Understanding Underlying Risks and Socio-technical Challenges of Human-Wearable Robot Interaction in the Construction Industry

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ABSTRACT

The construction industry, one of the largest employers of labor in the United States, has long suffered from health and safety issues relating to work-related musculoskeletal disorders. Back-related injuries are one of the most prevalent of all musculoskeletal disorders in the construction industry. Due to advancements in the field of wearable technologies, wearable robots such as passive back-support exoskeletons have emerged as a possible solution. Exoskeletons have the potential to augment human capacity, support non-neutral work positions, and reduce muscle fatigue and physical exertion. Current research efforts to evaluate the potential of exoskeletons in other industry sectors have been focused on outcome measures such as muscle activity, productivity, perceived discomfort and exertion, usability, and stakeholders’ perspectives. However, there is scarce evidence regarding the efficacy of using exoskeletons for construction work. Furthermore, the risks and sociotechnical challenges of employing exoskeletons on construction sites are not well documented. Thus, through the lens of human-centric and socio-technical considerations, this study explores the prospects of adopting back-support exoskeletons in the construction industry. Firstly, a laboratory experiment was conducted to quantify the impact of using a passive exoskeleton for construction work in terms of muscle activity, perceived discomfort, and productivity. In order to investigate the acceptance of exoskeletons among construction workers and the challenges of adopting exoskeletons on construction sites, field explorations evaluating usability, perceived discomfort and exertion, social influence, and workers user perceptions were executed. Using sequential mixed methods approach, the stakeholders and factors (i.e., facilitators and barriers) critical for the adoption of exoskeletons on construction sites were investigated. Thereafter, by employing the factors and leveraging the constructs of the normalization process theory, an implementation plan to facilitate the adoption of passive exoskeletons was developed. The study contributes to the scarce body of knowledge regarding the extent to which exoskeletons can reduce ergonomic exposures associated with construction work. This study provides evidence of the perceptions of the contextual use of wearable robots, and workers' interaction with wearable robots on construction sites. The study contributes to the normalization process theory by showing its efficacy for the development and evaluation of implementation frameworks for construction industry. Furthermore, this study advances the socio-technical systems theory by incorporating all its subsystems (i.e., human, technology, organization and social) for investigating the potential of using a passive back support exoskeleton in the construction industry.
Construction workers are often subjected to harsh working conditions and physically demanding work postures, which are ergonomics risks causing back-related musculoskeletal injuries. These injuries have the potential to cause permanent disabilities, lead to early retirement of experienced labor, and is one of the causes of the shortage of skilled workforce in construction. Wearable robots, such as passive back-support exoskeletons, are increasingly been looked upon as a potential solution to mitigate the problem. Exoskeletons are wearable technologies that can support and reinforce workers’ body parts. Studies have shown that the use of exoskeletons could lead to reduced muscle fatigue thereby decreasing injuries in the long run. However, most of the research on the use of exoskeletons is focused on other industrial sectors. Scarce evidence regarding the use of exoskeletons in construction is documented in the literature. Furthermore, the use of exoskeletons on construction sites could have certain unintended consequences. Thus, the objective of this research was to understand the risks and challenges of using passive exoskeletons in the construction industry. A laboratory experiment was conducted to measure the impact of using exoskeletons on physical demand and productivity while performing construction tasks. An increase in productivity and a reduction in discomfort in the lower back were observed while using an exoskeleton. Thereafter, field studies were conducted where construction workers performed their usual tasks using an exoskeleton to understand their user experience and acceptance. To help construction companies in the adoption of exoskeletons, facilitators and barriers to the adoption of exoskeletons were identified. Thereafter a plan was developed to facilitate the implementation of passive exoskeletons in construction organizations. This plan can guide construction companies in the adoption of passive exoskeletons. The outcomes of this study will help other researchers to conduct similar studies with other wearable technologies.
I would like to dedicate my research to my grandparents

*Late Mr. Joseph L. Gonsalves and Late Mrs. Johna J. Gonsalves*

&

*Mr. Crizan M. Menezes and Mrs. Veronica C. Menezes*
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CHAPTER 1: INTRODUCTION

1.1 Overview

Health, well-being, and productivity of the workforce have implications on the growth of any industry sector. The Construction industry, being one of the industries with the largest labor force in the United States (8% of the total workforce) (BLS 2022), has long suffered from productivity loss, workforce shortage, and safety issues. These challenges have been partly attributed to non-fatal injuries and illnesses associated with work-related musculoskeletal disorders (WMSDs). A report by the European Agency for Safety and Health at Work defines WMSDs as ‘impairments of bodily structures such as muscles, joints, tendons, ligaments, nerves and bones caused or aggravated primarily by the work itself or by the environment in which work is implemented’ (Fearnley et al. 2022). Wearable robots, in the form of exoskeletons, are increasingly being perceived as ergonomic solutions to address the risks triggered by WMSDs. Exoskeletons promise to reduce the physical demands of work while improving the productivity of workers. While there have been significant investigations into the efficacy of exoskeletons for reducing physical demands in other industry sectors, little is known of their impact on construction work. This chapter provides an overview of this research focused on exploring the potential, from the lens of risks and socio-technical challenges, of adopting exoskeletons in the construction industry.

1.2 Background and Problem Statement

Integration of humans (i.e., the construction workforce) and robotics could create opportunities to develop assistive technologies suitable for the construction industry. Wearable robots, i.e., exoskeletons are emerging as powerful devices to minimize the risk of WMSDs during construction work by providing lift support (Simon et al. 2021), weight dispersion (Banala et al. 2007), and posture correction (Hussain et al. 2020). As defined by De Looze et al. (2016), an exoskeleton is a “wearable, external mechanical structure that enhances the power of a person”. Exoskeletons can be classified as either active or passive (Howard et al. 2020). An active exoskeleton is powered through one or more actuators (e.g., electric motors, pneumatics, hydraulics) that actively augment power to the human body (Huo et al. 2014). Passive exoskeletons do not include actuators but use materials, springs, or dampers to store energy from human movements and power the device when required (De Looze et al. 2016). While active exoskeletons provide more support and enhance the capabilities of the users, passive exoskeletons are generally preferred in the construction sector due to their low cost and lightweight (Toxiri et al. 2019). Passive exoskeletons are typically designed to reduce physical load on workers by compensating for gravity, load being handled, and the arm weight (Huysamen et al. 2018). Furthermore, exoskeletons are also classified based on the type of body part supported. For example, an exoskeleton designed to assist a user’s shoulder is termed shoulder-support. Similarly, based on the body part, the exoskeleton types include back-support, leg-support, and full-body support (Zhu et al. 2021).
Studies have reported that back-related disorders are the most prevalent of all musculoskeletal disorders in the construction sector (Marcum and Adams 2017). The incidence rate of back-related disorders in the construction industry is almost two times the rate of all industries (BLS 2022). In 2020, back-related disorders was responsible for approximately 40% of WMSD cases in construction and resulted in an average of 7 lost workdays (BLS 2022). As evidenced by the research on the detrimental impact of workers' back pain on safety, productivity, and quality of the construction process (Boswell et al. 2007; Guo et al. 1999), this research is motivated to focus on passive exoskeletons for alleviating back-related WMSDs.

In recent years, passive back support exoskeletons (BSEs) such as Laevo, BackX, Kinetic Edge Flex, Apex, PLAD (Personal Augmentive Lifting, Device), BNDR (Bending Non-Demand Return), SPEXOR, and VT-Lowe’s exoskeleton (Kermavnar et al. 2021) are rapidly emerging as commercial products. Fig. 1.1 Shows some of the commercially available passive back support exoskeletons. Researchers (Kim et al. 2018; Koopman et al. 2020; Kozinc et al. 2021; Luger et al. 2021; Toxiri et al. 2019) have evaluated these commercially available exoskeletons for other industrial sectors such as manufacturing, automobile, and healthcare and found benefit in terms of reduced muscle activity, range of motion, perceived discomfort as well as increased productivity. Similar to these industries, construction work involves forward bending tasks, and considering the aforementioned benefits, one can envision the applicability of using a passive BSE for construction work.

![Figure 1.1. Passive back support exoskeletons (Ali et al. 2021)](image)

However, with the impending integration of passive back-support exoskeletons (BSEs) on construction sites, new concerns are bound to arise due to the transformation from a human-centric work environment to a human-technological collaborative workplace. Studies have demonstrated that exoskeletons could introduce new physical risk factors, including local muscular fatigue (Huysamen et al. 2018), joint hyperextension (Koopman et al. 2020), and incompatibility with work environments (e.g., caught around wires) (Kim et al. 2019), for the users. These may, in turn,
affect usability (Young-Corbett et al. 2010), productivity (Kim et al. 2018), fatigue (Rashedi et al. 2014), and safety (Rugelj and Sevšek 2011). Likewise, factors related to the introduction of a wearable device, such as cognitive overload (Marchand et al. 2021), lack of trust (Fosch-Villaronga et al. 2020), and decreased vigilance (Constantinescu et al. 2019), could also impact safety. In addition, several socio-technical aspects (benefits, concerns, needs and alternatives of the technology, social influence, and willingness of users) could affect the perception of the expected value of emerging technology in job sites and consequently impact their widespread adoption (Shin and Jin Park 2017).

The current body of knowledge does not allow for an extensive understanding of the safety risks and challenges of incorporating BSEs on construction sites. This deficiency arises due to a lack of understanding of the physical risks, and lack of studies to evaluate the socio-technological challenges associated with the implementation of BSEs on construction sites. As the construction industry gears toward widespread acceptance of exoskeletons, it is critical to conduct exploratory studies to evaluate their physiological impact on workers and socio-technical challenges in the construction sector. Thus, the objective of this study is to explore the potential of adopting passive BSEs in the construction industry by evaluating human-centric and socio-technical challenges.

1.3 Research Overview

1.3.1 Research questions and aims

To understand the feasibility of implementing passive BSEs in the construction industry, this study attempted to answer the following key research question: What are the underlying risks and socio-technical challenges associated with the use of passive BSEs in the construction industry? To address the main research question, the following sub-research questions (RQ) were developed:

- **RQ1:** To what extent does a passive BSE influence muscle activity, perceived discomfort, and productivity while performing construction work?
- **RQ2:** How does the use of passive BSE on construction sites influence construction workers’ perception of the usability of exoskeletons, and their perceived discomfort and exertion?
- **RQ3:** What strategies could be put in place to successfully implement passive BSEs in the construction industry?

To answer the aforementioned research questions, this study is guided by the research aims mentioned as follows:

- **Aim 1:** Examine the effect of a commercially available passive BSE on muscle activity, perceived discomfort, and productivity for construction work. (RQ1)
- **Aim 2:** Evaluate the usability of a commercial passive BSE for construction work and its impact on construction workers’ perceived discomfort and exertion on construction sites. (RQ2)
• **Aim 3:** Formulate an implementation strategy for the adoption of commercially available passive BSEs by incorporating perspectives of stakeholders regarding factors significant for the adoption of exoskeletons in the construction industry. (RQ3)

### 1.3.2 Research scope

The research aims listed in Section 1.3.1 were achieved by conducting the studies in Table 1.1. The proposed studies, approach and scope of work are described in this section.

A mixed-method approach was adopted in this research work. The participants were students, construction workers, and exoskeleton technology manufacturers. Firstly, a lab study was conducted to identify the impact of using commercially available BSEs for construction work (Study 1). Construction tasks were executed in a controlled environment with student participants who have a background in construction/civil engineering. Participants were required to perform the construction tasks with and without a BSE. During the lab study, participants' muscle activity, level of perceived discomfort, and task completion time were recorded. Thereafter, the BSE was evaluated using field trials. During the field exploration, a field study was conducted to understand construction workers' perceptions of using BSE on construction sites in terms of usability, perceived discomfort, and subjective feedback (Study 2). Construction workers performed their usual daily tasks using a BSE for four hours after which the aforementioned outcome measures were collected. Based on the provided feedback, some of the changes suggested by the participants during the field study were addressed to upgrade the existing exoskeleton. Thereafter, using the upgraded BSE, another field study was conducted to understand if there are changes in workers' perceptions regarding usability, workers' perspective, and perceived discomfort and exertion with time (Study 3). Construction workers were required to perform their usual daily tasks with and without a BSE for one week during which, the outcome measures mentioned above were collected. Through these field explorations, construction workers' perceptions of using BSEs were recorded. Furthermore, industry professionals completed an online survey to identify the stakeholders and factors (i.e., facilitators and barriers) critical for the implementation of BSEs in the construction industry (Study 4). Using focus group discussion involving the stakeholders identified from the survey, stakeholders' perspectives regarding these factors were collected. Thereafter, by incorporating the stakeholders' and end users' perceptions, an implementation plan was formulated (Study 5). This plan was validated by conducting a focus group discussion involving the critical stakeholders identified from the above-described survey. A scenario-based case study was conducted to evaluate the developed plan and to identify facilitators and barriers to the adoption of the implementation plan. Through the aforementioned aims, this research study attempted to understand the extent of the impact of using a BSE for construction work, the feasibility of using BSEs on construction sites, construction workers’ perceptions of using a BSE, and formalize an implementation strategy for the adoption of BSEs in the construction industry. The timeline for this research is shown in Table 1.2.
Table 1.1. Research aims and studies

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<td>Study 1: Conduct a laboratory experiment to measure the extent of impact of using a commercial passive BSE on muscle activity, perceived discomfort, and productivity for construction work.</td>
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<tr>
<td>Aim 2: Evaluate the usability of a commercial passive BSE for construction work and its impact on construction workers’ perceived discomfort and exertion on construction sites. (RQ2)</td>
<td>Study 2: Conduct a short-term* field study to capture construction workers' perspective of the usability of exoskeletons, and perceived discomfort of using a commercially available passive BSE.</td>
</tr>
<tr>
<td>Aim 3: Formulate an implementation strategy for the adoption of commercially available passive BSEs by incorporating perspectives of stakeholders regarding factors significant for the implementation of exoskeletons in the construction industry. (RQ3)</td>
<td>Study 3: Conduct a long-term* field study to determine workers perception of usability, and perceived discomfort and exertion of using a passive BSE.</td>
</tr>
<tr>
<td>Aim 4: Encapsulate perspectives of significant stakeholders with regard to factors which are critical for successful adoption of passive back support exoskeletons in the construction industry.</td>
<td>Study 4: Develop an implementation strategy to facilitate the adoption of passive back support exoskeletons in the construction industry.</td>
</tr>
<tr>
<td>Study 5: Developing implementation plan</td>
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*Note: The terms short-term and long term studies are used to denote use of wearable technologies for at least 30mins (Schwerha et al. 2022) and 5 days (Abeysekera and Shahnavaz 1988), respectively.

Table 1.2. Schedule for research completion

<table>
<thead>
<tr>
<th>STUDIES</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>Year 4</th>
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<td>F19</td>
<td>S20</td>
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<td>Study 1: Conducting laboratory experiment</td>
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<td>Study 2: Conduct short-term field study</td>
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<td>Study 3: Conduct extended field testing</td>
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<td>Study 4: Encapsulate stakeholder perspectives</td>
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<td>Study 5: Developing implementation plan</td>
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1.3.3 Research contributions

Answers to the research questions mentioned in Section 1.3.1 will contribute to the body of knowledge and state of practice in the following ways:
• Studies have shown that the use of passive BSEs could cause a reduction in back muscle activity and increase users’ productivity (Alemi et al. 2020; Kim et al. 2020). However, there is little evidence regarding the impact of using a BSE for construction work. By executing Study 1, **Aim 1** addresses this gap by quantifying changes in muscle activity and productivity between construction work performed with and without an exoskeleton. **Aim 1** also reveals unintended consequences of passive BSEs such as increased discomfort at the chest region and activations of some of the muscles.

• Studies have shown the suitability of exoskeletons for different industrial sectors (Kim et al. 2020; Schwerha et al. 2022). However, scarce studies have explored the suitability of exoskeletons for construction tasks. Thus, Study 2 of **Aim 2** contributes to literature by illustrating workers’ perception of the usability of passive BSEs, discomfort triggered by passive BSEs, and potential design modifications to make the devices suitable for construction tasks. The suggested modifications study could help exoskeleton manufacturers in re-designing the existing commercially available passive exoskeletons, to suit the requirements of the construction industry.

• The Unified Theory of Acceptance and Use of Technology (UTAUT) is a theory that explores the acceptance and adoption of technology, which is influenced by several factors such as the perceived impact on performance, the ease of use, social influence, and the availability of resources to facilitate its use (Williams et al. 2015). **Aim 2** contributes to this theory by explaining the aforementioned constructs in the context of passive BSE use for construction related work.

• **Study 4** establishes the factors (i.e., facilitators and barriers) that could influence the adoption of passive BSEs in the construction industry. **Study 4** also identifies the construction stakeholders who should be considered during the implementation of passive BSEs.

• Employing the factors from study 4, **Aim 3** puts forth a framework for the implementation of exoskeletons in the construction industry. Through the development of this framework, additional stakeholders, needed for the implementation of passive BSEs, are identified.

• Normalization Process Theory (NPT) is a theory that conceptualizes the implementation and integration of innovation in practice (Huddlestone et al. 2020). Also, the theory assists in understanding the factors that can affect the use of implementation framework. **Study 5** contributes to the NPT theory by developing and evaluating an implementation plan.

• The implementation plan developed from **Aim 3** can be used by researchers to develop similar frameworks for the implementation of other wearable technologies in the construction industry. The implementation plan can guide construction companies in the implementation of passive exoskeletons in their organizations.
1.3.4 Research significance

WMSDs are a major concern in the construction industry, as their occurrences have social and financial implications. This research contributes to the efforts of the construction industry to address the occurrences of WMSDs. It can potentially lead to increased awareness among construction professionals and researchers, ultimately leading to the adoption of these exoskeletons, potentially reducing the occurrences of WMSDs among construction workers, and improving workers' health and safety. The reduction in injury rates could also reduce direct workers' compensation costs, providing financial relief to construction companies. Furthermore, these injuries have the potential to cause permanent disabilities, contributing to the problem of labor shortages and increasing the demand on the existing workforce, leading to inefficiencies. Thus, this intervention could help address the problem of labor shortages in the construction industry.

This research also contributes to the scarce literature regarding the use of wearable robots in the construction industry. However, successful adoption of wearable robots is dependent on construction workers' willingness to use the device. This research is one of the first field studies capturing construction workers' acceptance of wearable robots on construction sites. Also, the proposed implementation plan is the first plan developed for the implementation of passive exoskeletons specifically for the construction industry. The development of the plan utilized the constructs of the Normalization Process Theory (NPT), commonly employed in the healthcare industry. However, there is scarce evidence regarding the use of NPT in the construction industry and for the adoption of exoskeletons. Thus, this research shows the efficacy of developing and evaluating an implementation framework to facilitate the implementation of exoskeletons in the construction industry. This research also highlights the importance of academia-industry partnerships, which can help in the development of interventions and processes for the construction industry.

1.4 Literature Review

1.4.1 WMSDs in the construction industry

“Work injuries and illnesses can affect every aspect of life for workers and their families”
Maine Department of Labor

Construction workers perform physically demanding tasks exposing them to well-known risk factors such as awkward postures, repetitive moments, lifting and carrying heavy loads, vibrations, bending, twisting, kneeling, prolonged squatting and standing, environmental risks, and contact force. These factors impose significant strain on the musculoskeletal system and increase workers' exposure to WMSDs, which is a growing concern in the construction industry. In simple terms, WMSDs are muscle-related injuries occurring in different parts of a worker's body as a consequence of the work performed over a prolonged period of time. Wang et al. (2017) defines WMSDs as “conditions that affect the muscles, tendons, joints, nerves and supporting blood
vessels that occur due to work-related activities, such as working in the same position for long periods of time, overexertion in carrying and lifting heavy objects, repetitive tasks, awkward body postures, and whole-body vibrations”. As highlighted by Wang et al. (2015), these injuries are also termed as “repetitive strain injuries, repetitive motion disorders, and overuse syndrome”. Furthermore, WMSDs are classified into cumulative trauma disorders, sprains, and strains depending on the cause of the injury (Inyang et al. 2012). Cumulative trauma disorder is a consequence of prolonged stress on a particular body part due to the work performed (e.g., maintaining awkward work posture and repetitive tasks). Whereas sprains and strains are muscular tears or joint abrasion arising due to high force from a single event (e.g., lifting and carrying heavy loads). Pain, discomfort, swelling, and aching are some of the common symptoms of WMSDs experienced by workers.

One of the most frequently reported causes of lost work time are WMSDs, which account for 33% of all the non-fatal cases of work-related injuries and illness in the construction industry (BLS 2022). According to the United States Bureau of Labor and Statistics (BLS), 15,330 construction trades (40.6 per 100,000 full-time workers (FTE)) sustained WMSDs in 2020 (BLS 2022). This rate is about 1.5 times the rate of 26.9 per 10,000 FTE for all industries (BLS 2022). These disorders have resulted in workers staying away from work for an average of 7 days, which is about 1.5 times the absenteeism experienced in other industry sectors (BLS 2022). These injuries are not restricted to any specific construction occupation or work activity, rather multiple construction trades (e.g., rebar workers, pipe workers, carpenters, and bricklayers) are affected (Rwamamara et al. 2010). Among these affected trades, the incidence rates for carpenters, rebar, and pipe workers are some of the highest in the construction industry (Akanmu et al. 2020; Rosecrance et al. 1996; Umer et al. 2017). These trades account for approximately 33% (5000 cases) of all the cases of WMSDs in the construction industry in the year 2020 (BLS 2022). Some of the most commonly affected body parts include back, knee, neck/shoulder, hands/wrists, and legs (Choi et al. 2016). However, among these affected body parts, back-related injuries account for 43% of all cases in the construction industry (Kim et al. 2019). Carpenters, rebar, and pipe workers spend a significant amount of time in a forward bending position which places a tremendous toll on their lower backs causing back injuries (Akanmu et al. 2020; Forde and Buchholz 2004; Rosecrance et al. 1996). In 2020, the rate of back injuries per 10,000 FTE amongst the carpenters and pipe workers was 1.4 and 4 times the rate for all the construction workers (13.6 per 10,000 FTE) respectively (BLS 2022). Although the rate of back injuries amongst rebar workers was equal to the rate of all construction workers, an ergonomic risk assessment conducted by Buchholz et al. (2003), indicated that these workers spend 58% of their time in non-neutral trunk positions when working causing back injuries (Buchholz et al. 2003). Back problems have been linked to worker illness, decreased productivity, and financial loss (Dagenais et al. 2008). Also, some cases of severe back conditions have led to permanent disability causing early retirement from the workforce (Frymoyer and Cats-Baril 1991).

Furthermore, contractors can incur economic losses from WMSDs. For example, according to the Center for disease control and prevention (CDC), workers’ compensation costs due to
WMSDs amount to about $13.4 billion annually (CDC 2020). In addition to direct workers’ compensation costs, contractors may also incur a variety of indirect costs, including the cost of keeping absent injured workers on the job, cost incurred from stopped work, cost of replacing injured workers and training new workers, and administrative time to document injury (Safety and Administration 2012). WMSDs have resulted in an early exit from the workforce (Antwi-Afari et al. 2018; Hoy et al. 2014). The costs to employees accumulate as WMSD becomes chronic and they end up cycling through different treatment modalities over time (Nobel et al. 2017). Increasing awareness of the long-term impact of WMSDs amongst workers has been attributed to the shortage of skilled construction workforce in the construction industry. Therefore, it is important to seek viable solutions to WMSDs in the construction industry.

1.4.2 Efforts to address WMSDs in the construction industry

Due to the high occurrences of WMSDs in the construction industry, researchers (Alwasel et al. 2013; Choi et al. 2016; Dias Barkokebas and Li 2021; Diego-Mas et al. 2020; Holmström and Ahlborg 2005; Vi 2006) have been exploring potential solutions to address this problem. For example, the impact of early warm-up exercises on the musculoskeletal fitness of construction workers was examined by Holmström and Ahlborg (2005). These exercises lasted 10 minutes each morning at the construction site which resulted in a significant improvement in thoracic and lower back mobility, as well as an improvement in hamstring and thigh muscle stretch-ability. Stretching and site exercise programs have been suggested and widely implemented on construction sites to reduce WMSDs and increase workers' performances (Rajendran 2013). Taking frequent breaks to stretch while performing tasks in forward bending and stooping positions has been suggested by the Occupational safety and health administration (OSHA) and construction companies have taken started mandating pre-work warm-ups (Cable 2007). Furthermore, to address the ergonomic and postural problems, health and safety-related organizations such as OSHA and the National institute for occupational safety and health (NIOSH) have also proposed some guidelines. For example, graphical guidelines for carrying out construction work using alternative tools and equipment were put forth by Moore (2011) and Albers (2007). These instructions also included alternatives for awkward work postures such as squatting, bending, kneeling, bending wrist, and twisting. However, these recommendations are typically provided through instructor-led instruction and online resources, with the assumption that the workers will learn and adopt a safe posture by absorbing verbal or visual information. The workers seldom get the opportunity to practice these skills and do not receive constant feedback for improvement. Thus, despite the implementation of stretching programs and guidelines, no significant reduction in the rate of WMSDs was observed (Wang et al. 2017).

In order to create a safe and effective workplace, ergonomic interventions involving tailoring tasks, tools, and environment to the needs of workers have been suggested by researchers (Abdul-Tharim et al. 2011; Ahankoob and Charehzehi 2013; Albers 2007). The use of ergonomic interventions to lessen musculoskeletal risk factors can range from alteration of very basic tools to the creation of complex material handling equipment or the automation of construction procedures.
For example, Albers (2007) suggested the use of equipment such as an auto-feed screw gun with an extension and rebar tying tools for flooring installation and rebar tying respectively. The author suggested that using these tools would reduce the time spent by the workers in forward bending and stooping positions thereby reducing the chances of lower back and knee injuries. However, concerns regarding the quality of the ties and the cost-effectiveness of using screws for certain projects were raised.

Moreover, advances in the use of wearable technologies have led to the use of wearable sensors (e.g., Inertial Measurement Unit (IMU) and Electromyography (EMG)) and vision-based systems for tracking workers' ergonomic risks. For example, an EMG-based biomechanical model was developed by Jia et al. (2011) to predict the load on workers' lower backs. This model was assessed for panel erection tasks and the results indicated a reasonable level of predictability compared to actual EMG readings. Despite the fact that surface EMG sensors directly detects muscle activations, EMG devices may be regarded as intrusive and cannot be used outside of the laboratory setting or in a real-world work environment. Furthermore, Nath et al. (2017) proposed the use of built-in smartphone sensors to autonomously identify ergonomic risks by monitoring the angles of workers' trunk and shoulder body parts. The trunk and shoulder flexion measured by the system has proximity to observation-based measurements thereby showing the potential for assessing the level of ergonomic risks. Valero et al. (2017) demonstrated the use of a wearable wireless motion sensor network for masonry work. The system integrates IMU devices in a wireless body area network and the data processing makes use of a state machine-based methodology to evaluate inappropriate working postures based on standard positions specified by the International Organization for Standardization (ISO). Zhao et al. (2021) developed a wearable IMU sensing system consisting of inertial measurement units and a mobile application user interface. The sensed movements tracked by the IMU are assessed and daily reports illustrate the type, frequency of occurrence, and extent of the ergonomic risks. A vision-based system was developed by Ray and Teizer (2012) which used a 3D range camera for human motion analysis by employing OpenNI middleware. Based on the body pose variants, the author categorized body posture according to a set of predetermined rules to ascertain whether a worker is assuming the correct posture while performing construction work in real-time. However, providing workers with feedback on work postures after they are been exposed to ergonomic risks does not help in preventing the occurrences of WMSDs.

In recent times, the use of immersive and interactive virtual environment to train workers and students has become popular and some researchers (Akanmu and Anumba 2015; Dias Barkokebas and Li 2021; Diego-Mas et al. 2020) have explored the possibility of using virtual reality devices for addressing WMSDs. For example, Dias Barkokebas and Li (2021) assessed ergonomic risks associated with the performance of construction tasks using a virtual reality environment. Diego-Mas et al. (2020) used an immersive virtual environment to train construction workers to avoid ergonomic risks while performing construction work. The results indicated that participants were more engaged in the learning process which led to an increased perception of ergonomic risks compared to the traditional training methods employed. However, it was also
observed that three months after the training, little influence of the immersive training program was observed on construction sites. Training through virtual environments takes place before or after regular working hours which does not establish a connection between workers’ learning and their work performance on construction sites. As a result, on-the-job intervention such as wearable robots which can protect workers against ergonomic risks without requiring them to assume specific postures is necessary.

1.4.3 Wearable robots: A way forward

BSEs are devices that help the user by providing a portion of the force required to perform physical tasks (e.g., lifting). As specified by Toxiri et al. (2019), BSEs are designed such that the “forces/torques are applied in the sagittal plane, between the user’s torso and thighs, to assist with extension of the back and/or hip joints”. In the past, researchers (Bosch et al. 2016; dos Anjos et al. 2022; Kim et al. 2018; Luger et al. 2021) have explored the possibility of using a passive BSE for other industrial sectors such as manufacturing, automobile, healthcare, and agriculture. For example, Luger et al. (2023) performed a laboratory experiment (n=36) to evaluate Laevo exoskeleton in terms of muscle activity (for the erector spinae, biceps femoris, rectus abdominis, vastus lateralis, gastrocnemius medialis, and trapezius descendens muscles), flexion and heart rate for industrial tasks (involving bending) and stair climbing activity. The results show a significant reduction in erector spinae (up to 19%) and biceps fermoris (up to 36%) muscle activities and trunk flexion (6%). However, no significant impact on heart rate was observed. Maurice et al. (2022) evaluated Laevo exoskeleton in terms of muscle activity (i.e., for the erector spinae muscle group) and trunk flexion for simulated patient transfer tasks. The results show a reduction in muscle activity of the erector spinae muscle group of up to 44%, however, an average increase in trunk flexion by 13% was identified. Laevo was also evaluated by dos Anjos et al. (2022) during a laboratory study (n=10) for static bending and lifting tasks in terms of trunk muscle activity and joint angles (lower limb). The results indicate a reduction in muscle activity by 10% (static bending task) and 5% (dynamic bending task) as well as a reduced range of motion for lower limb. Another laboratory experiment conducted by Luger et al. (2021) assessed Laevo V2.56 (n=36) in terms of muscle activity (erector spinae, biceps femoris, rectus abdominius, trapezius descendens), joint angles (knee and hip), and heart rate. Reduction in activity at erector spinae, biceps femoris, and rectus abdominis muscles up to 6%, 28% and 6% respectively, and heart rate (1.5bpm) was observed. However, an increase in the muscle activity of vastus lateralis and trapezius descendens up to 69% and 19% respectively and flexion at the median knee (≤6%) and hip (≤11%) was observed. So et al. (2022) assessed passive back support exoskeleton named ‘Muscle Suit Every’ for repetitive lifting tasks (n=20) in terms of trunk muscle activity (for the thoracic erector spinae and lumbar erector spinae muscles), spine kinematics and physical capacity. The results show a significant reduction in thoracic erector spinae and lumbar erector spinae muscle activity by up to 7% and 3% respectively. However, no significant impact on spine kinematics and physical capacity was observed. van Sluijs et al. (2023) evaluated LiftSuit2.0, a passive back support exoskeleton, for lifting tasks (n=30) in terms of muscle activity and whole-body kinematics. A
reduction in muscle activity by 25.59% and 20.52% was observed during forward leaning and lifting tasks respectively. However, there was no impact on body kinematics. SPEXOR exoskeleton was assessed by Koopman et al. (2020) in terms of compression force and muscle activity for lifting and static bending tasks (n=10). It was observed that the use of the exoskeleton reduced back muscle activity by 20-27% for lifting tasks. The compression force was reduced by 13-21% and 14% for static and lifting tasks respectively. Alemi et al. (2019) evaluated Virginia Tech Lowe’s exoskeleton in terms of muscle activation and level of perceived discomfort for symmetric and asymmetric lifting using 18 participants. A reduction in peak and mean activity of back muscle by 31.5% and 29.3%, respectively, for symmetric lifting and by 28.2% and 29.5%, respectively, for asymmetric lifting was observed. PLAD was assessed by Frost et al. (2009) in terms of muscle activations (erector spinae) for stooping, squatting and freestyle lifting tasks. Results showcased a reduction in muscle activity for erector spinae muscle by 37%, 38%, and 37% for stooping, squatting, and freestyle lifting respectively. Kazerooni et al. (2019) conducted a laboratory experiment (n=8) to evaluate BackX exoskeleton in terms of muscle activity at the thoracic and lumbar erector spinae for stooping tasks. Average muscle activity reduced by 75% and 56% at the thoracic and lumbar erector spinae respectively when using the exoskeleton. Ulrey and Fathallah (2013) tested BNDR (n=18) exoskeleton in terms of compression and shear force levels during stooping positions at erector spinae muscle. Compression and shear forces at the muscle reduced by 13% and 12% when using the exoskeleton. Bosch et al. (2016) observed an increase in endurance time from 3.2 min to 9.7 min using Laevo for a simulated industry assembly task. Reduction in trunk muscle activity, flexion, perceived discomfort and exertion, and increased endurance time were observed through the aforementioned studies thereby highlighting the potential of using BSEs to address WMSDs.

However, without the willingness of end users to use the exoskeleton regularly, the occurrences of WMSDs cannot be addressed. For the exoskeleton to be acceptable to the end users, it is critical that the exoskeleton attains a certain level of usability. In recent years, studies have been conducted to evaluate the usability of BSEs for diverse tasks. For example, Baltrusch et al. (2020) evaluated SPEXOR exoskeleton (n=24) in terms of user impression of donning/doffing, length adjustment, range of motion, interference with tasks, reduction of backloading, support of tasks, and use at work using a structured questionnaire (responses collected on a 7-point scale). The results show that the participants found donning/doffing and adjusting of the exoskeleton easy (1.3/7 to 1.9/7). The participants did not report the exoskeleton to have interfered with the work environment (2/7). However, they reported that the exoskeleton slightly restricted their range of motion (ROM) (1.4/7). Moderate (3.9 to 4.6) rating for support of tasks and reduction of back loading was registered. Two passive exoskeletons (Laevo and SuitX) were assessed by Alemi et al. (2020) in terms of usability by employing a structured questionnaire which the participants responded to on a continuous scale (0 to 100) for symmetric and asymmetric lifting tasks in standing and kneeling conditions. Results indicate that the participants reported the use of exoskeletons to be slight (50) to very helpful (70) and preferred BackX over Laevo for the tasks performed. Alemi et al. (2019) also assessed the PLAD exoskeletons for repetitive symmetric and
asymmetric lifting tasks in standing and kneeling positions in terms of usability. Participants provided a usability rating ranging from slightly (30/100) to extremely helpful (70/100) for the tasks. But the individuals (n=18) noted more soreness in their chest, waist, and thigh body parts. Although the aforementioned studies show the acceptable usability of passive BSEs, the participants were not the end users. In order to improve the acceptance of the technologies among the targeted users, perspectives of end-users are required in the design and evaluation of wearable technologies (Angelini et al. 2013).

Additionally, in recent times, usability tests have been conducted with actual end users in field settings. For instance, Amandels et al. (2019) evaluated Laevo V2.4 for industrial working environment (n=9). Perceived discomfort was measured using body map where participants rated 9 body parts on a 10-point Likert’s scale and user experience questionnaire was obtained using a 7-point scale ranging from -3 to 3. The perceived discomfort was measured using a questionnaire. The results indicated an increase in discomfort at the chest and thigh body parts. Neutral user experience (-0.8 to +0.8) in terms of attractiveness, perspicuity, efficiency, dependability, and stimulation whereas positive user experience (> +0.8) for novelty was identified. Motmans et al. (2019) assessed Laevo V2.5 exoskeleton (n=10) for load picking activity in the logistics industry in terms of user impression of physical load, stepping, body part support, and donning and doffing, using a structured questionnaire based on a 5-point Likert’s scale. The participants reported a high rating (4.5/5) for reduced physical load and the lowest reading (1.75/5) was associated with stepping on/off with the exoskeleton. For questions related to donning and doffing, posture of back, and support to chest and leg body parts, the participants provided moderate ratings ranging from 3.25/5 to 3.75/5. Siedl and Mara (2021) evaluated a passive BSE amongst logistic workers (n=14) in terms of workers' using a structured questionnaire which the participants responded to using a 5-point Likert’s scale. It was observed that the workers experienced a reduction in strain at the lower back which led to an increase in perceived self-efficacy thereby increasing their willingness to use the exoskeleton in the workplace. Ziaei et al. (2021) evaluated Ergo-vest, a passive exoskeleton, for waste collection in terms of perceived exertion (Borg’s scale) and usability through the system usability scale (SUS). Participants reported a reduction in perceived exertion (13%) when using the exoskeleton and provided an acceptable usability rating (83.6/100).

Furthermore, there have been studies in construction exploring the possibility of BSEs for construction work. For example, Golabchi et al. (2023) conducted a laboratory experiment (n=12) to evaluate BackX exoskeleton for manual material handling tasks (including static and dynamic movements) in terms of perceived exertion, discomfort, and usability. The results show a reduction in discomfort at the lower back body part and an increase in discomfort at the chest body part. Overall, the participants provided moderate level of rating for the usability questionnaire. Ojelade et al. (2022) evaluated passive back support exoskeletons (BackX, Paexo Back, and HeroWear Apex) for simulated construction-relevant static and dynamic tasks in terms of task performance and usability (perceived effort). The results show a reduction in perceived effort of up to 29%, however, increased task completion time between 10%-25% was observed. Antwi-Afari et al. (2021) evaluated BSE for manual material handling work (i.e., lifting and carrying heavy loads)
in a laboratory setting in terms of muscle activity, perceived discomfort, and usability. It was observed that the use of an exoskeleton significantly reduced erector spinae muscle activity (32.71%) and perceived discomfort in the lower back (42.40%). Also, the majority of the participants reported acceptable usability for material handling tasks. Cho et al. (2018) designed and assessed a BSE in terms of range of motion for brickwork. The use of the exoskeleton helped in keeping the participants' lower back flexion within a safe range thereby reducing their exposure to ergonomic risks. Thus, the results from the above-described studies show the potential of using BSEs to address WMSDs on worksites through subjective and objective measures.

1.4.4 Research gap

From the aforementioned studies, it is evident that the adoption of BSEs could help address the occurrences of WMSDs in the construction industry. However, there is limited evidence of the impact of implementing BSEs on construction sites. Thus, before proceeding with the adoption of BSEs to address WMSDs in the construction industry, the following research gaps would need to be addressed:

- Tasks studied in previous work largely involve restricted body movement. For example, participants were restricted to only performing forward bending or static bending tasks. However, construction work involves dynamic body movements (e.g., twisting, squatting, climbing, and reaching out). Thus, the extent of impact of using BSEs for such diverse movements need to be examined.

- Construction work involves multiple subtasks that the workers need to undertake to complete a given task. For example, rebar work would involve subtasks such as lifting, placing, and tying. However, previous studies on evaluation of exoskeletons have mainly focused on a single task i.e., static bending or lifting only. Hence, the use of BSEs across the different subtasks executed for construction work should be assessed.

- Construction workers are exposed to harsh working conditions such as confined spaces, humidity, extreme temperatures, heavy winds and rain, and dusty environments (Moda et al. 2019). These extreme conditions have impact on the workers' fatigue and cognitive workload which might affect user acceptance. Thus, the usability of exoskeleton, an additional wearable layer, under such conditions and the impact of this on workers' acceptance should be investigated.

- Use of exoskeletons on construction sites could pose safety and usability challenges (Kim et al. 2019). For example, the added weight of BSEs on workers' bodies might cause imbalance when walking on uneven surfaces and the BSEs might be incompatible with some of the equipment being used on construction sites. The use of BSEs under such conditions should be taken into consideration.

- Given that BSEs are external wearables, the efficacy of the devices for addressing WMSDs depends on the end users' willingness to use the exoskeleton regularly. Willingness of workers to use exoskeletons is governed by their perception of exoskeletons (Siedl and
Mara 2021). However, there is limited evidence of the perception of construction workers regarding the use of BSEs for construction tasks.

- Adoption of new technology is often driven by factors that have the potential to either facilitate or act as barriers to the implementation process (Glyptis et al. 2020). Although studies (Cha et al. 2020; Elprama et al. 2022; Kim et al. 2019) have highlighted factors could influence adoption of exoskeletons, there is scarce evidence in the literature concerning applicability or relevance of the factors to the construction industry.

- Involvement of stakeholders’ perspectives in the implementation of any technology is critical for the success of new technologies (Kamal et al. 2011). However, scarce knowledge is available regarding the relevant construction stakeholders and their perspectives regarding the implementation of BSEs in the construction industry.

- An implementation framework/strategy is key for the successful adoption of new technology (Atkinson 2006). Poor implementation strategy could lead to failure in adopting a promising technology (Gichoya 2005). However, there is currently no framework to assist construction companies in successfully implementing BSEs.

### 1.4.5 Theoretical underpinning

#### 1.4.5.1 Socio-technical systems theory

Modern-day organizations are complex and constitute multiple interdependent subparts that work together to create performances (Clegg 2006). Change in any one subpart could have an impact on the functioning of another subpart and could limit the effectiveness of the implemented change. Hence, even when adopting technology for one subpart, it is important that all the parts are taken into consideration. This is the basis of socio-technical systems (STS) theory which is defined by Baxter and Sommerville (2011) as “an approach to design that considers human, social, and organizational factors as well as technical factors in the design of organizational systems”. The theory is a result of a study conducted by Tavistock Institute in the UK regarding the introduction of coal mining machinery which highlighted that technological and social aspects are interrelated (Trist et al. 2013; Trist and Bamforth 1951). Without considering behavioral issues, implementation of new technology could lead to sociological complications. When deploying new technology or making business changes within an organization, the belief that design is systemic and requires consideration of both social and technological issues led to the emergence of socio-technical systems theory (Cherns 1976; Mumford 2000).

In recent years, different researchers have explored STS for diverse applications e.g., manufacturing (Dankbaar 1997), organization development (Appelbaum 1997), development and diagnostics of information technologies (Clegg 2000; Hester 2014), and accident analysis and causation (Salmon et al. 2016). While the specific concepts and applications have evolved to match the dynamic nature of work, technology, and design methods, the basic philosophy has generally remained the same. The focus has evolved from a concentration on heavy industry to advanced manufacturing technologies (Dankbaar 1997), and office-based work and services (White et al.
For example, Mumford (2000) suggested using the value system of socio-technical systems theory for designing new systems. The study suggested raising different approaches and questions which can assist in considering the human, organizational, and social aspects when designing a new system. In the study, the designers and the users are considered as humans, the environment in which the new system will be implemented, and its impact is considered as the social aspect, and coordination between different groups and effective implementation of the proposed change is termed as the organizational aspect. Appelbaum (1997) used STS and organization theories to create organization development intervention in terms of self-regulating work groups to perform interrelated technological tasks. The study also presents a list of 31 questions that can be used to assess the STS intervention to keep a check on the involvement of different elements (i.e., people, environment, structure, technology, task, and leadership procedures) of the STS theory. The employees represent people, the impact of change on the work environment represents the environment, structures are the hierarchy of decision-making in the organization, technology is the change, the task is the goal, and leadership is the influence and capability of decision makers. Hester (2014) designed a survey using STS theory to understand the underutilization of wiki technology. The study considered the interaction between the different components of the STS model (i.e., task, technology, structure, and actor) to identify the cause of underutilization. The technology in the study is the wiki page, members of the organization and stakeholders are the actors, systems of communication, authority, and workflow is considered as structure and tasks represent the goals and the way work is done. Wang et al. (2010) proposed a model named the multi-dimensional system flexibility scale to evaluate the success of distance learning through the lens of STS theory by involving the social and technical aspects. The model considers the design of course management system to be the technical aspect and the goal of the distance learning course to be the social aspect. The study evaluated the proposed model from the instructors’ perspective using an online questionnaire and found the model reliable. Thus, based on the aforementioned studies, human, organization, technology and social aspects can be considered as basic sub-systems within the framework of STS (shown in Fig. 1.2).

With respect to this research, the proposed ‘change’ in the construction industry is the introduction of exoskeletons to improve the safety and health of construction workers. In the context of the overall goal of this research, the human are the construction workers who are the potential end users, the organization comprises the decision makers and the stakeholders within the construction industry, the technology under consideration is a passive back-support exoskeleton and social sub-system will include the involvement of work environment, regulatory bodies (i.e., Occupational Safety Health Administration), and social influence on the end users’ intention-to-use. Thus, this research is underpinned under the STS theory.

1.4.5.2 Socio-technical systems theory within the context of this research

Although STS theory suggests considering the interaction between human, technology, organization, and social aspects, the notion of user participation lies at the heart of STS theory (Baxter and Sommerville 2011). The theory suggests that end users should participate in integrated
systems development to create a system that incorporates social and organizational perspectives and not just technical aspects. Since this research considers the human and wearable robot interaction in the construction industry, human aspects are at the core of all the studies. Table 1.3 summarizes the studies adopted to answer the research questions, assessment tools, analysis methods, and outcome measures of each study.

The use of wearable robots has the potential to reduce muscle activity which could lead to reduced muscle fatigue thereby addressing the occurrences of WMSDs (Koopman et al. 2020; Madinei et al. 2019). However, the use of an exoskeleton could have unintended consequences such as increase in discomfort to body parts (Giustetto et al. 2021) and reduced productivity (Toxiri et al. 2019). These factors could impact the adoption of BSEs in the construction industry. Scarce evidence is available in the literature regarding the impact of using an exoskeleton for construction work. Thus, Study 1 will investigate the interaction between humans (i.e., a participant using technology) and technology (i.e., exoskeletons) and will be viewed from the lens of the human and wearable robot interaction (Fig. 1.2).

The effectiveness of wearable robots or back-support exoskeletons (BSEs) to address the occurrences of work-related musculoskeletal disorders (WMSDs) is subject to end users' willingness to don (i.e., put on) and use exoskeletons regularly. If an exoskeleton is not easy to use and comfortable, and if an exoskeleton affects the user's ability to work, end users will not be willing to adopt exoskeletons on their job sites (Moyon et al. 2019). Furthermore, exoskeletons being desirable to the end users is just as important as it is safe and usable (Davis et al. 2020). Thus, within the context of the construction industry, it is important to consider construction workers' perspectives for designing, evaluating, and implementing exoskeletons. Furthermore, as mentioned by Davis et al. (2020), the short- and long-term implications of using exoskeletons are critical for its adoption. Assessing the short-term impact of using exoskeletons could help identify the initial acceptance which is critical for the workers' willingness to try exoskeletons for work. Furthermore, evaluating the extended use of exoskeletons can help understand the impact on workers' acceptance with respect to time. Thus, Studies 2 & 3 are underpinned in the human-centered design principle related to human-wearable robot interaction and can be viewed primarily from the perspective of the Unified theory of acceptance and use of Technology (UTAUT) theory (Fig. 1.2).

The STS theory highlights the need for involving all the subparts in the adoption of new technology. Within the context of the implementation of BSEs in the construction industry, different stakeholders could be considered as subparts. Thus, to incorporate different stakeholders in the adoption of exoskeletons, it is necessary to consider their perspectives in the design, evaluation, and implementation process as highlighted by Crea et al. (2021) and Welch et al. (2015). However, for the implementation of new technology, it is important to identify the critical factors which could influence the adoption of exoskeletons. Thus, owing to the importance of stakeholders’ perspectives on technology adoption, Study 4 is underpinned under the socio-technical systems theory and aims to involve stakeholders’ perspectives for the adoption of BSEs in the construction industry (Fig. 1.2). Furthermore, Study 5 will consider all four sub-systems
(i.e., human, technology, organization, and social) of the STS theory and develop an implementation strategy for the adoption of exoskeletons in construction organizations through the lens of Normalization Process Theory (Fig. 1.2). This could help ensure that the implementation strategy can become fully operationalized in the daily work practice of construction organizations. Fig. 1.2 provides an overview of theoretical underpinning theories, the sub-theories, and how they are been utilized in this research.

**Figure 1.2. Theoretical underpinning**

**1.5 Project Implementation, Data Analysis and Expected Outcomes**

The research encompasses five studies each addressing the three aims identified in Section 1.3.1. The research entails laboratory and field explorations as well as online surveys, semi-structured interviews, and focus groups (as shown in Table 1.3). These are described in more detail in this section.

*Aim 1:* Examine the effect of a commercially available passive BSE on muscle activity, perceived discomfort, and productivity for construction work.

**Study 1:** Conduct a laboratory experiment to measure the extent of impact of using a commercial passive BSE on muscle activity, perceived discomfort, and productivity for construction work.
The effects of a commercially available BSE on work performance and physical demands during stooped work and repetitive lifting tasks was determined through a lab study. The results show the efficacy of using an exoskeleton for rebar tasks. Participants (n=10) were recruited with a background in civil engineering/construction to ensure that the study population has a basic understanding regarding construction work tasks. Owing to the high ergonomic risk exposure observed amongst rebar workers (mentioned in Section 2.1), this study required the participants to simulate common tasks in rebar work (placing and tying) that place high demands on the low-back. Participants performed the tasks with BSEs (exoskeleton condition) and without BSEs (control condition). A broad set of subjective and objective measures of the following outcomes were obtained: (1) performance – productivity of the workers; and (2) physical demands – muscle activations in the back body-part, and participant’s ratings of discomfort. Analysis of variance (ANOVA) was performed on outcome measures from each task, to compare the effect of using BSE. Through this study, the extent of the impact on workers’ muscle activity, discomfort and productivity when using a BSE for construction work were identified.

**Aim 2: Evaluate the usability of a commercial passive BSE for construction work and its impact on construction workers' perceived discomfort and exertion on construction sites.**

**Study 2:** Conduct a short-term field study to capture construction workers' perspective of the usability of exoskeletons, and perceived discomfort of using a commercially available passive BSE.

This study identified the effectiveness and acceptability of BSE use in the field. The commercially available BSE used in the laboratory experiment was evaluated through short-term field explorations. At the end of each testing session, surveys on usability, safety, comfort, perceived discomfort at different body parts, and workers' perceptions of using BSEs were obtained. A field-based study of up to 14 pipe workers was conducted to determine the efficacy and effectiveness of using BSEs on construction sites. Each study session constituted construction workers performing their usual work tasks for a period of 4 hours with a BSE. This is a controlled, pre and post-evaluation design, and a mixed-method approach was used. At the mid and end of each session, participants provided inputs on discomfort of the body parts. After using the BSE, input were obtained from workers regarding the following outcome measures: (1) usability (e.g., ease of use and comfort); (2) safety concerns; (3) level of perceived discomfort at different body parts; and (4) workers’ user experience. Participants were trained on how to use BSE and were free to decide if/when to use the device. This field study was executed in collaboration with Allan Myers who provided access to their sites. Descriptive statistics was employed to analyze the usability data, whereas the physical discomfort was analyzed using Wilcoxon signed rank test. The influence of discomfort on workers perception of usability was analyzed using Spearman’s rank correlation analysis. Participants’ user experience was analyzed using thematic analysis. The results identify the (1) Benefits of and barriers to the practical use of BSEs – including the suitability of BSEs for
various tasks, work requirements, and environment; and (2) Recommendations for improving exoskeleton designs for construction use.

**Study 3:** Conduct a long-term field study to determine workers' perception of usability, and perceived discomfort and exertion of using a passive BSE. We conducted a second phase of the field study to determine the effectiveness and acceptability of BSE use in the field. At the end of each workday, surveys on usability, safety, comfort, and exertion were obtained. A field-based study of 15 workers was conducted to determine the efficacy and effectiveness of the BSE. Construction workers performed their usual job tasks over 10 days (i.e., 5 days without and 5 days with a BSE). This was a controlled, pre-post evaluation design, and a mixed-method approach was used. At both the start, mid, and end of each day, participants provided inputs on body part discomfort and exertion. After using the BSE, inputs were obtained from workers regarding the following outcome measures: (1) usability (e.g., ease of use, comfort); (2) feasibility and extent of use; (3) performance (i.e., productivity); (4) safety concerns; and (5) long term user experience. Participants were trained for BSE use and were free to decide if/when to use the device. Using the ordinal logistic regression analysis, the perceived discomfort and exertion was analyzed. The change in the usability of BSE with time was analyzed using Wilcoxon rank sum test. The subjective feedback data collected from the participants was analyzed using thematic analysis. Spearman’s rank correlation analysis was conducted to measure the impact of outcome measures on workers' intention-to-use. The results identify the (1) Change in workers' perceived physical demand with time; (2) Acceptance amongst workers for different work tasks, and environments; and (3) Recommendations for improving exoskeleton designs for construction use.

**Aim 3:** Formulate an implementation strategy for the adoption of commercially available passive BSEs by incorporating perspectives of stakeholders regarding factors significant for the implementation of exoskeletons in the construction industry.

**Study 4:** Encapsulate perspectives of significant stakeholders with regard to factors which are critical for successful adoption of passive back support exoskeletons in the construction industry. We investigated the factors which can affect the adoption of BSEs in the construction industry. From literature, a list of facilitators which can help promote adoption and barriers which can obstruct the implementation of exoskeletons were identified. Through an online survey, industry professionals' perceptions regarding the factors (i.e., facilitators and barriers) and their level of importance, and critical stakeholders for exoskeleton implementation were collected. Two focus group discussions involving stakeholders identified from the survey was conducted to validate the result of the online survey. The survey results were analyzed using Analytical Hierarchy Process. The focus group discussion was analyzed using thematic analysis. Through this study, we identified the critical factors (i.e., facilitators and barriers) which can affect the implementation of BSEs in the construction industry.
**Study 5:** Develop an implementation strategy to facilitate the adoption of passive back support exoskeletons in the construction industry.

We investigated an implementation plan for BSEs in the construction industry based on the barriers and factors identified in Study 4. Data was collected via surveys to identify stakeholder considerations for adopting and implementing exoskeletons, and the extent to which the considerations are important. Based on the results of the survey and literature review of other strategies, an implementation plan was formulated. Semi-structured interviews were conducted for pilot testing. We selected participants from the survey to partake in a follow-up focus group discussion to further establish the plan for implementing BSEs in the construction industry. A scenario-based case study was conducted to evaluate the developed plan. Qualitative analysis was conducted on the semi-structured interview and focus group data to identify modifications to the BSE implementation plan whereas descriptive statistics was employed to analyze usability data. In this study we developed a framework that will guide contracting firms on how to adopt and implement exoskeletons in the construction industry.

<table>
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<tr>
<th>Table 1.3. Research Implementation: Questions, Studies, Assessments, Analysis and Outcomes</th>
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<td><strong>Question 1</strong></td>
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<td><strong>Study 1</strong></td>
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<td><strong>Assessment</strong></td>
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<td><strong>Question 2</strong></td>
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<td><strong>Study 2</strong></td>
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<td>Outcome</td>
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group discussion was then employed to validate the plan and scenario. A scenario-based case study was used to evaluate the plan. A usability questionnaire was employed to evaluate the acceptance of the implementation plan among construction industry stakeholders.

<table>
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<tr>
<th>Analysis</th>
<th>Thematic analysis was conducted to analyze qualitative data whereas descriptive statistics was employed to analyze questionnaire data.</th>
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<tbody>
<tr>
<td>Outcome</td>
<td>Development of a framework to facilitate the implementation of passive exoskeletons in the construction industry.</td>
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### 1.6 Dissertation Structure

This dissertation adopts a manuscript-based format. Chapters 2 and 3 have been published in credible journal outlets such as Information Technology in Construction (ITCoN) and ASCE Journal of Construction Engineering and Management (JCEM). Chapters 4, 5 and 6 have been submitted to journals such as JCEM and Engineering, Construction and Architectural Management (ECAM). The organization of this dissertation and brief description of each chapter is presented as follows:

**Chapter One: Introduction**

In the first chapter, a broad outline of the research is provided through an introduction to the background and problem statement, an examination of the literature, and identification of research gaps. Furthermore, the research questions that were formulated for the studies are also introduced in this chapter. A brief summary of the research aims and methods utilized in this research is also presented.

**Chapter Two: Assessment of a passive wearable robot for reducing low back disorders during rebar work**

Chapter two measures the extent of impact of using a commercial passive BSE on physical demand, and users’ performance for construction work. Aim 1 was achieved in this chapter. A laboratory experiment was performed during which participants’ muscle activity, perceived discomfort, and completion time were measured.

**Chapter Three: Industry perception of the suitability of wearable robot for construction work**

Chapter three contributes to Aim 2. This chapter captures construction workers’ perspectives on the usability of exoskeletons and perceived discomfort of using a commercially available passive BSE. These measures were assessed through a field study of pipe workers.

**Chapter Four: Assessment of workers’ acceptance of passive back support exoskeletons for construction work**

Chapter four determines workers' perception of usability, discomfort and exertion, and the impact of social influence on workers' acceptance of a passive BSE after prolonged use of the device. This
chapter also contributes to Aim 2. User acceptance of passive BSE among pipe and concrete workers after prolonged use was measured.

**Chapter Five: Industry perspective of the factors inferencing the adoption of passive wearable robots on construction projects**

Chapter five encapsulates the perspectives of construction professionals regarding the stakeholders and factors which are critical for the successful adoption of passive BSEs in the construction industry. The chapter also explains how these factors influence the adoption of passive BSEs. This chapter contributes to Aim 3.

**Chapter Six: Exo-Implant: An implementation plan for exoskeleton adoption in the construction industry**

In Chapter six, an implementation strategy to facilitate the adoption of passive BSEs in the construction industry is developed. This chapter also contributes to Aim 3.

**Chapter Seven: Conclusion**

This chapter summarizes the findings of this research, presents the contributions and suggests recommendations for future research. This includes contributions to the body of knowledge and state of practice. Additionally, Chapter seven discusses possible future work that can be done to further build upon the findings of this study.
CHAPTER 2: ASSESSMENT OF A PASSIVE WEARABLE ROBOT FOR REDUCING LOW BACK DISORDERS DURING REBAR WORK

2.1 Abstract

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

2.2 Introduction

Work-related musculoskeletal disorders (WMSDs) make up about 37% of non-fatal injuries and illnesses experienced by construction workers (Statistics 2016). Construction workers are constantly exposed to awkward work postures which are repetitive and physically demanding in nature leading to WMSDs. According to the United States Bureau of Labor and Statistics (BLS), 18,070 construction trades (44.6 per 100,000 full-time workers (FTE)) sustained WMSDs in 2019 (BLS 2020). This rate is about 60% higher than the rate of 27.8 per 10,000 FTE for all industries (BLS 2020). Rebar workers are one of the construction trades with the highest rates of non-fatal injuries and illnesses (Umer et al. 2017; Yan et al. 2018). Rebar work involves tying and placing reinforcing bars in formworks prior to filling the formworks with concrete. A National Institute for Occupational Safety and Health (NIOSH) evaluation of iron workers’ exposures found that rebar workers are prone to a high risk of low back disorders. This is because rebar workers spend approximately 40–48% of their working time in prolonged non-neutral trunk working posture (Forde and Buchholz 2004).
Low back disorders or injuries are the most prevalent of all musculoskeletal disorders (Wang et al. 2017). These disorders were responsible for approximately 40% of WMSD cases and resulted in an average of 7 lost workdays in 2019 (BLS 2019). Back disorders have been known to trigger worker ill-health, reduced productivity, and financial loss. For example, according to a 2019 report by Liberty Insurance (Mutual 2019), workers’ compensation costs due to musculoskeletal disorders amounted to about $5.99 billion annually. There were reports of severe back disorders resulting in permanent disability and premature exits from the workforce (Wang et al. 2015). In 2018, lost work days due to back disorders among rebar workers was about 4 times more compared to the average of 14 days for all construction trades (BLS 2020). One of the leading causes of back injuries is overexertion. Rebar workers are constantly exposed to well-documented risk factors of overexertion such as awkward postures and repetitive motions (Everett 1999; Ray and Teizer 2012; Wang et al. 2015; Wang et al. 2017).

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

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

2.3 Background

2.3.1 Interventions to address WMSDs in the construction industry

Over the years, efforts to reduce WMSDs have been largely focused on educating and training construction workers on how to perform work safely, tracking workers’ performance and alerting
them of unsafe postures, and using wearable robots such as exoskeletons to reduce ergonomic risks during work performance (Akanmu et al. 2020; Antwi-Afari et al. 2019; Gillen 2010). Safety and health organizations such as the Occupational Safety and Health Administration (OSHA) and NIOSH published guidelines for addressing general ergonomic and postural issues experienced during general material handling tasks. Moore et al. (2011) and Albers and Estill (2007) provided graphical ergonomic guidelines for executing construction tasks with alternative tools and equipment such as a power tier. Albers and Hudock (2007) suggested that the use of power tier could allow workers to have one hand free which can help to support their trunk and consequently increase their productivity. Unfortunately, such technological interventions are merely used as a tool to increase productivity with little attention on addressing WMSDs. However, advances in virtual technology have triggered developments of immersive and interactive work training environments. For example, Akanmu et al. (2020) developed and assessed a virtual reality (VR) based environment where workers can practice work in safe postures and get feedback based on their performance. Dias Barkokebas and Li (2020) also proposed a VR environment for assessing ergonomic risks associated with performance of industrialized construction tasks. Training with manuals and within the VR environments occur before or after workers’ actual workday, thus the linkage between the actual performance of the worker and learning for continuous improvement is not established. In contrast, on-the-job interventions have also been investigated. Yan et al. (2018) proposed a wearable inertial measurement units-based personal protective equipment for tracking and alerting rebar workers about the risks associated with their trunks. While this effort has potential for reducing ergonomic risks of construction work, alert system used could be a distraction which could affect workers’ productivity. Furthermore, compliance with the feedback is at the discretion of the workers as they might choose to neglect the alert, thereby disrupting the sole purpose of this intervention. Thus, a wearable system independent of the workers feedback to mitigate WMSDs has inspired the assessment of wearable robots such as exoskeletons.

2.3.2 Exoskeleton for WMSD prevention

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

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

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

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

2.4 Methodology

This section presents the approach employed in the assessment of the exoskeleton (Fig. 2.1), including an overview of the back-support exoskeleton, participants involved, simulated rebar task, experimental procedure, data collection, and analysis.

![Figure 2.1. Overview of methodology](image-url)
2.4.1 Exoskeletons

The passive exoskeleton, BackX™ S (https://www.suitx.com/backX), used in this study is shown in Fig. 2.2. BackX™ S is intended to reduce the load on a wearer’s lower back while performing work that involves bending, stooping, or reaching. BackX™ S weighs 3.4 kg and is designed to provide 13.6 kg of support to the lower back. The exoskeleton consists of a frame and a harness. The frame comprises of a torque generator, chest-plate and thigh straps. The torque generator serves as the activation point for the exoskeleton. The chest-plate and thigh straps are connected on both sides of the body with metal frames. The harness consists of a chest pad, hip belt, and straps (for the shoulder, chest, and legs), all of which are secured to the frame to the body. The frame is overlaid on the harness.

![Exoskeleton Diagram](image)

(a) Frame  (b) Harness  (c) Complete exoskeleton

Figure 2.2. BackX exoskeleton

2.4.2 Participants

Ten individuals were recruited from the Virginia Polytechnic Institute and State University to participate in the study. The participants signed a consent form after being informed about procedures of the experiment. The consent form was approved by the Virginia Tech Institutional Review Board (IRB-19-796). All the participants reported having no current or prior musculoskeletal issues that affect their ability to stand, walk, bend, and lift. The participants were male with the demographic information presented in Table 2.1.
Table 2.1. Participants’ demographics

<table>
<thead>
<tr>
<th>Demographic Characteristic</th>
<th>Mean</th>
<th>SD</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>23</td>
<td>2</td>
<td>21</td>
<td>25</td>
</tr>
<tr>
<td>Weight (Kg)</td>
<td>75.14</td>
<td>8.74</td>
<td>56.6</td>
<td>86</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>175.95</td>
<td>4.70</td>
<td>167.74</td>
<td>185.42</td>
</tr>
<tr>
<td>BMI (Kg/m2)</td>
<td>24.36</td>
<td>3</td>
<td>18.5</td>
<td>28.1</td>
</tr>
</tbody>
</table>

Note: SD = Standard Deviation, Min. = Minimum, Max. = Maximum

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

2.4.4 Task description – Simulated rebar work
The simulated rebar task (see Fig. 2.3) involved repetitive placing and tying (subtasks) of four prefabricated gates. Each gate has a cross-sectional area of 600mm by 400mm, with #6 rebars placed at 127mm on center (both ways). Participants were asked to place each prefabricated gate on the ground and tie the joints with pre-cut ties using a plier. To replicate the repetitive nature of rebar tasks, the participants placed the gate and tied 6 joints which represented as one cycle. Each participant completed four cycles without and with the exoskeleton.

Figure 2.3. Participant performing simulated rebar task.
2.4.5 Data collection

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

2.4.5.1 Completion time

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

2.4.5.2 Muscle activity

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

2.4.5.3 Discomfort

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

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

2.4.6.1 Pre-processing

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

2.4.6.2 Statistical analysis

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

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

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

2.5.1 Task completion time

Table 2.2 presents the summary of the ANOVA (F-Value, P-Value and effect sizes (η²)) and Post Hoc tests performed for completion time, across the subtasks, cycles, and exoskeleton condition. P-values with ‘*’ have a confidence level < 0.05.

Table 2.2. Completion time of participants with and without BackX exoskeleton during rebar tasks.

<table>
<thead>
<tr>
<th></th>
<th>F-Value</th>
<th>P-Value</th>
<th>η²</th>
<th>Post Hoc</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Exo</strong></td>
<td>6.033</td>
<td><strong>0.034</strong></td>
<td>0.006</td>
<td>Noexo &gt; BackX</td>
</tr>
<tr>
<td><strong>Subtasks</strong></td>
<td>51.01</td>
<td><strong>3.13e-05</strong></td>
<td>0.65</td>
<td>Tying &gt; Placing</td>
</tr>
<tr>
<td><strong>Cycles</strong></td>
<td>4.293</td>
<td><strong>0.012</strong></td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td><strong>Exo X Subtask</strong></td>
<td>4.258</td>
<td>0.066</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td><strong>Exo X Cycles</strong></td>
<td>7.486</td>
<td><strong>0.0007</strong></td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td><strong>Subtask X Cycles</strong></td>
<td>5.913</td>
<td><strong>0.003</strong></td>
<td>0.005</td>
<td>Tying (1) &gt; Tying (4)</td>
</tr>
<tr>
<td><strong>Exo X Subtask X Cycles</strong></td>
<td>7.814</td>
<td><strong>0.0005</strong></td>
<td>0.005</td>
<td>Noexo Tying (1) &gt; BackX Tying (1, 2, 3, 4) Noexo Tying &gt; BackX Tying</td>
</tr>
</tbody>
</table>

**Note:** Exo = Exoskeleton Condition

Fig. 2.4 shows the overall mean completion time for the exoskeleton conditions across four cycles during placing (Fig. 2.4a) and tying (Fig. 2.4b) subtasks, and the error bars indicate the standard deviation of the mean as a measure of variations across all participants. Overall, the effect of the exoskeleton reduced rebar task completion time (p = 0.034). During the placing subtask, the use of the exoskeleton reduced the completion by at least 20% for the first, second, and third cycles (Fig. 2.4a). However, the exoskeleton reduced task completion time by only 15% at the fourth cycle. The results revealed that the completion time of the tying subtask was significantly higher than the placing subtask (p = 3.13e-05). Hence, the effect of the exoskeleton was revealed differently across these subtasks. For the tying subtasks, there was a significantly lower completion
time at the first cycle \((p = 0.0005)\). When tying subtasks was performed with the exoskeleton, the task completion time was reduced by 50\% for the first cycle (Fig. 2.4b). The effects of the exoskeleton on completion time during cycle 1 was significantly higher than the other cycles, although, for subsequent cycles, the task completion time was reduced by at least 7\%.

![Figure 2.4](image-url)

**Figure 2.4.** Completion time across cycles with and without exoskeleton conditions

Note: The error bars represent standard deviations and ‘*’ indicates a significant difference, and blue and orange bars represent NoExo and Exo (BackX) conditions respectively.

### 2.5.2 Muscle activity

Tables 2.3, 2.4 and 2.5 presents summary of the ANOVA (F-Value, P-Value and effect sizes (\(\eta^2\))) and post Hoc tests performed for the EMG data, across the subtasks, cycles, and exoskeleton condition. P-values with ‘*’ have a confidence level < 0.05.

During the rebar task, no statistical effects of the exoskeleton was observed on the muscle activations. Results show some increase in the Erector spinae (ES) and Latissimus dorsi (LD) muscle activations. Static muscle activations were significantly higher during placing subtask than during tying subtask for ES \((p = 1.22e-05)\) and LD \((p = 0.049)\). There was a correspondingly large effect size for both muscles (Table 2.3). Significant statistical difference was observed in latissimus dorsi muscle \((p = 0.041)\), with left latissimus dorsi being higher than right latissimus dorsi. The median muscle activations of the left ES was higher than the right ES during placing subtask \((p = 0.047)\) [Table 2.4]. For erector spinae muscle, placing subtask was higher than tying subtask for median \((p = 3.84e-05*)\) [Table 4] and peak \((p = 0.00048)\) [Table 2.5] muscle activations.
Table 2.3. ES and LD Muscle activations of participants with and without BackX exoskeleton during rebar tasks for static muscle activation level.

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

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

Table 2.4. ES and LD Muscle activations of participants with and without BackX exoskeleton during rebar tasks for median muscle activation level

<table>
<thead>
<tr>
<th>Median (ES, LD)</th>
<th>F-value</th>
<th>P-Value</th>
<th>$\eta^2$</th>
<th>Post Hoc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exo</td>
<td>0.436,</td>
<td>0.526,</td>
<td>0.046,</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>1.336</td>
<td>0.275</td>
<td>0.118</td>
<td></td>
</tr>
<tr>
<td>Subtasks</td>
<td>55.700,</td>
<td>3.84e-05*,</td>
<td>0.861,</td>
<td>Placing &gt;Tying</td>
</tr>
<tr>
<td></td>
<td>3.077</td>
<td></td>
<td>0.235</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.110</td>
<td></td>
</tr>
<tr>
<td>Muscle sides</td>
<td>3.907,</td>
<td>0.079,</td>
<td>0.303,</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>3.368</td>
<td>0.096</td>
<td>0.252</td>
<td></td>
</tr>
<tr>
<td>Exo X Subtask</td>
<td>0.067,</td>
<td>0.801,</td>
<td>0.007,</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>0.094</td>
<td>0.765</td>
<td>0.009</td>
<td></td>
</tr>
</tbody>
</table>
Table 2.5. ES and LD Muscle activations of participants with and without BackX exoskeleton during rebar tasks for peak muscle activation level.

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

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

Fig. 2.5 shows the overall mean static (Fig.2.5a), medium (Fig. 2.5b), and peak (Fig. 2.5c) muscular efforts for the exoskeleton conditions during placing subtasks, and the error bars indicate standard deviation of the mean as a measure of variations across all participants. For the placing
subtasks, the effects of the exoskeleton did not substantially influence the muscle activities. Static muscle activations for the left and right ES during placing subtasks were increased by 4% and 7% respectively (Fig. 2.5a) and reduced by 3% and 5% for the left and right LD, respectively. The median EMG was reduced by 1% for left ES and increased by 8% for right ES. There was no observed change in the left LD, but an 11% reduction was observed for the right LD (Fig. 2.5b). However, the effects of the exoskeleton were more prominent on the peak EMG, muscle activations were reduced by 16% for left ES, and increased by 5% for right ES, while the muscle activity levels reduced by 3% and 11% for the left and right LD muscles respectively (Fig. 2.5c).

Likewise, Fig. 2.6 shows the overall mean static (Fig. 2.6a), medium (Fig. 2.6b), and peak (Fig. 2.6c) muscular efforts for the exoskeleton conditions during tying subtasks, and the error bars indicate standard deviation of the mean as a measure of variations across all participants. During tying subtasks, there was a 2% increase in static muscle activations for both left and right ES, but the use of the exoskeleton reduced muscle activities by 7% and 4% at the left and right LD respectively (Fig. 2.6a). The median EMG for the right ES increased by 13%, but the exoskeleton showed no effects on muscle activation in the left ES (Fig. 2.6b). The left and right LD peak muscle activities were reduced by 6% and 10% respectively. Although there was an increase in the left ES (3%), and right (10%) peak ES muscle activities, the effect of the exoskeleton was prominent at the LD, as results revealed a 6%, and 10% decrease in left and right peak muscles activations, respectively (Fig. 2.6c).

![Figure 2.5](image.png)

**Figure 2.5.** Mean EMG values across different muscle groups for placing subtasks.

Note: Error bars represent standard deviations and blue and orange bars represent NoExo and Exo (BackX) conditions respectively.
Figure 2.6. Mean EMG values across different muscle groups for tying subtasks.

Note: Error bars represents standard deviations and blue and orange bars represent NoExo and Exo (BackX) conditions respectively.

2.5.3 Discomfort

Table 2.6 presents summary of (F-Value, P-Value and effect sizes ($\eta^2$)) the ANOVA and Post Hoc tests performed for level of discomfort, across the different body parts and Exoskeleton condition. P-values with ‘*’ have a confidence level < 0.05.

Table 2.6. Perceived level of discomfort of participants with and without BackX exoskeleton during rebar tasks.

<table>
<thead>
<tr>
<th></th>
<th>F-Value</th>
<th>P-Value</th>
<th>$\eta^2$</th>
<th>Post Hoc</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Body parts</strong></td>
<td>10.440</td>
<td>6.67e-09*</td>
<td>0.223</td>
<td>(C, LB, T, LL) &gt; (N, UA, S, H)</td>
</tr>
<tr>
<td><strong>Exo</strong></td>
<td>0.003</td>
<td>0.957</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Body parts X Exo</strong></td>
<td>7.745</td>
<td>6.50e-07*</td>
<td>0.080</td>
<td>BackX (C) &gt; Noexo (C)</td>
</tr>
</tbody>
</table>

The perceived discomfort significantly varied across different body parts (Table 2.6). With the highest discomfort felt in the chest, perceived discomfort in the chest, lower back, thigh, and lower leg was significantly higher than the neck, upper arm, shoulder, and hand ($p = 6.67 \times 10^{-9}$). Fig. 2.7 shows the overall mean perceived discomfort across different body parts (hand/wrist, upper arm, shoulder, low back, thigh, neck, chest, lower leg/foot) for the exoskeleton conditions, and the error bars and the error bars indicate standard deviation of the mean as a measure of variations in the perceived discomfort across all participants. Results also revealed substantial effects of the exoskeleton in the form of reduced discomfort across the lower back and leg (Fig. 2.7), and no effects were observed across the shoulder, upper arm, and wrists. However, results showed a significantly higher discomfort (383%) in the chest ($p = 6.50 \times 10^{-7}$) when the exoskeleton was used to perform the tasks. Conversely, participants experienced over 100% reduction in discomfort at their lower back when the tasks were performed with the exoskeleton (Fig. 2.7).

![Figure 2.7. Mean perceived discomfort across different body parts](image)

Note: The error bars represent standard deviations and ‘*’ indicate a significant difference, and blue and orange bars represent NoExo and Exo (BackX) conditions respectively.

### 2.6 Discussion

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

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

The study revealed significant effects of the exoskeleton on reducing discomfort on different body parts of the users during rebar tasks. The chest, lower back, thigh, and lower leg are the body parts mostly impacted by the exoskeleton. While discomfort was significantly reduced in the lower back, an unintended discomfort was consequently imposed at the chest region when the exoskeleton was worn ($\eta^2 = 0.08$). Similarly, Bosch et al. (2016) and Alemi, 2020, reported high discomfort in the chest and low discomfort in the lower back when a passive exoskeleton (Laevo and BackX respectively) was used for forward bending tasks. Perceived discomfort in lower leg which is a potentially affected body part during bending and lifting tasks was also reduced when the exoskeleton was worn. From Fig. 2.7, it can be inferred that the use of BackX has minimal effects on the discomfort of the wrists, upper arms, shoulder, and neck.

Overall, the use of the exoskeleton reduced muscle activities (3% - 11%) in the LD for both placing and tying subtasks. This is consistent with the findings of Madinei et al. (2020) who reported reduced back muscle activations (6% – 13% of MVIC) for asymmetric lifting when BackX was used. This differed for the muscle activities in the ES for both subtasks. Although there was an increase in the muscle activities for tying subtasks, mixed effects of the exoskeleton were observed in the ES during the placing subtask. The effects of the exoskeleton for reducing muscle activations in the ES were more pronounced during the placing subtask ($p = 0.0469$). The exoskeleton consistently increased the static, median, and peak muscle activation in the right ES, and reduced the medium and peak muscle activities at the left ES. While the medium activity levels at the left ES was reduced by 1%, the peak muscle activations were reduced by 16%. This may be because the placing subtask requires forward bending often requiring activation of the ES. During the tying subtasks, the exoskeleton consistently reduced the static, median, and peak muscle activations at the LD, but triggered an increase in the static and peak ES muscle activity levels. Moreover, the exoskeleton had no impact on the medium muscle activations for the left ES. The overall ES muscle group results are not in accordance with other studies conducted on BackX by Alemi, 2020 and Kazerooni, 2019 which reported a consistent reduction in back muscle activity up to 2% and 75% respectively.
The disparity in the effects of the exoskeleton across the muscles and subtasks can be explained by the location of these muscles, and the required postures for both subtasks. The LD is attached to the spine but actions are perceived from the shoulder during lateral bends and axial twists (Gerling and Brown 2013) while the ES is closer to the spine. Therefore, the effects of the exoskeleton in reducing muscle activations were more prominent in the LD than in the ES during tying subtasks because tying involves more arm actions, and twists, while placing involves a forward bending posture. It is also important to state that although tying subtask requires significantly more completion time than placing subtasks (Table 2.2), the effects of the exoskeleton on reducing muscle activations did not substantially increase while the participants performed the tying subtask. This may be because the muscle activities during placing subtasks was significantly more than during tying subtasks. This can suggest that the duration of use of the exoskeleton may not substantially increase the effect of the exoskeleton on reducing the muscle activities.

2.7 Conclusion

This study assessed the effects of a wearable robot (BackX) during rebar works, by exploring the impact of the exoskeleton on task completion time, perceived discomfort, and muscle activity. The exoskeleton reduced the task completion time, and thus improved the task performance of rebar task. This is an interesting finding because exoskeletons are often perceived as an invasive ergonomic innovation that may restrict the movement of construction workers during task performance. However, findings from this study indicate increased task performance which can possibly inform the decisions of construction stakeholders on investing in exoskeleton. With more impact observed for the shorter duration activity (placing subtask), it is imperative to state that the effect of BackX on task performance may be prominent for activities involving shorter durations.

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

Similarly, the exoskeleton reduced muscle activations in the LD during the rebar task, but induced more muscle activations in the ES, especially during the tying subtasks. This suggests that the postures assumed, and the actions involved in different tasks are critical to selecting an appropriate and suitable exoskeleton. Therefore, it is imperative that construction companies critically evaluate the appropriateness and suitability of BackX for each trade as it is pertinent that workers are protected against extensive muscle activations and discomfort while using the exoskeleton.

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

The findings of this study theoretically imply an increase in the productivity of the workers once they are comfortable with the functioning of the exoskeleton considering the shorter completion time. Furthermore, reduction in muscle activity suggests less stress on the workers' back muscle groups which can help reduce the occurrences of back-related WMSDs in the construction industry. Also, the lesser the back muscle stress and perceived discomfort for the lower back, the lesser would be the fatigue which could in turn help to further increase the productivity of the workers. The managerial implication of the increased productivity could suggest a reduction in project timeline thereby achieving earlier project completion leading to cost benefits. The improved health of the workforce would mean lesser lost workdays and higher retention of skilled labor thereby helping to mitigate the problem of labor shortage. Also, lesser occurrences of WMSDs would result in financial savings due to lesser workers' compensation.

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

Additionally, the sample size for this study involved only 10 participants, which may impact generalizability of the findings. It is recommended that future studies involve a larger sample size and varying demographics. Furthermore, the Level of Perceived Discomfort (LPD) was not measured after each cycle. As the tasks are repeated, the LPD may vary across cycles. In addition, this study only involved two muscle groups (latissimus dorsi and erector spinae), but considering the results of LPD, the stress levels in the muscle groups of different body parts such as thigh, chest, abdomen will be assessed in the future studies. Lastly, the effects of the exoskeleton on other physiological factors such as kinematics, and users’ heart rate will be explored in future studies.
CHAPTER 3: INDUSTRY PERCEPTION OF THE SUITABILITY OF WEARABLE ROBOT FOR CONSTRUCTION WORK

3.1 Abstract

Work-related musculoskeletal disorder 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 body parts and workers’ perception of usability of the exoskeleton. Health benefit such as reduction in stress in the back muscle was 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.

3.2 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 United States Bureau of Labor Statistics (BLS), cases of WMSDs in the construction industry are amongst the highest in the United States (BLS 2022). In 2020, cases of WMSDs amongst construction workers were approximately 1.6 times higher than the cases in all the 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. Although, the type of work performed by these trades differ, 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 FTE (full-time employees) amongst pipe workers is 1.5 times the average of all workers in the construction industry (BLS 2022). Cases of WMSDs amongst 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, amongst 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 amongst 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 worker’s 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 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, 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, ship-building, and healthcare have found value in the use of back-support exoskeletons in terms of reduced trunk muscle activity, range of motion, 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. Ogunseiju 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’s experience (Karahanoğlu and Erbuğ 2011), perceived discomfort (Bosch et al. 2016), and usability in terms of ease of use, tasks performance, and workers safety (Kim et al. 2019) have been identified as critical factors that could impact end-user’s 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 amongst 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, 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.

3.3 Background

3.3.1 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're performing work (Yan et al. 2017) and the use of wearable robots such as exoskeletons (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 ties 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 squatting posture, Umer et al. (2017) assessed a low height stool attached to workers’ pants to enable them to perform work in 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 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) 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 (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 WMSD in the construction industry.

3.3.2 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 will need to be comfortable, and easy to learn and use, and should not affect worker’s performance and safety. The devices need to have reduced unintended consequences such as discomfort to other body parts (De Looze et al. 2016; Kuber and Rashedi 2020). Thus, 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 PLAD exoskeleton on 10 participants performing automotive assembly tasks and assessed the exoskeleton using 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 Laevo V2.56 exoskeleton for twelve 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 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 the 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 above-mentioned studies demonstrated acceptable usability of back-support exoskeleton, the studies were laboratory-based and the participants are not end-users. Perspectives of end-users are needed in the design and evaluation of wearable technologies, as this is critical to improving the acceptability of the technologies amongst 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 Laevo exoskeleton for automotive work (i.e., assembling car parts and disassembling press tools) amongst 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’s scale. Results indicate a reduction in discomfort at 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 back-support exoskeleton for construction work.

3.3.3 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 scarce studies on the use of BSEs for construction work. Recently, some researchers (Antwi-Afari et al. 2021; Cho et al. 2018; Ogunseiju 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 Gonsalves et al. (2021) and Ogunseiju 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 exoskeleton on construction sites). Thus, this study aims to address this gap by involving construction workers for assessing user acceptance of BSEs.
3.3.4 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 towards 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, that align with users’ expectations, and reduce negative attitudes towards technology (Rohracher 2003). 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 the 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 on (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: (a) What impact would the use of exoskeletons have on the different body parts?; (b) What are pipe workers’ perceived usability of exoskeletons?; and (c) What is the perception of pipe workers regarding the use of exoskeleton?

3.4 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. 3.1, provides a graphical overview of the adopted methodology.
3.4.1 Wearable robot

The wearable robot employed in this study is a commercially available back support exoskeleton called the BackX (version 2) from SuitX industry (BackX 2022). BackX, which weighs 3.4 kg, consists of a metal torso and a harness. The metal torso, shown in Fig. 3.2(a), consists of the chest plate, thigh pad, 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 to 13 kg to support workers lower back during forward bending tasks. The torque generator has two modes: the instant and standard modes which facilitate support at 30 and 45 degrees, respectively. The harness which supports the metal torso, shown in Fig. 3.2(b), consists of a shoulder strap, leg strap, chest strap, chest pad, hip belt, and the hip pads.
3.4.2 Participants

Construction workers performing pipe laying work participated in this study. The workers included pipe layer (connects new pipe to existing pipe), tail man (supports the tail man 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 (1992) 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 Section 3.3.2 and literature reviews conducted by Kermavnar et al. (2021) and Zhu et al. (2021). Thus, this study adopted a convenience sample size of fourteen pipe workers. All the participants were men, with two participants aged less than 30, three were between 30 and 40, six between 41 and 50 years and three were 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 participants signed the informed consent (IRB-19-1180) form approved by the Institutional Review Board at Virginia Tech.

3.4.3 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 in-person 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, the participants performed their daily work duties for a period of approximately four hours. Some (n=4) of the participants used the exoskeleton in conjunction with the safety harness (for fall protection) to meet their work requirements. The participant’s 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 above, the tasks performed during the experiment varied depending upon the role of the participants (i.e., pipe layers, tail man, or top man). For instance, 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? Furthermore, based on the responses provided by the participants, they were further probed to provide more details which were written by the investigators. Verbal feedbacks are often employed by researchers to engage the participants in a conversation so that they can freely express their perception (Ogunseiju et al. 2022; Olmsted-Hawala et al. 2010). Additionally, participants feedback was also registered through structured questionnaire which
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 level of perceived discomfort (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 exoskeleton were collected through a descriptive questionnaire and verbal feedback which was obtained at the end of the session and through prompts during the session respectively.

3.4.4 Data collection and analysis

3.4.4.1 Level of perceived discomfort

Research question (a) was answered using the level of perceived discomfort (LOD). Data on the LOD was collected using the 10-point Borg’s 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. Since the data was collected using a scale, Wilcoxon signed rank test; a commonly used non-parametric 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 the R studio (Version 1.2.5042).

3.4.4.2 Usability

In response to the research question (b) (Section 3.3.4), data on the usability of the exoskeleton was 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 twenty usability questions on a 5-point Likert’s 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 (α > 0.9) of the developed questionnaire. The collected usability data were analyzed using descriptive statistics such as mean and standard deviation using MS Office Excel. Furthermore, to check if there is any correlation between LOD and usability, Spearman’s r correlation analysis, which is a widely employed method for non-parametric data (Hensel and Keil 2019), was conducted using R studio.

3.4.4.3 Subjective feedback

The participants’ perception of the back-support exoskeleton was employed to answer research question (c) (Section 3.3.4) which was captured via four descriptive questions which 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, the Cohen-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 whereas 1 is considered a complete agreement. A substantial agreement with a Cohen-kappa coefficient of 0.62 was attained and a strong percentage agreement of 78% was observed between the coders.

3.5 Results

3.5.1 Level of perceived discomfort

Fig. 3.3 represents the mean perceived discomfort across the different body parts (H = Hand/wrist, UA = Upper arm, S = Shoulder, LB = Lower back, T = Thigh, N = Neck, LL = Lower leg and foot, and C = Chest). The error bars indicate the standard deviation across all the participants. As shown in Fig. 3.3, the participants reported the highest discomfort in the chest, thigh, and shoulder compared to the hand, upper arm, low back, neck, and lower leg. Since 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., mid-way into the session and at the end of the session). However, as shown in Fig. 3.3, an increase in the mean perceived discomfort between the conditions was observed in the chest (20%), thigh (73%), shoulder (250%), and upper arm (100%).

![Figure 3.3. Level of perceived discomfort](image)
3.5.2 Usability (Questionnaire)

The overall usability assessment of the back-support exoskeleton was conducted based on four factors which include ease of use (Fig. 3.4), comfort (Fig. 3.5), performance (Fig. 3.6), and safety (Fig. 3.7). Furthermore, the impact of LOD on usability was investigated using correlation analysis. Tables 3.1 – 3.4 provide the correlation coefficients between LOD and usability. The significant correlations (i.e., p<0.05) are shown in bold.

3.5.2.1 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 3.1. A strong (p<0.05) negative correlation was observed between the perceived discomfort at the shoulder (-0.59) and thigh (-0.59) body parts 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) body parts 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>
<thead>
<tr>
<th>Ease of Use</th>
<th>C</th>
<th>S</th>
<th>T</th>
<th>H</th>
<th>LL</th>
<th>N</th>
<th>UA</th>
<th>LB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Don and Doff</td>
<td>-0.51</td>
<td>-0.40</td>
<td>-0.27</td>
<td>-0.38</td>
<td>-0.38</td>
<td>-0.38</td>
<td><strong>-0.66</strong></td>
<td>-0.38</td>
</tr>
<tr>
<td>Ease of adjustment</td>
<td>-0.46</td>
<td>-0.33</td>
<td>-0.23</td>
<td><strong>-0.48</strong></td>
<td>-0.48</td>
<td>-0.48</td>
<td><strong>-0.57</strong></td>
<td>-0.48</td>
</tr>
<tr>
<td>Work as desired</td>
<td>-0.53</td>
<td>-0.19</td>
<td><strong>-0.58</strong></td>
<td>-0.42</td>
<td>-0.42</td>
<td>-0.42</td>
<td>-0.45</td>
<td>-0.42</td>
</tr>
<tr>
<td>Use without assistance</td>
<td>-0.18</td>
<td><strong>-0.60</strong></td>
<td>-0.26</td>
<td>-0.37</td>
<td>-0.37</td>
<td>-0.37</td>
<td>-0.63</td>
<td>-0.37</td>
</tr>
</tbody>
</table>

Table 3.1. Correlation analysis results for ease of use criteria
Use without technical help

<table>
<thead>
<tr>
<th></th>
<th>-0.36</th>
<th>-0.25</th>
<th>-0.42</th>
<th>-0.44</th>
<th>-0.44</th>
<th>-0.50</th>
<th>-0.44</th>
</tr>
</thead>
</table>

Meets task perf. needs

<table>
<thead>
<tr>
<th></th>
<th>-0.53</th>
<th>-0.37</th>
<th>-0.68</th>
<th>-0.48</th>
<th>-0.48</th>
<th>-0.40</th>
<th>-0.48</th>
</tr>
</thead>
</table>

Task accomplishment

<table>
<thead>
<tr>
<th></th>
<th>-0.43</th>
<th>-0.55</th>
<th>-0.65</th>
<th>-0.47</th>
<th>-0.47</th>
<th>-0.50</th>
<th>-0.47</th>
</tr>
</thead>
</table>

Prefer working with exo.

<table>
<thead>
<tr>
<th></th>
<th>-0.51</th>
<th>-0.59</th>
<th>-0.59</th>
<th>-0.44</th>
<th>-0.44</th>
<th>-0.51</th>
<th>-0.44</th>
</tr>
</thead>
</table>

3.5.2.2 Comfort

Five questions, out 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 as 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 3.2 shows the correlations between LOD and comfort. Perceived discomfort at the chest (-0.6) and thigh (-0.74) body parts 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.

![Usability Ratings](image)

**Figure 3.5. Comfort with using the exoskeleton**

**Table 3.2. Correlation analysis results for comfort criteria**

<table>
<thead>
<tr>
<th>Comfort</th>
<th>C</th>
<th>S</th>
<th>T</th>
<th>H</th>
<th>LL</th>
<th>N</th>
<th>UA</th>
<th>LB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Movement restriction</td>
<td>0.31</td>
<td>0.52</td>
<td>0.46</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.22</td>
<td>0.26</td>
</tr>
<tr>
<td>Interference with environment</td>
<td>0.19</td>
<td>0.37</td>
<td>0.37</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.05</td>
<td>0.03</td>
</tr>
<tr>
<td>Uncomfortable</td>
<td>0.27</td>
<td>0.44</td>
<td>0.44</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.39</td>
<td>0.18</td>
</tr>
<tr>
<td>Satisfaction</td>
<td>-0.6</td>
<td>-0.48</td>
<td>-0.74</td>
<td>-0.48</td>
<td>-0.48</td>
<td>-0.48</td>
<td>-0.54</td>
<td>-0.48</td>
</tr>
<tr>
<td>Usable during summer</td>
<td>-0.57</td>
<td>-0.35</td>
<td>-0.69</td>
<td>-0.44</td>
<td>-0.44</td>
<td>-0.44</td>
<td>-0.37</td>
<td>-0.44</td>
</tr>
</tbody>
</table>

3.5.2.3 Performance

Two positive and one negative question were asked to assess the participants' performance while using the exoskeleton. When asked 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 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) body parts 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) body parts 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 represented in Table 3.3.

![Figure 3.6. Performance using the exoskeleton](image)

**Table 3.3. Correlation analysis results for performance criteria**

<table>
<thead>
<tr>
<th>Performance</th>
<th>C</th>
<th>S</th>
<th>T</th>
<th>H</th>
<th>LL</th>
<th>N</th>
<th>UA</th>
<th>LB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Able to work for longer</td>
<td>-0.64</td>
<td>-0.27</td>
<td>-0.65</td>
<td>-0.49</td>
<td>-0.49</td>
<td>-0.56</td>
<td>-0.49</td>
<td></td>
</tr>
<tr>
<td>duration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perform work faster</td>
<td>-0.51</td>
<td>-0.37</td>
<td>-0.58</td>
<td>-0.43</td>
<td>-0.43</td>
<td>-0.47</td>
<td>-0.43</td>
<td></td>
</tr>
<tr>
<td>Affects productivity</td>
<td>-0.19</td>
<td>0.49</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.38</td>
<td>0.26</td>
<td></td>
</tr>
</tbody>
</table>

3.5.2.4 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 that the exoskeleton would interfere with the safety harness. The workers did not feel that the exoskeleton was heavy and created an imbalance on-site as 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) body parts 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) body parts. Table 3.4 represents the correlation between safety and LOD.

![Figure 3.7. Impact on worker’s safety](image)

Table 3.4. Correlation analysis results for safety criteria

<table>
<thead>
<tr>
<th>Safety</th>
<th>C</th>
<th>S</th>
<th>T</th>
<th>H</th>
<th>LL</th>
<th>N</th>
<th>UA</th>
<th>LB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interference with safety harness</td>
<td>0.22</td>
<td>0.27</td>
<td>0.12</td>
<td>-0.11</td>
<td>-0.11</td>
<td>-0.11</td>
<td>0.10</td>
<td>-0.11</td>
</tr>
<tr>
<td>Imbalance on site</td>
<td>0.64</td>
<td>0.05</td>
<td>0.49</td>
<td>0.47</td>
<td>0.47</td>
<td>0.47</td>
<td>0.22</td>
<td>0.47</td>
</tr>
<tr>
<td>Heavy</td>
<td>0.37</td>
<td>0.06</td>
<td>0.14</td>
<td>0.43</td>
<td>0.43</td>
<td>0.43</td>
<td>0.211</td>
<td>0.43</td>
</tr>
<tr>
<td>Pressure on body parts</td>
<td>0.83</td>
<td>0.34</td>
<td>0.61</td>
<td>0.18</td>
<td>0.18</td>
<td>0.18</td>
<td>0.40</td>
<td>0.18</td>
</tr>
</tbody>
</table>

3.5.3 Subjective feedback

Table 3.5 summarizes the categories, sub-categories, 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).

Table 3.5. Categories, subcategories, and frequency of user feedback

<table>
<thead>
<tr>
<th>Category</th>
<th>Sub-category</th>
<th>Frequency of feedback</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benefits</td>
<td>Health</td>
<td>Thigh pad support (9); Stress reduction (9)</td>
</tr>
<tr>
<td></td>
<td>Design</td>
<td>Light weight (1); Chest and thigh support (2)</td>
</tr>
<tr>
<td></td>
<td>Application</td>
<td>Shoveling, stormwater invert, applying pipe lubricant, and leveling (4)</td>
</tr>
<tr>
<td>Adoption Barriers</td>
<td>Design Barriers</td>
<td>Discomfort due to metal torso (3); Heavy (1); Bulky (2)</td>
</tr>
<tr>
<td></td>
<td>Comfort</td>
<td>Straps getting in the way (1); Pressure on chest and thigh (3); Use of exoskeleton with harness and tool strap (4)</td>
</tr>
<tr>
<td></td>
<td>Work Environment</td>
<td>Working in confined spaces (6)</td>
</tr>
<tr>
<td></td>
<td>Safety Barriers</td>
<td>Incompatibility with safety harness (4); Metal parts could cause damage (1)</td>
</tr>
<tr>
<td></td>
<td>Work Preference</td>
<td>Prefer not to use (2)</td>
</tr>
<tr>
<td></td>
<td>Weather Barriers</td>
<td>Discomfort during summer (1)</td>
</tr>
<tr>
<td></td>
<td>Safety harness</td>
<td>Integrating safety harness (4)</td>
</tr>
<tr>
<td></td>
<td>Light weight</td>
<td>Reducing weight of exoskeleton (1)</td>
</tr>
<tr>
<td></td>
<td>Metal torso</td>
<td>Torso closer to body (1)</td>
</tr>
<tr>
<td></td>
<td>Pressure modifications</td>
<td>Chest pressure modifications (1)</td>
</tr>
<tr>
<td></td>
<td>Back support</td>
<td>Pressure at the back body part (1)</td>
</tr>
<tr>
<td></td>
<td>Tool strap</td>
<td>Integrating tool strap (1)</td>
</tr>
<tr>
<td></td>
<td>Weather adaptability</td>
<td>Change color to white (1)</td>
</tr>
</tbody>
</table>

3.5.3.1 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 sub-category as the workers (n=9/14) could feel support from the thigh pads (Table 3.5) and reduction in stress in the back while performing their regular duties: “(exoskeleton) it is very beneficial as it provides support to the thighs and chest which helps me reduce the stress from the back.” Two third (n=9/14) of the participants perceived some reduction
in stress in the back muscle and suggested adopting the exoskeletons 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 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”.

3.5.3.2 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 sub-categories. Using the exoskeleton with the safety harness during summer, when the temperature was between 80-98 deg. 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”, “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 that the pipe workers are exposed to, 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 were regarding 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”.

3.5.3.3 Exoskeleton design suggestions

Most of the participants (n=10/14) suggested potential modifications to the exoskeleton to ensure that the device is better suited for pipe work. The most common amongst 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 the 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 participant 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”.

3.6 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.

3.6.1 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 body part, which is in line with the findings of Alemi et al. (2020). Even though, 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 body parts was observed. This could mean that the long term use of the exoskeleton might cause an increase in discomfort which is a concern as 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 a) and might diminish once the workers get used to the device.

3.6.2 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 body parts. 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 as 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, due to which 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/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 body parts negatively affected workers' satisfaction and perception of usability of exoskeleton during summers. This could affect user acceptance of exoskeletons amongst the end users after prolonged use.

The assessment of performance revealed that the exoskeleton did not have a negative impact on workers’ productivity as they felt that 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 that 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 body parts,
participants reported good usability of the exoskeleton given that they reported moderate to high rating for ease of use, comfort, performance, and safety.

### 3.6.3 Subjective feedback

The subjective feedback provided by the participants suggests that the use of 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 that 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 wouldn't 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 chest and thigh pads, some participants reported discomfort on chest and body parts. This is also reflected in the level of perceived discomfort data provided by the participants. Furthermore, in order to make the exoskeleton more suitable for similar work environments that pipe workers work in (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 the confined spaces.

### 3.7 Conclusion and Future Work

A commercially available passive back support exoskeleton (BackX V2), 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 to 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 exoskeleton 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 amongst 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 which need to be addressed in future studies to facilitate the adoption of exoskeletons. Firstly, this was a short-term field study which allowed the workers to use the exoskeleton for four hours. Prolonged use of the exoskeleton could reveal increased discomfort and spark different feelings regarding the intention to use the exoskeleton for pipework. Secondly, this study did not involve female participants, thus in future studies, a more representative sample size would provide a better user assessment. Thirdly, even though the participants perform similar tasks, depending upon 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 exoskeleton adoption process. Fourthly, the exoskeleton was only tested during the Summer. It would be beneficial to assess workers' intention to use the exoskeleton during different climate conditions. Fifthly, 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. Lastly, adoption of exoskeletons in the construction industry would require a proper maintenance strategy which is dependent on the service life of the exoskeleton. Future study could investigate the service life of the exoskeleton and evaluate maintenance strategies.
CHAPTER 4: ASSESSMENT OF WORKERS’ ACCEPTANCE OF PASSIVE BACK SUPPORT EXOSKELETONS FOR CONSTRUCTION WORK

4.1 Abstract

Work-related musculoskeletal injuries are a major concern in the construction industry, particularly for trade workers such as pipe and concrete laborers who perform physically demanding tasks that can lead to back-related musculoskeletal injuries. With the emergence of wearable technologies like back-support exoskeletons, there has been growing interest among researchers to address these injuries. However, there is limited evidence regarding the acceptance of exoskeletons for construction tasks. This study aimed to assess a commercial exoskeleton for pipe and concrete work in terms of perceived discomfort and exertion, usability, intention-to-use, and user perception. A field study involving fifteen construction workers was conducted, with workers performing their usual tasks for two weeks (one week with and one week without an exoskeleton). The use of an exoskeleton led to a reduction in workers' perceived exertion and discomfort. Participants reported acceptable usability (75/100), but the restriction in movement due to the exoskeleton affected their comfort. A strong positive correlation was observed between usability and social influence on workers' intention-to-use the exoskeleton. Participants perceived that the use of an exoskeleton could reduce musculoskeletal disorders, but it caused discomfort due to hot weather conditions. This study contributes to the limited literature on the user acceptance of exoskeletons for construction work and sets a precedent for further studies on human-wearable robot collaboration in the construction industry.

4.2 Introduction

The construction industry is one of the largest employers of labor in the United States, with 7.36 million workers in 2021 (BLS 2022). However, construction workers are exposed to health and safety-related risks, leading to harsh working conditions, productivity loss, and injuries (Shamsuddin et al. 2015). Cross-sectional studies show that chronic musculoskeletal complaints and disorders are very common among construction workers (Goldsheyder et al. 2004; Silverstein et al. 2002; Spector et al. 2011). Construction workers perform physically demanding and repetitive work, such as manual material handling, in awkward and non-static postures. Construction jobs have been top-ranked for physical demands resulting from climbing, twisting, bending, and stooping (Tak and Calvert 2011). Prolonged work in these postures results in overexertion of the body parts, triggering sprains and strains, which are common types of injuries associated with the musculoskeletal system, also known as musculoskeletal disorders (Alavinia et al. 2007)). Musculoskeletal disorders are painful non-fatal injuries of the soft tissues (i.e., muscles, tendons, nerves, joints, cartilage, and ligaments). Musculoskeletal disorders sustained while performing work or from the environment in which employees operate are referred to as work-related musculoskeletal disorders (WMSDs) (Meleger and Krivickas, 2007).
The construction industry has one of the highest rates of WMSDs, with construction workers being 1.7 times more likely to sustain WMSDs than workers in all industries combined (BLS 2023). In 2020, 40.6 workers per 10,000 full-time workers (FTW) sustained WMSDs resulting in 16 days away from work (BLS 2023). Pipe and concrete workers have some of the highest rates of WMSDs in the construction industry, with pipe workers having an incidence rate of 1.6 times the average of the construction industry (BLS 2023). The back is the most affected body part, accounting for 40% of all cases for pipe and concrete workers (Wang et al., 2017). These workers spend a significant amount of time in awkward postures, causing overexertion of the back. Concrete workers spend 71% of their time in forward bending and repetitive postures, leading to back injuries (CPWR 2018). Between 2019 and 2020, the rate of back injuries among pipe and concrete workers increased by 2.3 and 1.5 times, respectively (BLS 2023). These injuries led to 11 and 40 days away from work among pipe and concrete workers, respectively (BLS 2023). In severe cases, back-related injuries have resulted in permanent disability of workers (Welch et al. 2010) and triggered early retirement of experienced workers (Cheng et al. 2016). This in turn, leads to labor shortages which is also attributed to productivity loss in the construction industry.

In recent years, wearable robots, also known as exoskeletons, have been developed to address work-related musculoskeletal disorders. Lee and Cha (2021) defined wearable robots as mechanical devices that enable wearers to perform work with reduced or no force. Exoskeletons can be broadly classified based on the type of body part supported by the device. For example, exoskeletons designed to support the back, legs, shoulders, and full body are termed back-support, leg-support, shoulder-support, and full-body support exoskeletons, respectively. Furthermore, depending on the type of actuation, exoskeletons are categorized as active or passive. Active exoskeletons can increase human strength or reduce the body's energy consumption by using systems like motors, hydraulic systems, or pneumatic systems. On the other hand, passive systems do not require actuators. Rather, they use materials, springs, or dampers that can store energy generated from human motion to support postures or movements of wearers. The reduced cost of passive back-support exoskeletons compared to active exoskeletons makes them attractive ergonomic interventions for several industry sectors (Gonsalves et al. 2021). Furthermore, Ali et al. (2021) explained that passive back-support exoskeletons relieve the spine by providing some torque required for completing physical tasks. Studies have shown that the use of passive back support exoskeletons can reduce back muscle activity and discomfort in the lower back (Alemi et al. 2020; Gonsalves et al. 2021; Kernavnar et al. 2021; Kim et al. 2020). For example, Golabchi et al. (2022) evaluated a passive back-support exoskeleton for manual material handling tasks and observed a reduction in perceived discomfort in the lower back (69.44%). Antwi-Afari et al. (2021) assessed the exoskeleton for manual repetitive handling tasks and found a reduction in erector spinae muscle activity (33%) and discomfort in the lower back (42.40%). Although the aforementioned studies have shown the benefit of passive back-support exoskeletons for reducing ergonomic risks associated with construction work, the adoption of the device will be hinged on users' acceptance or willingness to use the device (Mahmud et al. 2022). Therefore, it is critical to understand factors that may influence workers' adoption of passive back-support exoskeletons.
The unified theory of acceptance and use of technology (UTAUT) theory provides guidance on essential constructs, such as performance and effort expectancy, social influence, and facilitating conditions, for examining users' intention-to-use technologies. Studies have identified perceived discomfort (Baltrusch et al. 2018) and exertion (So et al. 2020), user experience (Hill et al. 2017), social influence (Shore et al. 2018), usability in terms of ease of use, performance, comfort, safety (Omoniyi et al. 2020), and intention-to-use technology (Elprama et al. 2020), as critical for measuring the acceptance of exoskeletons among end-users. Furthermore, prolonged use of exoskeletons could affect workers' perception of the aforementioned measures, thereby affecting their intention-to-use the device. However, there are scarce studies exploring the acceptability of exoskeletons among the construction workforce, such as pipe and concrete workers. Furthermore, while real work conditions are critical for quantifying the effect of exoskeletons, only a few studies have examined acceptance of exoskeletons in real-life settings (Baldassarre et al. 2022). Most of these studies are for other industry sectors, such as the automobile and healthcare industries (Bogue 2018). The objective of this study is to investigate the acceptance of passive back-support exoskeletons among the construction workforce (i.e., pipe and concrete workers) in terms of usability, perceived discomfort and exertion, user experience, and social influence. The rest of the paper comprises five sections. The next section introduces background studies on exoskeleton acceptance in occupational settings and the theoretical underpinning. The research method section elaborates on the research methodology, describing the participants, technology, and data collection and analysis techniques. The findings of the quantitative and qualitative analysis are presented in the results section of the paper. The last two sections discuss the theoretical and practical contributions of this study, and conclusions are drawn.

4.3 Literature Review

4.3.1 Adoption of exoskeletons in occupational settings

Studies evaluating the potential of exoskeletons for different industrial sectors, such as the automobile, healthcare, and manufacturing, have demonstrated reduced muscle activity (Madinei et al. 2020), range of motion (Iranzo et al. 2020), and perceived discomfort (Kermavnar et al. 2021), as well as increased productivity (Bosch et al. 2016) from the use of back-support exoskeletons. These benefits have triggered a growing interest in the use of back-support exoskeletons in the construction industry. However, for exoskeletons to benefit construction workers, the device should be desirable to the workers. If workers do not want to use exoskeletons, they will not derive the benefits. Thus, it is necessary to examine user acceptance of exoskeletons.

In recent years, several studies (Gonsalves et al. 2023; Maurice et al. 2022; Schwerha et al. 2022; Ziaei et al. 2021) have investigated measures of acceptance of passive back-support exoskeletons. For example, Maurice et al. (2022) evaluated a passive back support exoskeleton for a simulated patient bed bathing task (n=9) for a duration of t = 5 mins 30 sec in terms of perceived discomfort and found reduced discomfort in the back. Schwerha et al. (2022) investigated the use of two exoskeletons (Laevio and SuitX) for 17 commonly performed tasks (t < 30 mins.) in the manufacturing industry (n=17) in terms of usability and user acceptance. The results indicated
acceptable usability of the exoskeletons as the participants provided positive responses to all the questions. Furthermore, four emerging themes were observed from the responses to the interview questions: utility for task, wearability, working metrics, and ease of use. The Ergo-vest exoskeleton was assessed by Ziaei et al. (2021) for a manual waste collection task (n=20) in terms of exertion and usability (t = 8 hours). Lower exertion was observed while using the exoskeleton compared to without an exoskeleton. Acceptable usability (83.6/100), adjustability, visibility, accessibility, applicability, effectiveness, and freedom, as well as low perceived discomfort ratings, were reported by the participants. Gonsalves et al. (2023) conducted a field study with pipe workers (n=14) to evaluate a BackX exoskeleton with respect to usability (i.e., ease of use, comfort, performance, and safety), perceived discomfort, and user perspective (t = 4 hours). The results showcased acceptable usability since participants provided moderate (3/5) to high (4/5) ratings to the usability questionnaire. The benefits of using exoskeletons, barriers to the adoption of exoskeletons, and modifications to exoskeleton designs were the three main categories identified from the qualitative responses. Furthermore, it was observed that perceived discomfort at different body parts increased with time. Thus, from the aforementioned studies, it is evident that usability, exertion, discomfort, and user perception are critical for investigating the acceptance of exoskeletons among end-users. Hensel and Keil (2019) evaluated a Laevo exoskeleton for use in the automobile industry (n=30) in terms of discomfort, usability, and user acceptance (t = 4 weeks). The participants reported a high user rating for task performance, donning, and doffing (i.e., wearing and taking off). There was a reduction in perceived discomfort in the lower back, but increased discomfort in the chest was reported. However, the participants’ intention-to-use the exoskeleton decreased with time.

Most of the above-mentioned studies exposed workers to short-term use of the exoskeletons (up to 8 hours). Very few studies have explored the potential of back-support exoskeletons from the perspective of prolonged or long-term use. Prolonged exposure could lead to a change in workers’ perception of the acceptability of exoskeletons (Schwerha et al. 2022) . Thus, this study exposed workers to prolonged use (i.e., one week) of exoskeleton for construction tasks.

4.3.2 Theoretical underpinning

Various theories have been proposed to understand the factors influencing acceptance of technologies. These include the theory of planned behavior (Ajzen 1991), the theory of reasoned action (Dillard and Pfau 2002), the technology acceptance model (TAM) (Davis and Venkatesh 1996), and TAM2 (Venkatesh and Davis 2000). Venkatesh et al. (2003) synthesized elements of these theories to formulate four primary determinants of intention and usage, as defined by the UTAUT theory. These include performance expectancy, effort expectancy, social influence, and facilitating conditions. The UTAUT framework defined "Performance Expectancy" as a device's perceived usefulness, which is an individual’s perception that their performance will improve while using a device. "Effort Expectancy", also referred to as perceived usability, is defined as a user’s perception that using a device will require no effort. "Social Influences" refers to an individual’s
perception of being able to shape other’s behavior to use a device while "Facilitating Conditions" refers to the availability of resources, both in terms of organizational and technical infrastructure, that support the use of the device.

The UTAUT model has been used in various studies to assess the acceptance of different technologies. For instance, Sok Foon and Chan Yin Fah (2011) utilized the UTAUT model in an online survey to measure the adoption of internet banking, finding that performance expectancy, effort expectancy, social influence, and facilitating conditions were positively correlated with behavioral intention. Gao and Deng (2012) used the UTAUT model to evaluate the user acceptance of mobile e-books and discovered that performance expectancy and effort expectancy had a significant positive impact on behavioral intention. In contrast, perceived cost and facilitating conditions had no effect on the adoption of mobile e-books. Similarly, Puriwat and Tripopsakul (2021) employed the UTAUT model to assess the adoption of social media for businesses and found that performance and effort expectancy, social influence, and facilitating conditions influenced users' intentions.

In addition, the UTAUT model has also been utilized to measure the acceptance of exoskeletons. For example, Elprama et al. (2020) used the UTAUT model to evaluate the acceptability of exoskeletons among industrial workers and found that effort expectancy had the highest influence on workers' acceptance, followed by social influence and performance expectancy. However, the participants in this study had no prior experience with exoskeletons. Siedl and Mara (2022) conducted a focus group discussion to understand the acceptance of occupational exoskeletons among workers in food retail and corporate logistics and found that performance and effort-related constructs had a significant impact on the acceptance of exoskeletons. Additionally, both Siedl and Mara (2022) and Kim et al. (2019) identified comfort and safety as crucial factors for the adoption of exoskeletons, which are also included in the usability questionnaire employed in this study. Drawing on these previous studies, this study uses constructs such as performance expectancy, effort expectancy, social influence, comfort, and safety to understand the acceptance of exoskeletons for pipe and concrete work as shown in Fig. 4.1. The figure shows the impact of different measures on workers’ intention to use.

![Figure 4.1. Theoretical underpinning](image-url)
4.4 Methodology

This section provides a detailed understanding of the methodology adopted in this study. The subsections include participants, exoskeleton, experimental setup, data collection, and data analysis. Fig. 4.2 provides an overview of the adopted methodology. This includes the sample size, construction trades considered in this study, the exoskeleton, study duration, outcome measures, mode of data collection for each measure and the analysis method.

![Methodology Diagram]

Figure 4.2. Methodology.

4.4.1 Participants

A convenience sample size of 16 participants was adopted in this study, which include pipe workers (n=6) and concrete workers (n=10), since these trades are one of the highest affected trades in the construction industry (as mentioned in Section 4.2). However, one participant from the pipe crew opted out of the study, so the data for 15 participants (5 for pipe workers and 10 for concrete workers) was used for the analysis. The pipe workers include two pipe layers, two tail men and one top man while the concrete workers include ten carpenters. Table 4.1 describes the tasks performed by the pipe and concrete workers who participated in this study. The demographic
characteristics of the participants are shown in Table 4.2. The average age, weight, height and experience of the participants was $43 \pm 7.70$ years, $77.86 \pm 10.90$ Kgs., $160 \pm 10$ cm, $46.07 \pm 10.54$ years respectively. All participants signed the informed consent form approved by the Virginia Tech Institutional Review Board (IRB - 22 - 466) before participating in the study. Participants did not report any musculoskeletal injuries or health problems that could affect their ability to perform work tasks.

Table 4.1. Participants’ job roles and tasks.

<table>
<thead>
<tr>
<th>Participants Job Roles</th>
<th>Primary Tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe layer</td>
<td>Join new pipe to existing/previously laid pipe</td>
</tr>
<tr>
<td>Tail men</td>
<td>Support pipe layers in laying pipe</td>
</tr>
<tr>
<td>Top men</td>
<td>Support pipe layer and tail men</td>
</tr>
<tr>
<td>Carpenters</td>
<td>Erecting and removing formwork, concrete finishing, and manual material handling.</td>
</tr>
</tbody>
</table>

Table 4.2. Participants’ demographics.

<table>
<thead>
<tr>
<th>Demographic Characteristics</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Maximum</th>
<th>Minimum</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>43</td>
<td>7.70</td>
<td>58</td>
<td>32</td>
<td>45</td>
</tr>
<tr>
<td>Weight (Kgs.)</td>
<td>77.86</td>
<td>10.90</td>
<td>100</td>
<td>61</td>
<td>80</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>160</td>
<td>10</td>
<td>179</td>
<td>152</td>
<td>167</td>
</tr>
<tr>
<td>Experience (years)</td>
<td>46.07</td>
<td>10.54</td>
<td>65</td>
<td>32</td>
<td>45</td>
</tr>
</tbody>
</table>

4.4.2 Exoskeleton

BackX Version 3, a passive back support exoskeleton from SuitX industries (https://www.suitx.com/backx), was used in this study. Figure 4.3 shows the exoskeleton, its parts, and a worker using the exoskeleton. The device weighs 3.2 kg and consists of a hip belt (Fig. 4.3(a)) and a metal torso (Fig. 4.3(b)). The metal torso comprises a chest pad, thigh pad, and torque generator. When the device is activated, the torque generator can generate a force of 9 to 13 kg to support workers when bending forward. Additionally, the torque generator has two modes: smart mode and instant mode. The smart mode maximizes mobility and allows workers to walk freely, climb stairs and ladders, and use work vehicles. The instant mode provides support at every posture and restricts movement. The hip belt supports the metal torso and prevents the exoskeleton from sliding. Both the hip belt and metal torso are adjustable to fit different body types. The metal torso is connected to the hip belt via the torque generator. Fig. 4.3(c) shows a worker using the exoskeleton.
4.4.3 Experimental setup

The participants signed the informed consent form before commencing the study. The workers participated in the study for a period of two weeks, or 10 working days. In the first week (or 5 working days), the participants performed their usual daily tasks without the exoskeleton (NoExo condition). During this period, data on their perceived discomfort and exertion were collected three times a day (i.e., at the beginning, middle, and end of the day) to understand changes in discomfort and exertion over time. At the beginning of the second week, participants received in-person toolbox training on the use of the exoskeleton, which included donning (i.e., wearing it), adjusting the fit, activation, engaging different modes (i.e., smart and instant modes), and doffing (i.e., taking off). Participants were subsequently allowed to practice using the exoskeleton, and once comfortable, they performed their usual daily tasks while wearing the exoskeleton (Exo condition) for five working days (i.e., a full workweek). Participants' daily work tasks included manual material handling, lifting and carrying heavy tools, equipment and materials (e.g., metal chains, hooks, plywood, and formwork), shoveling, grading, and erecting and taking off formwork. During the second week when the participants used the exoskeleton, data on their perceived discomfort and exertion were also collected. Furthermore, during the week the exoskeleton was used, data on the usability of the exoskeleton was collected at the end of days 1, 3, and 5 using a questionnaire. On the last day (i.e., day 5), the participants provided verbal feedback on their experience with the exoskeleton and also completed a social influence questionnaire. During the experiment, participants were allowed to don and doff the exoskeleton at their discretion. The study was conducted in Virginia during the summer where the temperature ranged between 55 deg. F to 95 deg. F and the dew point ranged between 44 deg. F to 70 deg. F.

Figure 4.3. BackX V3 exoskeleton: (a) Hip belt; (b) Metal torso; (c) Worker using the exoskeleton.
4.4.4 Data collection and analysis

4.4.4.1 Survey instruments

4.4.4.1.1 Questionnaire: Level of perceived discomfort and exertion

The participants in the study reported their level of perceived discomfort using a 10-point Borg scale that ranged from no discomfort (i.e., 0) to severe discomfort (i.e., 10). This C-10 Borg scale is a commonly used scale in similar studies (Kim et al. 2021) to evaluate the discomfort perceived by participants. Participants rated eight body parts including the chest, thigh, shoulder, upper arm, lower leg, hand/wrist, lower back, and neck (see Fig. 4.4). The exertion data was collected using the Borg exertion scale, which ranges from 6 (i.e., no exertion) to 20 (i.e., very high exertion). Borg's exertion scale is widely used to measure exertion among study participants (Kim et al. 2021; Qu et al. 2021). Both the exertion and discomfort data were collected at the beginning, middle, and end of the day for the entire study duration (i.e., 2 weeks or 10 working days) to understand the changes in these measures with respect to time on a given day, as well as within a given week.

4.4.4.1.2 Questionnaire: Usability and social influence

The study utilized the System Usability Scale (SUS), a commonly used questionnaire to evaluate the usability of technology (Hwang et al. 2021; La Bara et al. 2021; Luger et al. 2021). The SUS questionnaire consists of five positively and negatively worded questions. Additionally, a custom questionnaire was developed for this study, which included construction-related constructs and elements from the UTAUT theory, such as performance, effort (ease of use and comfort), safety, and intention to use (Kim et al. 2019; Venkatesh and Davis 2000). The UTAUT theory suggests that social influence can affect workers' intention to use technology. Therefore, a Social Influence (SI) questionnaire was used to understand the participants' beliefs about what their peers and supervisors think of them using the exoskeleton. Two questionnaires, one for peers (i.e., other workers) and one for supervisors, were developed to assess the impact of social influence on participants' intention-to-use the exoskeleton. The participants rated all the questions on a 5-point Likert scale where 5 indicated ‘strongly agree’ and 1 indicated ‘strongly disagree,’ based on their level of agreement with the questions. The participants provided usability ratings during the week they used the exoskeleton (i.e., on day 1, day 3, and day 5), allowing for the measurement of changes in workers' perceived usability and intention to use over time. The social influence data was collected at the end of the study on day 5.

4.4.4.1.3 Semi-structure Interview: User perception

The user perception was assessed through a semi-structured interview conducted at the end of the study. The participants answered five questions aimed at understanding the advantages and disadvantages of using the exoskeleton, modifications to make the device more suitable for construction work, strategies required for maintenance, and suggestions for handling and storing the device on construction sites. Thematic analysis was used to analyze the data. An inductive
coding approach was adopted to identify emerging themes from the qualitative data. Similar meaning codes were further grouped under categories (Saldaña 2014). The codes were developed by the first author and verified by two researchers. To check the reliability of the codes, the Cohen-Kappa coefficient was employed. The coefficient ranges from 0 to 1 and is commonly used to check inter-rater reliability.

4.4.4.2 Statistical analysis

Descriptive statistics such as mean and standard deviation were used to analyze the data collected from the SUS, custom usability, and social influence questionnaires. To calculate the overall SUS score, this study adopted a method outlined by Harrati et al. (2016). The rating provided by the participants for each SUS question was converted from a 5-point to a 4-point scale. To do this, the score contribution of positively worded questions (i.e., odd questions) was determined by subtracting 1 from the provided rating, while the score contribution for negatively worded questions was determined by subtracting 5 from the provided rating. Once the scores were converted, the sum of all the scores was multiplied by 2.5 to compute the SUS score using equation 1, where \( U_i \) is the rating of the \( i \)th question. The SUS score ranges from 0 to 100, where a higher score indicates better usability.

\[
SUS = 2.5 \times \left[ \sum_{n=1}^{5} (U_{2n-1} - 1) + (5 - U_{2n}) \right]
\] (1)

Since the collected data was not normally distributed, non-parametric tests were employed in this study. In order to understand the change in workers’ perception of usability with time, the Wilcoxon rank sum test was employed to identify any statistical significance between the days (i.e., day 1, day 3, and day 5). Ordinal logistic regression was employed to identify if there is any significant difference between the conditions (i.e., Exo and NoExo conditions), day (i.e., day 1 to day 5), and time (i.e., start, mid, and end) independent variables. A p-value of less than 0.05 is considered to be statistical significance for the aforementioned tests. To identify the impact of outcome measures (i.e., usability, discomfort, and exertion) on the participants’ intention to use the exoskeleton, Spearman’s \( r \) correlation test was employed. A p-value of less than 0.05 was considered to be a strong correlation. The spearman’s correlation coefficient is a value between -1 to 1, wherein a negative value denotes a negative correlation, and a positive value denotes a positive correlation. All the statistical analysis was performed using R studio and MS Office.

4.5 Results

4.5.1 Physical demand: Perceived exertion and discomfort

Fig. 4.4 shows the comparison of perceived discomfort ratings provided by the participants for different body parts between the Exo and NoExo conditions at the start, mid and end of the day. The red color signifies an increase in discomfort when using the exoskeletons, as compared to the NoExo condition. The green color signifies a reduction in discomfort compared to the Exo condition. A significant difference was observed in the participants’ perceived exertion between
the Exo and NoExo conditions \((p=2.382\times10^{-06})\), and time \((p=2.2\times10^{-16})\). The exertion for the NoExo condition was expected to be 6.7 times greater than that of the Exo condition. Overall, the participants perceived exertion at the start \((p = 1.0253\times10^{-05})\) and end \((p = 2.22\times10^{-16})\) of the day was significantly less compared to the exertion at the end of the day. No statistical significance was observed in the exertion between the days for both conditions (i.e., \(p>0.05\)).

![Diagram showing level of discomfort for body parts]

**Figure 4.4. Level of discomfort for the body parts.**

The participants’ perceived discomfort was significantly different (i.e., \(p<0.05\)) for condition, day, and time-independent variables for all the body parts (i.e., chest, upper arm, hand, lower back, lower leg, neck, shoulder, and thigh). It was observed that perceived discomfort was expected to be significantly higher for the NoExo condition compared to that of the Exo condition for the chest (13.4 times), upper arm (9.9 times), hand (10.3 times), lower back (17.4 times), lower leg (9.9 times), neck (4.8 times), shoulder (14.7 times) and thigh (9.7 times) body parts. However, the discomfort was not found to be significantly distinct between the days (i.e., \(p>0.05\)). Significantly lower discomfort at all the body parts during the mid and start of the day was observed compared to that at the end of the day.

The discomfort at the start of the day decreased by 28.99%, 64.44%, 64.44%, 41.33%, 86.67%, 46.67%, 89.99% at the hand/wrist, upper arm, shoulder, low back, thigh, neck, and lower leg, respectively, during Exo condition. However, the discomfort in the chest increased by 273%.
In the middle of the day, the perceived discomfort during the Exo week was lesser for the hand (52.58%), upper arm (56.36%), shoulder (57.80), lower back (70.03%), thigh (48.29%), neck (30.77%), lower leg (54.78%) and chest (61.62%) body parts compared to the NoExo week. The discomfort at hand, upper arm, shoulder, lower back, thigh, neck, lower leg, and chest body parts also decreased by 65.98%, 55.81%, 65.73%, 76.09%, 51.43%, 60.40%, 63.50%, and 54.61%, respectively, at the end of the day during the Exo week.

### 4.5.2 Social influence

To assess the participants' perception of their peers' thoughts regarding the use of exoskeletons, five questions were utilized (Fig. 4.5). Fig. 4.5 shows the ratings provided by the participants for social influence questionnaire. Participants gave moderate to high ratings when asked if their peers believed that: (a) they would benefit from using exoskeletons (3.69 ± 1.62), (b) using exoskeletons is important (3.63 ± 1.41), (c) the participants themselves would use exoskeletons (3.56 ± 1.46), and (d) they should use exoskeletons (3.63 ± 1.54). However, when asked whether their peers were willing to use exoskeletons, the participants provided a moderate rating of 2.94 ± 1.53.

![Figure 4.5. Social influence due to the use of the exoskeleton.](image)

To understand what the participants think about their supervisors' perception of workers using the exoskeleton, four questions were employed (Fig. 4.5). Participants provided moderate to high ratings when asked whether their supervisors think that it is important to use exoskeletons (3.81 ±
1.28) and should use the exoskeletons (3.31 ± 1.40). When asked if their immediate supervisors (i.e., site foreman) would want them to use the exoskeleton, the participants gave a moderate to high rating of 3.56 ± 1.41. Participants provided a high rating (4.06 ± 1.39) when asked about their supervisors' perception of the workers' ability to use the exoskeleton.

4.5.3 Usability

4.5.3.1 System usability scale

The overall user acceptance was measured using the SUS questionnaire, which included five positive and five negative questions (Fig. 4.6). Fig. 4.6 shows the average ratings provided by the participants for the SUS questionnaire. Usability scores were calculated using the method explained in Section 4.4.4.2. The participants' perceived usability increased from day 1 (71.50/100) to day 3 (75.83/100); however, it decreased slightly on day 5 (75/100). Overall, the participants provided moderate to very high ratings for positive questions (i.e., odd questions), whereas they gave very low to moderate ratings for negative questions (i.e., even questions) (see Fig. 4.6).

Figure 4.6. System usability scale rating from use of exoskeleton.
4.5.3.2 Ease of use

Seven questions were employed to measure the ease of use of the exoskeleton (Fig. 4.7). The average usability ratings provided by participants for ease of use is shown in Fig. 4.7. The participants consistently provided moderate to high ratings for the ease of use questions. No significant difference was observed between day 1, day 3, and day 5 (i.e., \(p>0.05\)). The participants' perceived ease of use rating increased between day 1 to day 5, when asked about donning and doffing (4.06 ± 1.46 to 4.86 ± 0.35), adjustability (4.50 ± 1.13 to 4.79 ± 0.56), meeting the need for task completion (3.44 ± 1.65 to 4.00 ± 1.22), task accomplishment (3.44 ± 1.71 to 3.86 ± 1.22) and use without assistance (4.06 ± 1.44 to 4.64 ± 0.62). The participants' preference for using the exoskeleton increased from low to moderate (2.53 ± 1.71) on day 1 to moderate to high (3.14 ± 1.79) on day 5.

![Figure 4.7. Ease of use of exoskeleton.](image)

4.5.3.3 Comfort

The participants' perceived comfort was measured using five questions (Fig. 4.8). Fig. 4.8 shows the ratings provided by participants for the comfort questionnaire. When asked if the exoskeleton restricted their movement and interfered with the work environment, the usability rating decreased from day 1 (2.31 ± 1.45 and 2.44 ± 1.46 respectively) to day 3 (1.57 ± 0.83 and 1.79 ± 0.88)
respectively), however, it increased on day 5 (2.57 ± 1.60 and 2.36 ± 1.33 respectively). In terms of satisfaction and ability to use the exoskeleton during summer, the rating increased from day 1 (2.81 ± 1.80 and 3.38 ± 1.71 respectively) to day 3 (4.00 ± 1.62 and 3.64 ± 1.67 respectively) but decreased on day 5 (3.50 ± 1.55 and 3.21 ± 1.63 respectively). In terms of the exoskeleton being uncomfortable, the user rating decreased between day 1 (2.25 ± 1.39) to day 3 (2.07 ± 1.46), however, increased on day 5 (2.50 ± 1.76). No significant difference (i.e., p>0.05) was observed between day 1, day 3 and day 5.

![Figure 4.8. Comfort from using exoskeleton.](image)

4.5.3.4 Performance

The participants' perception of performance was assessed using three questions as shown in Fig. 4.9. The average usability ratings provided by the participants for the performance questions is shown in Fig. 4.9. While using the exoskeleton, participants moderately felt that they can work for a longer duration on day 1 (3.19 ± 1.33), however, the ratings decreased significantly (i.e., p<0.05) on day 5 (2.86 ± 1.89). In terms of their ability to work faster with the exoskeleton and impact on productivity, participants' ratings consistently increased between day 1 (2.88 ± 1.36 and 2.19 ± 1.22), day 3 (3.00 ± 1.73 and 2.86 ± 1.67) and day 5 (3.29 ± 1.64 and 3.36 ± 1.74). However, a significant difference (i.e., p>0.05) in the performance ratings between days was not observed.
The impact on workers' safety while using the exoskeleton was assessed using four parameters (Fig. 4.10). The average ratings provided by participants for the safety questions is shown in Fig. 4.10. Participants perceived impact regarding the interference of the exoskeleton with the safety harness was constant on day 1 (3.00 ± 1.59) and day 5 (3.00 ± 1.96). However, significant difference (i.e., \( p<0.05 \)) was observed between day 1 and day 3 (2.29 ± 1.57). Participants’ perception of the exoskeleton causing imbalance on sites, being too heavy, and applying pressure on body parts increased from day 1 (2.31 ± 1.49, 1.63 ± 0.89, and 3.06 ± 1.73) to day 3 (2.36 ± 1.58, 2.29 ± 1.70 and 3.36 ± 1.78), however, it decreased on day 5 (2.14 ± 1.53, 2.00 ± 1.49 and 3.29 ± 1.77). No other statistical significance (i.e., \( p>0.05 \)) was observed in the safety ratings between the days.
4.5.3.6 Intention-to-use

Participants’ intention-to-use was measured using three questions as shown in Fig. 4.11. Fig. 4.11 shows the average ratings provided by participants for intention-to-use questions. Moderate to high intention-to-use was reported for all three days when asked if the participants were willing to use the exoskeleton if their employers provide the device and if the employer requires them to use it. When asked if the participants would purchase and use the device, if it is affordable, and use it if their employers provide it, the rating increased between day 1 (2.75 ± 1.88 and 3.25 ± 1.48) and day 3 (3.14 ± 1.94 and 2.50 ± 1.76), however, it reduced on day 5 (2.57 ± 1.87 and 3.36 ± 1.81). The participants’ intention to use the exoskeleton if the employers require it, increased slightly between day 1 (3.44 ± 1.46) and day 5 (3.50 ± 1. 84). No significant difference was observed in participants intention to use between days 1, 3 and 5 (i.e., p>0.05).

![Figure 4.11. Intention-to-use exoskeleton.](image)

4.5.4 Impact on intention-to-use

Tables 4.3, 4.4 and 4.5 provide an overview of the results of the correlation analysis conducted to understand the impact of discomfort, social influence, and usability (respectively) on workers’ intention-to-use. The participants' perceived exertion caused a reduction in their intention-to-use the exoskeleton, however, a strong correlation (i.e., p>0.05) was not observed on any days. Similarly, no significant relationship (i.e., p>0.05) was observed between discomfort and intention-to-use. On the other hand, Peer influence has a strong correlation (i.e., p<0.05) with the participants' intention-to-use the exoskeleton. A strong positive relationship (i.e., p<0.05) between participants' perception of their peers thinking that the user would benefit by using the exoskeleton (r=0.609) and that it is important to use the device (r=0.697) and intention-to-use the exoskeleton. Participants' intention-to-use the exoskeleton increased when their peers felt that they should use
the exoskeleton ($r=0.716$) and were willing to use the exoskeleton ($r=0.571$). A strong impact on the participants' intention-to-use the exoskeleton was observed when their supervisors ($r=0.698$) and foremen (i.e., immediate supervisors) ($r=0.684$) felt that they should use the exoskeleton.

Several strong correlations ($p<0.05$) were found between the usability parameters and intention-to-use. On day 1, positive correlations were observed between workers' preference ($r=0.564$), ability to use the exoskeleton during summer ($r=0.069$), and their ability to work faster ($r=0.703$), and the intention-to-use. The participants' intention-to-use the exoskeleton reduced with an increase in perception of the exoskeleton being uncomfortable ($r = -0.578$). On day three, an increase in workers' perception of the exoskeleton working the way they want to work ($r=0.732$), meeting needs for task completion ($r=0.757$), ability to work during summer ($r=0.741$), feeling satisfied ($r=0.559$), ability to work for longer duration ($r=0.688$), working faster ($r=0.826$) and work preference ($r=0.689$) led to an increase in intention-to-use. Correlations were also observed between the usability parameters and intention-to-use on day 5. Positive impact on workers' intention-to-use with an increased perception of the exoskeleton working the way participants want it to work ($r=0.847$), meeting task completion needs ($r=0.855$), helping in accomplishing tasks ($r=0.652$), ability to use without assistance ($r=0.549$) and work preference ($r=0.673$) was observed. The participants' perception of the exoskeleton restricting their movement ($r= -0.618$), interfering with the work environment ($r= -0.538$), and being uncomfortable ($r= -0.625$) reduced their intention-to-use. However, satisfaction with the exoskeleton ($r=0.88$) and the ability to use it during the summer ($r=0.857$) increased the intention-to-use. A positive correlation between the participants' ability to work for a longer duration ($r=0.762$) and working faster ($r=0.715$) and the intention-to-use was observed. Overall, a strong positive correlation ($p<0.05$) was observed between the usability parameters (i.e., ease of use, comfort, performance, and safety) and the workers' intention-to-use the exoskeleton for all three days. It was observed that the correlation increased from day 1 to day 5, for comfort, performance, and safety. However, for ease of use, the correlation reduced between day 3 ($r=0.82$) and day 5 ($r=0.59$).

<table>
<thead>
<tr>
<th>Body parts</th>
<th>Intention-to-Use: Day 1</th>
<th>Intention-to-Use: Day 3</th>
<th>Intention-to-Use: Day 5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$p$</td>
<td>$r$</td>
<td>$p$</td>
</tr>
<tr>
<td>Chest</td>
<td>0.7398</td>
<td>-0.097</td>
<td>0.6</td>
</tr>
<tr>
<td>Upper Arm</td>
<td>0.599</td>
<td>0.154</td>
<td>0.132</td>
</tr>
<tr>
<td>Hand</td>
<td>0.629</td>
<td>0.141</td>
<td>0.133</td>
</tr>
<tr>
<td>Low Back</td>
<td>0.59</td>
<td>0.155</td>
<td>0.165</td>
</tr>
<tr>
<td>Lower Leg</td>
<td>0.936</td>
<td>0.023</td>
<td>0.319</td>
</tr>
<tr>
<td>Neck</td>
<td>0.858</td>
<td>-0.052</td>
<td>0.602</td>
</tr>
<tr>
<td>Shoulder</td>
<td>0.766</td>
<td>-0.087</td>
<td>0.349</td>
</tr>
<tr>
<td>Thigh</td>
<td>0.973</td>
<td>0.0098</td>
<td>0.71</td>
</tr>
</tbody>
</table>
### Table 4.4. Results of correlation analysis for social influence (p values in bold are significantly different)

<table>
<thead>
<tr>
<th>Social Influence</th>
<th>Intention-to-Use</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Peers’ Influence</strong></td>
<td></td>
</tr>
<tr>
<td>Willingness to use</td>
<td>0.29</td>
</tr>
<tr>
<td>I will benefit</td>
<td>0.015</td>
</tr>
<tr>
<td>Important to use exoskeleton</td>
<td>0.003</td>
</tr>
<tr>
<td>I would use exoskeleton</td>
<td>0.02</td>
</tr>
<tr>
<td>I should use an exoskeleton</td>
<td>0.002</td>
</tr>
<tr>
<td><strong>Supervisors’ Influence</strong></td>
<td></td>
</tr>
<tr>
<td>I should use exoskeleton</td>
<td>0.0037</td>
</tr>
<tr>
<td>Immediate superior: I should use an exoskeleton</td>
<td>0.004</td>
</tr>
<tr>
<td>I have the ability and knowledge to use exoskeleton</td>
<td>0.269</td>
</tr>
<tr>
<td>It is important that I use exoskeleton</td>
<td>0.175</td>
</tr>
</tbody>
</table>

### Table 4.5. Results of correlation analysis for usability (p values in bold are significantly different)

<table>
<thead>
<tr>
<th>Usability</th>
<th>Intention-to-Use: Day 1</th>
<th>Intention-to-Use: Day 3</th>
<th>Intention-to-Use: Day 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ease of Use</td>
<td>p</td>
<td>r</td>
<td>p</td>
</tr>
<tr>
<td>Don and doff</td>
<td>0.523</td>
<td>0.179</td>
<td>0.136</td>
</tr>
<tr>
<td>Adjustability</td>
<td>0.528</td>
<td>-0.175</td>
<td>0.121</td>
</tr>
<tr>
<td>It works the way I want it to work.</td>
<td>0.15</td>
<td>0.389</td>
<td>0.0019</td>
</tr>
<tr>
<td>Needs for task completion</td>
<td>0.051</td>
<td>0.51</td>
<td>0.00106</td>
</tr>
<tr>
<td>Task accomplishment</td>
<td>0.402</td>
<td>0.233</td>
<td>0.0705</td>
</tr>
<tr>
<td>Use without assistance</td>
<td>0.218</td>
<td>0.337</td>
<td>0.1367</td>
</tr>
<tr>
<td>Prefer working</td>
<td>0.028</td>
<td>0.564</td>
<td>0.0044</td>
</tr>
<tr>
<td>Comfort</td>
<td>p</td>
<td>r</td>
<td>p</td>
</tr>
<tr>
<td>Movement restriction</td>
<td>0.665</td>
<td>-0.12</td>
<td>0.303</td>
</tr>
<tr>
<td>Interference with work environment</td>
<td>0.17</td>
<td>-0.37</td>
<td>0.2902</td>
</tr>
</tbody>
</table>
### 4.5.5 User perception

Analysis of the interview responses revealed four themes (or categories). The categories, including benefits, barriers, modifications, and implementation, and their subcategories are shown in Fig. 4.12. The figure provides an overview of workers’ perception of using passive back-support exoskeletons for construction work.

<table>
<thead>
<tr>
<th>Benefit</th>
<th>p</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced musculoskeletal injuries and disorders</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Productivity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Body support</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ease of exertion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compatibility with PPE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weather</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cognitive load unaffected</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Barriers</th>
<th>p</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perception of change in movement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Device</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weather</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Durability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Movement restriction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Catch and snag risks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incompatibility with PPE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Discomfort</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Modifications</th>
<th>p</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder strap</td>
<td>Covering</td>
<td>Ease of cleaning</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Implementation</th>
<th>p</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode of use</td>
<td>Suggestion</td>
<td>Storage</td>
</tr>
</tbody>
</table>

Figure 4.12. User perception of exoskeleton.
4.5.5.1 Benefits

The benefits category presents the advantages of using an exoskeleton as perceived by the participants. These include reduced musculoskeletal injuries and disorders, productivity gain, body support, ease of exertion, compatibility with PPE and weather conditions, and unaffected cognitive load. Participants believed that using the exoskeleton could help reduce musculoskeletal disorders by relieving pressure on their back (reduced musculoskeletal injuries and disorders). They also reported increased productivity (productivity gain) while using the exoskeleton as they could work for longer periods without breaks. The chest and thigh pads provided support, which helped the participants in performing their tasks (body support). The exoskeleton was found to be helpful while performing forward bending tasks such as shoveling, lifting, and concrete finishing (ease of exertion). It was also considered to be compatible with weather conditions and PPEs used on construction sites (compatibility with PPE). Additionally, the use of the exoskeleton did not affect participants’ cognitive workload, as they felt no difference compared to when they were not using an exoskeleton (cognitive load unaffected).

4.5.5.2 Barriers

The “Barriers” category presents the challenges and hindrances faced by participants in adopting exoskeletons for construction work. Participants identified several themes, including device weight, weather, durability, perception of change in movement, movement restriction, discomfort, catch and snag risks, and incompatibility with safety gear. Participants reported that using the exoskeleton during the summer caused discomfort due to increased sweating (weather). They also expressed concerns about the durability of the exoskeleton in site conditions, as it could be damaged by impact from various tools used on the site (durability). The participants felt that the exoskeleton was not compatible with the safety harness and tool belt used by workers on site (incompatibility with PPE). Participants also reported that the exoskeleton caused movement restrictions and discomfort, as the chest and leg pads applied pressure on their body parts (movement restriction). Additionally, participants perceived the exoskeleton to pose a catch-and-snag risk, as the metal torso could get hooked onto other equipment on site (catch and snag risk).

4.5.5.3 Modifications

The modification category refers to changes recommended by the participants to make the exoskeleton more suitable for construction work. Participants suggested having a covering on the torque generator to ensure that dust does not cause damage to the device (covering). Also, using a washable covering will ensure that the exoskeleton is easy to clean (ease of cleaning). The use of exoskeletons restricted participants’ movement, which prompted the comment on increasing the range of motion (increased range of motion). Although the exoskeleton is adjustable, having a loose hip strap was considered important (loosening hip belt). To ensure that the exoskeletons do not slide while squatting, the hip belt was tightened, which prompted the comment of loosening the hip belt. Thus, having a shoulder strap to ensure that the exoskeleton does not slide while
Squatting was also suggested (shoulder strap). Using the exoskeleton while chipping concrete could cause the debris to be lodged between the workers’ chest and the chest pad, causing discomfort. This prompted the comment about having a tight chest pad (chest pad). Integrating the safety harness used on the sites with the exoskeleton was also considered important (integrated safety harness). The metal torso of the exoskeleton caused discomfort to the participants while twisting, which led to the comment of making the metal torso less sharp (metal torso). Depending on the workers’ body shape and size, the legs could differ; thus, participants suggested having an adjustable thigh pad (thigh pad) with better springs to reduce resistance (better springs) while walking. Also, using damage-resistant material to withstand harsh environmental conditions was recommended (damage resistance). Overall, shoulder strap, covering, ease of cleaning, loosening hip belt, increased range of motion, metal torso, integrated safety harness, better springs, thigh pad, and damage resistance were themes identified under the modification category.

4.5.5.4 Implementation

The implementation category describes the recommendations made by the participants for the adoption of exoskeletons on construction sites. The themes identified include mode of use, suggestions, storage, maintenance, and hygiene. Participants suggested greasing the springs to maintain the torque generator in good condition (maintenance). Most participants recommended that the exoskeleton should be used as a personal device to ensure that workers handle it with more care (mode of use). However, given that the device can be adjusted to different body shapes and sizes, sharing the device was also considered a possibility (mode of use). To facilitate the sharing of devices, cleaning the exoskeleton after every use was considered crucial (hygiene). Additionally, participants suggested storing the exoskeleton in a hard case and a conex box to keep it safe (storage).

4.6 Discussion

Pipe and concrete workers often perform physically demanding tasks that can cause work-related musculoskeletal disorders (Choi et al. 2016; Ekpenyong and Inyang 2014). Wearable robots, such as back support exoskeletons, are considered a potential solution to address the occurrence of musculoskeletal disorders. However, for this intervention to be successful, exoskeletons should be acceptable to end-users. From the literature, constructs of the UTAUT theory (such as performance, ease of use, social influence), comfort, safety, discomfort, and exertion were found to have an impact on workers’ intention-to-use the exoskeleton. Thus, the user acceptance of a commercially available back support exoskeleton among pipe and concrete workers was assessed in terms of the aforementioned measures.
4.6.1 Perceived exertion and discomfort

The results of the study showed that the use of the exoskeleton significantly reduced participants' perceived exertion and discomfort in various body parts. These findings are consistent with the results of previous studies on exoskeletons, including Ziaei et al. (2021), who found a reduction in perceived exertion during manual waste collection tasks. The decrease in discomfort observed in the lower back suggests that the exoskeleton may help to reduce stress in this area. However, the decrease in discomfort observed at the chest and thigh body parts is inconsistent with the results of some previous studies. For example, Kim et al. (2020) and Gonsalves et al. (2021) observed increased discomfort in these areas during manual assembly and rebar work tasks, respectively. It is possible that the participants in this study became adapted to using the exoskeleton over the course of the week-long study, which may have contributed to the decrease in discomfort observed at these body parts. However, it is important to note that subjective measures were used in this study, so the practical or clinical significance of the observed reductions in exertion and discomfort is unclear. This could be addressed in future studies by employing objective measures such as muscle activity and range of motion.

4.6.2 Usability and social influence

The SUS score suggests that the exoskeleton has acceptable usability for pipe and concrete work, which is in line with the findings of Hwang et al. (2021) who also found acceptable usability for patient transfer tasks. This is critical because acceptable usability could mean that the participants would be more likely to adopt the exoskeleton. Overall, the exoskeleton was easy to use, suggesting that workers would not have a problem learning how to use it. This could mean that irrespective of workers' individual differences, they can easily learn how to use the exoskeleton. The ease of use increased as the week progressed, which also led to an increase in workers' preference. However, their preference was moderate, which is similar to the finding of Gonsalves et al. (2023). The exoskeleton was considered somewhat comfortable to use, as workers were satisfied with its usage and felt that it could be used during the summer. However, workers' perception of the exoskeleton restricting movement, interfering with the work environment, and being uncomfortable increased between day 1 and day 5. This finding is consistent with workers' user perception of feeling pressure on body parts and experiencing discomfort when using an exoskeleton. This could mean that it might take more than a week for the workers to get used to the exoskeleton. The exoskeleton was not considered to be a safety hazard, but interference with safety harnesses was a concern that was also reiterated under the user perception. Social influence could be an influencing factor of exoskeleton adoption, as the participants' peers felt that the exoskeleton was beneficial. This could be attributed to the positive feedback provided by the participants to their peers.
4.6.3 Intention-to-use

The perceived discomfort and exertion did not significantly influence workers' intention-to-use the exoskeleton, which is contrary to the findings of Hensel and Keil (2019), who observed that discomfort affected workers’ acceptance of exoskeletons. Social influence, on the other hand, had a positive impact on workers' intention-to-use exoskeletons, which is consistent with the findings of Elprama et al. (2020). This implies that strategies could be put in place to influence the perception of other workers (e.g., through training) to promote the implementation of exoskeletons on construction sites. The participants' intention-to-use the exoskeleton was influenced by their perception of the exoskeleton’s usability, which aligns with the inference of Hensel and Keil (2019). The correlation between workers' intention-to-use and usability parameters (e.g., comfort, performance, and safety) increased as the week progressed, but not for ease of use. This could mean that even though ease of use can impact workers' intention-to-use technology, after prolonged use, ease of use might not be a decisive factor compared to perceived comfort, performance, and safety.

4.6.4 User perception

The participants' user perception suggests that using exoskeletons for pipe and concrete work could reduce the risk of musculoskeletal disorders, which is consistent with the reported reduction in perceived discomfort and exertion. This is significant as it could encourage workers to use exoskeletons to avoid injuries. Additionally, the reduction in perceived exertion and discomfort might have enabled the participants to work for longer periods, which could have increased their productivity. This is consistent with their responses to the usability questionnaire.

Some participants reported that the exoskeleton was compatible with personal protective equipment (PPE) and weather conditions, while others viewed it as a barrier. Participants who were willing to try the exoskeleton were more likely to perceive it as compatible with PPE and weather conditions, while those who were unwilling to use it had a different perception. To avoid resistance from reluctant workers, the participants suggested integrating the exoskeleton with a safety harness. The durability of the exoskeleton was a major concern among participants, as construction workers are exposed to harsh working conditions in varying climates, which could damage the exoskeleton. Therefore, participants recommended using durable and easy-to-clean materials to help maintain the device and storing it in a hard case to prevent damage to the exoskeleton.

The pressure from the chest and thigh pads was a concern, consistent with the findings of Alemi et al. (2020) where participants also complained about pressure from the chest and thigh pads. This was also reflected in the usability questionnaire, where participants gave a moderate rating when asked whether the exoskeleton applied pressure to their body parts. However, this contrasts with the perceived discomfort ratings provided by the participants, where discomfort at the chest and thigh decreased when using the exoskeleton. To address this issue, participants suggested using adjustable pads and smoother springs.
4.7 Conclusion

The study aimed to evaluate the user acceptance of a commercially available back support exoskeleton among pipe and concrete workers in terms of discomfort, exertion, usability, and user perception. The findings suggest that the exoskeleton was effective in reducing perceived exertion and discomfort in all body parts. The usability evaluation showed that the exoskeleton had acceptable usability and was easy to use, but participants' comfort and productivity were affected after prolonged use. The participants' preference to use the exoskeleton increased with time, and social influence and usability had a significant impact on workers' intention-to-use it. The study also identified four main categories from the participants' user perception, namely benefits, barriers, modification, and implementation. Overall, considering the reduction in discomfort and exertion, acceptable usability, moderate intention-to-use, and increased preference with time, the exoskeleton can be concluded as acceptable for pipe and concrete workers.

This study contributes to the scarce literature on the acceptance of exoskeletons among construction workers. The results of this study show the applicability of the UTAUT theory for measuring the user acceptance of exoskeletons. There are scarce existing benchmarks to support the usability evaluation of exoskeletons. Thus, this study could provide a benchmark against which future studies can assess usability. The findings of this study can assist researchers and practitioners in developing an implementation framework for the adoption of exoskeletons in the construction industry. Furthermore, the workers' feedback can help exoskeleton manufacturers to upgrade the devices to make them more suitable for construction work.

This research has several limitations that should be addressed in future studies. First, the sample size was small, which limits the generalizability of the results to the wider construction industry. Moreover, the study only included male participants, so future studies should include a more diverse sample to increase the representation of the construction population. Second, the study only focused on pipe and concrete workers, so further research is needed to understand the acceptance of exoskeletons among other construction trades. Third, workers with back pain were excluded from the study, but they may benefit from using exoskeletons, so future research should include these workers. Fourth, the study only used subjective measures to assess the impact of exoskeleton use and acceptance among workers. Future studies could include objective measures such as muscle activity and range of motion to better understand the impact of exoskeletons on workers' fatigue. Fifth, the study did not include a comparative analysis between different construction trades, so future research could examine which trades could benefit most from using exoskeletons. Sixth, the study did not analyze the influence of individual differences on workers' acceptance, so further research is needed to understand how individual differences affect workers' intention-to-use exoskeletons. Finally, a follow-up study could be conducted to evaluate whether the modifications suggested by workers lead to increased user acceptance.
CHAPTER 5: INDUSTRY PERSPECTIVE OF THE FACTORS INFERENCING THE ADOPTION OF PASSIVE WEARABLE ROBOTS ON CONSTRUCTION PROJECTS

5.1 Abstract

The emergence of passive back-support exoskeletons has opened new opportunities to reduce the occurrence of back injuries in the construction industry. Perspectives of construction stakeholders regarding factors that influence adoption of exoskeletons, would inform successful implementation of exoskeletons in the construction industry. The goal of this study was to understand factors that are critical for the adoption of back support exoskeletons in the construction industry. A survey of industry practitioners was conducted to identify the important stakeholders whose perspectives are critical to decisions regarding the adoption of exoskeletons. The survey also identifies the factors which could influence the implementation of exoskeletons in the construction industry. Analytical hierarchy process was employed to evaluate and rank the factors. Informed by the survey results, two focus groups were conducted to understand how the factors influence the implementation process. The results identified construction workers, supervisors, regulatory bodies, ergonomists, corporate management, and safety professionals as the key stakeholders for exoskeleton adoption in the construction industry. Exoskeleton features such as usability, durability, long-term benefits and compatibility with work tasks are the most important facilitators, whereas catch and snag risks, fit, weight, and cost justification are the most critical barriers. The focus group discussions highlighted the benefits and applications of back-support exoskeletons, design modifications to exoskeletons, and challenges to adopting exoskeletons in the construction industry. Construction companies could leverage these findings to develop exoskeleton implementation strategies. Researchers and designers could use the design modifications to improve adaptability of exoskeletons for construction work. This study contributes to the socio-technical systems theory by defining key decision-makers and factors influencing exoskeleton adoption.

5.2 Introduction

The construction industry is one of the largest industry sectors in the United States, contributing to 4.1% of the nation’s gross domestic product (Analysis 2022). Despite its economic significance, the construction industry has one of the highest rates of non-fatal injuries and illnesses associated with musculoskeletal disorders. Compared with other industries, construction workers are approximately 1.7 times more likely to sustain musculoskeletal disorders (BLS 2022). The rate of musculoskeletal disorders has doubled over the past three years (BLS 2022). Musculoskeletal disorders sustained in the workplace, also known as work-related musculoskeletal disorders (WMSDs), affect different body parts mostly, the back, shoulders, wrists, neck, hips, knees, and feet (Abas et al. 2018). WMSDs have been known as one of the leading causes of absenteeism from work and, in severe cases, have resulted in premature disability (Bevan 2015). According to
Liberty Mutual (a major insurance provider), the direct cost of workplace injuries in the United States due to WMSDs amounts to $18.39 billion annually (Howard et al. 2020). Risk factors of WMSDs include bending, lifting heavy objects, twisting, awkward posture, vibration, kneeling, contact stress, environmental risk, and static force.

Wearable robots, also known as exoskeletons, are increasingly being recognized as promising interventions for reducing the risk factors of WMSDs. Studies have documented the potential of exoskeletons for reducing muscle activities. For example, (Bosch et al. 2016) observed a reduction in the back muscle activity by 35% to 38% when using a passive back-support exoskeleton for static forward bending assembly tasks. A reduction in the back muscle activity by about 48% was observed by Thamsuwan et al. (2020) when a passive back-support exoskeleton was employed for farm work. Kazerooni et al. (2019) found out that the use of a passive trunk supporting exoskeletons for forward bending postures can reduce muscle activity by 75% and 56% at the thoracic and lumbar erector spinae muscles respectively. In the construction industry, Cho et al. (2018) tested a passive back-support exoskeleton for masonry work and observed that the exoskeleton enabled the workers to maintain safe working postures.

The aforementioned benefits of using exoskeletons are inspiring the construction industry to adopt exoskeletons to address the occurrences of WMSDs. However, previous studies (Choi et al. 2017; Coert et al. 2021; Park et al. 2012; Son et al. 2012) have shown that adoption of new technologies would require understanding the perspectives of key stakeholders regarding the factors which can affect implementation of technologies in the workplace. For example, Coert et al. (2021) investigated stakeholders’ perspectives regarding the facilitators of -and barriers to the adoption of virtual clinical trials. Low degree of acceptance amongst the regulatory bodies, technical issues, and lack of knowledge were identified as barriers, whereas involvement of regulators, stakeholders’ exposure to the results of pilot studies, and simple instructions were considered as key facilitators. Choi et al. (2017) delved into construction workers' perspective regarding the adoption of wearable technology and identified perceived usefulness, social influence, and perceived privacy risk as key factors impacting workers’ intention to adopt wearable technology. Son et al. (2012) investigated factors that influence construction professionals' willingness to adopt mobile computing devices and found determinants of perceived usefulness and ease of use as critical for the successful implementation. Moreover, Crea et al. (2021) highlighted the importance of involving stakeholders in the adoption of exoskeletons since different stakeholders could potentially have different understanding of the exoskeletons in terms of use, benefits, and cost, which could influence their opinions regarding the adoption of exoskeletons. Limited understanding of stakeholders’ perspectives regarding the factors that could enable or obstruct the adoption of exoskeletons could result in the failure of exoskeleton implementation in the construction industry.

Thus, the objective of this study is to understand critical stakeholders’ perspectives of the facilitators of -and barriers to the adoption of back-support exoskeletons in the construction industry. An online survey was conducted to identify factors (i.e., facilitators and barriers) which can impact the adoption of exoskeletons and stakeholders whose perspectives is necessary to be
considered for the implementation of exoskeletons in the construction industry. Thereafter, two focus group discussions were conducted to formalize the findings from the survey.

5.3 Background

5.3.1 Potential of exoskeletons in the construction industry

According to De Looze et al. (2016), exoskeletons are “wearable, external mechanical structures that enhance the power of a person”. Depending on the form of enhancement or actuation, exoskeletons can be broadly classified as ‘active’ and ‘passive’ systems. Active systems could consist of electric, hydraulic or pneumatic actuators that augment the wearer’s capabilities and help in supporting human joints. On the other hand, passive exoskeletons employ springs or dampers to store the energy acquired through human motions to provide support to the wearer’s body parts. Furthermore, depending on the supported body part, exoskeletons are further classified into full body, back, shoulder, and leg-support exoskeletons which can be employed depending on the task performed by the workers and the body part at risk for WMSD. For example, workers performing overhead work will benefit more from shoulder-support exoskeletons compared to back-or leg-support exoskeletons. Amongst the different body parts affected by WMSDs, back related injuries account for 43% of all the cases in the construction industry (Kim et al. 2019). Thus, considering the size of the construction workforce and given that back related injuries are dominant in the construction industry, passive back support exoskeletons could be a potential solution to address back related WMSDs.

In recent times, researchers (De Looze et al. 2016; Madinei et al. 2019; Schmalz et al. 2022) have looked into the use of passive back-support exoskeletons in different industrial sectors such as manufacturing and automobile. These studies measured different outcome measures such as muscle activity (using electromyography sensors), kinematics (using an inertial measurement unit), compression force (computed using muscle activity and kinematics), discomfort (using a questionnaire), and oxygen rate (using spiroergometric systems) thereby showcasing their potential to address WMSDs. For instance, Koopman et al. (2020) evaluated (n=10) SPEXOR passive exoskeleton in terms of compression force, muscle activity, and kinematics for static bending and lifting a 10 kg box. Results showed a reduction in back muscle activity by 22%. Schmalz et al. (2022) tested Paexo Back, a passive back-support exoskeleton, using a repetitive lifting task to replicate working conditions in terms of oxygen rate, muscle activation, and joint compression forces. A significant reduction in participants’ (n=10) oxygen rate (9%), back compression forces (21%), and back and thigh muscle activity (18%) was observed indicating increased metabolic efficiency, lower back loading, and reduced back muscle activity. Another passive back-support exoskeleton called Laevo V2.56 was tested in terms of muscle activity in the trunk and hip extensor muscle, using 36 participants, for symmetric and asymmetric repetitive lifting tasks by assuming squatting and stooping positions. It was observed that the use of the exoskeleton decreased mean/peak muscle activity of the erector spinae (6%), biceps femoris (28%), and rectus abdominis (6%) muscles. However, an increase in muscle activity at vastus lateralis (69%), trapezius descendens (19%), and flexion of knee (6%) and hip (11%) was observed.
Using eighteen participants, (Madinei et al. 2019) tested two rigid passive back-support exoskeletons viz. BackX V2 and Laevo V2.56 for precision manual assembly tasks and observed a reduction in back muscle activity by 37.9% (BackX V2) and 23.9% (Laevo V2.56).

Although the tasks performed in the above-mentioned studies involve forward bending, construction work involves a wide range of activities performed in environmental conditions which are different when compared to other industries (e.g., manufacturing and automobile). For example, construction workers are exposed to dusty sites and varying climatic conditions as opposed to the manufacturing and automobile industry which involve working in controlled conditions of factories. This has prompted studies aimed at evaluating back-support exoskeletons specific for construction tasks. For example, Gonsalves et al. (2021) evaluated the BackX V2 exoskeleton for rebar work in terms of completion time, muscle activity, and discomfort. A reduction of 50% and 100% for task completion time and discomfort at the back, respectively, was observed. Antwi-Afari et al. (2021) designed and tested a passive exoskeleton for manual material handling and found a reduction of 33% at the erector spinae muscle groups as well as reduced discomfort at the lower back (42%). While these studies have unveiled the suitability of exoskeletons for construction work, successful adoption of new technologies, in occupational sectors, has also been linked to the implement-ability of technologies in the workplace (Hrebiniak 2006). An ill-devised implementation strategy could affect adoption or success of new technology in any industry sector. Therefore, to enhance successful adoption of exoskeletons in the construction industry, it is significant to understand the factors which could impact the implementation of exoskeletons specific to the construction industry.

5.3.2 Factors influencing implementation of exoskeletons in the workplace

A few studies have investigated factors influencing exoskeletons in different industrial sectors such as healthcare, construction, manufacturing, and agriculture (Cha et al. 2020; Elprama et al. 2022; Kim et al. 2019; Schwerha et al. 2021; Wolff et al. 2014). For example, Cha et al. (2020) identified barriers and potential need for adoption of exoskeleton amongst surgical teams via a focus group consisting of fourteen surgical team members. The results revealed 17 factors which were broadly classified into characteristics of individuals, perceived benefits, environmental/societal factors, and intervention characteristics. A literature review was conducted by Elprama et al. (2022) to identify factors that influence the use of exoskeletons. A total of 24 factors were identified and broadly grouped under physiological factors, psychological factors, policy-related factors, work-related factors, and implementation-related factors. An acceptance model for passive upper limb exoskeleton was developed by Moyon et al. (2019) through field testing. The model includes 15 factors which are divided into four main categories, namely, physical aspects, occupational aspects, cognitive aspects, and affective aspects. Schwerha et al. (2021) investigated the adoption potential for five different exoskeletons using focus group discussions. The authors identified 25 barriers which were divided into personnel, safety, job tasks, implementation, and work environment categories and 13 adoption benefits which were classified into personnel, safety, and performance categories. Upasani et al. (2019) surveyed professionals
in the health and safety, and farm services (n=18) to investigate the potential of exoskeleton for agriculture use. The results indicated usability, compatibility with farming environment, immediate benefit, familiarity and confidence, and affordability as critical factors for adopting exoskeletons. The results also highlighted unexpected failure, overuse and overconfidence, stress on the body, failing, and getting caught in farming equipment as safety/health risks.

Despite the significance of these studies, there is a paucity of similar investigations in the construction sector. One of such studies is the work of Kim et al. (2019). The objective of the study was to understand the potential of using exoskeletons in the construction industry from the perspective of industry stakeholders and workers. The authors conducted semi-structured interviews with 26 construction industry professionals and workers which included project managers/engineers, safety and health manager, carpenters, and a vice president. The qualitative data were analyzed using cluster analysis, from which 21 factors were identified and broadly classified under expected benefits, perceived barriers to exoskeleton use, and exoskeleton technology adoption. The study further provided suggestions for future research regarding exoskeleton use in construction. However, this study only conducted semi-structured interviews for identifying the factors and the factors were not validated. Mahmud et al. (2022) conducted a study to identify the facilitators, barriers and corresponding solutions for the adoption of exoskeletons in the construction workplaces. A Delphi method involving eighteen participants was employed. The study identifies 52 factors which were classified under business, technology, organization, policy/regulation, ergonomics/safety, and end users. Also, the solutions for the identified barriers were also proposed in the study. However, this study did included a systematic literature review for identifying the factors. Delgado et al. (2019) investigated the industry specific factors that limit the adoption of robotics and automated systems including exoskeletons in the construction industry. Through online survey and focus groups 11 factors were identified which were categorized under contractor side economic factors, client-side economic factors, technical and work culture factors, and weak business case categories. However, these factors are not specific to exoskeletons. From the aforementioned studies, a total of 139 factors were identified. These factors were classified into facilitators and barriers, and factors with similar meanings were merged under the same category to avoid repetition. This study included a total of 56 factors classified under facilitators (25) (see Table 5.1) and barriers (31) (see Table 5.2).

<table>
<thead>
<tr>
<th>Categories of facilitators</th>
<th>Facilitators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perceived Benefits</td>
<td>Long-term benefits (Cha et al. 2020)</td>
</tr>
<tr>
<td></td>
<td>Ergonomics training (Cha et al. 2020; Kim et al. 2019)</td>
</tr>
<tr>
<td></td>
<td>Cost benefit (Crea et al. 2021)</td>
</tr>
<tr>
<td></td>
<td>Productivity gain (Kim et al. 2019; Schwerha et al. 2021; Upasani et al. 2019)</td>
</tr>
<tr>
<td>Psychosocial</td>
<td>Awareness of problem/ indication of a need for exoskeletons (Cha et al. 2020)</td>
</tr>
</tbody>
</table>
Curiosity (Openness to innovation) (Cha et al. 2020)
Existing knowledge about exoskeletons (Elprama et al. 2020)
Light cognitive workload (Moyon et al. 2019)
Perceived usefulness of exoskeletons (Elprama et al. 2020)
Overall appearance of exoskeletons (Wolff et al. 2014)
Champion (Cha et al. 2020; Elprama et al. 2020)

Immediate pain relief from using exoskeletons (Cha et al. 2020; Upasani et al. 2019)
Familiarity with exoskeletons (Kim et al. 2019)
Team buy-in (i.e., team willingness to use exoskeleton) (Cha et al. 2020)
Tribality of exoskeleton (Kim et al. 2019)
Exoskeletons to enable performance and attract other workers (Elprama et al. 2020)
Compatibility of exoskeleton with work tasks (Elprama et al. 2020)
Few errors and efficient for quality standards (i.e., no impact on quality of construction) (Moyon et al. 2019)
Minimum disturbances of construction process (Moyon et al. 2019)
Ability to use the restroom (Wolff et al. 2014)
Ease of maintenance (Upasani et al. 2019)
Durability / ruggedness of the exoskeleton (Elprama et al. 2020; Kim et al. 2019; Schwerha et al. 2021)

Policy-related
Mandatory use of an exoskeleton (Elprama et al. 2020)
Client driven (Wolff et al. 2014)

Usability
Ease of using an exoskeleton / Ease of putting on and off / comfort (Cha et al. 2020; Elprama et al. 2020; Moyon et al. 2019; Schwerha et al. 2021)

Table 5.2. List of barriers employed in this study.

<table>
<thead>
<tr>
<th>Categories of barriers</th>
<th>Barriers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cultural beliefs</td>
<td>(Elprama et al. 2020)</td>
</tr>
<tr>
<td>Social perception of an exoskeleton by the user and others / Peer acceptance</td>
<td>(Elprama et al. 2020; Kim et al. 2019)</td>
</tr>
<tr>
<td>General attitude towards exoskeletons</td>
<td>(Elprama et al. 2020)</td>
</tr>
<tr>
<td>Perception of weakness</td>
<td>(Schwerha et al. 2021)</td>
</tr>
<tr>
<td>Resistance to change</td>
<td>(Schwerha et al. 2021)</td>
</tr>
<tr>
<td>Sterilization/Hygiene</td>
<td>(Cha et al. 2020; Elprama et al. 2020; Schwerha et al. 2021)</td>
</tr>
<tr>
<td>Wear time of exoskeleton parts</td>
<td>(Moyon et al. 2019)</td>
</tr>
<tr>
<td>Limited space</td>
<td>(Schwerha et al. 2021)</td>
</tr>
<tr>
<td>Storage</td>
<td>(Cha et al. 2020; Elprama et al. 2020; Schwerha et al. 2021)</td>
</tr>
<tr>
<td>Duration of maintenance</td>
<td>(Cha et al. 2020; Elprama et al. 2020; Schwerha et al. 2021; Upasani et al. 2019)</td>
</tr>
<tr>
<td>Durability and ruggedness of the exoskeleton</td>
<td>(Elprama et al. 2020; Kim et al. 2019; Schwerha et al. 2021; Upasani et al. 2019)</td>
</tr>
</tbody>
</table>
## 5.3.3 Theoretical underpinning

According to Baxter and Sommerville (2011), socio-technical systems theory is a design approach that considers the human, social, organizational as well as design factors during the design and implementation of organizational systems. This is critical because in any organization, various parts of a system come together to form different processes (Dekker 2016). Changes in one part of a system without considering the effect on other parts could impact the effectiveness of the adoption of new processes or technology (van Eijnatten 2013). Dillon and Morris (1996) suggested that new technology cannot be analyzed only in isolation from its intended audience, rather emphasis on the holistic job satisfaction across the organization is important. Thus, it is essential to consider all subsystems of a system in an organization.

In the context of adopting back-support exoskeletons in the construction industry, stakeholders can be considered as the subsystems of a system and it is necessary to understand the perspectives of all the stakeholders (Welch et al. 2015). However, there is scarce evidence regarding stakeholders’ perspectives on exoskeleton adoption (Wolff et al. 2014). Crea et al. (2021) identified workers, union and workers associations, policy makers, ergonomists, corporate management, insurance companies, and certifying bodies as critical stakeholders for the adoption
of exoskeletons. Wolff et al. (2014) conducted a survey to identify stakeholders’ perception regarding exoskeleton technologies used for rehabilitation. The stakeholders involved in the study included wheelchair users (i.e., end users) and healthcare professionals working directly with the wheelchair workers. Toxiri et al. (2019) identified managers, end users, manufacturers and researchers as critical stakeholders for promoting occupational use of back support exoskeletons. The stakeholders identified from the above studies are not specific to the construction industry. Thus, this research underpins this study in socio-technical systems theory by identifying the key stakeholders and capturing their perspectives regarding the adoption of exoskeletons in the construction industry. In accordance with the socio-technical systems theory, as a first step, it is necessary to identify the important stakeholders (Di Maio 2014) which leads us to the first research question (RQ1): Which stakeholders’ perspectives are important to be considered during decisions regarding the adoption or implementation of exoskeletons in the construction industry?

Once the stakeholders have been identified, it is necessary to incorporate their perspectives into the adoption process. This is important because different stakeholders can have different expectations from the device. Harmonizing multiple viewpoints and expectations is an essential balancing process which is a part of socio-technical systems theory (Di Maio 2014). To incorporate stakeholders’ perspective on technology adoption, researchers (BenMessaoud et al. 2011; Delgado et al. 2019; Kim et al. 2019) have focused on identifying the factors (barriers and facilitators) for technology adoption. For example, Delgado et al. (2019), investigated industry specific challenges for the adoption of robotics and automated systems in the construction industry. The authors found 28 factors classified under contractor-side economic factors, client-side economic factors, technical and work-culture factors, and weak business case factors. Bademosi and Issa (2021) investigated factors (i.e., benefits, barriers, cost, and risk) which could potentially impact the adoption of robotics and automation technology in the construction industry. Elprama et al. (2022) created a framework for the adoption of exoskeletons and highlighted the importance of identifying relevant factors. These studies point out the need to capture facilitators which can enhance the adoption of exoskeletons as well as barriers which could obstruct the adoption of exoskeletons in the construction industry. This leads to the second research question (RQ2): What are the key stakeholders’ perceptions of the facilitators of and barriers to the adoption of exoskeletons in the construction industry?

5.4 Research Methodology
A mixed method approach (Fig. 5.1) was adopted in this study to answer the research questions raised in the previous sections. Mixed method approach provides researchers with a wider scope to investigate industry perceptions using both qualitative and quantitative methods (Almalki 2016). An online survey (involving participants with demographics as shown in Table 5.3) was developed to identify the facilitators and barriers to the adoption of back-support exoskeletons in the construction industry. The analytical hierarchy process was conducted to rank the factors in the order of the most important to the least important (Tables 5.4 and 5.5). The results of the survey were validated with a focus group consisting of industry practitioners identified from the survey
as key decision makers in the adoption of back-support exoskeletons in the construction industry. Using an inductive coding process, the focus group data was analyzed, and the emerging themes were identified (Fig. 5.5).

5.4.1 Survey

An online survey (IRB #22-017) was developed using QuestionPro which was informed by the results of the literature review and includes key stakeholders whose opinions are necessary for the adoption of exoskeletons at workplace and the factors that could impact decisions regarding the adoption of exoskeletons, as indicated in Fig. 5.1. Surveys are commonly employed in the construction industry to identify critical factors (Reinaldo et al. 2021). The survey was administered between January 2022 and June 2022 to industry practitioners via LinkedIn and listservs of construction companies, construction associations and university industry partners. A total of 883 construction industry practitioners viewed the survey from which 196 partially completed the survey and 105 completed the survey, yielding a response rate of 11.89%. The sample size of 105 could be considered reasonable, owing to the difficulty in eliciting responses due to the immaturity of the technology in the construction industry (Chan et al. 2017). The beginning of the survey had background information on back-support exoskeletons including pictorial information on applications and context for use of exoskeletons. Studies (Huang et al. 2022; Khan et al. 2014; Yang et al. 2016) have used pictorial information to solicit and support responses to their surveys. In safety and health related research, pictorial information, representing facial expressions or feelings, have been used to capture perceptions of effort, exertion, and fatigue. The survey consists of four sections, eliciting information on the following: (a) Participants’ demographics; (b) Participants’ level of awareness of back-support exoskeletons; (c) Key stakeholders that should be involved in decisions regarding the adoption of exoskeletons in the construction industry; and (d) facilitators and barriers to the adoption of back-support exoskeletons. The participants’ demographic information is represented in Table 5.3. Furthermore, to gauge the participants' awareness of back-support exoskeletons, the participants were asked to rate their level of awareness using a 5-point Likert’s scale ranging from 1 (very low awareness) to 5 (very high awareness). Similar methods have been adopted by other construction related studies (Sichali and Banda 2017; Son et al. 2011) to measure participants' level of awareness.

A comprehensive list of 8 potential stakeholders, whose feedback is critical in decisions regarding adoption of exoskeletons, was identified from literature review (Crea et al. 2021; Toxiri et al. 2019). These stakeholders include supervisors, tradesmen, laborers, union and workers association, ergonomists/occupational health therapists, insurance companies, and certifying bodies (e.g., OSHA). Participants were presented with this list and asked to select the most suitable stakeholders. The participants also had the option to provide stakeholders that were not included in the list. From the literature review, 56 factors were identified as possibly impacting the adoption of exoskeletons (see Tables 5.1 and 5.2). These factors were classified into facilitators of and
barriers to the adoption of exoskeletons. These facilitators were further classified into five main categories which include perceived benefits, psychosocial factors, work-related factors, policy-related factors, and usability. The barriers were also classified into eight categories including psychosocial factors, work-related factors, usability, safety, policy-related factors, implementation factors, physiological factors, and work environment. The participants were provided with a list of the facilitators and barriers, and asked to rate them according to the level of importance of each factor on a 5-point Likert’s scale (i.e., 1: very low importance, 2: low importance, 3: neutral importance, 4: high importance, and 5: very high importance). Before administering the survey, a pilot testing was conducted involving eight participants which included four academics and four construction industry professionals including a senior manager, field worker, project engineer, and safety professional. The objective of this pilot testing was to ensure that the survey covers all the required factors and provides the investigators the opportunity to revise the questionnaire if required.

Figure 5.1. Methodology
5.4.2 Focus group

Two focus groups were conducted to understand how the facilitators and barriers identified from the survey would influence the adoption of exoskeletons in the construction industry. Focus groups are a type of research technique where a small group of participants are gathered to respond to questions in a controlled environment to obtain consensus (Onwuegbuzie et al. 2009). Focus groups are commonly employed to validate survey results (Oyedele 2013; Yu et al. 2006). The focus groups consisted of the stakeholders identified from the survey as key decision makers when considering the adoption of exoskeletons in the construction industry. The participants include a construction worker, site supervisor, corporate management, safety manager, ergonomist, and certifying body (e.g., OSHA) representative. Both focus group sessions (i.e., one for facilitators and one for barriers) consisted of the same participants. Images and videos of workers using a back-support exoskeleton were shared with the participants prior to the session to ensure they understand the use of exoskeleton on construction sites. At the beginning of the sessions, participants were asked to provide verbal consent and were briefed regarding the procedure of focus group discussion. A list of the factors (i.e., facilitators and barriers) were shown to the group members one at a time, and were asked to provide feedback regarding the importance of the factors during decisions regarding the adoption of exoskeletons in the construction industry. Participants were encouraged to contribute and discuss amongst themselves. During the discussion, the moderator probed the participants to get deeper insights into their feedback which prompted further discussions within the group. Participants were allowed to express their thoughts, and no time constraints were imposed. After all the members expressed their views, the next factor was discussed. Both the sessions lasted one hour each, and were conducted online via Zoom, and audio and video recorded. The transcripts were anonymized before being transcribed and analyzed.

5.4.3 Data analysis

In this study, the survey data was analyzed using the Analytical Hierarchy Process (AHP) which is a commonly adopted method in construction and other industries to identify importance of factors (Cakmak and Cakmak 2013; Kumar et al. 2015; Luthra et al. 2013; Raviv et al. 2017). The goal of employing AHP in this study was to identify factors critical for the adoption of exoskeletons. AHP is a multi-criteria decision-making approach that was developed by Saaty (1990). It involves pairwise comparisons of alternatives/criteria based on specified criteria, and the resulting comparison matrix is used to determine the ranking of alternatives to aid the decision-making process. AHP technique consists of three steps (Saaty 1994; Saaty 2008): (1) establishing a hierarchical structure with decision elements (as shown in Fig. 5.2); (2) constructing pairwise comparison matrices, and (3) calculating consistency. As shown in Fig. 5.2, a hierarchy was developed. The hierarchy was created considering two criteria (i.e., facilitators and barriers) which were further divided into different factors (Tables 5.1 and 5.2). After constructing the hierarchy, the factors can be ranked to determine their relative importance at each level of the hierarchy using pairwise comparison. To conduct pairwise comparison matrices, the mean score (Nnaji and Awolusi 2021) for each factor was calculated based on the responses provided by the survey
participants to the level of involvement for each factor, on a 5-point Likert’s scale. Survey responses are commonly employed to identify the relative importance of different criteria in AHP which is analyzed using the mean score (Cheng and Li 2001; Wong and Li 2008). Using the formula in Equation I, the mean score for each factor was calculated as outlined by Nnaji and Awolusi (2021):

\[ \text{Mean score} = \frac{\text{Sum } s_i \cdot p_i}{\text{Sum } p_i} \]  

(Eq. I)

Where, \( s_i \) is the weight assigned to \( i \)th response (\( s_i = 0, 1, 2, 3, 4 & 5 \) for \( i = 0, 1, 2, 3, 4 & 5 \)); \( p_i \) represents the frequency of the \( i \)th response, and \( i \) represents the response category, 0, 1, 2, 3, 4, & 5, ranging from the least important (1) to the most important (5) and not important (0).

Using the mean score, separate pairwise comparison matrices were constructed for facilitators and barriers to identify priority weightage for each factor. The calculated priority weightage was used to rank the factors based on their level of importance (Tables 5.4 and 5.5). In AHP, the consistency index is used to judge the rationality and consistency of the weights assigned to each criterion for calculating the priority weightage. Since the mean scores from the survey were employed to calculate the priority weightage and were not assigned, the consistency index was not calculated in this study. Furthermore, descriptive statistical analysis such as mean was also employed to analyze the survey data. All Statistical analysis was conducted using MS Office Excel.

The qualitative data from the focus group were analyzed using NVivo 11, a qualitative analysis software (Kim et al. 2019). A codebook was generated based on the transcribed data to identify why the participants deemed a particular factor critical. Furthermore, an inductive coding process was adopted to categorize codes of similar meaning into categories (Fig. 5.5). Inductive coding is a process in which, the themes emerging from the raw data are identified through repeated examinations (Chandra and Shang 2019). Inductive coding is a commonly adopted method to analyze qualitative data in the construction industry (Goel et al. 2021; Kim et al. 2019; Lingard et al. 2022).

Figure 5.2. AHP hierarchy
5.5 Results

5.5.1 Survey

5.5.1.1 Demographics and awareness of exoskeletons

A total of 112 responses were received from which 7 incomplete responses were excluded and 105 responses were considered in this study. Table 5.3 summarizes the demographics of the survey participants. The respondents were grouped according to the type of construction company they work for, the company size, their work experience, gender, race, and job role. Regarding the respondents’ level of awareness of exoskeletons, about 57% of the participants have medium to high level of awareness, while the rest of the participants have low to very low level of awareness.

Table 5.3. Demographic characteristics of survey participants.

<table>
<thead>
<tr>
<th>Categories</th>
<th>Frequency</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type of construction</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residential Construction</td>
<td>18</td>
<td>17.14%</td>
</tr>
<tr>
<td>Commercial Construction</td>
<td>53</td>
<td>50.48%</td>
</tr>
<tr>
<td>Specialized Industrial</td>
<td>22</td>
<td>20.95%</td>
</tr>
<tr>
<td>Construction</td>
<td>Heavy</td>
<td>72</td>
</tr>
<tr>
<td><strong>Company size</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(No. of employees)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Less than 10</td>
<td>3</td>
<td>2.86%</td>
</tr>
<tr>
<td>10 to 19</td>
<td>0</td>
<td>0%</td>
</tr>
<tr>
<td>20 to 49</td>
<td>7</td>
<td>6.67%</td>
</tr>
<tr>
<td>50 to 99</td>
<td>4</td>
<td>3.81%</td>
</tr>
<tr>
<td>100 to 249</td>
<td>5</td>
<td>4.76%</td>
</tr>
<tr>
<td>250 to 499</td>
<td>9</td>
<td>8.57%</td>
</tr>
<tr>
<td>500 to 999</td>
<td>13</td>
<td>12.38%</td>
</tr>
<tr>
<td>1000+</td>
<td>61</td>
<td>60.95%</td>
</tr>
<tr>
<td><strong>Experience</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(years)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 to 5 years</td>
<td>29</td>
<td>27.62%</td>
</tr>
<tr>
<td>6 to 10 years</td>
<td>19</td>
<td>18.10%</td>
</tr>
<tr>
<td>11 to 15 years</td>
<td>13</td>
<td>12.38%</td>
</tr>
<tr>
<td>Above 15 years</td>
<td>44</td>
<td>41.90%</td>
</tr>
<tr>
<td><strong>Gender</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>92</td>
<td>87.62%</td>
</tr>
<tr>
<td>Female</td>
<td>13</td>
<td>12.38%</td>
</tr>
<tr>
<td><strong>Race</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>American Indian or Alaska</td>
<td>2</td>
<td>1.90%</td>
</tr>
<tr>
<td>Native</td>
<td>Asian</td>
<td>5</td>
</tr>
<tr>
<td>Black or African American</td>
<td>9</td>
<td>8.57%</td>
</tr>
<tr>
<td>Native Hawaiian or Other</td>
<td>1</td>
<td>0.95%</td>
</tr>
<tr>
<td>Pacific Islander</td>
<td>Hispanic</td>
<td>12</td>
</tr>
<tr>
<td>White</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Job role</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Construction workers</td>
<td>12</td>
<td>11.43%</td>
</tr>
<tr>
<td>Field engineer</td>
<td>12</td>
<td>11.43%</td>
</tr>
<tr>
<td>Project engineers</td>
<td>17</td>
<td>16.19%</td>
</tr>
<tr>
<td>Safety managers</td>
<td>9</td>
<td>8.57%</td>
</tr>
<tr>
<td>Field managers/Foremen</td>
<td>14</td>
<td>13.33%</td>
</tr>
<tr>
<td>Project managers</td>
<td>19</td>
<td>18.10%</td>
</tr>
</tbody>
</table>
5.5.1.2 Stakeholders

Participants were provided with a list of eight stakeholders, which include laborers, certifying bodies (for e.g., OSHA), ergonomists, supervisors, tradesmen, union and workers association, corporate management, and insurance companies to choose from. About 74.29% and 69.5% of the participants selected laborers and tradesmen respectively. Supervisors were selected by 66.67% of participants, followed by ergonomists (56.19%), certifying bodies (55.24%), and corporate management (55.24%). Fewer participants chose union and workers association (38.10%) and insurance companies (40.95%). Laborers received the highest rating for level of involvement (4.65) in decisions regarding the adoption of exoskeletons, whereas insurance companies (4.10) received the lowest rating. From the AHP analysis, laborers, supervisors, certifying bodies, ergonomists, and corporate management were identified as the crucial stakeholders to be involved in decisions regarding the implementation of exoskeletons in the construction industry. Furthermore, some of the participants provided qualitative feedback regarding involving safety professionals in the adoption of exoskeletons.

5.5.1.3 Exoskeleton adoption facilitators

Overall, an average mean score of 2.15 was provided by the participants. ‘Ease of using an exoskeleton / Ease of putting on and off / comfort’ received the highest mean score of 3.62 whereas ‘Light cognitive workload’ received the lowest mean score of 1.08. Also, in terms of the number of participants, 83 participants (out of 105) suggested ‘Ease of using an exoskeleton / Ease of putting on and off / comfort’ as a critical facilitator, whereas ‘Light cognitive workload’ was selected by only 28 participants as shown in Fig. 5.3. Based on the AHP analysis, the facilitators were arranged from most important to the least important (see Table 5.4). ‘Ease of using exoskeletons’, ‘Long term benefits’, ‘Durability/ruggedness of the exoskeletons’, ‘Immediate pain relief from using exoskeletons’ and ‘Compatibility of exoskeletons with work’ were the top five facilitators. ‘Mandatory use of an exoskeleton’, ‘Existing knowledge about exoskeletons’, ‘Overall appearance of exoskeletons’, ‘Tribality of exoskeleton’, and ‘Light cognitive workload’ had the lowest weightage based on the AHP analysis. In terms of the mean values, the highest rating of 4.73 was assigned to ‘Compatibility of exoskeleton with work tasks’ whereas the lowest rating of 3.23 was assigned to ‘mandatory use of an exoskeleton’. Table 5.4 shows the MS, AHP weightage, and percentage rating of the facilitators.
Table 5.4. List of facilitators of the adoption of exoskeletons in the construction industry.

<table>
<thead>
<tr>
<th>No.</th>
<th>Facilitators</th>
<th>MS</th>
<th>Priority weightage</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>Ease of using an exoskeleton / Ease of putting on and off / comfort</td>
<td>3.62</td>
<td>0.067</td>
<td>79.05%</td>
</tr>
<tr>
<td>F2</td>
<td>Long-term benefits</td>
<td>3.50</td>
<td>0.065</td>
<td>76.19%</td>
</tr>
<tr>
<td>F3</td>
<td>Durability / ruggedness of the exoskeleton</td>
<td>2.92</td>
<td>0.054</td>
<td>62.86%</td>
</tr>
<tr>
<td>F4</td>
<td>Immediate pain relief from using exoskeleton</td>
<td>2.85</td>
<td>0.053</td>
<td>62.86%</td>
</tr>
<tr>
<td>F5</td>
<td>Compatibility of exoskeleton with work tasks</td>
<td>2.84</td>
<td>0.053</td>
<td>60.00%</td>
</tr>
<tr>
<td>F6</td>
<td>Awareness of problem/ indication of a need for exoskeletons</td>
<td>2.80</td>
<td>0.052</td>
<td>62.86%</td>
</tr>
<tr>
<td>F7</td>
<td>Team buy-in (i.e., team willingness to use exoskeleton)</td>
<td>2.51</td>
<td>0.047</td>
<td>58.10%</td>
</tr>
<tr>
<td>F8</td>
<td>Productivity gain</td>
<td>2.47</td>
<td>0.046</td>
<td>55.24%</td>
</tr>
<tr>
<td>F9</td>
<td>Minimum disturbances of construction process</td>
<td>2.27</td>
<td>0.042</td>
<td>49.52%</td>
</tr>
<tr>
<td>F10</td>
<td>Ease of maintenance</td>
<td>2.17</td>
<td>0.040</td>
<td>47.62%</td>
</tr>
<tr>
<td>F11</td>
<td>Ergonomics training</td>
<td>2.17</td>
<td>0.040</td>
<td>48.57%</td>
</tr>
<tr>
<td>F12</td>
<td>Perceived usefulness of exoskeletons</td>
<td>2.17</td>
<td>0.040</td>
<td>49.52%</td>
</tr>
<tr>
<td>F13</td>
<td>Cost benefit</td>
<td>2.17</td>
<td>0.040</td>
<td>51.43%</td>
</tr>
<tr>
<td>F14</td>
<td>Champion (i.e., willingness to lead the testing of exoskeletons)</td>
<td>2.16</td>
<td>0.040</td>
<td>49.52%</td>
</tr>
<tr>
<td>F15</td>
<td>Ability to use the restroom</td>
<td>2.11</td>
<td>0.039</td>
<td>48.57%</td>
</tr>
<tr>
<td>F16</td>
<td>Curiosity (Openness to innovation)</td>
<td>1.91</td>
<td>0.036</td>
<td>46.67%</td>
</tr>
<tr>
<td>F17</td>
<td>Client driven</td>
<td>1.91</td>
<td>0.036</td>
<td>53.33%</td>
</tr>
<tr>
<td>F18</td>
<td>Few errors and efficient for quality standards (i.e., no impact on quality of construction)</td>
<td>1.75</td>
<td>0.033</td>
<td>39.05%</td>
</tr>
<tr>
<td>F19</td>
<td>Exoskeletons to enable performance and attract other workers</td>
<td>1.70</td>
<td>0.032</td>
<td>40.95%</td>
</tr>
<tr>
<td>F20</td>
<td>Familiarity with exoskeletons</td>
<td>1.52</td>
<td>0.028</td>
<td>39.05%</td>
</tr>
<tr>
<td>F21</td>
<td>Mandatory use of an exoskeleton</td>
<td>1.48</td>
<td>0.027</td>
<td>45.71%</td>
</tr>
<tr>
<td>F22</td>
<td>Existing knowledge about exoskeletons</td>
<td>1.31</td>
<td>0.024</td>
<td>34.29%</td>
</tr>
<tr>
<td>F23</td>
<td>Overall appearance of exoskeletons</td>
<td>1.20</td>
<td>0.022</td>
<td>33.33%</td>
</tr>
<tr>
<td>F24</td>
<td>Tribality of exoskeleton</td>
<td>1.12</td>
<td>0.021</td>
<td>27.62%</td>
</tr>
<tr>
<td>F25</td>
<td>Light cognitive workload</td>
<td>1.08</td>
<td>0.020</td>
<td>26.67%</td>
</tr>
</tbody>
</table>
5.5.1.4 Exoskeleton adoption barriers

The results of the survey show that the participants provided a mean score ranging from 3.10 to 0.83 with ‘Catch and snag risks’ having the highest score and ‘Cultural beliefs’ having the lowest score. The average mean score rating of 2.02 was observed for barriers. Based on the results of the AHP analysis, the barriers were arranged from highest priority to the lowest priority (see Table 5.5). ‘Catch and snag risks’, ‘Weight of the exoskeleton’, ‘Incompatibility with other devices (e.g., tool belt)’, ‘Anthropometric fit (i.e., proper fit for each user)’ and ‘Durability and ruggedness of the exoskeleton’ were the most prominent barriers, whereas ‘Dusty environment’, ‘Location of site’, ‘Storage’, ‘Perception of weakness’ and ‘Cultural beliefs’ were the least important barriers. In terms of mean ratings, the participants rated the barriers from 4.71 to 3.48 with ‘Catch and snag risks’ having the highest rating and ‘Cultural beliefs’ having the lowest rating. Also, based on
percentage of respondents, ‘Catch and snag risks’ was rated by 65.71% of the participants, whereas the least rated barrier (23.81%) was ‘Cultural Beliefs’ (Fig. 5.4). Table 5.5 shows the MS, AHP weightage, and percentage ratings of the barriers.

Table 5.5. List of barriers to the adoption of exoskeletons in the construction industry.

<table>
<thead>
<tr>
<th>No.</th>
<th>Barrier</th>
<th>MS</th>
<th>Priority Matrix</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>B 1</td>
<td>Catch and snag risks</td>
<td>3.10</td>
<td>0.050</td>
<td>65.71%</td>
</tr>
<tr>
<td>B 2</td>
<td>Weight of the exoskeleton</td>
<td>2.93</td>
<td>0.047</td>
<td>62.86%</td>
</tr>
<tr>
<td>B 3</td>
<td>Incompatibility with other devices (e.g., tool belt)</td>
<td>2.89</td>
<td>0.046</td>
<td>61.90%</td>
</tr>
<tr>
<td>B 4</td>
<td>Anthropometric fit (i.e., proper fit for each user)</td>
<td>2.87</td>
<td>0.046</td>
<td>60.95%</td>
</tr>
<tr>
<td>B 5</td>
<td>Durability and ruggedness of the exoskeleton</td>
<td>2.82</td>
<td>0.045</td>
<td>60.95%</td>
</tr>
<tr>
<td>B 6</td>
<td>Personal exoskeleton vs. shared exoskeletons</td>
<td>2.79</td>
<td>0.045</td>
<td>64.76%</td>
</tr>
<tr>
<td>B 7</td>
<td>Hot / Cold weather</td>
<td>2.55</td>
<td>0.041</td>
<td>60.00%</td>
</tr>
<tr>
<td>B 8</td>
<td>Cost justification</td>
<td>2.52</td>
<td>0.040</td>
<td>55.24%</td>
</tr>
<tr>
<td>B 9</td>
<td>Fall risk</td>
<td>2.45</td>
<td>0.039</td>
<td>53.33%</td>
</tr>
<tr>
<td>B 10</td>
<td>False sense of safety</td>
<td>2.45</td>
<td>0.039</td>
<td>55.24%</td>
</tr>
<tr>
<td>B 11</td>
<td>Purchasing exoskeletons / Affordability / Investment</td>
<td>2.27</td>
<td>0.036</td>
<td>50.48%</td>
</tr>
<tr>
<td>B 12</td>
<td>Resistance to change</td>
<td>2.24</td>
<td>0.036</td>
<td>52.38%</td>
</tr>
<tr>
<td>B 13</td>
<td>Climb stairs and ladders</td>
<td>2.17</td>
<td>0.035</td>
<td>47.62%</td>
</tr>
<tr>
<td>B 14</td>
<td>Amount of energy needed for use</td>
<td>2.11</td>
<td>0.034</td>
<td>54.29%</td>
</tr>
<tr>
<td>B 15</td>
<td>Walk on uneven surfaces</td>
<td>2.05</td>
<td>0.033</td>
<td>44.76%</td>
</tr>
<tr>
<td>B 16</td>
<td>Length of training for proficiency</td>
<td>1.96</td>
<td>0.031</td>
<td>47.62%</td>
</tr>
<tr>
<td>B 17</td>
<td>Convincing management to buy-in</td>
<td>1.94</td>
<td>0.031</td>
<td>42.86%</td>
</tr>
<tr>
<td>B 18</td>
<td>Wear time of exoskeleton parts</td>
<td>1.84</td>
<td>0.029</td>
<td>43.81%</td>
</tr>
<tr>
<td>B 19</td>
<td>Social perception of an exoskeleton by the user and others / Peer acceptance</td>
<td>1.83</td>
<td>0.029</td>
<td>45.71%</td>
</tr>
<tr>
<td>B 20</td>
<td>Externalities (i.e., affecting other workers and their abilities)</td>
<td>1.81</td>
<td>0.029</td>
<td>40.95%</td>
</tr>
<tr>
<td>B 21</td>
<td>Identification of suitable exoskeletons</td>
<td>1.68</td>
<td>0.027</td>
<td>40.00%</td>
</tr>
<tr>
<td>B 22</td>
<td>General attitude towards exoskeletons</td>
<td>1.50</td>
<td>0.024</td>
<td>37.14%</td>
</tr>
<tr>
<td>B 23</td>
<td>Duration of maintenance</td>
<td>1.45</td>
<td>0.023</td>
<td>33.33%</td>
</tr>
<tr>
<td>B 24</td>
<td>Sterilization/Hygiene</td>
<td>1.45</td>
<td>0.023</td>
<td>34.29%</td>
</tr>
<tr>
<td>B 25</td>
<td>Limited space</td>
<td>1.43</td>
<td>0.023</td>
<td>33.33%</td>
</tr>
<tr>
<td>B 26</td>
<td>Personal history of complaints about exoskeletons</td>
<td>1.40</td>
<td>0.022</td>
<td>34.29%</td>
</tr>
<tr>
<td>B 27</td>
<td>Dusty environment</td>
<td>1.38</td>
<td>0.022</td>
<td>35.24%</td>
</tr>
<tr>
<td>B 28</td>
<td>Location of site</td>
<td>1.30</td>
<td>0.021</td>
<td>33.33%</td>
</tr>
<tr>
<td>B 29</td>
<td>Storage</td>
<td>1.29</td>
<td>0.021</td>
<td>32.38%</td>
</tr>
</tbody>
</table>
Table 1.1. Critical factors influencing the adoption of exoskeletons in the construction industry.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Weight</th>
<th>Std Dev</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>B 30 Perception of weakness</td>
<td>1.22</td>
<td>0.020</td>
<td>34.29%</td>
</tr>
<tr>
<td>B 31 Cultural beliefs</td>
<td>0.83</td>
<td>0.013</td>
<td>23.81%</td>
</tr>
</tbody>
</table>

5.5.2 Focus group

During the focus group, participants were shown the factors (i.e., facilitators and barriers) in their order of importance as identified from the AHP analysis. Overall, the participants agreed with the critical factors and provided instances and examples of how each of the factors would influence the implementation of exoskeletons in the construction industry. Through qualitative analysis of the results of the two focus groups (i.e., for facilitators and barriers), six categories were identified (Fig. 5.5). These include applications, challenges, modifications, benefits, compatibility, and implementation which are explained further in this section. Fig. 5.5 describes the categories and sub-categories identified from this focus group.

Figure 5.4. Barriers to the adoption of exoskeletons in the construction industry.
5.5.2.1 Applications and compatibility

The participants suggested that exoskeletons would be most suitable for groundwork operations involving repetitive tasks such as shoveling stones. Furthermore, working in limited spaces such as inverted and trench boxes was not considered to be an issue since the participants believed the exoskeleton will fit the construction workers well: ‘they're pretty tight fitting and I don't think there's any spaces that we would work on a daily basis, that it would be a problem. We had the guys going in the manhole and doing inverted, that is tight, and nobody complained’. Furthermore, the participants mentioned that the exoskeleton can be adopted for pipe, concrete, and carpentry crews: ‘.... it’s very compatible with pipe work that we do........ carpenter crews’.

Although the participants felt that exoskeletons can be employed for diverse work tasks, they emphasized that the exoskeleton should be compatible with transitions between work tasks: ‘there might come a time in the day when he's got a shift between different duty, he’s not going to want to wear this and be able to take it off and have to put it back on. So, I could see where it could pose some challenges’. Compatibility of exoskeletons with jackets and coveralls worn by the workers during the winter conditions was also discussed: ‘......as we move into colder temperatures and the guys start donning heavier and heavier coveralls and jackets and things like that, if it's not something that they could readily adjust to fit with the outer garments......can be problematic’.

5.5.2.2 Challenges

The use of exoskeletons with safety harnesses used on construction sites was considered a challenge to the adoption of exoskeletons. This will add on to the weight carried by the workers thereby making the tasks more cumbersome. The participants mentioned that additional weights and layers during the hot weather conditions could potentially cause discomfort to the workers: ‘....even though it seems like it's just five pounds for someone to be wearing that and working in that all day could prove challenging.....’, ‘if you just keep lumping more and more stuff on top of the person, it becomes quite cumbersome.....you're draining the employee because he's........not just carrying now five extra pounds, it was five extra pounds, on top of the other five that he was already carrying or ten’. Furthermore, the participants suggested that the exoskeleton might not be compatible with all the work tasks performed on the construction sites, thereby requiring the workers to don on and off (i.e., wear and take off) the exoskeleton multiple times a day which could discourage the workers from using the device.

It was also highlighted that the use of an exoskeleton may help address back injuries but might create other problems. For example, the back-support exoskeleton was not considered to be a fall risk. However, while putting on and off the device or when climbing ladders, the device could be caught around objects thereby increasing the risk of fall (Kim et al. 2019). The participants did not feel that the risk was any more than that experienced by workers when using a safety harness or tool belts: ‘.... the carpenters…they wear a tool belt with tools hanging off of
it, and they have snagging but, once you get accustomed to it you're aware that you have it on….‘.

Also, since the exoskeleton is a new technology, the participants did not believe that it has enough buy-in amongst the users. An estimate of the long-term benefits of using exoskeletons, particularly, any reduction in injury rates over time could be a challenge. Furthermore, given the high initial cost of exoskeletons, construction companies might consider exploring other avenues for reducing back injuries: ‘We would start looking into other avenues……like we have a 50-pound rule……we have things already in place that prevent back injuries, we could just increase it, you know before they spend $4,000 a pop’, ‘It could be policy-driven’. Besides, participants also raised concerns regarding the use of exoskeleton in confined spaces and during the summer. A false sense of safety amongst construction workers was another challenge discussed: ‘we had one guy who tested it said he felt it was easier to lift things and he goes now…. I’m stronger, I can lift more because I have the back-support’.

5.5.2.3 Benefits

The participants suggested that reduction in fatigue, strains, and rate of lower back injuries could be some of the potential benefits of using a back-support exoskeleton - ‘our hope is that long-term benefits of this is, we see less fatigue and strain on employees’, ‘if it could prevent low back injuries and also help prevent a recordable injury, may pay off in the long run’. Although an increase in workers’ productivity was not the intent of implementing exoskeletons, the participants mentioned that it could be an advantage: ‘We got guys that can produce more work in a day……..you know they felt like they could get more done……in the time frame than if they didn't have it….’. Furthermore, it was deemed necessary that the exoskeleton should be comfortable and have free range of motions which could positively influence their willingness to use the device. Also, workers’ perception of the exoskeleton was considered as critical: ‘If the employee likes wearing it and he sees that it does help them, word will spread pretty fast, you know you got to try this on’. Despite the exoskeleton being an additional load, it wasn’t considered to be a fall risk as the workers who tested the back-support exoskeleton did not raise any concerns. Also, it was considered beneficial that the exoskeleton can be adjusted to different body sizes. This is critical for a company who buys the device, as the device can be shared by different workers. However, they also emphasized that this could trigger maintenance issues and that the exoskeleton should be easy to maintain.

5.5.2.4 Modifications

Construction workers are rough with the equipment that they use. As a result, any technology being implemented needs to possess a high level of durability. Therefore, it is significant that the exoskeleton is made using rugged material: ‘……so the more rugged, if you're able to do without sacrificing functionality and comfort, the better off it's going to be’. However, considering that the workers will be using the device during harsh weather conditions, it was suggested to make the device durable without increasing the weight of the exoskeleton as it could be a problem: ‘the
more stuff you're carrying you're done so, the guys have to be like lightweight out in the field’. Furthermore, to reduce the effect of hot weather, changing the color from black to a heat repellent color and using breathable materials could be helpful: ‘probably a way to make it like an open material that allows wind or air to go through it and cool off whatever body part it's touching right’, ‘change the color as it is black’. Also, for improved safety, flame resistant material can also be used.

The participants suggested making the device easy to don and doff with few unbuckles so that workers can easily transition between different work tasks. Also, an extra padding could be beneficial as it will cause lesser discomfort. A device that can be used by all genders can also facilitate the adoption of exoskeletons: ‘…. we have quite a few female workers that are finding their way out here.....it might be easy for a man to be able to use it, but you know, a woman has some additional challenges…’. Integrating the safety harness and tool belt with the exoskeleton will eliminate the need to don multiple devices. Participants also raised the need for reducing the cost of the exoskeletons to promote its widespread use. Considering the high cost, a shared-use approach amongst workers could be a way to reduce the number of devices to be purchased. This will require a plan for maintaining proper hygiene and maintenance of the devices: ‘breathable material that's not prone to odors and fungus’, ‘material resistance to mold and bacteria’ and ‘set up where you could kind of remove the outer cover to the padding and whatnot if it was made in a way that you could easily remove it and wash it and put it back on’. Sanitizing the device at the end of each shift could enhance the sustainability of the shared approach.

5.5.2.5 Implementation

To facilitate adoption of exoskeletons, it is necessary to get buy-in amongst the end users and field managers to carry out extensive field testing that could help understand their perception towards the use of the device in the field. The participants mentioned that most of the technologies adopted in the past were adopted by large size companies followed by small and medium size companies. A similar strategy was suggested for the adoption of exoskeletons: ‘you could watch the history in construction and see that the leading companies take over and set the example and a lot of smaller companies follow....... getting those first main companies lined up and bought into the program and then it sets the example for the rest’. However, for these companies to be interested in the adoption of exoskeletons, cost benefit analysis was deemed to be necessary: ‘Demonstrate the cost benefit this just makes it easier to sell.’. To justify the cost of the exoskeleton, the participants suggested quantifying the potential impact of using the exoskeleton in terms of productivity, injuries, and financial loss from lawsuits to justify the return on investments: ‘if it's already increase in production, you just extrapolate that into the work that's done that day and what the increase is and then how long it's going to take to recover the original costs’, ‘Being able to show in a......longer term study, obviously, because back injuries occur over time.......like we could easily spend a million bucks in going into lawsuits, and all this other stuff for injuries and issues’.

One of the major aspects of technology adoption is maintenance. The participants highlighted the need for understanding the service life of the exoskeleton through extensive field testing. Also, it
is important that the use of the exoskeleton does not require extensive training: ‘should be a quick 10–15-minute toolbox talk’ and should reinforce the existing ergonomic training. The participants also mentioned the possibility of forcing the adoption of exoskeletons, similar to the approach employed for the implementation of hard hats and gloves: ‘It was forced they were told; you will wear them or you will go home, but that motivated them to start wearing them’.

There was a split between the perspectives of stakeholders regarding having personal exoskeletons vs. shared exoskeleton. Some of them believed ‘you're going to need one for each member because….you can't have one that fits all no such thing, just like a harnesses’ whereas others believed ‘again at that cost, even if you get it down substantially it's still at that cost I would think the shared one, is more feasible’. It was also suggested to conduct regular visual inspections to identify wear and tear to the exoskeletons as executed with other equipment such as straps and safety harnesses. Furthermore, it is the responsibility of safety supervisors to identify the most suitable exoskeleton for specific work tasks. Besides the initial cost, it is necessary to consider hidden costs such as cost of maintenance, replacement, and training.

Figure 5.5. Summary of categories and sub-categories regarding exoskeleton adoption
5.6 Discussion

This study identified the key stakeholders and critical factors (i.e., facilitators and barriers) influencing the adoption of back-support exoskeletons in the construction industry. Using a mixed-method approach, a survey of industry practitioners and a focus group discussion with the stakeholders, identified from the survey, was conducted to determine the important factors to be considered when adopting exoskeletons. The focus group discussion also elaborated on the ways by which the factors could impact the adoption of exoskeletons.

5.6.1 Stakeholders

Construction workers were ranked as the most important stakeholder group whose input is critical for the adoption of exoskeletons. Since construction workers will be the end users of the device, their perception is of prime importance. This is in line with the findings of (Kuber and Rashedi 2020), who highlighted the importance of involving end-users in the design of and decision making about exoskeleton use. Without the willingness of construction workers to use exoskeletons, the adoption of the device will not be successful. Given that they are the intended users, they will be able to provide better feedback on the safety risks associated with the use of exoskeletons on construction sites. Involvement of certifying bodies such as OSHA, is also critical since most of the private and public sectors have to abide by standards for safe and healthful working conditions (OSHA 2022). Furthermore, occurrences of musculoskeletal disorders are usually associated with workplace ergonomic factors (Stock 1991), having ergonomists or occupational health professionals involved in the adoption will help make informed decisions to ensure systematic implementation. Supervisors such as superintendents and foremen will help bring in the perspective of the project management team in terms of the impact on productivity of workers as highlighted by Peansupap and Walker (2005). Safety professionals play a significant role in the Implementation of technologies to enhance safety on construction sites (Azhar 2017). Thus, it is necessary to include the safety professionals’ perspective in the exoskeleton adoption process. Moreover, as suggested by Neufeld et al. (2007), the adoption of new technology in any organization cannot be undertaken without the willingness of the corporate management, which was also identified in this study.

5.6.2 Facilitators

‘Compatibility of exoskeleton with work tasks’ was identified as one of the top five facilitator for the adoption of exoskeletons. Bademosi and Issa (2021) mentioned that if a new technology is incompatible with construction work tasks, the technology will not be adopted. Therefore, it is essential that exoskeletons are compatible with construction work tasks, imposing minimum disturbances to work. Thus, ‘Minimum disturbances of construction process’ is also a critical facilitator. With reduced disturbances to work, it is expected that exoskeleton-use will trigger minimal negative impact on workers’ quality of work and cognitive workload. This makes ‘Few
errors and efficient for quality standards (i.e., no impact on quality of construction)’ a critical factor.

Owing to the rough handling of equipment by construction workers and harsh environmental conditions in which equipment’s are being used, ‘Durability/ruggedness of the exoskeleton’ is also one of the most critical factors. This is supported by the findings of Kim et al. (2019). ‘Long-term benefits’ of exoskeletons in terms of reduction in fatigue, strain, and decrease in back injuries are essential in promoting the adoption of exoskeletons. Although the results highlight these long-term benefits, this study is not enough to provide scientific evidence. Further experimental work is required to draw scientific conclusions. ‘Immediate pain relief from using exoskeleton’ is also a facilitator because if workers do not perceive benefit from using exoskeleton, they will not be willing to use the device regularly. This is in accordance with the findings of Crea et al. (2021), who also highlighted the short- and long-term benefits of exoskeleton use and signaled the facilitator as a critical element of an adoption road map. Also, positive workers’ feedback is important to get ‘Team buy-in’ to motivate more workers to use the exoskeleton. To facilitate the perceived benefits, it is necessary that workers are provided with the opportunity to test exoskeletons, as a result of which ‘Exoskeletons to enable performance and attract other workers’ and ‘Tribality of exoskeleton’ are also important facilitators.

According to Cha et al. (2020), individual curiosity regarding exoskeletons is a major facilitator. This facilitator relates to the factor, ‘Curiosity (openness to innovation)’, which can help with identifying ‘Champions (i.e., willingness to lead the testing of exoskeletons)’ and thus were identified as important facilitators in this study. Workers are generally resistant to change. Workers who are willing to take the lead on trying the exoskeletons and provide feedback on their experience, can help motivate their colleagues to use the device and generate more team buy-in. Moreover, if a technology is difficult to use, workers will not be motivated to work with it. Use factor ‘Ease of using an exoskeleton / Ease of putting on and off / comfort’ is therefore a crucial facilitators which was also identified as the most important facilitator from the survey. This is in line with the studies conducted by Kim et al. (2019) and Wolff et al. (2014). Furthermore, from the corporate management's perspective, it is important to prove the ‘Cost-benefit’ of adopting exoskeletons by quantifying the impact of the device through ‘Productivity gain’ and recordable injuries. Although ‘Mandatory use of exoskeleton’ was not considered as a critical facilitator in the results of the survey, the focus group participants suggested employing the forced adoption process currently employed for PPE for enforcing the adoption of exoskeletons. Thus, ‘Mandatory use of exoskeleton’ can also be considered an important facilitator.

5.6.3 Barriers

The most critical barrier to the implementation of exoskeletons on construction sites was identified as ‘Catch and snag’ risks. Although exoskeletons are not a fall risk, the possibility of the components of the device being caught around wires, thereby causing accidents (‘Fall risk’), exists. This is similar to snag risks which are observed with safety harnesses and tool belts as documented by Kim et al. (2019). However, as workers get used to working with exoskeletons, they learn to be
aware of triggers of snag risks such as protruding objects. The fit of safety harnesses used on construction sites is considered crucial. The ‘Anthropometric fit (i.e., proper fit for each user)’ of exoskeletons, being wearable devices, is also important because the device could affect the workers’ range of motion (Sposito et al. 2020). If the exoskeleton is too tight, the device could cause discomfort to the workers. Likewise, if the device is too loose, it might increase the risk of snagging. Furthermore, given the high initial cost, it is necessary that exoskeletons have a good anthropometric fit for people (i.e., a one-size fits all). This could reduce the burden on companies to purchase exoskeletons for each worker. The ‘Weight of the exoskeletons’ is another important factor. Given that workers are exposed to harsh working conditions such as high temperatures, any additional weight carried by workers could cause major discomfort. Harsh working conditions are also the reason why ‘Durability and ruggedness of the exoskeleton’ is seen as a critical factor. ‘Incompatibility with other devices’ used on construction sites is very important, because if exoskeletons cannot be used with existing equipment or resources such as ladders, this might affect work performance e.g., affecting workers’ safety. This makes ‘Climb stairs and ladders’ another significant factor. Climbing a ladder with tools while wearing an exoskeleton could be challenging because exoskeletons affect workers’ range of motion as mentioned by (Säfsten and Elgh 2020). Some exoskeletons restrict movement of the thigh when climbing.

‘Cost justification’ was another important factor since exoskeletons are currently expensive. This makes ‘Convincing management to buy-in’ a challenge. Quantifiable return on investment is critical for convincing company leaderships to adopt new technologies (Grudin 2004). Thus, scarce studies regarding the return on investment (cost-benefit analysis) of exoskeletons use in the construction industry is considered a barrier to the adoption of exoskeletons. Furthermore, limited evidence regarding the service life of exoskeletons led to considerations of ‘Wear time of exoskeleton parts’ as a critical barrier. Given the high cost of exoskeletons (‘Purchasing exoskeletons / Affordability / Investment), it is critical to understand the life of different components or parts of exoskeletons in terms of the service life and ‘Duration of maintenance’. From an implementation standpoint, the identification of the right exoskeleton for a given task is important. Workers performing overhead work may not benefit from back support exoskeletons, thus ‘Identification of suitable exoskeletons’ could be a critical barrier. Peer perception of technology is considered as a major driver of successful implementation of technologies (Campenhout 2021). However, ‘Social perception of an exoskeleton by the user and others / Peer acceptance’ was not considered as a major barrier in this study. This may be due to the respondents’ low level of awareness of and exposure to exoskeletons in the construction industry. This could have also been the reason why other factors such as ‘Personal history of complaints about exoskeletons’ and ‘General attitude towards exoskeletons’ were not considered as barriers.

5.6.4 Limitations
This study has some limitations which should be addressed in the future studies. Firstly, given the limited awareness of exoskeletons amongst construction professionals, the sample size of the
survey is relatively small. However, this does not invalidate the importance and reliability of the results. Given the immaturity of exoskeleton use in the construction industry, the sample of practitioners with some awareness could provide reliable results that can set the stage for increased research in this area. However, increased awareness of exoskeletons in the construction industry is important to achieve results that can be more reflective of the industry. Secondly, although the stakeholders had the opportunity to observe the workings of a back-support exoskeleton prior to the focus group discussion, some of them did not have any prior experience with its use. It is possible that with some prior experience of using the exoskeletons, the participants could have provided more in-depth perspectives. Future studies could involve conducting in-person focus group discussions wherein the participants would be provided opportunities to interact with an exoskeleton prior to the discussion. Furthermore, given the limited sample size across the different demographic groups, this study did not compare the results between the demographic classifications. Also, given the format of the survey, the sample was restricted to participants who had access to computers or smartphones and were fluent in English. Conducting the survey in Spanish language would help reach the Spanish (or Latino) community, given the recent increase in this demographic group in the US construction industry. This study employed an inductive coding method to analyze the focus group data. Future studies could consider using text mining to validate and analyze qualitative data. Also, future studies could undertake a systems design approach to understand the interaction of different factors with each other.

5.7 Conclusion

There is a growing interest amongst the research community in exploring the potential of back-support exoskeletons for addressing back-related musculoskeletal disorders in the construction industry. Although studies have shown the potential of exoskeletons, successful adoption would require involving the perspective of critical stakeholders in the implementation process. This study contributes to the body of knowledge by identifying the key stakeholders and critical factors that could help industry practitioners in making decisions to facilitate adoption of exoskeletons. A comprehensive list of 8 stakeholders and 56 factors was identified through literature. Through an online survey, 6 stakeholders which include construction workers, safety professionals, supervisors, corporate management, ergonomists, and certifying bodies (RQ1), and 42 factors (facilitators and barriers) were identified as critical for exoskeleton adoption. Then, through focus group discussions, these factors were further validated, and a thematic analysis of the results resulted in six themes including applications, compatibility, challenges, modifications, benefits, and implementation of exoskeletons (RQ2).

The present study contributes to the emergent literature on the adoption of back-support exoskeletons in the construction industry. The study contributes to socio-technical systems theory by defining the key stakeholders whose inputs are significant for adoption of exoskeletons and the facilitators of and barriers to the implementation process. The study sets precedence for the scientific community to identify solutions to the barriers which could impact the adoption of exoskeletons. Furthermore, these factors could help companies and researchers formulate
implementation strategies to facilitate successful implementation of exoskeletons in the construction industry. Exoskeleton designers can use the suggestion of the stakeholders to design new or modify existing devices that can be more adaptable to construction work. This study also provides suggestions for conducting cost-benefit analysis and quantifying the impact of exoskeleton use in the construction industry to aid leadership teams in the decision-making process. The study highlights the need for a long-term field study to understand the impact of varying climatic conditions on the durability of exoskeletons and quantifying the service-life of the device. As part of future work, the results of this study will be used to develop an implementation strategy that can assist construction companies in the adoption of back support exoskeletons. This could include guidance on identifying workers who could benefit from back-support exoskeletons (i.e., workers that have high exposure to ergonomic risks), type of trainings to be provided to the workers, and exoskeleton maintenance and replacement procedures. Also, this implementation strategy could be further developed to incorporate different types of exoskeletons (e.g., shoulder-support and leg-support) and could assist in formulating similar frameworks for other safety-related technologies in the construction sector. The results of this study also sets precedence for exploring the impact of exoskeletons on muscle fatigue, strains, and rate of injuries in the construction industry.
CHAPTER 6: EXO-IMPLANT: AN IMPLEMENTATION PLAN FOR EXOSKELETON ADOPTION IN THE CONSTRUCTION INDUSTRY

6.1 Abstract

Wearable technology, such as passive exoskeleton, has the potential to address the occurrences of work-related musculoskeletal disorders in the construction industry. However, sparse evidence is available on how to implement this technological intervention in construction organizations. The objective of this study was to develop a plan to support the implementation of exoskeletons in the construction sector and to identify factors that could influence the adoption of the plan. The steps of the plan were identified through literature review. Elements needed to execute the steps were established by identifying the stakeholders and factors critical for the adoption of passive exoskeletons in the construction industry. The proposed implementation plan, Exo-Implant, was developed by contextualizing the elements through the lens of the Normalization Process Theory. Exo-Implant was evaluated using a scenario-based case study. Feedback was obtained using usability questionnaire and focus group. Participants perceived Exo-Implant to be useful and trusted the elements of the plan to facilitate passive exoskeleton implementation process in construction organization. Moderate intention to use Exo-Implant was observed. Feasibility analysis, identifying stakeholders, creating buy-in, conducting cost-benefit analysis and involving champions, were identified as key facilitators of the plan. The extensiveness of the plan and limited details on some of the elements were the key barriers. Through the development of Exo-Implant, this study contributes to the scarce literature on the implementation of exoskeletons in the construction industry. This study provides academics and industry practitioners with a holistic view of the elements necessary for the implementation of passive exoskeletons in construction organizations. This study also contributes to the Normalization Process Theory by introducing the factors that would influence the embrace or normalization of Exo-Implant in construction organization.

6.2 Introduction

Workforce health and safety are primary concerns in the construction industry (Okpala et al. 2020). Health and safety concerns in the construction industry has been identified as one of the most dangerous occupations because of high exposure to ergonomic risks (Chen et al. 2022; Roy 2022). The prevalence of ergonomic risks in the industry has been attributed to the nature of construction activities which involve manual material handling, repetitive movements as well as awkward body postures in dynamic environments (CPWR 2018). These result in overexertion and ultimately work-related musculoskeletal disorders (WMSDs). WMSDs are nonfatal injuries associated with the workplace that affect different body parts (Gonçalves et al. 2022). Low-back pain is one of the most prominent WMSDs (Abas et al. 2018) in the construction industry (CPWR, 2018) and a leading cause of disabilities worldwide (Hoy et al. 2014). Low back pain accounts for about 42% of WMSDs in the construction industry (Dong 2019). Also, within a space of three months, more than one-third of construction workers experience low back pain (CPWR 2018). Hence, several
measures such as workers training (Roy 2022), mechanical handling devices (Kumar et al. 2016) and modifications of work layout (Albers et al. 2005) have been introduced to mitigate the occurrences of WMSDs. However, Cho et al. (2018) noted that these measures have not produced very promising results, hence the need for task-specific ergonomic intervention to curb WMSDs in the construction industry.

Exoskeletons are new ergonomic interventions which are being used in the military, healthcare, manufacturing and agricultural sectors (Okpala et al. 2019). Exoskeletons are body-worn mechanical devices capable of augmenting the wearer's performance and reducing risk of over-exertion of the body (Delgado et al. 2019). Exoskeletons can be passive (mechanical power-driven) or active (electric power-driven) (Koopman et al. 2020). However, passive exoskeletons (shown in Fig. 6.1) are more appealing to curb WMSDs because they are lighter and cheaper (Gonsalves et al. 2023). Passive back-support exoskeletons such as Laevo™ and BackX™ use mechanical actuators to provide support to the lower back (Madinei et al. 2020). Okpala et al. (2022) reported that exoskeletons can prevent 30-40% of injuries associated with WMSDs. In addition, considering the huge annual financial cost of WMSDs, the relatively low cost of passive back-support exoskeletons which is about $4,000 (Wang et al. 2018) makes them a viable option for construction organizations. Therefore, the rate of adoption of exoskeletons in the construction industry has been on the increase (Cho et al. 2019). However, strategies for the implementation of exoskeletons by construction organizations seems lacking in literature. Therefore, Schwerha et al. (2021) opined that studies are required on the implementation strategies of exoskeletons.

To pave the way for the implementation of exoskeletons by construction organizations, previous studies have identified the barriers, facilitators, and stakeholders in the adoption of exoskeletons in the construction industry (Kim et al. 2019; Mahmud et al. 2022). Also, the potential of exoskeletons to curb WMSDs have been well reported in literature (Gonsalves et al. 2023; Okpala et al. 2019). In addition, statutory organizations (e.g., ASTM) are also developing standards to aid exoskeleton adoption (Gonsalves et al. 2023; Howard et al. 2020; Okpala et al. 2019). However, without adequate strategy, implementation of new interventions like exoskeletons may be challenging in the construction industry which is known for the apathy of its stakeholders toward innovation (Sartipi 2020). As shown by extant studies, given the current state of the body of knowledge on exoskeletons, the stage is set for a wide range of implementation of exoskeletons but the strategy to drive such implementation within construction organizations is lacking. Therefore, to contribute to the aforementioned efforts, this study presents a strategy for the implementation of passive back-support exoskeletons in construction organizations. This is important because construction organizations are critical stakeholders in the diffusion of innovations in the construction industry (Gambatese and Hallowell 2011). This study aims to answer the following research questions:

- How can a strategy be designed for the implementation of exoskeletons in construction organization?
- What factors would influence the adoption of the developed strategy in construction organizations?
This paper is organized as follows: The next section presents a review of existing studies on adoption of exoskeletons, implementation of technologies and the theoretical underpinning of the study. Next, the methods adopted in the study and the results of the study are presented. The implications of the results and conclusions of the study are discussed in the subsequent sections.

Figure 6.1. Passive back support exoskeleton (BackX 2022)

6.3 Background
6.3.1 Exoskeletons in the construction industry: Need and adoption

Exoskeleton is one of the promising innovations in the construction industry owing to its ability to curb the prevalence of WMSDs (Okpala et al. 2019). Construction activities are physically demanding resulting in over-exertion which has made WMSDs a rife phenomenon in the industry (CPWR 2018). In fact, the industry is one of the most affected by WMSDs (Roy 2022). WMSDs are major concerns for the industry due to resultant physical suffering and discomfort (Dong et al., 2019), huge financial cost in terms of workers’ compensation (Anwer et al. 2021), low productivity resulting from days away from work (CPWR 2018; Govaerts et al. 2021) and negative social impact because of ensuing attrition and permanent physical disabilities of affected workers (Govaerts et al. 2021). However, the potential of exoskeletons to reduce WMSDs and its attendant’s problems which are prevalent in the construction industry has triggered both industry attention and research efforts. For example, several studies have investigated the potential and usage of exoskeletons for different construction trades and activities with overall positive results (Gonsalves et al. 2021; Ogunseiju et al. 2021). Similarly, industry reports have underscored its importance as an ergonomic intervention in the construction industry (NIOSH, 2017; Exoskeleton Report, 2019). In the same vein, industry practitioners have also lent their voice to its benefits for the industry (Kim et al. 2019). Consequently, reports (CPWR, 2018, Dong et al., 2019) have
revealed downward trends in the rate of WMSDs in the industry which could be attributed to growing adoption of ergonomic solutions such as exoskeletons.

The construction industry has been adjudged reluctant in the adoption of innovations (Peansupap and Walker 2005; Shapira and Rosenfeld 2011). However, the need to be more competitive, improve health and safety as well as achieve higher productivity is driving greater adoption of innovations in the industry (Okpala et al. 2020). Exoskeleton is one of the innovations with increasing levels of adoption. According to Market Analysis Report (2022), the Exoskeleton market in the United States increased from $99.1M in 2020 to $116M in 2021 with a projection of 18% increase from 2022 to 2030. Therefore, construction organizations have begun exploring the adoption of exoskeletons in their operation to mitigate the risk of WMSDs and other related challenges in the industry (Nnaji et al. 2023). In response to the growing adoption of exoskeletons, in September 2017, American Society for Testing and Materials and United States National Institute of Standards and Technology (NIST) constituted International Technical Committee on Exoskeletons and Exosuits (ASTM F48) (Lowe et al. 2019; Okpala et al. 2019). The first set of standards regarding the use of exoskeleton was released by the committee in May 2019 (Howard et al. 2020). Also, about 70% of construction firms surveyed by Okpala et al. (2020) are already using exoskeletons as a measure to ensure occupational safety and health while 10% of the firms planned to use the device in the future. Cho et al. (2019) also revealed that exoskeleton is one of the technologies being adopted in the construction industry. In addition, Crea et al. (2021) provided a roadmap for the large-scale adoption of exoskeletons. In the same vein, Mahmud et al. (2022) also provide insights to improve the adoption of exoskeleton in the construction industry.

6.3.2 Technology implementation in the construction industry

The construction industry is dynamic and project-centered with several stakeholders at various levels (Chen et al. 2022). Studies (Gambatese and Hallowell 2011; Xue et al. 2014) have indicated the roles of several factors and stakeholders such as top management, client, innovation champion, organizational climate, and structure in the implementation of technologies. The increasing rate of adoption of technologies in the industry (Okpala et al. 2019) has necessitated the development of frameworks and strategies to help organizations navigate the implementation process. These technologies include 3D printing, BIM, smart devices, and distributed ledger technologies (Khosrowshahi and Arayici 2012; Li et al. 2019; Silverio-Fernández et al. 2021; Wu et al. 2018). Using the BIM maturity framework combined with the existing knowledge about BIM implementation in Finland and the current status of BIM implementation in the UK, Khosrowshahi and Arayici (2012) used expert opinion and questionnaire survey to develop a roadmap for the implementation of BIM in construction. The study suggests organizational culture, education and training, and information management as the three structured patterns to systematically circumvent the technology, process and people issues in BIM implementation. Mellor et al. (2014) created a conceptual framework for the implementation of additive manufacturing. The study noted that external forces and internal strategy influence the adoption of additive manufacturing. The study identified that the implementation of additive manufacturing will be influenced by five constructs
of factors such as strategic, technology, organizational, operational and supply chain factors. The study adopted a single case study to test the framework by interviewing critical stakeholders. Similarly, using structural equation modeling on the factors influencing 3D printing adoption in the construction industry to show the interconnectivity of explained and explanatory variables, Wu et al. (2018) developed a conceptual framework based on survey and expert review for the implementation of 3D printing technology in the construction industry. The study showed the interplay between technology readiness, organizational support, and effectiveness of technology, policies and regulation.

Li et al. (2019) used systematic literature review informed by socio-technical systems approach and focus group discussion to propose a multi-dimensional framework as basis for implementation of distributed ledger technologies in the construction industry. The framework was developed after a focus group discussion comprising eight participants and encapsulated three overlapping dimensions: technical, social, and political. Also, based on critical success factors, drivers, and implementation challenges of smart devices in the construction industry, Silverio-Fernández et al. (2021) developed a strategic framework for the implementation of smart devices in the construction industry. The framework consists of persuasion and implementation sub frameworks patterned after a five-stage innovation–decision paradigm. The five stages are knowledge, persuasion, decision, implementation, and confirmation. The framework was validated through semi-structured interviews with five senior professionals. Chen et al. (2013) combines multiple e-business strategies to develop a six-phase e-business implementation framework for construction firms. Mixed methods consisting of industry survey and multiple case studies were used to formulate the framework. The framework captured the impact of internal (management, people, process, and technology) and external environment. The framework was evaluated by six industry practitioners via structured interviews. After a systematic review on implementation of technologies in the construction industry, Chen et al. (2022) opined that extant studies provide limited information on the conditions that are required for successful implementation of these technologies. Schwerha et al. (2021) noted that lack of implementation strategies is a barrier to the adoption of exoskeletons. Hence, to advance the adoption of exoskeleton in the construction industry, implementation strategies are required to provide a roadmap for construction organizations. Therefore, this study sets forth a strategy for the implementation of passive back-support exoskeletons in construction organizations.

6.3.3 Theoretical underpinning

To understand how to design and evaluate an implementation plan for adopting exoskeletons in construction organization, this study is grounded in the Normalization process theory (NPT). NPT describes how new technologies, methods and operations can become “normalized” (May et al. 2020), that is fully operationalized in daily work practice in institutional settings. NPT helps to achieve implementation, which is putting a practice into action; embedding, which is regular usage of a practice by individuals and groups in day-to-day operations; and integration, which is the process by which a practice is fully entrenched and perpetuated in the social structure of an
organization (May and Finch 2009). NPT explains that practice becomes a routine both by individual and joint efforts. However, this can be facilitated or hindered by factors that affect behavior (such as coherence, cognitive participation, collective action, and reflexive monitoring) which allow for the expression of human action. Also, continuing commitment by stakeholders is requisite for the integration of a practice (May and Finch 2009; May et al. 2007). The theory is expressed in four constructs: coherence, cognitive participation, collective action, reflexive monitoring (as shown in Fig. 6.2). The proponents of NPT explained that these constructs define and organize the objectives (coherence), engagement of stakeholders (cognitive participation), implementation (collective action) and the body of knowledge to evaluate a practice (reflexive monitoring). NPT provides a guide for making a new intervention to become a part of normal practice (Finch et al. 2013).

NPT is an action-based theory that explains how and what people do in the implementation of something new (Alverbratt et al. 2014). The theory approaches implementation as an ongoing process which culminates when an intervention is regarded as ‘the way we do things here’ (Hall et al. 2017; May 2013). Finch et al. (2013) used NPT in the implementation of healthcare interventions. The study interviewed experts and sought feedback from users. The participants were required to work through an implementation problem using the NPT process items provided, identify needs for modification, and share their experience. Alverbratt et al. (2014) also used the analytical framework of NPT to highlight the implementation of a new assessment tool called Daily Life Dialogue Assessment among psychiatric nursing staff. Focus group interviews were used to engage stakeholders and data analysis was conducted using NPT constructs. Similarly, Hall et al. (2017) used NPT for the implementation of monitoring technologies in care homes for people with dementia in a multiple-case study scenario. The study adopted a mixed-method approach guided by NPT mechanism for data collection: data extracted from care records, direct observations and semi-structured interviews of stakeholders. Given the characteristics and wide-range applications of NPT in the implementation of new interventions, the theory is deemed suitable to guide the implementation of passive back-support exoskeletons which are new interventions to curb the problem of low-back pain in the construction industry. Therefore, to this end, it is important to ask the following research questions: 1) How can a strategy be designed for the implementation of exoskeletons in the construction organization? 2) What factors would influence the adoption of the developed strategy in construction organizations?

![Figure 6.2. Normalization process theory](image-url)
6.4 Research Methodology

A multi-method research approach was adopted in this study. This section describes the approach employed in the development and evaluation of the proposed implementation plan. The approach and methods utilized are described as follows and illustrated in Fig. 6.3.

![Figure 6.3. Research methodology](image)

6.4.1 Development of the implementation plan

The implementation plan was developed through a formal process of identifying key steps and constituents of implementation plans, identifying elements of the steps needed to execute the proposed implementation plan, blending the implementation process (i.e., the steps and elements) with the workplace setting and validating the proposed plan.

6.4.1.1 Identification of key steps of implementation plans

A literature review was conducted to identify typical constituents of implementation plans. Multiple databases (Google Scholar, Scopus, EBSCO, Engineering Village, Science Direct, and Web of Science) were used to search papers on developed implementation plans and strategies for industry sectors. In the databases, the field labeled ‘title/abstract/keyword’ was extensively and systematically searched using relevant keywords such as implementation strategy, implementation framework, implementation plan and technology implementation in construction. Conference proceedings, reports, and research articles were included, and the search was restricted to English language only. Fig. 6.4 shows the distribution of search results based on industry (such as construction healthcare, logistics, and information technology). The search results were synthesized into seven key steps, namely organizational decision to adopt technology (Peansupap
and Walker 2005), preparation for initial use of technology (Ngai et al. 2010), creating awareness and buy-in (Ruikar et al. 2006), training (Arayici et al. 2009), operational strategy (Stewart et al. 2002), deployment (Feldmann et al. 2020), and monitoring and evaluation (Arayici et al. 2011).

Figure 6.4. Classification of implementation plans based on industry

6.4.1.2 Identification of elements of key steps of implementation plans

To formulate the elements of the aforementioned steps, Breimaier et al. (2015) as part of the Consolidated Framework for Implementation Research suggested executing the following processes: (1) identifying the factors influencing the implementation of interventions (i.e., defining the effects of the intervention in the workplace) and (2) identifying the key stakeholders who should be involved in implementation process and their roles in the process. Therefore, the elements of the steps of the proposed implementation plan were defined by executing process (1) and (2). These processes were executed using a mixed-methods approach to identify factors (i.e., facilitators and barriers) that could influence the implementation of exoskeletons in the construction industry and key stakeholders that should be included in the implementation. This approach included a literature review using the databases mentioned in the previous section but different keywords such as implementation, adoption, exoskeletons, factors, stakeholders, facilitators and barriers. The review was synthesized to generalize stakeholders to be included in the implementation of exoskeletons and factors influencing the implementation of exoskeletons in industry sections. Using the results of the review, industry practitioners were surveyed and engaged in focus group discussions to establish the key stakeholders and their roles in the implementation of exoskeletons, the factors applicable to the construction industry, and how the factors influence the implementation of passive back-support exoskeletons in the construction
industry (Gonsalves et al. 2023). These guided the elements of the steps of the proposed implementation plan.

6.4.1.3 Blending the implementation process with the workplace setting

In addition to the processes mentioned in the previous section, Breimaier et al. (2015) also suggested blending the implementation process (i.e., the steps and elements identified from the previous section) with the workplace setting to facilitate embrace by intended users and adaption to the workplace. This was executed in this study by underpinning the steps and elements in the NPT. This helps to ensure that the elements can become “normalized” (May et al. 2020) and fully operationalized in the daily work practice in the construction organization. The constructs of the NPT used in this study include coherence, cognitive participation, collective action, and reflexive monitoring. Table 6.1 shows the steps of the implementation plan, the elements needed to achieve the steps and the constructs of the NPT that the elements target. Coherence was achieved by identifying documented benefits of exoskeleton use and identifying required stakeholders for the adoption of exoskeletons (Steps 1 and 2). Cognitive participation was targeted in Step 3 by providing lectures, toolbox talks, and demonstrations of exoskeletons to create awareness and buy-in amongst the workforce. Collective action was addressed through Steps 4, 5, and 6 by developing manuals, guidelines, checklists, and training materials, conducting training sessions and toolbox talks, and evaluating workers' learning of exoskeleton use. Reflexive monitoring was addressed through Step 7 which supports monitoring of the deployment of exoskeletons, obtaining periodic feedback from workers, collaborating with manufacturers for updates to exoskeleton designs, conducting cost-benefit analysis, and revising training materials.

6.4.1.4 Validation of the implementation plan

The implementation plan was validated by piloting the plan with professionals, with experience in exoskeleton research and implementation of technologies in the construction industry and conducting focus group discussions with prospective users of the plan (identified from previous sections).

6.4.1.4.1 Pilot testing

Once the implementation plan was developed, a pilot test was conducted to ensure that the plan includes the key elements required for the implementation of exoskeletons in construction organization. Nine participants (n=9) were part of the pilot test. These include construction industry practitioners with experience in implementing new technologies. Also, academics conducting exoskeleton research in construction participated in the pilot study. Each participant was engaged in semi-structured interviews which lasted for 1 hour. The sessions were conducted virtually using zoom, and were audio and video recorded. The investigators provided a step-by-step explanation of the implementation plan. Subsequently, the participants were probed on the
suitability of the steps, elements and sequence of the elements of the plan to the exoskeleton implementation process. The feedback was used to improve the implementation plan.

6.4.1.4.2 Focus group

A focus group discussion was also conducted as part of the validation process. The discussion included six stakeholders (n=6) identified as key for inclusion in decisions regarding the implementation of exoskeletons in the construction organizations. These stakeholders included general manager, superintendent, safety manager, ergonomist, experienced worker, and OSHA representative. The focus group discussion, which was conducted via online video meetings (i.e., Zoom), lasted for 1 hour and was audio and video recorded. During the focus group, each step and elements of the plan were explained to the participants. The participants were asked to reflect on how the elements were a representation of the processes that could be followed in a construction organization to implement exoskeletons. Participants were further asked to suggest modifications and stakeholders who should be responsible for the tasks in the plan. Based on the response provided by the participants, follow-up questions were posed by the investigator for more insights. The implementation plan was further improved based on the results of the focus group.

6.4.2 Evaluation of Exo-Implant

The implementation plan was evaluated through a case study of how potential end users would employ Exo-Implant to adopt exoskeletons. Given that exoskeleton-use is still in the early stages in the construction industry, a scenario was developed to facilitate the case study. Scenarios are significant for defining future developments (or use of innovations) to model contextual changes such as organization responses (Badham et al. 2019). The development of the scenario and implementation of the case study are described as follows:

6.4.2.1 Scenario development

The development of the scenario was guided by the feedback obtained from the focus group on how the aforementioned factors (i.e., facilitators and barriers) would impact the implementation of exoskeletons and the roles of the stakeholders in the implementation process. To ensure compliance of the contents of the scenario with construction industry practice, the scenario was validated using a focus group (Akanmu and Anumba 2015). The scenario and validation approach are described as follows:

6.4.2.1.1 Scenario

This scenario describes how 'Exo-Implant’ would be executed by a construction company for the implementation of exoskeletons. Company A is exploring the possibility of adopting exoskeletons to address the problem of work-related musculoskeletal disorders among their workers. To support this process, Company A employed the 'Exo-implant’, an exoskeleton implementation plan,
developed by Virginia Tech. The following illustrates the sequence of actions undertaken by Company A to implement ‘Exo-Implant’ (shown in Fig. 6.5):

- Management-level meetings (which included a general manager, project manager, safety vice-president, safety manager, and ergonomist) were held to discuss the potential of exoskeletons for the company and a decision was made to adopt exoskeletons to reduce the occurrences of musculoskeletal disorders. It was decided to conduct the implementation process in-house, and a timeline of 3 years was proposed.
- An ‘Exo Project Team’ (which included a foreman, superintendent, project manager/engineer, safety manager, risk manager, ergonomist, and champion (end user willing to use it and experienced)) was created to execute the implementation process.
- The ‘Exo Project Team’ conducted an exploratory study and identified the need for a passive back-support exoskeleton for the concrete crew(s). These are intended to be the pilot crews.
- The project manager and safety manager from the ‘Exo Project Team’ negotiated with the manufacturers and an order was placed. The manufacturing company offered to support the implementation process by providing demonstrations and training (for usage and maintenance).
- In coordination with the manufacturers, the ‘Exo Project Team’ created handling, storage, and maintenance guidelines.
- To create buy-in, lectures, and toolbox talks were conducted (by safety managers, ergonomists, foremen, and superintendents) with the pilot crews.
- Training sessions were conducted in coordination with the manufacturers which included the participation of safety managers, foremen, ergonomists, superintendents, and workers. Trained workers and professionals were issued certificates post-completion of their training and evaluation.
- The safety manager and ergonomist from the ‘Exo Project Team’ designed a data collection sheet to assess the impact of using the exoskeletons.
- A 3-month pilot test was conducted during which the workers' feedback and quantitative data were collected by the safety managers and foremen.
- The ergonomist analyzed the data and identified that the intervention reduced the risk of musculoskeletal disorders.
- The ‘Exo Project Team’ documented lessons learned and feedback from the crews to improve the implementation plan for future deployment.
6.4.2.1.2 Validation of the scenario

The participants of the focus group involved a safety manager, superintendent, corporate manager, ergonomist, experienced worker, and OSHA representative. These participants represent potential stakeholders of an exoskeleton implementation plan. The steps and flow of the implementation plan was described to the participants. Thereafter, the sequence of the scenario was explained to them. Participants were asked to provide feedback on how the scenario reflects how the implementation strategy would be executed in a construction company. Thereafter, they were asked to provide feedback on how the actions reflect the sequence of events that would take place to execute the implementation strategy and what action should be modified. The focus group session was also conducted via zoom, audio and video recorded and lasted for 1 hour.

6.4.2.2 Case study

The developed plan was evaluated using a case study facilitated by the developed scenario. Ten industry practitioners (n=10), including one exoskeleton manufacturer and nine construction
industry practitioners from a mid-size construction company, participated in the case study. The construction industry practitioners include a general manager, project manager, project engineer, risk manager, safety vice president, safety manager, superintendent, experienced worker, and field manager. The choice of these participants was guided by the roles represented in the implementation plan. The participants were engaged in a focus group discussion. Focus groups have also been used for evaluating implementation plans (Pollastri et al. 2020). During the case study, the scenario was explained to the participants. The participants were asked to familiarize themselves with their roles. Following this, the participants were provided with ‘Exo-Implant’ and asked to imagine executing the steps in the plan based on their roles in the scenario. The participants were probed on how the elements of the plan would help them achieve the objective of the steps of the plan. In addition, the participants provided feedback on modifications that would facilitate successful adoption of the plan. The focus group was conducted as a hybrid session with eight participants participating in-person and 2 participants on zoom. The session lasted for 2 hours and was audio/video recorded.

6.4.3 Data analysis

Qualitative data collected from the semi-structured interviews and focus groups were analyzed using thematic analysis. Based on the collected data, a codebook was developed using an inductive coding approach (Vanover et al. 2021). The extracted themes were cross-checked with the transcripts to ensure consistency. Also, agreement with the codes was rated by two researchers and moderate inter-rater agreement was achieved at a Cohen-Kappa coefficient of 0.6. To measure the acceptance of ‘Exo-Implant’ amongst the participants (or intended users), a usability questionnaire inspired from the constructs of the Technology Acceptance Model (Davis 1985) was developed. Cronbach Alpha value was calculated to validate the questionnaire. The usability data were analyzed using descriptive statistics.

6.5 Results

6.5.1 Developed implementation plan (Exo-Implant)

The steps and elements needed to execute the steps of Exo-Implant are described in this section (Fig. 6.6). Table 6.1 shows how different elements and steps of Exo-Implant tie into the NPT constructs.

<table>
<thead>
<tr>
<th>NPT Constructs</th>
<th>Steps</th>
<th>Supporting elements within Exo Implant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coherence</td>
<td>1</td>
<td>Identifying documented benefits and required stakeholders</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Conducting exploratory (or feasibility) study</td>
</tr>
<tr>
<td>Cognitive participation</td>
<td>3</td>
<td>Providing lectures and toolbox talks and demonstrating exoskeletons</td>
</tr>
<tr>
<td>-------------------------</td>
<td>---</td>
<td>---------------------------------------------------------------</td>
</tr>
<tr>
<td>Collective action</td>
<td>4</td>
<td>Developing manuals, guidelines and checklist</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Developing training module; Conducting training sessions; Evaluating workers learning</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Conducting toolbox talks to attract other workers</td>
</tr>
<tr>
<td>Reflexive monitoring</td>
<td>7</td>
<td>Collecting periodic feedback; Contacting manufacturers for potential updates to exoskeleton design; Conducting cost-benefit analysis; Revising training materials</td>
</tr>
</tbody>
</table>

6.5.1.1 Step 1: Managerial Go-NoGo decision on the adoption of exoskeletons

This step describes the decision-making process that the corporate management will follow to arrive at a decision on whether to proceed with the implementation of exoskeletons in their firm. As part of this step, the management will be evaluating the documented benefits of using exoskeletons which include the impact on site safety and productivity, cost savings due to reduced injuries and insurance claims, competitive advantage for winning bids and recruiting young workers, and evaluating the strategies adopted by their competitors and support provided by the manufacturing company. As part of the decision-making process, a cost-benefit analysis will be conducted which would require identifying the types of exoskeletons and an approximate quantity of the same. The management will also be required to identify if their organization have the required stakeholders for the implementation process. Furthermore, a decision will be made on whether to carry out the implementation process in-house or to hire a consultant. Based on the aforementioned evaluations, a decision to adopt of exoskeletons will be taken by the management.

6.5.1.2 Step 2: Preparing for the initial use of exoskeletons

This step involves the groundwork required for the implementation of exoskeletons in construction firm. Within this step, an ‘Exo Project Team’ consisting of a general manager/emerging technology manager, safety manager, ergonomist, superintendent, project manager, project engineer, and experienced workers (champion) will be created. This team would then conduct an exploratory study (or feasibility analysis) to understand (a) the types of crews that would benefit from exoskeletons and their risk exposures (i.e., physical strain and load characteristics), (b) impact of the use of the exoskeletons on site safety, (c) compatibility of exoskeletons with their work tasks and equipment, and (d) the infrastructure requirements of deploying exoskeletons. Through the study, pilot crews and the exoskeletons suitable for the crews will be identified. Thereafter, policy considerations relating to the required sizes of exoskeletons, shared or personal
use, and storage on-site or allowing workers to carry the device home would be determined. Then, negotiations will also be held with the manufacturers regarding the possibility of renting exoskeletons and discounts on bulk purchase. The decision to continue with the implementation process would then be re-evaluated and if the project team sees value in the adoption, exoskeletons will be procured.

Figure 6.6. Exo-Implant
6.5.1.3 Step 3: Creating awareness and buy-in

This step is aimed at creating buy-in among the workers. As part of Change model prescribed by Grol and Wensing (2004), if end users are aware of problems, they could be more accepting of solutions to the problem. Thus, if the workers are aware of the problem associated with WMSDs, they may be more willing to use exoskeletons. In this step, languages spoken amongst the workers would be identified, and lectures and toolbox talks would be developed accordingly to adapt trainings to them. Short 5-minute lectures and toolbox talks would be delivered during morning hurdles to make the workers aware of WMSDs. During the awareness campaign, exoskeletons would be demonstrated to inform workers of its potential to curb WMSDs.

6.5.1.4 Step 4: Operational strategy

In this step, the required guidelines and paperwork would be developed to ensure smooth operation of the implementation process. The ‘Exo Project Team’ will create a handling and storage manual which could include elements such as sterilization, storage space, use of hard case, inspection checklist, and instructions for use of exoskeletons under different weather conditions. The team will also create a maintenance manual, which could include information on the wear and tear of the device, duration of maintenance, warranty of the parts of the exoskeleton, cleaning guidelines, and manufacturer contact for emergencies. Based on the above-mentioned manuals, materials, and parts required for maintenance, storage, and handling will be procured. After that, a life cycle assessment plan will be developed to improve the service life of the exoskeletons. A data collection sheet will be developed to facilitate the monitoring process (Step 7). Thereafter, the members of the operations team will be assigned the responsibility of ensuring that the exoskeletons are used by the workers. A checklist will be prepared and provided to the team to assist the operations team with the daily use of the exoskeletons. All the necessary permissions will be obtained and a decision will be made, on whether to continue with the implementation process or not. Based on lessons learned from this step, the procedure for cost-benefit analysis will be revised.

6.5.1.5 Step 5: Training

This step is intended to facilitate training of workers on how to use exoskeletons. A ‘Training Team’ consisting of a safety manager, field engineer, superintendent, ergonomics, and foremen will be created. The training team will be trained by the manufacturers so that they can monitor and train the workers. Thereafter, the training team will prepare a training module that will include the training period, and how to don and doff exoskeletons, check the anthropometric fit, use different modes and maintain exoskeletons. Furthermore, elements of the Change model (Grol and Wensing 2004) could also be included in the training module. An evaluation metric will used to measure workers’ understanding of using the exoskeletons. Then workers’ training sessions will be conducted and the workers would be evaluated. If the workers fulfill the training requirements, they would be issued a certificate showing that they have the required knowledge to use the exoskeleton.
6.5.1.6 Step 6: Deployment

Within this step, a knowledge-based iterative process will be employed to deploy the exoskeletons across the organization. Firstly, the workers from the pilot crews will be allowed to use the exoskeletons for a pre-defined pilot period. During this period, the workers will perform their daily tasks using an exoskeleton, and the safety managers will collect workers' feedback using the data collection sheet designed in Step 4 and explained in Step 7. On completing the pilot testing, the data will be analyzed and a decision will be made on whether to continue with or end the implementation process. If the ‘Exo Project Team’ decides to continue with the process, the previously discussed steps will be followed on a larger scale. Lessons learned from the pilot testing will be used to upgrade the plan. Experiences of the workers from the pilot crews will be shared with other crews to leverage social influence for attracting more workers to use the exoskeletons. This process will be followed to increase deployment of exoskeletons at the organization level.

6.5.1.7 Step 7: Monitoring

This step is aimed at continuously monitoring the impact of using exoskeletons on construction sites. Periodic feedback, in terms of ease of use, perceived pain, discomfort, exertion, usefulness, cognitive workload, risks (such as loss of balance and fatigue), essential modifications, heart rate, temperature and blood pressure, and productivity, will be captured. The data will be analyzed, and a cost-benefit analysis will be conducted to understand if the use of exoskeleton is beneficial to the organization or not. Based on the feedback from the workers, the company can collaborate with the manufacturers to improve the device to make it more suitable for construction work. Furthermore, the lessons learned from the implementation process will be used to revise Steps 1 to 6.

6.5.1.8 Off-ramp strategy

The off-ramp strategy was included in the Exo-Implant in case of a no-go decision by the implementation team. As part of this step, the team will be required to document the findings and rationales of the decision-making for each step. In the event the process is not continued, the team will reevaluate the technology after 3 years and examine the reasons for the no-go decision prior to commencing the implementation process.

6.5.2 Evaluation of the developed implementation plan

This section presents results of the usability assessment of the implementation plan and qualitative feedback obtained from the focus group during the case study.

6.5.2.1 Usability

Fig. 6.7 shows the ratings provided by the participants to the constructs of the TAM questionnaire. These include ease of use, perceived usefulness, trust, attitude, and intention to use.
6.5.2.1.1 Ease of use

Four questions were employed to evaluate the ease of use of the developed implementation plan (Fig. 6.7). A near moderate rating of 2.89 ± 1.17 was provided by participants when asked whether Exo-Implant was easy to use (E1). Moderate to high ratings were provided by participants when asked if learning how to use Exo-Implant was easy (E2) (3.44 ± 0.88) and if the plan was easy to understand (E3) (3.44 ± 1.24). Participants felt that the use of Exo-Implant can help them to find the information required for their role in the implementation process (E4) as they provided a moderate rating (3.22 ± 0.67).

![Usability Rating](image)

**Figure 6.7. Usability rating.**

6.5.2.1.2 Perceived usefulness

Participants’ perceived usefulness of Exo-Implant was evaluated using six questions (Fig. 6.7). Participants moderately (2.89 ± 0.60) agreed when asked if the use of Exo-Implant will allow speedy completion of the implementation process (PU1). Moderate to high ratings were provided by the participants when asked if the use of Exo-Implant will make it easier to implement exoskeletons (PU2) (3.56 ± 0.73), enhance the effectiveness of implementation process (PU4) (3.89 ± 0.93) and guide them in the process (PU6) (3.78 ± 0.97). Participants felt that the use of Exo-Implant will be useful for their role in the implementation process (PU3) as they provided a high rating (4.00 ± 1.12). Also, a near-high rating (3.89 ± 0.78) suggests that the participants found Exo-implant useful (PU5).

6.5.2.1.3 Trust

Six questions were posed to the participants to evaluate their trust in Exo-Implant (Fig. 6.7). Participants highly agreed (4.00 ± 0.87) that Exo-Implant provides reliable information (T1). When asked if the plan takes into account the needs of the users (T2) (3.67 ± 0.87), is practical
and reasonable (T3) (3.33 ± 1.00), will be used regularly in the implementation process (T4) (3.44 ± 0.88), and has the necessary information for the effective implementation (T5) (3.67 ± 0.71), moderate to high rating was provided by the participants. Participants also provided moderate to high ratings (3.67 ± 0.71) when asked if they trust Exo-Implant to help in the implementation of exoskeletons (T6).

6.5.2.1.4 Attitude

The participants’ attitude towards the use of Exo-Implant for implementation of exoskeletons was evaluated using five questions (Fig. 6.7). Participants provided a moderate to high rating when asked if they were positive towards Exo-Implant (A2) (3.56 ± 0.88), believe that the Exo-Implant helps in the implementation of exoskeletons (A3) (3.56 ± 0.53), favor the use of Exo-Implant (A4) (3.33 ± 0.71), and think it is a good idea for their company to use Exo-Implant (A5) (3.33 ± 0.71). A high to very high rating (4.22 ± 0.83) was provided by participants when asked if the use of Exo-Implant for the implementation of exoskeletons is a good idea (A1).

6.5.2.1.5 Intention to use

The participants’ acceptance of Exo-Implant was evaluated using four questions (Fig. 6.7). Participants provided moderate ratings when asked if they intend to use the plan frequently in the implementation process (IU1) (3.33 ± 0.87), use it throughout the process (IU2) (3.44 ± 0.53), refer to Exo-Implant as often as possible in the process (IU3) (3.33 ± 0.50) and use Exo-Implant as often as their company intends to implement exoskeletons (IU4) (3.22 ± 0.44).

6.5.2.2 Factors influencing adoption of Exo-Implant

Table 6.2 describes the factors, identified for each step of the Exo-Implant, from the analysis of the case study results. The factors are classified as facilitators and barriers to the use of Exo-Implant for the implementation of exoskeletons in the construction industry.

<table>
<thead>
<tr>
<th>Steps</th>
<th>Facilitators</th>
<th>Barriers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Feasibility study; Impact assessment; Pilot testing; Modifications; Stakeholders; Manufacturer’s support; Competitive advantage; Cost-benefit analysis; Implementation approach; Buy-in</td>
<td>Rotational injuries; Difficulty to measure site safety; Compatibility with PPE and tasks; Device weight; Customization for workplace; Adjustability for different sizes; Timeline for execution</td>
</tr>
</tbody>
</table>
2 Crew identification; Renting plan; Manuals  
Service life; Key performance indicators; Redundancy of some of the elements

3 Crew composition; Language consideration; Workers’ testimonials; Demonstration; Manufacturers’ support; Toolbox talks  
Inclusion of other communication aids e.g., videos, mobile apps, prompts; Include trial opportunities; Buy-in through productivity benefits

4 Developing manuals; Weather compatibility; Operational strategy; Life cycle assessment; Workers’ responsibilities; Parts procurement; Maintenance requirements  
Device protection accessories; Assignment of responsibilities; Psychological considerations; Data collection and processing support

5 Champions; Manufacturers support; Hands-on training; Training module  
Multi-lingual trainers

6 & 7 Size considerations; Iterative process; Data collection; Implementation approach  
Large scale implementation; Simple data collection; Data on repair and use

Overall  
Includes necessary elements  
Condense plan; Provide more description; Need to simplify

6.5.2.2.1 Step 1: Managerial Go-NoGo decision on the adoption of exoskeletons

In this step the participants discussed the different elements that they would consider for the decision-making on the implementation of exoskeletons and agreed with the elements. Feasibility of the exoskeleton from a cost and implementation standpoint was considered to be a crucial element. The documented impact of exoskeleton on safety, productivity, reduction of injuries, and insurance claims were also considered critical considerations for decision-making. They mentioned that the owners or the general contractors carry the workers’ insurance on most of their projects. As such, they prefer to award contracts to sub-contractors who use new technologies to keep their workers safe. As a result, the possible competitive advantage that construction companies can have for attracting workers and winning bids was considered likely and one of the participants cited an example of Kask Safety helmets which are mandated on new projects. Participants also raised the concern of getting buy-in from workers. They felt that the use of exoskeletons is intended to reduce long-term musculoskeletal injuries which some of the workers might not currently be suffering from. Thus, motivating the workers to use the exoskeleton to
protect them against an injury that they have not yet suffered might be a problem. This process was further discussed in Step 3.

Some of the elements which were not part of this step were also considered important. Participants considered that the exoskeleton is designed for forward bending tasks and most of their injuries are a result of twisting movements. So, exploring the impact of the exoskeleton for tasks related to rotational movement was also considered important. To this end, participants suggested working with the manufacturers to improve the exoskeleton design to address risks from rotational movements. Participants also felt that measuring the impact on site safety could be difficult. Furthermore, the compatibility of the exoskeleton with different work environments, the weight of the device, adjustability to different shapes and sizes, suitable tasks for exoskeleton use, and customization to fit task requirements were considered as some of the major elements necessary for decision-making. The manufacturer's representative also suggested providing job and exoskeleton dictionaries to companies to aid the process of exploring compatibility. Creating a timeline for the implementation of exoskeletons was considered important, however, the participants felt that this step would require further information such as the availability of exoskeletons, support from manufacturers, required training, the adopted process of implementation, serviceability, and monitoring requirements. Although the aforementioned elements are part of other steps in Exo-Implant, the participants suggested moving them into this step.

6.5.2.2.2 Step 2: Preparing for the initial use of exoskeletons

The participants felt that some of the elements in Step 2 were redundant in comparison to the discussions they had in Step 1 and suggested relocating some of the elements from Step 2 to Step 1. For example, they suggested moving the exploratory study to Study 1. It was also suggested to move service life of exoskeletons, which was in Step 4, to this step. The participants discussed the warranty period of exoskeletons and the parts, maintenance, and serviceability requirements, wear indicators and different conditions in which the exoskeleton can be exposed. Furthermore, the manufacturer suggested identifying key performance indicators as part of the feasibility analysis which was originally part of Step 4. The participants agreed with other elements as part of this step and emphasized identifying specific crews for the implementation of exoskeletons as this decision could influence the selection of exoskeletons and policy considerations such as personal vs shared exoskeleton-use. Also, the participants felt that the option of renting the exoskeletons could facilitate the implementation of exoskeletons as it could be a cost-effective option.

6.5.2.2.3 Step 3: Creating awareness and buy-in

The participants felt that identifying the crew compositions and the different languages spoken by the crews is crucial for developing and delivering the material for creating buy-in. Testimonials of workers who have suffered from back injuries and are in favor of using exoskeletons can help in creating awareness and get buy-in as these workers can mention how the use of exoskeletons
improves their safety and health. Furthermore, the participants suggested that demonstrations can help in getting buy-in as the workers will get to see the device and not just hear about it. However, the participants suggested delivering the materials via videos using mobile apps. Furthermore, the participants suggested having prompts in common areas where the workers can look at flyers to create awareness of the problem and exoskeletons as potential solutions. This might make them more interested in trying the exoskeleton rather than feeling forced to try the devices. Having the workers use the exoskeleton on a trial basis was also considered as a potential way of getting buy-in. Lastly, it was considered that project teams may be reluctant to the implementation of exoskeletons on their sites, thus, knowledge of the impact on productivity could help in getting the project teams on board.

6.5.2.2.4 Step 4: Operational strategy

The participants agreed with majority of the elements, however they also felt that some of the considerations from the operational stage could be used in Step 1 for the decision-making process. For example, storage, handling and maintenance requirements. The manufacturer mentioned providing companies with manuals containing instructions relating to the handling, storage, maintenance, and cleaning of exoskeletons, but providing recommendations on how companies can develop manuals specific their requirements. Some of the recommendations could be provided upfront while others could be developed through field observations. The operability of exoskeletons in all weather conditions was considered to be critical by the participants. However, the manufacturer’s representative mentioned that exoskeletons might not be usable during freezing temperatures. Thus, the participants felt that the discussion on the compatibility of exoskeletons with weather conditions should be considered in Step 1. Life cycle assessment of exoskeletons was also considered an important factor and to be moved to Step 1. Furthermore, cleaning of exoskeletons and tool requirements were considered important for ensuring serviceability of exoskeletons. Procurement was also considered significant for identifying the required materials and parts. Knowing the lead time on exoskeleton orders can help in planning the procurement process. Ownership of exoskeletons is another factor that was discussed by the participants. They suggested that the workers be responsible for storing and maintaining the exoskeletons if their devices are not shared.

Participants also provided additional suggestions that were not considered in this step of the plan. For example, the manufacturer's representative suggested using additional accessories to increase the resistance of exoskeletons to heat, chemicals, and electricity. This prompted discussions on different combinations of accessories required, as having multiple accessories could make the process cumbersome and impact exoskeleton use. Furthermore, assignment of responsibilities to field managers was considered a barrier as field managers may be unwilling to take on the additional responsibility since they are responsible for production. To mitigate this, it was suggested that workers be assigned the responsibility of caring for their device. Psychological considerations were also deemed necessary as the workers might get used to working with the exoskeleton and if unavailable (e.g., due to damage), they may be uncomfortable working without
it, which could trigger risks. The participants suggested simplifying the data collection sheet. In response, the manufacturer's representative offered to provide a 10-questions sheet. The participants also raised concerns about interpreting the collected data since it is subjective.

6.5.2.2.5 Step 5: Training

The participants agreed with most of the elements of this step. The participants supported involving a champion worker to train workers. This way, other workers can relate with them and might be more willing to accept the exoskeleton. The participants felt that trainers who train the workers should be proficient in the use of exoskeletons. Thus, they suggested involving the manufacturers in the training. Ensuring that the workers are trained in using the exoskeleton as well as aware of the maintenance and cleaning requirements can help in keeping the exoskeleton in good working condition. Also, hands-on training on exoskeleton use will enable the workers to learn and accept the exoskeletons faster. However, the participants also suggested that having trainers who can speak multiple languages could help facilitate understanding of the training. Thus, trainers from manufacturers, as well as construction organizations, would have to be multi-lingual.

6.5.2.2.6 Steps 6 and 7: Deployment and Monitoring

Steps 6 and 7 were conducted simultaneously as monitoring is an integral part of the deployment process. For the deployment process, the participants felt that the implementation would be taking place at a larger scale as opposed to the smaller scale prescribed in Exo-Implant. For example, if the company decides to implement exoskeletons among carpenters, all the carpenters within the organization would be required to use exoskeletons. Thus, the iterative process part of Exo-Implant would be trade-specific and not crew or project specific. The data collection sheet was considered extensive. It was suggested that simplifying the data collection sheet to 5 simple questions would increase participation among workers. The participants did not anticipate any potential pushback from the workers for responding to the questions. They mentioned that the workers would respond as long as the safety managers, tasked with the data collection, has good relations with the workers. Furthermore, the participants recommended adding data on repair and using it as a key performance indicator. Knowing how often the exoskeletons require repairs and how often the workers use the device will help the implementation team to evaluate the effectiveness of a long-term use of exoskeletons.

6.5.2.2.7 Overall

Overall, the participants felt that the elements part of the Exo-Implant are in line with factors that they would consider for deciding on exoskeleton adoption. However, they felt that the plan could possibly be simplified and condensed. The participants felt that the plan was extensive and could be overwhelming for the users. Also, the participants suggested including images of exoskeletons and construction workers using exoskeletons for various applications in Exo-Implant.
### 6.6 Discussion

Construction workers are subjected to physically demanding tasks that can cause work-related musculoskeletal disorders (Chen et al. 2022; Roy 2022). Back-support exoskeletons are considered to be a potential solution to address this problem (Gonsalves et al. 2021; Ogunseiju et al. 2022). However, there is a lack of a structured process that can facilitate the implementation of passive exoskeletons in the construction industry. Using guidelines from existing implementation plans and constructs from the NPT theory, an implementation plan (Exo-Implant) was developed. A scenario-based case study was conducted to evaluate the acceptance of Exo-Implant among stakeholders and to establish factors that could influence its adoption in the construction industry.

#### 6.6.1 Usability of Exo-Implant

The participants felt that Exo-Implant was easy to understand and learn. This is critical because this will ensure that stakeholders from different backgrounds can easily learn and understand the details prescribed in the implementation plan. However, they felt that the developed plan was moderately easy to use. This could have been because the plan was very extensive, and participants had to go through different elements to achieve different objectives of each step of the implementation process. The extensive details might have led the participants to perceive the plan to be useful. This is critical because if the stakeholders perceive the plan to be useful, they would more likely be willing to use it regularly as observed by Malik and Annuar (2021). Participants also felt that the plan includes reliable and necessary information for implementing exoskeletons. As a result, they trust the plan because they provided a moderate rating. This is critical because if the stakeholders trust the plan to provide correct information, they will refer to it to achieve the objective of their roles in the plan. This is supported by the high ratings provided by the participants when asked if the plan was useful for their role in the process. Overall, the participants had a positive attitude toward the use of Exo-Implant for the adoption of exoskeletons since they provided a high rating when asked if the use of the plan is a good idea. This positive attitude could have been because the participants felt that the plan provides them with reliable and relevant information to help them contribute effectively to the implementation process. This positive attitude, trust in the contents of the plan and perceived usefulness of the plan might have led the participants to provide acceptable intention to use the plan. This is in line with the findings of Sari et al. (2021) who observed that attitude, perceived usefulness, and trust impacted the intention to use M-wallet, an intervention for making payments.

#### 6.6.2 Factors influencing adoption of Exo-Implant

Feasibility analysis was considered to be a facilitator for the adoption of Exo-Implant. This is critical because as part of the feasibility analysis, construction companies will be required to evaluate the crews and their risk exposure based on which they will identify crews for pilot testing and the type of exoskeletons. They will also consider the compatibility of the exoskeletons with
the tasks performed by workers, supporting tools and equipment, weather conditions (i.e., compatibility with hot and cold weather), and work environments (i.e., working at heights and working around fire hazards). This will help decide on the most suitable exoskeletons. This is in line with the implementation plan developed by Feldmann et al. (2020), who considered feasibility analysis as a crucial first step for exoskeleton implementation. Identifying the critical stakeholders was also considered to be an important facilitator. This will ensure that the key decision makers or the appropriate roles are represented in the process thereby facilitating better implementation as suggested by Crea et al. (2021).

Getting buy-in amongst end users and the project team is also important for the successful implementation of exoskeletons. This is significant because people are usually resistant to the adoption of new technology and systems (Ngai et al. 2010). Thus, getting buy-in by improving awareness of the problem and demonstrations of solutions can help in managing resistance to change as suggested by Grol and Wensing (2004). Owing to the importance of measuring the return on investment for the adoption of new technology in the industry (Schniederjans 2017), cost-benefit analysis was considered to be a facilitator. Pilot testing was considered crucial for the adoption of exoskeletons as it will help in evaluating the impact of using exoskeletons on construction sites in terms of injuries, cost, and productivity. This is also a key consideration in the plan developed by Feldmann et al. (2020) for the implementation of exoskeletons in intralogistics.

Involving experienced workers who are willing to use an exoskeleton (champion) was considered essential to attract other workers. This is important because, if workers listen to testimonials provided by their fellow workers they would be more willing to try the intervention. This is in line with the findings of Bunce et al. (2020) who suggested including champions in implementation plans to drive change. Data collection is another critical facilitator of the plan. This will help in continuously monitoring the intervention by collecting workers' feedback and improving the plan. Ngai et al. (2010) also considered monitoring as significant in the development of an implementation plan for adopting radio frequency identification systems in the construction industry. The participants also considered the iterative process for the implementation of exoskeletons important as this could help organizations use lessons learned to improve and execute the plan on a larger scale. A similar approach was used by Arayici et al. (2011) for the implementation of BIM for lean architectural practices.

The exclusion of prompts was considered one of the barriers of Exo-Implant. Prompts can improve workers’ awareness of risks that they could be exposed to while performing their regular tasks. Prompts could also improve workers’ understanding of how the use of exoskeletons could help in mitigating the risks. This will make the process of implementing the exoskeleton less directed. Participants mentioned that the use of Exo-Implant could be overwhelming for its users and suggested simplifying the plan by condensing it. This comment was in line with the usability rating provided by the participants. Although the participants think the entire plan is overwhelming, in practice, different teams will only need to execute the steps designated or assigned to them and not all the steps. Thus, it might not be overwhelming if they are only exposed
to the steps or elements they are required to execute. Collecting data on repairs and use of exoskeleton was considered to be a barrier as it was not included in Exo-Implant. Data regarding the frequency of repairs and maintenance is beneficial to keep the exoskeleton in good condition and can help in evaluating the life cycle cost of the devices. Furthermore, data on the frequency of use could help in understanding how often the workers prefer to use the exoskeleton. This could help understand how to target trainings that could help enhance usage of the device, thereby ensuring success of the intervention. The proposed plan provides elements that construction companies need to consider for the implementation of exoskeletons but does not include the specific procedures required to execute the elements. For example, the plan mentions conducting a cost-benefit analysis but does not provide a tool to conduct the analysis. A lack of awareness of the procedures for performing cost-benefit analysis could hinder execution of the element as proposed in the plan. However, a one-size-fits-all approach may be challenging to develop and adapt to the plan because organizations have different procedures and mechanisms for performing such analysis for technological interventions (Shenhar et al. 2002).

6.7 Conclusion
Studies have shown that passive exoskeletons have the potential to reduce musculoskeletal injuries and increase workers' productivity. This has triggered a growing interest in the use of passive exoskeletons in the construction industry. However, there is scarce literature regarding the process requirements for adopting exoskeletons. Thus, this study proposes ‘Exo-Implant’, an implementation plan designed to facilitate the adoption or implementation of passive exoskeletons in the construction industry. This study also evaluates the acceptance of the developed plan among stakeholders and identifies factors that could influence the adoption of the plan in the construction industry. A literature review was conducted to identify constituting elements of implementation plans. Thereafter, the factors and stakeholders critical for the adoption of exoskeletons in the construction industry were identified. A draft implementation plan was developed using the constituting elements of implementation plans, and factors and stakeholders for the adoption of exoskeletons. A scenario-based case study was conducted involving stakeholders from a mid-size construction company. The results indicate that the stakeholders found the plan to be helpful for the adoption of passive exoskeletons as they perceived the plan to be useful. However, some improvements, such as condensing the plan, supporting the plan with images, and including a procedure for assessing the feasibility of exoskeletons in terms of cost, safety, and productivity, were suggested to facilitate the adoption of Exo-Implant.

This study contributes to the scarce literature on the implementation of exoskeletons in the construction industry. The proposed implementation plan will provide academics and industry practitioners with a broad overview of the elements required to be considered for the implementation of exoskeletons in a construction company. Inspiration from the developed plan could enable academics and practitioners to develop implementation plans for adoption of other wearable technologies. Also, the developed plan could guide the implementation of exoskeletons in other industrial sectors. This study also contributes to the NPT through the factors that would
influence the normalization of Exo-Implant in the construction industry. Results from this study could help manufacturers improve their products and support to accommodate the requirements of the construction industry.

This study has some limitations that should be addressed as part of future studies. First, the case study included participants from a mid-size construction company (e.g., approximately 2200 employees). Some of the contents of the plan may not be suitable for small- and large-size companies. Furthermore, firms which do not self-perform construction work might have different outlook on the plan. Thus, similar case studies should be conducted for small-and large-size companies as well as different types of construction companies (such as consultants, specialized contractors and general contractors). Secondly, exoskeletons are relatively new technologies in the construction industry. Some infrastructure and financial requirements are not in place to support the adoption. This motivated the use of a scenario-based case study. However, using Exo-Implant to implement exoskeletons in the real world, may require additional considerations. Thus, future work should involve an actual case study involving the implementation of exoskeletons in a construction company. Thirdly, Exo-Implant includes different considerations deemed necessary for the adoption of exoskeletons. However, the plan does not outline a procedure for cost-benefit analysis, feasibility analysis, monitoring, and data analysis. In the future, procedures for the aforementioned procedures could also be included in the plan to make the plan more user-friendly. Fourthly, the proposed plan is developed for the implementation of passive exoskeletons. Additional consideration might be necessary for implementing active exoskeletons in the construction industry. Thus, future studies could consider developing a plan for adopting active exoskeletons in the construction industry. Continuous monitoring and updating are critical to ensure that the developed plan is relevant to changing markets and work environments. Future studies could consider creating a digital twin of the plan which could help in real-time monitoring and updating of the plan to make it adaptable to changing conditions. A follow-up study could also be conducted by including the results of the case study in the digital twin. This could help understand model the influence of the changes on the acceptance of Exo-Implant amongst the stakeholders involved in the implementation process.
CHAPTER 7: CONCLUSION

This section presents the summary, contribution to the body of knowledge, contribution to the state of practice, limitations, and future work.

7.1 Summary of the Research

Construction workers are often subjected to physically demanding work tasks that can lead to work-related musculoskeletal disorders (WMSDs), which have the potential to cause permanent disabilities. In recent years, there has been growing interest in the use of wearable robots, such as passive back support exoskeletons, to address back-related WMSDs in the construction industry. However, there are risks and unintended consequences (such as increase in discomfort, impact on productivity, and increased fall risk) of using wearable robots on construction sites. There is limited evidence in literature regarding the risks and socio-technical challenges of deploying exoskeletons for construction work. Therefore, this research seeks to investigate the potential of adopting passive back-support exoskeleton (BSE) in the construction industry.

Chapter one introduces the research and provides relevant background information, including the research gap, theoretical underpinnings, research questions and aims, and research scope. Chapter two attempts to answer the first research question: How does the use of a passive BSE affect muscle activity, perceived discomfort, and productivity during construction work? To answer this question, the Chapter presents an experimental investigation of the effects of using a passive BSE (BackX V2) on users’ back muscle activity, perceived discomfort, and productivity while performing rebar tasks. Both objective and subjective measures were used in this study to measure muscle activity and productivity, and perceived discomfort (respectively) from the use of the passive BSE. The results showed a mixed effect on back muscle activity, with a reduction in perceived discomfort at the back but an increase in discomfort at the chest region. However, increased productivity was observed when using the exoskeleton. This study provides a basis for further research with respect to using passive BSEs in construction sites.

Chapters three and four are aimed at answering the second research question: How does the use of passive BSE on construction sites influence construction workers’ perception of the usability of exoskeletons, and their perceived discomfort and exertion? This question was addressed by conducting a user evaluation of passive BSEs on construction sites. Chapter 3 involved a field experiment conducted to measure the acceptance of passive BSE (BackX V2) among pipe workers. The study used subjective measures, such as usability, perceived discomfort, and feedback to evaluate the usability of the exoskeleton. The results showed that passive BSEs are generally acceptable for use in pipework, although there was an increase in discomfort in several body parts. Thematic analysis of subjective feedback revealed the benefits of using exoskeletons, barriers to the adoption of exoskeletons, and modifications required to make exoskeletons more suitable for pipe work. However, it should be noted that the results are based on a 4-hour use of the BSE. Chapter 4 presents the impact of prolonged use of the passive BSE (BackX V3, an upgraded version of BackX V2 including some of the modifications from chapter
3 such as excluding harness and Velcro, and keeping the metal torso closer to the body) on workers' acceptance. A field investigation was conducted where pipe and concrete workers used the exoskeleton to perform their usual work tasks for a week. A usability assessment was conducted, and subjective measures such as usability, perceived discomfort, and exertion, workers' perception and intention to use, and social influence were studied. The use of exoskeletons led to a reduction in workers' perceived discomfort and exertion, and acceptable usability was reported. The results indicated that usability and social influence significantly impacted workers' intention to use passive BSEs, and there was acceptance of passive BSEs among pipe and concrete workers after prolonged use.

Chapters five and six are aimed at answering the third research question: What strategies could be put in place to successfully implement passive BSEs in the construction industry? To answer this question, Chapter five investigates the stakeholders and factors (i.e., facilitators and barriers) that are critical for the adoption of passive exoskeletons in the construction industry. Mixed-method research was employed, involving an online survey and focus group discussions. Construction professionals were surveyed to identify the key stakeholders and a list of critical construction-related factors significant for exoskeleton adoption. The factors were formalized through focus group discussions involving stakeholders identified from the survey. In Chapter six, Exo-Implant, a framework/strategy for the implementation of passive exoskeletons in the construction industry, is developed. The components of the implementation plan were identified from literature. The elements of the implementation plan were then conceptualized from the results of Study 4 (i.e., critical stakeholders and factors for the adoption of exoskeletons). A scenario-based case study was conducted to evaluate Exo-Implant. The results indicate acceptance of the developed framework amongst construction professionals. The developed framework could be employed by construction organizations, in the future, for the adoption of passive back-support exoskeletons.

7.2 Conclusions

Construction is a labor-intensive industry wherein the workforce is subjected to awkward work postures such as forward bending, squatting, and neck bending. These are ergonomic risks causing WMSDs among construction workers. Wearable robots such as passive back support exoskeletons are looked upon as a potential solution to address this problem. However, the use of exoskeletons on construction sites could have certain underlying risks and socio-technical challenges, which if not identified could limit the efficacy of the intervention. Thus, through laboratory and field explorations, the research identifies these risks and challenges associated with the use of wearable robots on construction sites. Furthermore, the research also develops a plan to aid the implementation of exoskeletons in the construction industry.

The results show that passive BSEs can reduce physical demand of construction tasks. The participants in the laboratory and field explorations perceived a reduction in discomfort in the lower back body part. This could mean that the use of a passive BSE could lead to a reduction in stress in the back muscle. This is in line with the findings of the laboratory experiment wherein a
reduction was observed in back muscle activity. However, a significant increase in discomfort in chest body parts was also observed from the laboratory and field exploration, suggesting that the use of passive BSEs could have certain unintended consequences. This could affect workers’ acceptance of passive BSEs and should be addressed to facilitate the adoption of the technology.

In both the short-term field study and extended field testing, participants perceived that the use of passive BSEs could help in reducing musculoskeletal disorders and suggested potential work tasks for which the technology would be beneficial. Despite upgrades in the exoskeleton design (i.e., excluding harness from the exoskeleton) between the field explorations (i.e., short-term field study and extended field testing), participants still raised concerns regarding the compatibility of the exoskeleton with safety harness and tool straps. This could affect construction companies’ willingness to adopt exoskeletons in their organizations and thus should be addressed. However, exclusion of the harness from the exoskeleton led to a reduction in discomfort to the shoulder body part in the extended field testing, which was found to be higher in the short-term field study. Furthermore, although the metal torso was re-designed to be closer to the body, participants still raised concerns regarding the use of the exoskeleton in confined spaces in the extended field testing which was similar to the short-term field study.

Although acceptable usability was observed in both field explorations, relatively lower ratings were observed in the extended field testing compared to the short-term field study. This could be due to the prolonged use of the exoskeletons. Furthermore, the extended use of the passive BSE also impacted workers’ perception of safety and comfort. This could mean that prolonged use of passive BSEs could potentially lead to a reduction in acceptance of exoskeletons. It would be beneficial to conduct a longitudinal investigation to understand the willingness of workers to use the exoskeleton daily. This can also help construction companies in decision-making processes regarding exoskeleton adoption and implementation. Participants in both the field explorations felt that they could work faster and for a longer duration with an exoskeleton, which could mean that the device might increase their productivity. This is in line with the findings of the laboratory experiment where a significant increase in productivity was observed. Although the participants of the laboratory experiment and field explorations were students and construction workers, respectively, similar outcomes were observed in both studies. This could mean that involving student participants in exoskeleton evaluations could also yield promising results. This is critical, as it could help the scientific community in laboratory experiments, wherein recruiting actual construction workers could be challenging. However, more scientific investigations (such as a comparative study of similar outcome measures for student participants and construction workers) are required in order to yield this inference. Some of the factors identified from the workers’ user experience with the exoskeleton were in line with the findings of Study 4. These factors contribute to the scarce literature regarding the adoption of exoskeletons in construction sector and are in accordance with literature on diffusion of technology in workplaces. These factors could be used by researchers and construction organizations for developing strategies to either mitigate the barriers or employ facilitators to enhance the adoption of passive BSEs in the construction industry.
7.3 Contributions to the Body of Knowledge

This research explores the potential of adopting passive BSEs in the construction industry. This research addressed the research gaps, mentioned in Chapter 1, by investigating the risks and socio-technical challenges of human and wearable robot interaction in construction. This study sets precedence for similar studies on the suitability of other exoskeletons (e.g., shoulder-support and leg-support exoskeletons) for the construction industry. This overall research is underpinned by socio-technical systems theory. This research contributes to the STS theory by incorporating all the subsystems (i.e., human, technology, organization, and social) in the evaluation of passive BSEs. Studies 1, 2 and 3, and 5 are viewed from lens of human-wearable robot interaction, Unified Theory of Acceptance and Use of Technology, and Normalization Process theories respectively.

7.3.1 Assessment of a passive wearable robot for reducing low back disorders during rebar work

A laboratory experiment was conducted, in Study 1, to measure the impact of using a passive BSE for construction tasks (e.g., rebar work). Scarce evidence is available in the literature regarding human and wearable robot interaction in the construction industry. Thus, the results contribute to the body of knowledge on the interaction between human and wearable robots by revealing the extent of influence of the interaction on muscle activity, task completion time (used to infer productivity), and discomfort to the body parts. The study reveals a decrease in muscle activity and discomfort to the body parts (except the chest region) and an increase in productivity due to the use of the exoskeleton. The study further contributes to the literature by identifying the aforementioned benefits and unintended consequences of using an exoskeleton for construction work. The reduction in the completion time of the rebar tasks could mean that the use of an exoskeleton would result in increased productivity. This could motivate the construction industry to adopt the device and explore task-specific applications of the exoskeletons. This has implications for reducing the rate of WMSDs in the industry.

7.3.2 Industry perception of the suitability of wearable robot for construction work

This study aims at understanding construction workers’ perception of using a passive BSE in terms of usability, level of perceived discomfort, and subjective perception. Most of the studies exploring the potential of exoskeletons involve simulated tasks conducted in the laboratory. However, this study was conducted with construction workers on actual construction sites. The study shows that the workers found the exoskeleton to be easy to use and did not impact their productivity. While the workers experienced reduced discomfort in the lower back, there was an increase in discomfort at the chest, thigh, and shoulder regions. These results contribute to some of the constructs of the UTAUT theory (i.e., the performance expectancy, effort expectancy, comfort, and safety constructs) in the context of the use of passive BSE for construction work. Furthermore, the study revealed some modifications to make exoskeletons more suitable for construction work. These could be useful for exoskeleton manufacturers to improve existing exoskeleton designs, thereby
making them more suitable for work in the construction industry. The study also highlighted barriers to the adoption of exoskeletons which can help construction companies to develop strategies or solutions to the barriers.

7.3.3 Assessment of workers’ acceptance of passive back support exoskeletons for construction work

The study aimed at understanding the acceptance of exoskeletons among pipe and concrete workers through the lens of UTAUT theory. The study shows that the use of the passive BSE resulted in reduction in workers' perceived exertion and discomfort. The usability of the exoskeleton was acceptable to the workers, but the device restricted their movement which in turn affected their comfort. The usability of the exoskeleton and social influence, due to the use of the exoskeleton, influenced workers' intention-to-use the exoskeleton. These results advance the body of knowledge and the UTAUT theory by explaining how constructs, such as performance, efficacy, and social influence, influence the acceptability of exoskeletons in the construction industry. The benefits, barriers, and implementation could help inform the development of strategies to normalize the use of exoskeletons in construction organizations. The strategies could include task-specific applications and training modalities. These could also inform future research directions in the area of design of adaptable exoskeletons i.e., exoskeletons that can adapt to the body depending on the posture and physical demands of tasks. The design suggestions will benefit construction organizations and manufacturers looking to explore suitable designs for construction work. The study sets precedence for similar studies to be conducted with other types of exoskeletons in the construction industry.

7.3.4 Industry perspective of the factors inferencing the adoption of passive wearable robots on construction projects

To develop an implementation plan which can facilitate the implementation of passive exoskeletons in the construction industry, this study sought to identify the critical factors (i.e., facilitators and barriers) and stakeholders that can influence the adoption of passive exoskeletons in the construction industry. The study identified 21 facilitators and 23 barriers as factors to be considered during exoskeleton adoption. The study also revealed the impact of influence of the factors through applications and benefits that illustrate context for use of exoskeletons, challenges with embracing exoskeletons on construction site, and solutions to the challenges. Thus, this study contributes to scarce literature by identifying the factors and stakeholders that are critical for the adoption of exoskeletons in the construction industry. This study further contributes to the socio-technical systems theory by identifying and considering the perspectives of the critical stakeholders to formalize the facilitators and barriers. The identified factors can be used by construction companies to identify strategies to facilitate the use of exoskeletons on their projects. The framework of the study could be employed by other researchers to formalize similar factors for their domain.
7.3.5 Exo-Implant: An implementation plan for exoskeleton adoption in the construction industry

An implementation framework, underpinned in the NPT theory, was developed to facilitate the adoption of passive exoskeletons in the construction companies. NPT theory is widely employed in the healthcare industry. Sparse literature is available on the use of NPT for other industrial sectors especially the construction industry. The study described the usability of the implementation framework in terms of ease of use, perceived usefulness, trust, attitude and intention to use. These contribute to the technology acceptance model (TAM) by explaining how construction industry practitioners could come to accept and use a passive BSE. By identifying the factors influencing the adoption of the implementation plan, this study advances the NPT theory. Thus, this study contributes to the body of knowledge by presenting the efficacy of using NPT to develop implementation frameworks for the construction industry. This study further contributes to the NPT theory by identifying the facilitators and barriers to the use of the developed plan. The developed plan could inspire academic and industry practitioners to develop similar implementation plans for the adoption of other wearable technologies in the construction industry.

7.4 Study Limitations and Future Work

This study has some limitations which should be addressed in future studies. These are described below.

Study 1 involved only student participants. Postures assumed by the participants may not be representative of those adopted by construction workers, which could affect the type and extent of activated muscles and levels of discomfort. Additionally, the sample size was small and may not be sufficient to generalize the findings. Therefore, future studies should involve actual construction workers with demographics that better reflect the industry. The results of this study do not provide sufficient evidence to determine the feasibility and effectiveness of passive BSEs in real-world settings. More rigorous field-based trials are necessary to establish the feasibility acceptance, and potential barriers to using BSEs for construction tasks.

Study 2 was conducted only during the summer, where temperatures ranged from 50 deg. F. to 98 deg. F. The workers’ perception of using the exoskeleton could change based on the weather conditions (i.e., during winter). Additionally, the exoskeleton was not used during rain. Therefore, similar studies should be conducted in different weather conditions to understand the exoskeleton’s usability during varying weather conditions. Furthermore, this study had a small sample size, which may be insufficient to generalize the results of the usability of exoskeletons for pipe work. In addition, the study included only pipe workers. Tasks performed by other trades may be different, requiring different usability and compatibility requirements. Thus, similar studies should be conducted with other trades to understand any task-specific application or use of exoskeletons.

Study 3 included only male participants and did not investigate acceptance among female workers. The acceptance requirements for female workers could differ from those of male workers. Additionally, this study had a small sample size for both concrete and pipe trades, which limits the
generalizability of the results. Therefore, future studies should include participants that are representative of the construction industry's demographics, including female workers. Furthermore, the use of passive BSEs could impact workers’ productivity, which has been shown to affect acceptance among workers. As such, future studies should also measure workers’ productivity due to exoskeleton use. This study only involved pipe and concrete workers; therefore, the results cannot be generalized to other trades. Similar studies should be conducted for other trades to evaluate exoskeleton acceptance. The findings of this study are only applicable to exoskeletons with designs similar to BackX. The impact of exoskeletons with different designs and actuation strategies could be different. Thus, similar studies should be conducted on other exoskeletons. This study only evaluated subjective measures. Objective measures such as muscle activity, heart rate, and range of motion could provide more scientifically credible results. Therefore, future studies should collect objective measurements.

Owing to the lack of awareness of exoskeletons, the online survey in Study 4 had a small sample size. A larger sample size could help to better understand and generalize construction professionals’ perspectives regarding the factors that could influence the adoption of passive BSEs in the construction industry. Given that exoskeletons are a futuristic technology, there is a lack of awareness regarding exoskeletons among construction professionals. To educate the survey participants regarding the use of passive BSEs, information and pictures describing the use of the device were provided at the beginning of the survey. The focus group participants were provided videos and images of workers using the exoskeleton before the discussion. However, having the opportunity to try the exoskeletons could have improved the participants' understanding of exoskeletons which might have yielded better results. Thus, future studies could consider in-person focus group sessions, where the participants could be allowed to test the exoskeleton before participating in the study. Future work could also entail using advanced analysis methods (such as text mining) to understand the interaction between different factors identified in this study.

Exoskeletons are a near future technology for the construction industry. Implementation of exoskeletons would require certain infrastructure and financial requirements which are currently not in place in the construction sector. As a result, a scenario-based case study was employed in Study 5. The actual implementation of exoskeletons might reveal the need for additional considerations which might not be a part of the current plan. Thus, future studies could consider conducting an actual case study. Furthermore, this study included participants from a mid-sized general contracting firm. The requirements of small and large organizations might be different from that of mid-size construction firms. Also, depending on the company type (i.e., self-perform contractor, general contractor, specialized contractor, and consultants), the considerations for the implementation of exoskeletons might differ. As a result, the findings of Study cannot be generalized to the entire construction industry. Thus, similar case studies should be conducted with different organizations (i.e., small and large size contractors, construction consultants, and specialized contractors). The proposed plan does not incorporate specific procedures which can facilitate the use of the plan (e.g., the procedure for cost-benefit analysis and feasibility analysis). Such procedures should also be incorporated into the plan.
7.5 Recommendations

7.5.1 Recommendations for future research

From this study, there are certain opportunities for future work which are explained as follows: The results of perceived discomfort indicate an increase in discomfort in the chest area. Additionally, the exoskeleton is designed to transfer the load to the thighs, which may lead to increased muscle fatigue in the legs. Moreover, construction workers are exposed to harsh working conditions, such as dusty environments and changing weather conditions, with strict quality and schedule requirements. Using an exoskeleton in such conditions over a prolonged period may have an impact on the psychobiological state of construction workers. Furthermore, using the exoskeleton while working at the edge of a building could increase fall risk. Therefore, future laboratory experiments could consider measures such as muscle fatigue and fall risks, which could be measured using electroencephalography sensors and insole pressure monitoring systems, respectively. In addition to the back-body part, future studies should include measurements of the chest and leg muscle groups to assess the impact of exoskeleton use while performing construction tasks.

The study found the usability of exoskeletons to be acceptable to construction workers after extended field testing. However, as more construction companies are considering adopting exoskeletons, it would be valuable to understand the acceptance of these devices after long-term use. Additionally, through long-term studies, the impact of the intervention on the incidence rate of work-related musculoskeletal disorders (WMSDs) can be observed, which could assist construction companies in their decision-making regarding the adoption of exoskeletons. Therefore, a longitudinal investigation (about 3 to 5 years) should be conducted to measure the acceptance of exoskeletons and their impact on incidence rates after long-term use.

Some of the participants in this study had little awareness of exoskeletons. However, more construction companies and researchers continue to explore the potential of exoskeletons in the construction industry, a Delphi study could be valuable. This would involve recruiting expert participants with working knowledge of exoskeletons as well as experience in the construction industry. Such a study could potentially provide deeper insights and identify more reliable factors for the implementation of exoskeletons in the construction industry.

With the changing dynamics in the construction industry, the proposed implementation plan (Exo-Implant) would need to be adapted to meet evolving needs. Furthermore, the plan would need to be modified to suit the requirements of different companies. Therefore, it would be valuable to develop a digital twin of the plan, which could facilitate real-time monitoring and improvement of the plan to meet the needs of the construction industry. Data collected from stakeholders and workers can be fed into the digital twin in real-time to improve the plan. Additionally, the digital twin can include detailed procedures for cost-benefit analysis, data analysis, life-cycle assessment, and feasibility analysis to further guide construction professionals in the implementation process.

As more exoskeletons become commercially available, it would be significant to have a test bed to assess the risks associated with the devices. This is significant because there could be
challenges associated with testing new products on construction sites. Deploying new technologies, such as exoskeletons, in work environments where the devices could potentially lead to fall risks, such as working on the edge of a building, might not be possible as it could harm the subjects. Virtual and mixed-reality environments provide opportunities for testing the device in such risky scenarios without putting workers' lives in danger. Thus, a testing environment could be developed that includes multiple what-if scenarios to assess the usability of the exoskeleton in difficult and challenging situations.

7.5.2 Recommendations for the construction industry

The researchers would like to provide some recommendations for the construction industry to facilitate the implementation of exoskeletons and innovations. In this research, construction workers suggested some design modifications to make the device more suitable for construction work. Construction companies could collaborate with exoskeleton manufacturers to assess the feasibility of incorporating the changes in the exoskeletons. Additionally, construction companies could provide researchers and manufacturing companies access to their job sites to assess the devices and understand their suitability for construction tasks. Construction companies interested in using exoskeletons, could employ Exo-Implant in their organizations to facilitate the adoption of passive exoskeletons and test the implementation frameworks. Furthermore, organizations could explore the possibilities of academia-industry partnerships and accommodate new practices to explore the potential of new technologies in their organizations. Organizations can also invest in new technologies and establish a research wing to explore the potential of different technologies for streamlining processes and improving safety.

7.6 Concluding Remarks

In this research, laboratory, and field explorations were conducted to understand the underlying risks and socio-technical challenges of human-wearable robot interaction in the construction industry. Furthermore, to facilitate the adoption of exoskeletons in the construction sector, critical stakeholders and factors were identified, based on which an implementation plan is proposed. The results suggest that the use of exoskeletons for construction work tasks has the potential to reduce the occurrences of WMSDs among construction workers since it reduces workers’ physical demand. Additionally, the exoskeleton was found to have acceptable usability for construction work tasks, resulting in the acceptance of exoskeletons among construction workers. However, certain design modifications are required to make the devices more suitable for construction tasks and improve their usability and acceptance in the construction industry. Moreover, certain unintended consequences of using an exoskeleton, such as increased discomfort at the chest body part, were observed and are required to be addressed to facilitate the adoption process. Furthermore, certain additional considerations for the use of exoskeletons have also been identified in this research, which can be utilized by researchers and industry practitioners to identify strategies to aid the implementation of exoskeletons. The most critical stakeholders and factors
necessary for adopting exoskeletons in the construction industry were also identified. The research proposed an implementation plan named ‘Exo-Implant’ to support the implementation of passive BSEs in the construction industry. Construction organizations can employ this plan to implement passive BSEs in their companies. This exploratory research shows the potential of passive BSEs for construction work and provides guidelines for their implementation in the construction industry.
REFERENCES


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Cable, J. (2007). "Don't Strain Yourself: It's not rocket science to figure out why sprains and strains plague many construction firms. Fortunately, the solutions aren't that complicated either." *Occupational Hazards*, 69(1), 36.


APPENDICES

Appendix A

Perceived level of discomfort questionnaire

a. For the condition you just completed, please use the scale and diagram in front of you to rate the level of discomfort you experienced in the following body parts during the task. For body parts with two sides (e.g., left and right legs), please rate the worst side of the two.

<table>
<thead>
<tr>
<th>Body Part</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand/Wrist</td>
<td></td>
</tr>
<tr>
<td>Upper Arm</td>
<td></td>
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<tr>
<td>Shoulder</td>
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<tr>
<td>Low Back</td>
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<tr>
<td>Thigh</td>
<td></td>
</tr>
<tr>
<td>Neck</td>
<td></td>
</tr>
<tr>
<td>Lower Leg and Foot</td>
<td></td>
</tr>
</tbody>
</table>

b. If you rated any body part more than ‘3’ above, please explain what you think is the source of that discomfort.

Scale Diagram

![Scale Diagram]

0  NOTHING AT ALL
0.5  VERY, VERY SLIGHT (just noticeable)
1  VERY SLIGHT
2  SLIGHT
3  MODERATE
4  SOMEWHAT SEVERE
5  SEVERE
6  VERY SEVERE
8  VERY, VERY SEVERE (almost maximal)
10  MAXIMAL
Appendix B
Usability questionnaire

<table>
<thead>
<tr>
<th></th>
<th>Strongly Disagree</th>
<th>Moderately Agree</th>
<th>Strongly Agree</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Usability</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a.</td>
<td>Ease of Use</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>i.</td>
<td>I can easily don and doff the exoskeleton.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ii.</td>
<td>I can easily adjust the exoskeleton to myfitting.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>iii</td>
<td>It works the way I want it to work.</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>iv.</td>
<td>It meets my needs for completing the task</td>
<td></td>
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<tr>
<td>v.</td>
<td>It makes the task I want to accomplish easier to get done.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>vi.</td>
<td>I can use this exoskeleton without assistance.</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>vii</td>
<td>I prefer working with it than without it.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>viii</td>
<td>I can use this exoskeleton again without the assistance of any technical personnel.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b.</td>
<td>Comfort</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>i.</td>
<td>I feel the exoskeleton restricts my movement.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ii.</td>
<td>I feel the exoskeleton interfered with my work environment.</td>
<td></td>
<td></td>
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<tr>
<td>iii</td>
<td>I am satisfied with using the exoskeleton.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>iv.</td>
<td>I feel I can work while wearing the</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Working with exoskeleton makes me uncomfortable.

### Performance

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</thead>
<tbody>
<tr>
<td>i.</td>
<td>I feel like I can work for longer duration with this exoskeleton</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>ii.</td>
<td>With this exoskeleton I can do my work faster than before</td>
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<td></td>
<td></td>
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<tr>
<td>iii.</td>
<td>I feel like working with the exoskeleton makes me more cautious which in turn affects my productivity</td>
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### Safety

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</thead>
<tbody>
<tr>
<td>i.</td>
<td>I feel like the exoskeleton will interfere with the safety harness</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ii.</td>
<td>I feel like walking on construction site while wearing the exoskeleton caused imbalance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>iii.</td>
<td>I feel like the exoskeleton is too heavy for me</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>iv.</td>
<td>I feel like the exoskeleton is applying pressure on my body parts</td>
<td></td>
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</tbody>
</table>

**Semi-structured interview questions**

1. Is there something about the exoskeleton you didn’t like?
2. Is there something in particular that you really liked about the exoskeleton?
3. Do you have any suggestions for the exoskeleton in terms of use?
4. Do you recommend any changes to the exoskeleton

**Perceived level of discomfort questionnaire**

For the condition you just completed, please use the scale and diagram in front of you to rate the level of discomfort you experienced in the following body parts during the task. For body parts with two sides (e.g., left and right legs), please rate the worst side of the two.

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<td></td>
</tr>
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</table>

If you rated any body part more than ‘3’ above, please explain what you think is the source of that discomfort.

**Appendix C**

**Usability questionnaire**

<table>
<thead>
<tr>
<th>Remarks</th>
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<th>Moderately Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>a.</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

180
<table>
<thead>
<tr>
<th></th>
<th>I can easily don and doff the exoskeleton.</th>
<th></th>
<th></th>
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<tbody>
<tr>
<td></td>
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<td></td>
<td>I prefer working with it than without it.</td>
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</tr>
<tr>
<td><strong>b. Comfort</strong></td>
<td>1 2 3 4 5</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td>I feel I can work while wearing the exoskeleton during summer</td>
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</tr>
<tr>
<td></td>
<td>Working with exoskeleton makes me uncomfortable</td>
<td></td>
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<tr>
<td><strong>2. Performance</strong></td>
<td>1 2 3 4 5</td>
<td></td>
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<tr>
<td></td>
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<tr>
<td><strong>3. Safety</strong></td>
<td>1 2 3 4 5</td>
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<td></td>
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</tbody>
</table>
ii  I feel like walking on construction site while wearing the exoskeleton caused imbalance

iii  I feel like the exoskeleton is too heavy for me

iv  I feel like the exoskeleton is applying pressure on my body parts

4. **Intention to Use**

   1. Assuming that I have access to the exoskeleton, then I intend to use it.
   2. If I have access to the exoskeleton, I predict that I will use it.
   3. Assuming that the company requires using the exoskeleton, then I intend to use it.

---

**System usability scale questionnaire**

<table>
<thead>
<tr>
<th></th>
<th>Strongly disagree</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>Strongly agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. I think that I would like to use the <em>Exoskeleton</em> frequently.</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td></td>
</tr>
<tr>
<td>2. I found the <em>Exoskeleton</em> unnecessarily complex.</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td></td>
</tr>
<tr>
<td>3. I thought the <em>Exoskeleton</em> was easy to use.</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td></td>
</tr>
<tr>
<td>4. I think that I would need the support of a technical person to be able to use the <em>Exoskeleton</em>.</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td></td>
</tr>
<tr>
<td>5. I found the various functions in this <em>Exoskeleton</em> were well integrated.</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td>□</td>
<td></td>
</tr>
<tr>
<td>Perceived exertion questionnaire</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>---------------------------------</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>For the condition you just completed, please rate the level of exertion you experienced during the task using the following scale: _________</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Borg’s Rating of Perceived Exertion (RPE) Scale</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perceived Exertion Rating</td>
<td>Description of Exertion</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>No exertion, Sitting &amp; resting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Extremely light</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Very light</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Light</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Somewhat hard</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Hard</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Very hard</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Extremely hard</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Maximal exertion</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Semi-structured interview questions**

1. Is there something negative about the exoskeleton you didn’t like?
2. Is there something in particular that you really liked about the exoskeleton?
3. What modifications are required for the exoskeleton system to make it more suitable for construction tasks?
4. Do you have any suggestions for maintenance and use of the exoskeleton?
5. Do you have any suggestions for proper handling and storage of the exoskeleton on the construction site?
Perceived discomfort questionnaire

For the condition you just completed, please use the scale and diagram in front of you to rate the level of discomfort you experienced in the following body parts during the task. For body parts with two sides (e.g., left and right legs), please rate the worst side of the two.

<table>
<thead>
<tr>
<th>Body Part</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hand/Wrist</td>
<td></td>
</tr>
<tr>
<td>Upper Arm</td>
<td></td>
</tr>
<tr>
<td>Shoulder</td>
<td></td>
</tr>
<tr>
<td>Low Back</td>
<td></td>
</tr>
<tr>
<td>Thigh</td>
<td></td>
</tr>
<tr>
<td>Neck</td>
<td></td>
</tr>
<tr>
<td>Lower Leg and Foot</td>
<td></td>
</tr>
<tr>
<td>Chest</td>
<td></td>
</tr>
</tbody>
</table>

b. If you rated any body part more than ‘3’ above, please explain what you think is the source of that discomfort.

Social influence questionnaire

<table>
<thead>
<tr>
<th>Remarks</th>
<th>Strongly disagree</th>
<th>Moderately agree</th>
<th>Strongly agree</th>
<th>Peer Influence:</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>My peers are willing to use Exoskeleton while working</td>
</tr>
<tr>
<td>ii</td>
<td>4</td>
<td>5</td>
<td></td>
<td>My peers think I will benefit from using Exoskeleton</td>
</tr>
<tr>
<td>iii</td>
<td>5</td>
<td></td>
<td></td>
<td>My peers think it is important I use</td>
</tr>
<tr>
<td>Peers who influence my behavior would think that I should use Exoskeleton while working</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peers who are important to me would think that I should use Exoskeleton while working</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>My superior, who influences my behavior would think that I should use Exoskeleton while working</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>My superior whom I report to would think that I should use Exoskeleton while working</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>My superior confirms my ability and knowledge to use Exoskeleton while working</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>My superior thinks it is important I use Exoskeleton while working</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2. **Superior’s Influence**

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ii</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>iii</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>iv</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix D

Online survey questionnaire

Demographics:
1. Which of the following type(s) of construction does your company engage in? Please select all that apply.
   a. Residential Construction
   b. Commercial Construction
   c. Specialized Industrial Construction
   d. Heavy Construction
   e. Other, please specify………………………………………………..

2. What is the approximate size of the company that you currently work for or own?
   a. Less than 10 employees
   b. 10 - 19 employees
   c. 20-49 employees
   d. 50 - 99 employees
   e. 100 - 249 employees
   f. 250 - 499 employees
   g. 500 - 999 employees
   h. 1,000+ employees

3. How many years of construction industry experience do you have?
   a. 1 - 5 years
   b. 5 - 10 years
   c. 10 - 15 years
   d. Above 15 years

4. What is your gender?
   a. Male
   b. Female
   c. Non-binary
   d. Other, please specify………………

5. What is your race?
   a. American Indian or Alaska Native
   b. Asian
   c. Black or African American
   d. Native Hawaiian or Other Pacific Islander
   e. Hispanic
   f. White
   g. Other, please specify………………

6. What is your Job title?
   ______________________

7. What department do you work in? (e.g., Operations, Safety, Estimating)
   ______________________
Awareness of exoskeletons

Work-related musculoskeletal disorders (WMSDs) are a growing concern in the construction industry. The back is one of the most commonly affected body parts. Exoskeletons are increasingly being explored as innovative ergonomic intervention options to control physical demands on body-parts.

Back support exoskeleton (BSE) (a) are external wearables that assist in reducing the physical demands on the back, by providing assistive moments about the hip or lower spine to support the muscles. In construction, one can envision a worker wearing a BSE to perform material handling work (b) more effectively and safely with less physical efforts and fatigue.
8. How much awareness do you have regarding the use of exoskeletons? (5-point Likert’s scale)

**Stakeholders:**
9. Which of the stakeholders listed below do you think should be involved in decisions regarding the implementation of exoskeletons in the construction industry and to what extent (5-point Likert’s scale) should they be involved?
   a. Supervisors
   b. Tradesmen
   c. Laborers
   d. Union and Workers Association
   e. Ergonomists/Occupational Health Therapists
   f. Corporate Management (Company’s decision makers)
   g. Insurance Companies
   h. Certifying Bodies (e.g., experts developing guidelines on the safe and effective use of exoskeletons, OSHA)
   i. Others, please specify________________________

10. Kindly list other stakeholders not included in the previous question that you feel should be involved in decisions regarding the implementation of exoskeletons in the construction industry and provide the extent to which they should be involved.

**Facilitators of exoskeleton implementation in the construction industry:**
11. Which of the factors listed below would facilitate the implementation of exoskeletons in the construction industry and to what extent (5-point Likert’s scale) would each factor facilitate the implementation process?

**Perceived Benefits**
   a. Long-term benefits
   b. Ergonomics training
   c. Cost benefit
   d. Productivity gain

**Psychosocial Factors**
   e. Awareness of problem/ indication of a need for exoskeletons
   f. Curiosity (Openness to innovation)
   g. Existing knowledge about exoskeletons
   h. Light cognitive workload
   i. Perceived usefulness of exoskeletons
   j. Overall appearance of exoskeletons
   k. Champion (i.e., willingness to lead the testing of exoskeletons)

**Work-related Factors**
1. Immediate pain relief from using exoskeletons
m. Familiarity with exoskeletons
n. Team buy-in (i.e., team willingness to use exoskeleton)
o. Tribality of exoskeleton
p. Exoskeletons to enable performance and attract other workers
q. Compatibility of exoskeleton with work tasks
r. Few errors and efficient for quality standards (i.e., no impact on quality of construction)
s. Minimum disturbances of construction process
t. Ability to use the restroom
u. Ease of maintenance
v. Durability / ruggedness of the exoskeleton

**Policy-related factors**
w. Mandatory use of an exoskeleton
x. Client driven

**Usability**
y. Ease of using an exoskeleton / Ease of putting on and off / comfort

12. Kindly list other factors not included in the previous question that you feel would facilitate the implementation of exoskeletons in the construction industry and provide the extent to which each factor could facilitate the implementation process.

**Barriers to exoskeleton implementation in the construction industry:**

13. Which of the factors listed below could serve as a barrier to the implementation of exoskeletons in the construction industry and to what extent (5-point Likert’s’ scale) would each of the barriers affect the implementation process?

**Psychosocial factors**
a. Cultural beliefs
b. Social perception of an exoskeleton by the user and others / Peer acceptance
c. General attitude towards exoskeletons
d. Perception of weakness
e. Resistance to change

**Work-related factors**
f. Sterilization/Hygiene
g. Wear time of exoskeleton parts
h. Limited space
i. Storage
j. Duration of maintenance
k. Durability and ruggedness of the exoskeleton
Usability
1. Weight of the exoskeleton
   m. Anthropometric fit (i.e., proper fit for each user)
   n. Incompatibility with other devices (e.g., tool belt)
   o. Externalities (i.e., affecting other workers and their abilities)

Safety
p. Catch and snag risks
   q. Fall risk
   r. Walk on uneven surfaces
   s. Climb stairs and ladders
   t. False sense of safety

Policy-related factors
u. Personal exoskeleton vs. shared exoskeletons

Implementation Factors
v. Length of training for proficiency
   w. Identification of suitable exoskeletons
   x. Purchasing exoskeletons / Affordability / Investment
   y. Convincing management to buy-in
   z. Cost justification

Physiological factors
   aa. Amount of energy needed for use
   bb. Personal history of complaints about exoskeletons

Work Environment
   cc. Hot / Cold weather
   dd. Location of site
   ee. Dusty environment

14. Kindly list other factors not included in the previous question that you feel would serve as a barrier to the implementation of exoskeletons in the construction industry and provide the extent to which each factor could affect the implementation process.

Follow-up interview:
- Would you be willing to participate in a follow-up interview to formalize the survey results?
  - Yes
  - No

Kindly provide the following information:
Name: ______________________________
Email: ______________________________
Appendix E
Exo-Implant

Following is a draft of a seven-step implementation plan developed for the adoption of passive exoskeletons in the construction industry.

<table>
<thead>
<tr>
<th>Steps</th>
<th>Stakeholders</th>
</tr>
</thead>
<tbody>
<tr>
<td>FS: Future Scenario</td>
<td>Possible future condition</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Steps</th>
<th>Stakeholders</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Managerial Go-NoGo decision on the adoption of exoskeleton</td>
<td>General managers, safety VPs, ergonomist and project managers.</td>
</tr>
<tr>
<td>1.1. Evaluate the documented benefits of using the exoskeleton.</td>
<td>Safety manager, ergonomist, and project manager.</td>
</tr>
<tr>
<td>• Impact on site-safety</td>
<td></td>
</tr>
<tr>
<td>• Impact on workers’ productivity</td>
<td></td>
</tr>
<tr>
<td>• Cost savings due to reduced injuries on site</td>
<td></td>
</tr>
<tr>
<td>• Cost savings from insurance (claims)</td>
<td></td>
</tr>
<tr>
<td>• Competitive advantage for winning bids</td>
<td></td>
</tr>
<tr>
<td>• Advantage for attracting and recruiting young workers</td>
<td></td>
</tr>
<tr>
<td>• Cost/affordability/investment</td>
<td></td>
</tr>
<tr>
<td>• Support from the manufacturers</td>
<td></td>
</tr>
<tr>
<td>• Evaluate the strategies adopted by competitors for the adoption of exoskeletons.</td>
<td></td>
</tr>
<tr>
<td>1.2. Identify the type of exoskeletons required and an approximate estimation of the required quantity.</td>
<td>Safety manager and ergonomist.</td>
</tr>
<tr>
<td>1.3. Identify if the required stakeholders are available within the organization.</td>
<td></td>
</tr>
<tr>
<td>1.4. Decide whether to explore the implementation in-house or hire a consultant.</td>
<td></td>
</tr>
<tr>
<td>1.5. Prepare a procedure for cost-benefit analysis which can be used for continuous monitoring of the exoskeleton usage.</td>
<td></td>
</tr>
<tr>
<td>1.6. Conduct a cost-benefit analysis using existing information.</td>
<td>Safety manager, ergonomist, and project manager.</td>
</tr>
</tbody>
</table>
1.7. Create a timeline for the implementation of exoskeletons.

<table>
<thead>
<tr>
<th>2.</th>
<th><strong>Preparing for initial use of exoskeletons</strong></th>
<th>General manager (project head), foreman, superintendent, project manager/engineer, safety manager, and ergonomists</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1. Create an ‘Exo Project Team’ to facilitate the implementation of exoskeletons.</td>
<td>Team: Foreman, Superintendent, Project Manager/Engineer, Safety Manager, Risk manager and Ergonomists, Champion (end user willing to use it and experienced)</td>
<td></td>
</tr>
<tr>
<td>2.2. Conduct a feasibility analysis for using exoskeletons / Exploratory study.</td>
<td>Safety manager and ergonomist.</td>
<td></td>
</tr>
<tr>
<td>• Exposure of workers to movements causing physical strain, load characteristics, safety-related requirements.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Site-safety related risk assessment (e.g., catch and snag risk, fall risk, walking on uneven surfaces, climbing ladders) due to the use of exoskeletons.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Compatibility of exoskeletons with work tasks and equipment.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Quantify the infrastructure requirement (e.g., storage space requirement).</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.3. Identify a pilot crew (champion) and the appropriate exoskeleton to begin deployment.</td>
<td>Safety manager, ergonomist and superintendent.</td>
<td></td>
</tr>
<tr>
<td>• Identify if the exoskeleton is required across the company or for certain projects.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.4. Create buy-in amongst field managers and project teams for the use of exoskeleton.</td>
<td>‘Exo Project Team’</td>
<td></td>
</tr>
<tr>
<td>• Include the materials from 3.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.5. Policy considerations (e.g., required sizes, required types of exoskeletons, shared vs personal exoskeleton, stored on-site vs allowed to carry home).</td>
<td>‘Exo Project Team’</td>
<td></td>
</tr>
<tr>
<td>2.6. Procure exoskeletons to test and attract workers.</td>
<td>Project manager, risk manager and safety manager.</td>
<td></td>
</tr>
</tbody>
</table>
- Identify the required quantity and negotiate with the manufacturers.
- Explore the possibility of renting instead of buying.

**2.7.** Determine whether to continue the implementation process or to abort the project. **‘Exo Project Team’**

<table>
<thead>
<tr>
<th>FS1</th>
<th>If modification is required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coordinate with exoskeleton manufacturers to implement the modifications identified from the studies focused on exoskeletons (similar to that of Virginia Tech).</td>
<td></td>
</tr>
<tr>
<td>Create a timeline required to improve the device and test it with the manufacturers.</td>
<td></td>
</tr>
<tr>
<td>Follow the process from 2.2 to 2.7.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FS2</th>
<th>If cost is low/increase in safety budget</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identify a pilot crew and the appropriate exoskeleton to begin deployment.</td>
<td></td>
</tr>
<tr>
<td>Follow processes 2.4 and 2.7.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>3.</th>
<th>Creating awareness and buy-in</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1.</td>
<td>Identify different languages in which the materials are required to be delivered.</td>
</tr>
<tr>
<td>3.2.</td>
<td>Create and evaluate lecture and toolbox talk materials in the identified languages.</td>
</tr>
<tr>
<td>3.3.</td>
<td>Provide lectures to create awareness of work-related musculoskeletal disorders amongst construction workers and the need for exoskeletons.</td>
</tr>
<tr>
<td>3.4.</td>
<td>Conduct toolbox talks to educate the workers regarding the risks associated with musculoskeletal disorders and the benefits of using an exoskeleton.</td>
</tr>
<tr>
<td>3.5.</td>
<td>Demonstrate the use of exoskeletons.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>4.</th>
<th>Operational strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1.</td>
<td>Prepare a handling and storage manual.</td>
</tr>
</tbody>
</table>
- Sterilization/hygiene
- Storage space for exoskeleton and materials
- Hard case
- Inspection checklist
- Instructions for using in hot/cold weather

4.2. Create exoskeleton maintenance guidelines (preventative maintenance and troubleshooting). Safety manager, foremen and superintendent.
- Wear and tear of the device
- Duration of maintenance
- Warranty on parts
- Cleaning guideline
- Manufacturers contact/emergency contact

FS1 **If modification is required**

<table>
<thead>
<tr>
<th>If modification is required</th>
<th>Revise the handling and storage manual and maintenance guidelines.</th>
</tr>
</thead>
</table>

4.3. Procure the required materials (e.g., brush, rug, sanitizer) and exoskeleton parts for maintenance and storage. Project engineer.

FS2 **If cost is low/increase in safety budget**

<table>
<thead>
<tr>
<th>If cost is low/increase in safety budget</th>
<th>Procure additional exoskeletons for potential replacements and continue from 4.3.</th>
</tr>
</thead>
</table>

4.4. Create a life cycle assessment plan. Safety manager and project engineer.

4.5. Develop a data collection sheet to collect workers’ feedback. Safety manager, foremen, ergonomist and superintendent.

- Ease of using an exoskeleton / Ease of putting on and off / comfort
- Pain
- Discomfort and exertion/Physical fatigue
- Perceived usefulness of exoskeleton
- Light cognitive workload
- Risks (e.g., loss of balance, mental and physical fatigue)
- Essential modifications
- Heart rate, respiration, blood pressure, and body temperature
- Productivity/efficiency

4.6. Consider designing an application for data collection.
4.7. Obtain the required permissions to facilitate the use of exoskeletons.

4.8. Assign responsibilities to the project team for supervising the use of exoskeleton daily (e.g., to foremen, safety managers, and superintendents).

4.9. Create a checklist to assist ground staff with the daily use of exoskeleton.

4.10. Determine whether to continue the implementation process or to abort the project.

4.11. Revise the procedure of quantifying the cost-benefit analysis, if required.

5. **Training**

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1.</td>
<td>Create a ‘Training Team’ to facilitate the training of workers.</td>
<td>Safety manager, field engineer, superintendent, foremen and ergonomist.</td>
</tr>
<tr>
<td>5.2.</td>
<td>Arrange a training session offered by the manufacturers for the training team.</td>
<td>‘Training Team’</td>
</tr>
<tr>
<td>5.3.</td>
<td>Create a training module for the workers.</td>
<td>‘Training Team’</td>
</tr>
<tr>
<td></td>
<td>• Decide on the training period</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Donning and doffing exoskeleton</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Checks for evaluating the anthropometric fit</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Different modes of use (e.g., smart mode and instant mode)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Maintenance of exoskeleton</td>
<td></td>
</tr>
<tr>
<td>5.4.</td>
<td>Involve the elements of the change model (change management steps attached)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Identify potential risks associated with change and address the risks.</td>
<td></td>
</tr>
<tr>
<td>5.5.</td>
<td>Prepare evaluation metrics to measure workers understanding of using an exoskeleton.</td>
<td>‘Training Team’</td>
</tr>
<tr>
<td>5.6.</td>
<td>Execute workers’ training sessions.</td>
<td></td>
</tr>
<tr>
<td>5.7.</td>
<td>Evaluate workers learning regarding the use of exoskeletons and issue a certificate.</td>
<td></td>
</tr>
</tbody>
</table>

**FS1**

If modification is required

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Revise the training module for the workers.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Execute workers’ training sessions.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Allow the workers to try the exoskeletons.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td><strong>Deployment (Iterative process)</strong></td>
<td>Workers, foreman, safety managers, ergonomists, superintendent, field engineer, and project manager/engineer</td>
</tr>
<tr>
<td>----</td>
<td>----------------------------------</td>
<td>--------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>6.1.</td>
<td>Create team buy-in amongst the identified crew (include 3.0).</td>
<td>Foremen, safety manager, ergonomist, field engineers and superintendents.</td>
</tr>
<tr>
<td></td>
<td>• Allocate time for data collection.</td>
<td></td>
</tr>
<tr>
<td>6.2.</td>
<td>Identify a worker willing to participate in the implementation (Champion).</td>
<td></td>
</tr>
<tr>
<td>6.3.</td>
<td>Allow the worker to use it.</td>
<td></td>
</tr>
<tr>
<td>6.4.</td>
<td>Periodically collect workers' feedback.</td>
<td></td>
</tr>
<tr>
<td>6.5.</td>
<td>Conduct toolbox talks to educate other workers regarding the use of exoskeletons.</td>
<td></td>
</tr>
<tr>
<td>6.6.</td>
<td>Provide exoskeleton to other workers of the crew.</td>
<td></td>
</tr>
<tr>
<td>6.7.</td>
<td>Periodically collect workers' feedback.</td>
<td></td>
</tr>
<tr>
<td>6.8.</td>
<td>Educate the different crews on the site regarding the benefit of using the exoskeleton.</td>
<td></td>
</tr>
<tr>
<td>6.9.</td>
<td>Deploy the exoskeleton for the entire site (i.e., for all the crews of an organization on a given site).</td>
<td></td>
</tr>
<tr>
<td>6.10.</td>
<td>Follow the process and deploy the exoskeleton on other sites of the company.</td>
<td></td>
</tr>
</tbody>
</table>

**FS2**

If cost is low/increase in safety budget

- Identify crews for the implementation of exoskeleton.
- Follow the process of deployment outlined above at a larger scale (i.e., start from all the crews on a site, rather than one crew, and scale it to the entire company in an iterative manner).

<table>
<thead>
<tr>
<th>7.</th>
<th><strong>Monitoring</strong></th>
<th>Workers, foreman, safety managers, ergonomists, superintendent, field engineer, and project manager/engineer</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1.</td>
<td>Collect periodic feedback from the workers.</td>
<td>Safety manager, ergonomist, and foremen.</td>
</tr>
<tr>
<td></td>
<td>• Ease of using an exoskeleton / Ease of putting on and off / comfort</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Pain</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Discomfort and exertion/Physical fatigue</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Perceived usefulness of exoskeleton</td>
<td></td>
</tr>
</tbody>
</table>
• Light cognitive workload
• Risks (e.g., loss of balance, mental and physical fatigue)
• Essential modifications
• Heart rate, respiration, blood pressure, and body temperature.
• Productivity/efficiency

7.2. Contact manufacturers to implement any modifications deemed necessary by the workers and continue the process of implementation.
7.3. Conduct a cost-benefit analysis based on the collected data.
7.4. Revise the training modules, toolbox, and lecture materials.
• Include workers testimonials
7.5. Re-evaluate the technology to identify if the technology needs upgrading or change.

Off-ramp strategy:
• Document the reasons for not proceeding with the plan or deciding against the use of exoskeletons.
• Plan to re-evaluate the market and the company requirements after 3 years to explore the possibility of exoskeleton implementation. Also, evaluate the parameters based on which the decision was taken to cancel the implementation process.

Usability questionnaire

<table>
<thead>
<tr>
<th>1. Ease of use</th>
<th>Strongly Disagree</th>
<th>Moderately Agree</th>
<th>Strongly Agree</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>i I find the Exo-Implant easy to use.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>ii Learning how to use Exo-implant is easy for me.</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>iii I think that Exo-Implant is easy to understand.</td>
<td></td>
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<tr>
<td>iv It will be easier for me to find information I need for my role in the implementation process through Exo-Implant.</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>2. Perceived usefulness</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>-------------------------</td>
<td>---</td>
<td>---</td>
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<td>---</td>
</tr>
<tr>
<td>i Exo-Implant will allow speedy completion of the implementation process.</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>ii Exo-Implant could make it easier to implement exoskeletons.</td>
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</tr>
<tr>
<td>iii Exo-Implant will be useful in my role as part of the implementation process.</td>
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<tr>
<td>iv Exo-Implant will enhance the effectiveness of exoskeleton implementation process.</td>
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<tr>
<td>v I find Exp-Implant useful for the implementation process.</td>
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</tr>
<tr>
<td>vi Exo-Implant will guide my implementation process.</td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>3. Trust</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>i Exo-Implant offers reliable information.</td>
<td></td>
<td></td>
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<tr>
<td>ii Exo-Implant takes into account the needs of the users.</td>
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<tr>
<td>iii I think the proposed plan is practical and reasonable.</td>
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<tr>
<td>iv Exo-Implant will be used regularly for exoskeleton implementation.</td>
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</tr>
<tr>
<td>v Exo-Implant has necessary information to effectively carry-out exoskeleton implementation.</td>
<td></td>
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</tr>
<tr>
<td>vi I trust Exo-Implant to help in the implementation of exoskeletons.</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>4. Attitude</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>i Using Exo-Implant is a good idea.</td>
<td></td>
<td></td>
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<tr>
<td>ii I feel positive towards using Exo-Implant</td>
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<tr>
<td>iii I believe that Ex-Implant helps in the implementation of exoskeletons.</td>
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<tr>
<td>iv I favour the use of Exo-Implant for implementation of exoskeletons.</td>
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<tr>
<td>v I think it is a good idea for our company to use Exo-Implant for the</td>
<td></td>
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</tr>
</tbody>
</table>
implementation of exoskeletons in the future.

<table>
<thead>
<tr>
<th>5. <strong>Intention to Use</strong></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>i</td>
<td>“I intend to frequently use Exo-Implant in our company’s implementation process.”</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ii</td>
<td>“I intend to use Exo-Implant throughout the implementation process.”</td>
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<td></td>
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</tr>
<tr>
<td>iii</td>
<td>“I intend to refer to Exo-Implant as often as possible in the implementation process.”</td>
<td></td>
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</tr>
<tr>
<td>iv</td>
<td>“I intend to use Exo-Implant as often as our company intends to implement exoskeletons.”</td>
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<td></td>
</tr>
</tbody>
</table>