants provided a moderate to high agreement (3.43 ± 1.76) when asked whether they think the exoskeleton would interfere with the safety harness. The workers did not feel that the exoskeleton was heavy and created an imbalance on site because they gave a very low to low rating of 1.50 ± 1.12 and 1.50 ± 0.82, respectively. The participants gave a low to moderate rating (2.21 ± 1.37) when asked whether the exoskeleton applies pressure on other body parts. Overall, the mean of all the responses suggests a low to moderate negative impact on the worker's safety (2.16 ± 0.91). Strong ($p < 0.05$) positive correlation was observed between discomfort at the chest (0.83) and thigh (0.61) and participants' perception of pressure on body parts. An increase in participants' perception of imbalance on site while donning the exoskeleton was observed with an increase in discomfort at the chest (0.64) and thigh (0.49). Table 4 presents the correlation between safety and LOD.

Subjective Feedback

Table 5 summarizes the categories, subcategories, and frequency at which these categories were identified during the qualitative analysis, broadly classified as benefits, adoption barriers, and design suggestions. Furthermore, these themes are further categorized based on other outcome measures (i.e., perceived discomfort and usability).

Exoskeleton Benefits

Overall, the participants reported benefits from the use of the exoskeleton for pipe work. These benefits can be broadly classified into health, design, and application, or task-specific benefits. Health benefits were a major subcategory because the workers ($n = 9/14$) could feel support from the thigh pads (Table 5) and reduction in stress in the back while performing their regular duties: "[The exoskeleton] it is very beneficial as it provides support to the thighs and chest which helps me reduce the stress from the back." Two-thirds ($n = 9/14$) of the participants perceived some reduction in stress in the back muscle and suggested adopting the exoskeleton to reduce back injuries: "The exoskeleton is very helpful for bending. I think it is good and should be definitely used if it can help save injuries." The participants also reported design benefits ($n = 3/14$): "I like the pressure points in the exoskeleton, i.e., chest and thighs, as that is where I feel the support" and "it is not heavy, rather lighter than the fall protection that we use." Task-specific benefit was another subcategory. The participants ($n = 4/14$) suggested construction tasks where the exoskeleton could be most beneficial. The tasks suggested by participants included activities requiring forward bending such as shoveling, stormwater invert, applying pipe lubricant, and leveling. The participants did not report any imbalance induced by the use of the exoskeleton while walking on uneven surfaces: "While walking in an uneven surface on a pile of dirt I did not have any problems and no imbalances out of the ordinary, rather while walking uphill the exoskeleton helped me."

Exoskeleton Adoption Barriers

The participants raised some concerns about the adoption of the back-support exoskeleton. Design barriers ($n = 8/14$), discomfort ($n = 8/14$), work environment ($n = 6/14$), safety barriers ($n = 5/14$), work preference ($n = 2/14$), and weather barriers ($n = 1/14$) were the emerging subcategories. Using the exoskeleton with the safety harness during summer, when the temperature was between 26°C (80°F) and 36°C (98°F), made the participants sweat a lot and this made them uncomfortable: "During summer it is very hot, and the use of exoskeleton makes me hotter and sweat more," "exoskeleton with safety harness and tool strap is a bit too much," and "with the exo I sweat a bit more." Furthermore, participants also felt that straps of the exoskeleton could get in the way of their work performance, which could be frustrating: "The straps sometimes fall and get in the way . . . which can be annoying." Some participants also felt some pressure exerted on their body parts by the exoskeleton: "The exoskeleton puts pressure on my body parts especially chest and hips." Considering the work environments to which the pipe workers are exposed, such as working in trench boxes and manholes, some participants felt that using the exoskeleton is not feasible: "I do not think it is suitable for pipework as we work in tight spaces. We frequently go in and out of the manhole and trench box and it might not work as the room for movement is very less." Some participants also reported some concerns with the design of the metal torso: "When I was shoveling sideways, the metal rods caused problems for my underarms" and "in tight places to pick and slide the load sideways, the metal rods would be a problem." Most of the safety concerns with the use of exoskeleton regarded the compatibility of the exoskeleton with the safety harness used on the construction sites: "I do not think we can use it with the safety harness" and "I do not think the exoskeleton would be beneficial when we must go into the trench box with the fall protection."

Exoskeleton Design Suggestions

Most of the participants ($n = 10/14$) suggested potential modifications to the exoskeleton to ensure the device is better suited for pipe work. The most common among these is the integration of the fall protection harness with the exoskeleton ($n = 4/14$): "If it (exoskeleton) was designed with in-built fall protection, it would be great." One worker also preferred the integration of the tool kit with the exoskeleton to reduce the number of layers of PPE and discomfort: "I would like to add that if there is a strap for tools . . . " One of the workers also mentioned the need for a simpler system: "I think it should be made easy to put on." Another participant suggested the provision of support at the back for resting: "It would have been better if the pressure was on the back." Although the participants liked the pressure points, one suggested flexibility for pressure modification: "Need more pressure on the chest pad in order to support me better" and "the chest pressure should be reduced." One of the participants suggested changing the color of the exoskeleton from black to white for better weather adaptability: "If we can change the color to white then maybe it would be much better." The participants ($n = 1/14$) also suggested some design changes such as "metal torso can be closer to the body," "lighter than what it is right now," and "more flexibility for legs and hips."

Discussion

Pipe workers are subjected to physically demanding work postures causing work-related musculoskeletal disorders, which have tremendous health, social, and economic implications (Rosecrance et al. 1996). Studies have found that the use of back-support exoskeletons for forward bending tasks can help in reducing activity in the back muscles and discomfort in the lower back (Alemi et al. 2019). However, for the exoskeletons to yield the intended benefits, end users need to be willing to use the device. Workers' willingness to use a device is dependent on the usability of the device, which includes ease of use, performance, and comfort. There also needs to be a reduction in unintended consequences such as the impact on safety and discomfort to the body parts (Kuber and Rashedi 2020). Thus, for successful adoption of exoskeletons, the aforementioned usability factors need to be evaluated by involving end users in real working conditions. This study assessed a commercially available back-support exoskeleton in terms of usability, level of perceived discomfort, and user perception of using the exoskeleton for pipe work.

Level of Perceived Discomfort

The results indicate that the use of the BackX exoskeleton for pipe work caused an increased perceived discomfort, particularly to the chest and thigh, which is in line with the findings of Alemi et al. (2020). Even though a significant difference between the initial and final discomfort reading was not found (based on Wilcoxon signed rank test), an increase in average discomfort with respect to time for shoulder, thigh, and chest was observed. This could mean the long-term use of the exoskeleton might cause an increase in discomfort, which is a concern because it might affect the users' intention to use the exoskeleton, as observed by Hensel and Keil (2019). However, these participants are first-time users of an exoskeleton and are used to performing pipe work without the exoskeleton. This might have caused the increased discomfort to body parts (Research Question 1) and might diminish once the workers get used to the device.

Usability

The usability assessment of the exoskeleton for pipe work reveals that the device is easy to use, which is consistent with the findings of Ziaei et al. (2021). Participants were able to easily don, doff, and adjust the exoskeleton for their fit and were confident of being able to use the device without any form of technical assistance. This may suggest that it could entice construction workers with different backgrounds and educational levels. However, the participants moderately preferred to use the exoskeleton for pipe work. This could be attributed to the fact that the participants are not used to using the exoskeleton and using the exoskeleton increased the discomfort at the chest, shoulder, and thigh. This prompted them to give a relatively lower rating for the suitability of the exoskeleton for pipe work, thus affecting their willingness to use the device.

Overall, the participants perceived the exoskeleton to be comfortable because they did not feel that the exoskeleton restricted their movement nor made them uncomfortable. This is important because if the workers are not comfortable working with the device, they will not be willing to adopt it. Furthermore, pipe workers are subjected to working in confined spaces and trench boxes, so the participants felt that the use of the exoskeleton interfered with their work environment. Despite this, the participants were satisfied with the use of the exoskeleton and showcased a willingness to don and work with the device during the summer. Construction workers are subjected to harsh weather conditions such as working in hot and cold climates, and the willingness of workers to use the device in summer conditions could suggest the suitability of the exoskeleton for harsh weather conditions. However, it was observed that the increase in discomfort at the chest, thigh, and upper arm negatively affected workers' satisfaction and perception of usability of the exoskeleton during summers. This could affect user acceptance of exoskeletons among the end users after prolonged use.

The assessment of performance revealed that the exoskeleton did not have a negative impact on workers' productivity because they felt they could perform work for longer periods of time with the device despite the increased perceived discomfort. This is crucial for the workers' perceived self-efficacy, which is an important determinant of the acceptability of new technology (Baltrusch et al. 2021). Overall, the participants did not feel that the use of the exoskeleton on site would pose safety issues because they did not feel the device was heavy enough to cause imbalance on uneven surfaces. This is important because if the workers feel unsafe while working with the exoskeleton, it will affect their willingness to use the device (Kim et al. 2019). However, the workers raised concerns regarding the compatibility of exoskeletons with the safety harnesses. This could be a problem because the compatibility of exoskeletons with on-site tools has been identified as important for the adoption of exoskeletons in the construction industry (Kim et al. 2019). Although there was a negative impact on workers' satisfaction and preference of using the exoskeleton due to increased discomfort at the chest, thigh, shoulder, and upper arm, participants reported good usability of the exoskeleton given they reported moderate to high ratings for ease of use, comfort, performance, and safety.

Subjective Feedback

The subjective feedback provided by the participants suggests that the use of an exoskeleton for pipe work can have health benefits such as reduction in back stress. This is critical because the workers could feel the reduction in back stress, which was also observed in past studies (Alemi et al. 2019) where the use of the exoskeleton yielded a reduction in muscle activity during forward bending tasks. Furthermore, participants provided positive feedback on the chest and thigh pads. This was contrary to the results of the level of perceived discomfort where an increase in the discomfort of chest and thigh body parts was observed. Also, participants felt that the weight of the exoskeleton was similar to the weight of the safety harness. This could mean the workers might not feel any additional load while working with the exoskeleton, which could be enticing for construction workers. This might have prompted the feedback that the use of exoskeletons did not pose any safety risk such as imbalance while walking on uneven surfaces; rather, the device was found to be beneficial while walking uphill.

Even though the participants reported benefits from the use of the exoskeleton, there were some concerns and suggested design modifications to make the device suitable for pipe work. One of the most common concerns raised by the participants was the compatibility of the exoskeleton with the safety harness. Participants felt that they would not be able to don the safety harness along with the back-support exoskeleton. However, this concern was addressed by allowing the exoskeleton to be used along with the harness, which made the workers uncomfortable due to high temperatures. This might have prompted the suggestion to integrate the exoskeleton with the safety harness instead of requiring workers to don two separate devices. Also, changing the color of the exoskeleton from black to white could further help in reducing discomfort during summers. Although some participants liked the pressure from the chest and thigh pads, some reported discomfort on chest and thigh body parts. This is also reflected in the level of perceived discomfort data provided by the participants. Furthermore, to make the exoskeleton more suitable for similar environments in which pipe workers work (e.g., confined spaces such as manholes and trench boxes), keeping the metal torso closer to the body could potentially help in reducing the chances of getting caught while going in and out of confined spaces.

Conclusion and Future Work

A commercially available passive back-support exoskeleton (BackX version 2), was assessed in the field in terms of usability and level of perceived discomfort, and subjective feedback was obtained during pipework. The usability assessment revealed that the exoskeleton is easy to use, and participants were able to perform pipework; however, they moderately preferred to work with the exoskeleton. Overall, the use of the exoskeleton showcased more discomfort to the chest and thigh compared with other body parts. Health-, design-, and application-related benefits were identified. Opportunities for improvement in the design of back-support exoskeletons were also identified.

This study contributes to the scarce body of knowledge regarding the use of exoskeletons in the construction industry, specifically for pipework. The findings contribute to theory and practice in the burgeoning literature on exoskeleton use by offering a theoretical lens through which exoskeletons could be adopted for and impact construction work. The modifications suggested by the workers could be used to improve or adapt exoskeleton designs for construction work. The findings of the study showcase acceptance among the pipe workers for the adoption of a back-support exoskeleton, which is significant. Thus, this study sets the precedence for long-term field evaluation of wearable robots in the construction industry.

This study had some limitations that need to be addressed in future studies to facilitate the adoption of exoskeletons. First, this was a short-term field study that allowed workers to use the exoskeleton for 4 h. Prolonged use of the exoskeleton could reveal increased discomfort and spark different feelings regarding the intention to use the exoskeleton for pipework. Second, this study did not involve female participants; thus, in future studies, a more representative sample size would provide a better user assessment. Third, even though the participants perform similar tasks, depending on the role of the worker (i.e., the pipe layer, the tail man, or the top man) the acceptance of construction workers might change. For future studies, assessing the acceptance based on the role of the participant should be conducted to aid the exoskeleton adoption process. Fourth, the exoskeleton was only tested during the summer. It would be beneficial to assess workers' intention to use the exoskeleton during different climate conditions. Fifth, a small sample size of 14 workers was adopted in this study, which is not enough to generalize the findings for the entire construction industry. A larger sample size is recommended for future work. Last, adoption of exoskeletons in the construction industry would require a proper maintenance strategy that is dependent on the service life of the exoskeleton. Future study could investigate the service life of the exoskeleton and evaluate maintenance strategies.

Data Availability Statement

Data, models, and code generated or used during the study are available upon reasonable request.

Acknowledgments

This work was supported by the Construction Industry Research Affiliates Program and Allan Myers.

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