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Exploring Opportunities and Challenges of Adopting Exoskeletons and Exosuits in Construction: Identifying Facilitators, Barriers, and Potential Solutions to Those Barriers

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Abstract

Exploring Opportunities and Challenges of Adopting Exoskeletons and Exosuits in Construction: Identifying Facilitators, Barriers, and Potential Solutions to Those Barriers

Dilruba Mahmud

Exoskeletons and exosuits (collectively termed as EXOs) have the potential to reduce the risk of work-related musculoskeletal disorders (WMSDs) by protecting workers from exertion and muscle fatigue due to physically demanding, repetitive, and prolonged work in construction workplaces. However, the use of EXOs in construction is in its infancy, and much knowledge for driving acceptance, adoption, and application of this technology is still lacking. This paper aims to identify the potential facilitators and barriers to adopting EXOs in the construction industry, along with potential solutions to those identified barriers to fostering the adoption of EXOs in construction workplaces through a sequential multistage Delphi approach. Eighteen experts from academia, industry, and government gathered in a workshop to provide insights and exchange opinions regarding facilitators, barriers, and potential solutions from a holistic perspective with respect to business, technology, organization, policy/regulation, ergonomics/safety, and end users (construction trades professionals). A consensus was reached on all these perspectives, including top barriers and potential solution strategies. The outcomes of this study will help the community have a comprehensive understanding of the potential for EXO use in the construction industry, which may enable the development of a viable roadmap for the evolution of EXO technology and the future of EXO-enabled workers and work in construction workplaces.

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Chapter 1. Introduction

1.1 Motivation

The construction industry is labor-intensive, physically demanding, and suffers from stagnant productivity and a high incidence rate of work-related musculoskeletal disorders (WMSDs). Occupational exoskeletons and exosuits (collectively called “EXOs” in this paper) are assistive devices that can support and reduce the physical load on workers performing demanding tasks (Monica et al. 2021; Zhu et al. 2021). Exoskeletons are mechanical devices that act as a frame with motorized joints, whereas exosuits are flexible, soft, and lightweight (Shein 2019). EXOs have the potential to augment workers’ physical abilities leading to improved productivity, reducing fatigue while performing repetitive tasks, and ultimately reducing the risk of WMSDs. The adoption of EXOs may also alleviate this situation of worker shortage that the construction industry is currently suffering from as EXOs may enable workers to work more safely and longer, help aged or physically incapable workers to maintain their employment for a more extended period and attract a larger diverse pool of workers. However, despite these potential benefits, adoption of the EXO technology in the construction industry is still deemed challenging and lags other industries.

1.2 Research Objectives

EXOs have long been used for medical, military, and manufacturing applications, but in the construction industry, the use of EXOs is in its infancy. While efforts in the extant literature have been led to gain an understanding of the benefits, limitations, challenges, and opportunities of EXO use in the construction industry, insights were primarily sought from the professionals within the construction industry only or by summarization of the existing literature. As successful acceptance, adoption, and application of EXOs in the construction industry depend on multiple relevant stakeholders such as EXO manufacturers, contractors, robotic and mechanical experts, psychologists, insurance companies, economic specialists, and government agencies, a holistic understanding of their collective input regarding the facilitators, barriers, and potential solutions to the barriers are still lacking. Having this comprehensive and multi-faceted perspective from all the stakeholders is essential to develop a roadmap for EXO development and adoption in construction.

To fill this knowledge gap, this research aimed to identify the potential facilitators and barriers to adopting EXOs in construction workplaces, along with potential solutions to those identified barriers, by acquiring convergent insights from multiple stakeholders through a sequential multistage Delphi study. Experts from academia, industry, and a key government agency participated in this study and shared insights and reached a consensus with respect to the issues identified above. The outcomes of this study will help understand the status quo and the potential use of EXOs in the construction industry and shed light on their future development.

1.3 Research Overview

A multiphase Delphi method is adopted for this research in which, through brainstorming and discussion among a group of experts, facilitators, barriers, and potential solutions to those barriers were identified to promote the adoption of EXOs in the construction industry to reach the most reliable consensus. The first step was to select an expert panel that comprised 18 representatives from academia (8), industry (5), and government (5) with sufficient knowledge to provide insights into the subject matter that was ensured with a series of questionnaires. The panel discussion focused on six categories: business, technology, organization, policy/regulation, ergonomics/safety, and end users (construction trades professionals).

In the first round, all the experts, divided into two groups, shared their written opinions in a tabulated handout containing spaces for providing written input on the facilitators, barriers, and potential solutions for each predetermined category mentioned earlier and evaluated others' viewpoints. Once done, these discussions from each group were collected and transcribed into a tabular format. In the second round, the experts were presented with the tabulated transcription of their discussion results. Together, they were asked for their opinions and explanations, if necessary, to better understand the collected discussion responses. During this round, disputed items were removed, and new items were added, resulting in a table that represented the complete consensus of the group. In the third round, outcomes from the workshop were refined and consolidated. The outcomes were then sent via email to all the experts for a final review and consensus. The finalized outcomes from this three-round Delphi process are discussed in detail in the next section.

1.4 Organization of Thesis

In *Chapter 1*, the motivation in terms of implications of EXOs in construction workplaces, an overview of the importance of this research, a brief description of the objective of the research, and the research overview has been discussed.

In *Chapter 2*, the description of the field of application of EXOs, benefits of EXOs, and reasoning for why EXO can be beneficial for the construction industry is discussed. In addition, an overview of the state of research on the application of EXOs in the construction industry and assessments and reviews performed on EXOs is provided in detail.

In *Chapter 3*, a brief background of organizing the workshop, an overview of the qualification of the participants, description of the complete process followed in this workshop to reach the consensus have been discussed.

In *Chapter 4*, the detailed discussion on the points from the handout provided to the expert panel during the workshop on facilitators, barriers, and potential solutions to solve those barriers according to six categories, including business, technology, organization, policy/regulation, ergonomics/safety, and end users (trade people) is provided. Additionally, the top priority on barriers identified while attaining consensus is also discussed.

In *Chapter 5*, a brief discussion on the implications of this research for the academia/research community, government & public agencies, EXO manufacturers, Construction firms, trade professionals (end users) and other industries have been presented.

In *Chapter 6*, conclusions, critical contributions of the study and future research works are discussed in brief.

Chapter 2. Background Study

2.1 Functions, Capabilities, and Potentials of EXOs

Exoskeleton or exosuit is defined as a wearable technology that can minimize tension and injury on different parts of the body of a person by providing joint support, distributing weight, and correcting postures (POMERLEAU 2022). The design of occupational EXOs is aimed at the smooth interaction of the devices with the user considering the whole workspace by improving the safety and comfort of the user and optimizing overall system performance without obstructing natural kinematics or resulting in any discomfort or injury (d'Elia et al. 2017). EXOs can be classified into different categories based on different characteristics. Based on the nature of assistance and power source, they can be categorized into active, passive, and semi-active EXOs. Active EXOs are equipped with power sources like electric motors, hydraulic actuators, pneumatic muscles, or other sources of stored energy for aiding the user to move faster or lift or carry heavier loads by providing additional energy to the system (De Looze et al. 2016). Passive EXOs store energy through springs, dampers, or other materials generated by the user's movement and then utilize that energy to augment power to other body parts that require support (De Looze et al. 2016; Monica et al. 2021). The third type of EXOs is termed semi-active EXOs (Crea et al. 2021; Grazi et al. 2020) or quasi-passive EXOs (De Bock et al. 2022), for which low-power actuation units are used to modify the spring-based actuation mechanisms of passive devices so as to enable passive exoskeletons with a certain degree of adaptivity. Based on the supported body parts, EXOs can be classified into upper extremity (arms, shoulders, and upper torso), lower extremity (legs, hips, and lower torso), and full body (both upper and lower torso) EXOs (De Looze et al. 2016). Another classification is also mentioned based on the robotic mechanism of the EXOs, which classifies

EXOs into three types: anthropomorphic, quasi-anthropomorphic, and non-anthropomorphic (Lee et al. 2012). Anthropomorphic EXOs are designed by aligning the rotation axis of the robot joint with the human joint, which enables it to mimic the user's motions. Quasi-anthropomorphic EXOs have joints functionally like human joints but not aligned with the rotation axis of the human joint. Non-anthropomorphic EXOs have the robot joint designed in misalignment with the human joint (Lee et al. 2012).

EXOs enable users to move faster, carry heavier loads, and perform repetitive tasks with greater endurance. These EXO-enabled capabilities can be leveraged in the construction industry for increased productivity and safer construction workplaces. Various types of EXOs may be employed in construction workplaces (POMERLEAU 2022). Power gloves and handling EXOs help lift and hold heavy objects and tools for a long duration. Arm and shoulder EXOs support those body parts in lifting, holding, and repetitive arm movement activities such as cutting, drilling, and scraping by reducing strain during job performance. Back support EXOs play a vital role in reducing lower back disorders while lifting heavy objects and working in a forward-leaning posture diminishing the stresses on back muscles. Leg support EXOs enable the users to perform prolonged standing and crouching postures, common in various construction tasks, and reduce the stress on knees and legs by transmitting the force directly to the ground (POMERLEAU 2022). A full-body EXO has the potential to turn a user into a super worker with the capability of safely lifting and manipulating up to 200 pounds (Zhu et al. 2021). Non-anthropomorphic EXOs' joints are misaligned with the human joints and provide more diverse functionality for more convenient motions and effective energy consumption in performing tasks (Lee et al. 2012).

2.2 State of Research on Application of EXOs in Construction

The construction industry, a major contributor to the global economy, is slow to adopt automation. Nnaji and Karakhan (2020) conducted a survey among 102 construction practitioners to identify the benefits and limitations of using technologies in the construction industry for safety and health management and provided invaluable information regarding barriers to technology adoption and strategies to overcome those barriers. This study pointed out the barriers to technology adoption in the construction industry in general and provided valuable insights for understanding the barriers to adopting EXOs (Nnaji and Karakhan 2020). Kim et al. (2019), on the other hand, carried out a qualitative content analysis through phone interviews among 26 representatives of the construction industry, including a vice president of a company, project manager/engineer, safety and health manager/director, and carpenters to gain their perspectives regarding benefits, factors, and barriers in adopting EXOs. Zhu et al. (2021) reviewed 85 research articles to synthesize insights regarding the potential for using EXOs in the construction industry. The authors also generated a map suggesting types of EXOs for different trades by evaluating the benefits and challenges (Zhu et al. 2021). Through an evidence mapping systematic review, De Bock et al. (2022) provided an overview of the literature relating to the assessment of occupational EXOs and proposed a literature-based framework for benchmarking the effect of future EXOs on the user. In this study, they reviewed 139 articles by which the effect of one or more EXOs on the user was summarized, including 33, 25, and 18 unique back, shoulder, and other EXOs respectively. Okpala et al. (2022) conducted a study of a multiphase process that includes a detailed literature review, an online survey, and a lab-simulated usability study. In this study, the authors evaluated the suitability of 11 EXOs for the construction industry and determined that these EXOs could prevent about 60% of WMSDs and 30-40% of accidents. They also identified the barriers to accepting these EXOs (Okpala et al. 2022).

Research has also been conducted to collect scientific data to examine the efficacy of EXOs. Kim et al. (Kim et al. 2018a; Kim et al. 2018b) carried out laboratory assessments in two consecutive studies to identify expected and unexpected effects of a passive EXO for arm elevation on discomfort, shoulder muscle activity, and task performance and observed that it reduced shoulder muscle activity and task completion time substantially. Antwi-Afari et al. (2021) assessed a passive exoskeleton system on spinal biomechanics during repetitive manual material handling tasks with the help of surface electromyography (sEMG) in the laboratory and observed that the system reduced extensor moments and stresses in internal muscle and lumber region. The participants reported that perceived discomfort level scores for the lower back regions were also reduced. Golabchi et al. (2022) evaluated the rate of perceived exertion, level of discomfort, overall fit and comfort, effectiveness, and interference level while wearing EXOs adopting different postures during dynamic and static material handling tasks. Though the participants reported an elevated level of discomfort, especially on the chest, they rated EXOs for usability and effectiveness, and the authors concluded that EXOs have the potential to reduce MSDs in construction after proper training for appropriate postures. Gonsalves et al. (2021) assessed a back support EXO in terms of task performance and physiological conditions while performing a rebar placement task to conclude that the EXO has the potential to reduce low back disorder. The study indicated that the EXO improved productivity and decreased perceived discomfort, although the participants reported discomfort in the chest. Cho et al. (2018) designed and developed an EXO that can effectively keep workers in safer postures while performing a task and be used as a safety training tool. The effectiveness of a postural-assist EXO was examined by Ogunseiju et al. (2021)

for manual material handling tasks, revealing that the participants were significantly responsive to the feedback from the EXO to rectify any unsafe posture.

Chapter 3. Methodology

This research adopted a consensus development method known as Delphi, in which brainstorming and discussion occurred among a group of experts familiar with this subject matter and having adequate knowledge to provide inputs for a better understanding of the facilitators, barriers, and potential solutions to the barriers to driving adoption of EXOs in the construction industry. The Delphi method is designed to reach the most reliable consensus from the collected opinions among a group of experts (Dalkey and Helmer 1963). The detailed procedure of the Delphi method implemented in this research is presented below.

The first step was to select an expert panel that included individuals with relevant knowledge and experience. A survey questionnaire was prepared on Qualtrics to ask about experts' level of education, years of work experience, current position, level of familiarity with EXOs, and their point of interest in this new technology for implementation in the construction industry. The questionnaire was sent via email to potential experts to determine the relevance of their credentials in fields related to EXOs and their interests in EXO implementation in construction workplaces. Based on the responses received, 18 experts were invited to participate in a workshop where the Delphi method was applied in three rounds. In this process, six categories, namely, business, technology, organization, policy/regulation, ergonomics/safety, and end users (construction trades professionals), were chosen for brainstorming and input. These categories were developed based on their relevance to EXO use in construction in terms of goals, outcomes, processes, and beneficiaries, as well as the review of relevant literature on technology adoption (Daim et al. 2010; Rogers et al. 2014; Stornelli et al. 2021) that form the lens allowing for viewing the barriers and enablers from a holistic perspective.

It was essential to have at least one expert in each category so that all possible perspectives could be discussed, and the ideas could be verified from a practical point of view. The expert panel comprised representatives from academia, industry, and government, as shown in **Table 3.1**.

Table 3.1: Composition of the Expert Panel.

Academia	Industry	Government Agency
Construction × 2	Contractors × 2	NIOSH* × 5
Mechanical × 2	EXO Manufacturers × 2	
Robotics × 1	Risk Consultancy & Insurance × 1	
Occupational Safety & Health × 1		
Psychology × 1		
Economics × 1		

* NIOSH = National Institute for Occupational Safety and Health. Five experts participated from NIOSH representing three different relevant divisions.

Table 3.2 depicts the work experiences of the experts and the percentage of attendees in each group of experts (academia, industry, and government agency).

Table 3.2: Demographic information and percentage composition of the panel.

Years of Work Experience		Composition of the Expert Panel	
0-5 years	2 (11.1%)	Academia	8 (44.4%)
6-10 years	4 (22.2%)	Industry	5 (27.8%)
11-20 years	6 (33.3%)	Government Agency	5 (27.8%)
21-30 years	5 (27.8%)		
>30 years	1 (5.6%)		

The workshop was held in Morgantown, WV, for the duration of one day. At the beginning of the workshop, the experts were presented with the preliminary findings of field experiments (Bennett et al. 2022) conducted by the team to keep them up to date regarding the EXO studies in construction. The experts were also informed about the procedure and expected outcomes of this activity. Then, the Delphi process was initiated, as illustrated in **Figure 3.1**.

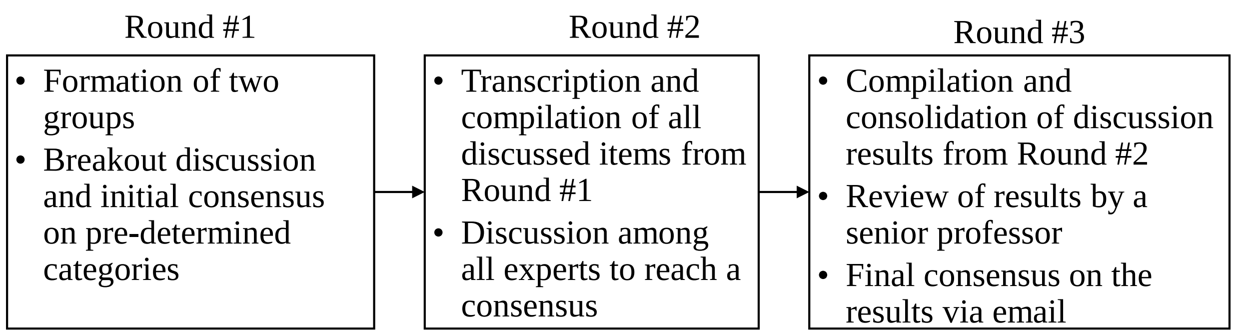

Figure 3.1: Schematic diagram of the three-phase Delphi process.

In the first round, the experts were divided into two groups with an equal number of participants for brainstorming and discussion. Each group discussed the facilitators, barriers, and potential solutions to those barriers according to the six predetermined categories mentioned earlier. The group cohesion was maintained by equally distributing experts from each sector in academia, industry, and government and evenly separating experts of the same work area, if any (e.g., EXO manufacturers). Each expert was provided with a tabulated handout containing spaces for providing written input on the facilitators, barriers, and potential solutions for each category. All the experts in each group shared their written opinions and evaluated others' viewpoints. The "include reasons" method was adopted to minimize the effects of bias, which is a potential concern with the Delphi process (Hallowell and Gambatese 2010). The "include reasons" method required each expert to explain their reason for each issue or item that they raised for discussion. Once done, these discussions from each group were collected and transcribed into a tabular format during recess by four delegated graduate students. In the second round, the experts were presented with the tabulated results from the first round of discussions. Together they were asked for their opinions and explanations, if necessary, to gain a better understanding of the collected discussion responses. During this round, disputed items were removed, and new items were added to the group discussion in the tabulated form, resulting in a table that represented the complete consensus of the group. Additionally, among the identified barriers, those with high priority were also identified by group consensus. In the third round, following the workshop, the outcomes from the workshop were refined and consolidated. The outcomes were then reviewed by a senior professor to enhance the comprehensibility of the items following peer debriefing (Creswell and Creswell 2017) and sent via email to all the experts for a final review and consensus. The finalized outcomes from this three-round Delphi process are discussed in detail in the next section.

Chapter 4. Outcomes of the Delphi Process

The expert panel discussed the facilitators, barriers, and potential solutions in six categories: business, technology, organization, policy/regulation, ergonomics/safety, and end users (construction trades professionals). The following presents the discussion outcomes in detail.

4.1 Business

From a business standpoint, EXOs have to provide perceived job relevance and usefulness that allow for their incorporation into the process of a construction project. The business values that the EXO use can bring about are vital for construction companies to make any adoption decision.

4.1.1 Results

Table 4.1 summarizes the outcomes from the discussion of the expert panel regarding the facilitators, barriers, and potential solutions to solve these barriers in the business category.

Table 4.1: Summary of business category outcomes.

	Business

Facilitators	• Increased efficiency (morale and productivity)
	• Potential economic impacts
	  ○ Create job opportunities for individuals with expertise in EXO use, training & certification
	  ○ Reduce injuries & worker compensation costs
	  ○ Alleviate labor shortages

Barriers	• Cost of EXO ownership

	○ Initial purchase costs and ongoing maintenance costs ○ Owned by worker or by company? • Lack of belief on claimed benefits ○ Not enough objective scientific/case study data to validate EXO manufacturer claims • Return on Investment (ROI) quantification ○ Difficult to determine benefits associated with EXO-enabled work practices ○ How to measure/quantify EXO impact on injury prevention and the corresponding economic impact on businesses • Staffing and implementation ○ Too busy to trial ○ Lack of professionals to train workers on efficient use of EXOs ○ Lack of management of EXO inventory and allocation to workers as well as maintenance of EXOs ○ Lack of experts for implementation (certification, education, healthcare) • Inadequate EXO product options • Unknown impacts on work-pattern shift
Potential Solutions to Solve Barriers	• Work with unions, trade schools, contractors, associations, and apprentice training programs ○ Provide training to workers ○ Increase awareness among construction stakeholders • Provide opportunities to use and conduct trials with EXOs outside the workplaces

	• More general education in high school and higher education • Doctors' recommendations • Work with EXO experts • More scientific data to validate EXO benefits • More real-world case studies

4.1.2 Facilitators

EXOs are designed to limit the risk of injuries and increase workers' productivity. If a worker needs a companion to lift a heavy weight, then by using exosuits, s/he alone may be able to lift the load. Therefore, fewer workers might be required to perform a task and can be utilized for different tasks, significantly increasing workers' productivity. Moreover, wearing EXOs can be assistive in providing psychological support to workers and enable them to work more efficiently, as the worker may intuitively derive aspiration and inspiration from EXO use. Eventually, increased productivity yields higher profits for businesses, thereby driving higher adoption of EXOs in the industry.

EXOs are new technologies in the construction industry. If EXOs are adopted in this industry, then construction firms will hire more professionals to monitor and maintain the products and keep them in good working condition and train workers for effective EXO use. Also, experts will be needed in the industry for the certification of the products. This will create more job opportunities in the construction industry. Since EXOs can reduce the risk of WMSDs among workers, this will lead to a reduction in worker compensation costs for construction companies. Moreover, the construction industry has been facing a shortage of skilled trades workers for a long time. If workers can perform more tasks per time unit with the use of EXOs, the additional production per time unit will be a significant benefit and help businesses mitigate the challenges of worker availability.

4.1.3 Barriers

EXO products can currently range in price from $5,000 to $100,000 and hence are not affordable for workers to purchase for their use. The initial investment for purchasing EXOs can be prohibitive if a company wants to provide EXOs to all its workers. Moreover, there is an additional cost for ongoing maintenance of EXOs to ensure workers' safety. Even if a company were to purchase EXOs for its workers, there is a possibility of reluctance and even rejection by the workers to use this new technology. Therefore, companies are hesitant to invest in EXOs.

In the business category, a prime barrier to EXO adoption is the lack of data providing validated evidence regarding the benefits that EXOs can offer to contractors and businesses. The use of EXOs is currently so limited in construction workplaces that there is a dearth of data to justify EXOs' usefulness and benefits relative to financial and other risks. EXO manufacturers claim various benefits based on EXO uses in other industry sectors, but these may not be valid for the construction industry due to the differences in the nature of tasks and requirements in construction relative to other industries. Hence, this lack of data and low usage of EXOs in the construction industry causes skepticism among construction companies regarding the potential benefits of EXOs.

As EXOs have not been widely used in the construction industry, the potential return on investment (ROI) and even how to estimate ROI are unknown. For this reason, the industry is hesitant to invest in EXOs without having a proven ROI. There needs to be a standard approach for linking benefits to the changes enabled by EXOs, allowing for measurement and quantification of EXO impacts on injury prevention and/or production improvement, and thus the resulting financial benefit to companies.

Currently, there are not enough professionals in the industry with the requisite knowledge and expertise in testing, implementing, and maintaining EXOs. This lack of skilled professionals is a barrier to the adoption of EXOs in the construction industry. As there are no clear assignments for the mandatory use of EXOs in construction companies, staff (contractors, engineers) are reluctant to spend time on trials as they are already swamped with their daily duties. Besides, workers need training in the efficient use of EXO products, but there are not enough experts in the industry to provide the necessary training. Even when skilled training on EXOs is available, construction companies have to be willing to invest money in training their employees. Furthermore, if EXOs are adopted by construction companies, the products need to be adequately maintained to avoid accidents from being worn out and faulty. For proper maintenance, businesses will need staff employed for this duty with proper expertise and skills, which would further add to the cost of adopting EXOs. Finally, as EXOs are new technologies, and even more so in the construction industry, there need to be more experts who can certify the products and provide proper training and healthcare personnel who can verify if the use of the product is appropriate for a particular worker.

Currently, EXO products in the market only have limited options for construction companies. This limited selection of EXOs further hinders the ability of construction companies to conduct trials and evaluate EXOs for adoption in construction workplaces.

Additionally, the impact of the use of EXOs on work pattern shifts is unknown. As workers work in shifts, based on who will use EXOs, for which task, when, and for how long, the work patterns in projects may change. Further, there is no established decision-making process to determine how EXOs will be assigned to workers, by whom and based on which criteria.

4.1.4 Potential Solutions to Barriers

As the lack of knowledge regarding EXOs among construction businesses and trades workers has been identified as a barrier to EXO adoption, one potential solution is for EXO manufacturers to offer training programs in partnership with trade schools, contractors, associations, and apprentice training programs to increase awareness and knowledge about EXOs and their use in industry. Campaigns can be conducted to inform the workers, contractors, and relevant firms about the benefits and risks of using EXOs. As EXOs are designed to help workers with heavy work with ease and reduce the risk of injuries, the adoption of EXOs is expected to benefit construction workers, which is a primary aim of unions. As a result, unions may help promote the use of EXOs by advocating this technology and educating workers during various occasions such as meetings and speeches by opinion leaders.

The more opportunities that workers have for using and practicing with EXOs, the more confident and efficient they can be with EXO use. Hence, it would be beneficial for the workers if they were provided opportunities to use the EXO products outside of workplaces (e.g., home remodeling).

EXOs can be incorporated into high school and college curricula to build awareness among students before they join the workforce as a professional upon graduation. Providing access to EXOs to students will allow them to study, experiment, and assess the technology, which will eventually help reduce the gaps in knowledge about EXO use and improve the EXO products to make them more viable in construction. Moreover, colleges can provide EXO education to working professionals in the construction industry and thereby create more EXO experts and trainers.

The involvement of healthcare professionals (including doctors and physiotherapists) can aid in the propagation of information regarding the benefits of EXOs and thereby help in the adoption of EXOs. They can promote EXOs during various meetings with worker patients and informational campaigns sent to patients. Besides, if the working capacity of a worker is compromised after an injury, then with the help of EXOs, they may gain the ability to return to work, saving them from unemployment. Healthcare professionals can thereby assist this process by recommending EXOs to appropriate patients.

Construction businesses can grow their understanding of EXOs by working with EXO experts. Conducting trials with EXOs within companies can also be facilitated by these experts.

Additional scientific research on the use of EXOs in construction will help collect more data such as benefits, pains, injuries, discomforts, and soreness. The data and findings from such research efforts will not only help support the use of EXOs but also help the EXO manufacturers in improving their products.

It will also be beneficial to conduct more real-world case studies to collect companies' feedback regarding their experiences with EXOs. If companies participate in the case studies, then data collection on the impacts of the use of EXOs will be quicker, more relevant, and more credible.

4.1.5 Mapping Solutions to Barriers

During the workshop, the expert panel identified barriers in the business category as well as potential solutions to those barriers. **Figure 4.1** shows the mapping of the potential solutions to the identified barriers. No obvious solutions were identified for the barrier of the "cost of EXO ownership", calling for further studies to explore solutions to this issue.

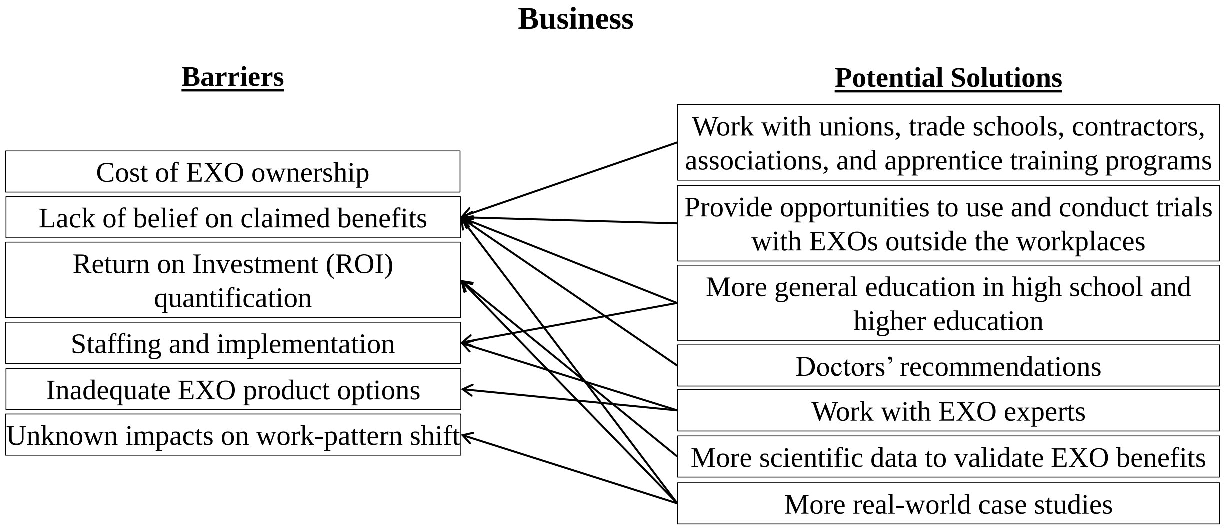

Figure 4.1: Mapping of potential solutions to identified barriers in the business category.

4.2 Technology

From a technological standpoint, the level of readiness and functional or operational maturity of the current EXO products play an important role in the decision-making process for adoption in the construction industry.

4.2.1 Results

Table 4.2 depicts the compiled outcomes from the discussion of the expert panel regarding the facilitators, barriers, and potential solutions to solve these barriers in the technology category.

Table 4.2: Summary of technology category outcomes.

	Technology
Facilitators	• Technology investment sector • Real-time feedback technologies

Barriers	• Cost for research and development (R&D)
	  ○ Risk of investment
	• Imposed constraints on work performance
	  ○ Bulky size
	  ○ Donning & doffing
	  ○ Motion constraints
	• Customization
	  ○ Compatibility and interaction with existing personal protective equipment (PPE) (e.g., safety harness)
	  ○ Mostly task specific
	  ○ Active vs. passive EXOs
	• Lack of standard metrics
	  ○ Testing procedure differences
	• Privacy concerns

Potential Solutions to Solve Barriers	• Iterative development of products
	  ○ Improved time of adjustment
	  ○ Ease of immediate use
	  ○ Lighter devices
	• Integration with PPE (e.g., safety harness) and other tools
	• Near real-time feedback of use impact
	• Task-oriented EXOs vs. function-oriented EXOs vs. anatomy-oriented EXOs
	• Niche or generalization
	• Privacy regulations

4.2.2 Facilitators

Venture capital and private equity firms in the technology investment sector can help drive accelerated development of EXO technology and its adoption in various industries, including the construction sector.

State-of-the-art real-time feedback technologies such as iWatch and other sensors can be facilitators for the technological advancements of EXOs. While the workers are wearing EXOs during work, these technologies can provide physiological measurements of the impact of EXOs on the workers' bodies and signal warnings if potential risks (e.g., high stress) are identified. Such real-time feedback technologies, in turn, may help workers feel more confident about using EXOs in construction workplaces.

4.2.3 Barriers

As EXOs are new in the construction industry, research is needed on the performance of EXOs in construction applications. For construction companies, making investments in EXO research and development can be perceived as risky from an ROI perspective. Similarly, EXO manufacturers face the cost challenges of R&D as well, given the uncertainty of sustainable financial gains from the investment in technological development for the construction industry.

EXOs can impose a variety of constraints on work performance in construction jobsites, and these can hinder the adoption of this technology. Bulky size and limited movement may cause additional risks for accidents. The additional time needed for donning and doffing may reduce the amount of time during a work shift when a worker can be productive. To mitigate this negative impact on project productivity, construction workers who use EXOs will need to wear them for a relatively long duration, possibly the entire shift. Hence, it is essential for the EXOs to be lightweight, comfortable, easy for donning and doffing, and flexible enough not to constrain the worker's movement, which is not the case at present for commercially available EXOs.

Construction workers must wear personal protective equipment (PPE) at construction sites whenever necessary. For example, a safety harness is required for working at an elevated height. If workers wear EXOs together with PPE, then compatibility with each other could be a concern. The EXOs must be used in a way without compromising the functional use of PPE that protects the safety and health of workers. In elevated settings, EXOs need to be incorporated with safety gears gracefully so that the gears do not restrict workers' movement and cause imbalance. Otherwise, EXOs could be a source of additional injury risk for workers wearing PPE. Furthermore, most of the EXOs are task-oriented, which requires additional time to switch from one task to another. Finally, active EXOs tend to be heavy and bulky and harder to carry, making it challenging to integrate with PPE.

Currently, there are no standard performance metrics to assess EXOs in terms of improved safety, increased productivity, reduced cost, and others. Likewise, testing procedures are also different for different types of EXOs and are dependent on the testing location and setup. This lack of standardization of performance metrics makes it difficult to assess and compare the performance of EXOs and, consequently, justify investment in this technology.

EXO products may have a built-in tracking unit that tracks the equipment's position, and trajectory, as well as the user's physiological responses and other private data. These data help monitor the worker's condition and oversee the project activity but can contain confidential information about the worker. Therefore, there is a privacy concern for the workers regarding how these data would be used, shared, and protected.

4.2.4 Potential Solutions to Barriers

Incremental improvements in EXO design and functionality that address current challenges and limitations of the technology (such as weight and motion constraints) can help grow EXO adoption in the construction industry. Such progressive upgrades can help improve the time of adjustment for using the products while switching from one task to another and ease up on immediate use. Making ongoing incremental improvements to the EXOs will require smaller amounts of investment capital, thereby reducing investment risks.

PPE, such as safety harnesses, is an integral part of a construction worker's outfit. Therefore, it is essential for EXOs to perform seamlessly with PPE and other tools used by workers for their jobs. More investigations and assessments are needed to integrate PPE and tools with the use of EXOs in elevated settings.

Data regarding the impact of EXO use by workers, if collected in near real-time with the help of wearable sensors, can provide essential feedback for improving the products and warn the user regarding any safety issue associated with the use of EXOs. Additionally, such data will offer evidence to illustrate the benefits of EXO usage, leading to a greater understanding and adoption of EXOs in the industry.

Task-oriented EXOs are designed to perform a specific task. For instance, power gloves are targeted for gripping tasks, and tool-handling EXOs are used for holding heavy tools such as drilling equipment (POMERLEAU 2022). While these types of EXOs are less complex and efficient for performing a single task, switching between tasks takes time. Function-oriented EXOs are based on their functionality, such as preventing accidents, reducing fatigue, and increasing capability. Anatomy-oriented EXOs are classified based on which part of the body is supported by the EXO, such as upper or lower extremity EXOs. Among all these types of EXOs, it is essential to identify which type of EXOs are most suitable for the construction jobsite depending on their effectiveness, efficiency, and comfort. For instance, if a worker is tasked with a drilling job, then task-oriented (tool handling) EXOs are most suitable, whereas if the worker has to stand for an extended duration to perform their job, s/he needs support to lower extremities, and a hybrid or full-body EXO would seem more appropriate in this case.

Currently, there is no clear research-based evidence regarding which types of EXOs are most effective for use at construction sites. Task-oriented EXOs are suitable for specific tasks but limit the worker to a specific task, thus consuming more time for donning and doffing of EXOs during the work shift. A full-body EXO may be more suitable for performing several tasks, but it can present additional movement constraints. Therefore, more investigations are required to assess the advantages and disadvantages of developing task-specific EXOs versus generalized EXOs for performing common tasks in construction workplaces.

Additionally, to protect the privacy of workers, regulations are needed regarding the collection and use of personally identifiable data collected from EXOs during their use by workers in construction workplaces.

4.2.5 Mapping Solutions to Barriers

The panel of experts discussed potential solutions for all the barriers in the technology category identified above. **Figure 4.2** shows the mapping of barriers to potential solutions.

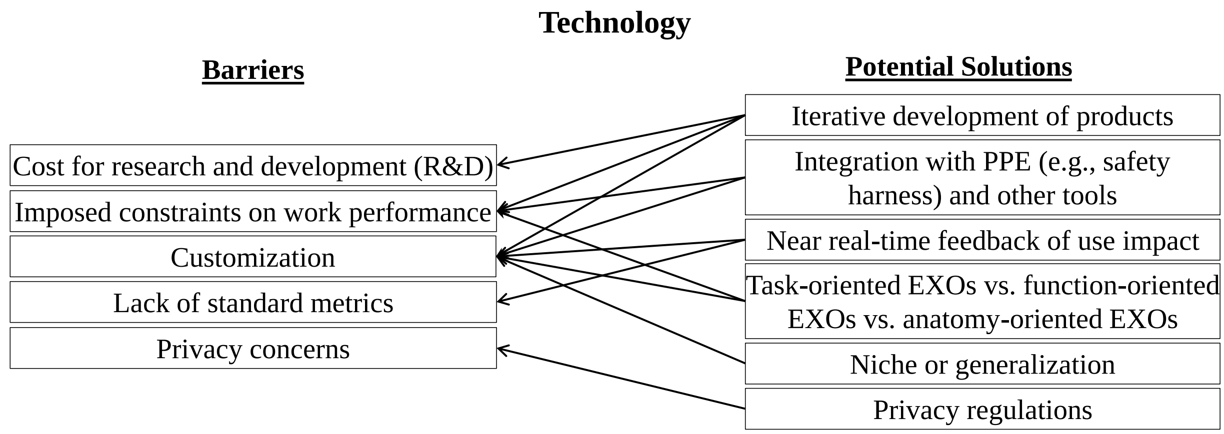

Figure 4.2: Mapping of potential solutions to identified barriers in the technology category.

4.3 Organization

At the organizational level, the adoption decision of any technology is typically affected by factors such as technical-organizational match, organizational structure accommodation, management burden, and organizational culture. Therefore, perspectives from the organizational standpoint are important to exploring the adoption potential of EXOs in the construction industry.

4.3.1 Results

Table 4.3 depicts the compiled outcomes from the discussion of the expert panel regarding the facilitators, barriers, and potential solutions to solve these barriers in the organization category.

Table 4.3: Summary of organization category outcomes.

	Organization
Facilitators	• Unions • Insurance industry
Barriers	• Organizational readiness ○ Financial decisions

	○ Use of technology ○ More administrative work ○ Additional training arrangements ○ Liabilities • Lack of standards • Corporate culture • Dominant small businesses
Potential Solutions to Solve Barriers	• Proven studies and real-world data from jobsites • Pilot studies on implementation • Established procedure on liability management • Ongoing education and awareness building

4.3.2 Facilitators

Unions can play an influential role in driving the adoption of EXOs in the industry. Unions can promote the use of EXOs in their campaigns, meetings, and interactions with the industry trades and thereby create greater awareness and appreciation for the potential benefits of using EXOs.

EXOs have the potential to reduce the risk of injuries among construction workers. If the number of injuries is reduced, insurance companies incur lower costs for workers' compensation, thereby increasing profits for their businesses. Therefore, insurance companies can also be motivated to promote the adoption of EXOs by promoting these products to relevant business clients. Additionally, insurance companies can offer incentives such as a reduction of insurance premiums for construction companies that adopt EXOs at their jobsites.

4.3.3 Barriers

At the organizational level, construction companies are required to make financial decisions for making investments in EXOs based on factors such as benefits, costs, safety concerns, and staffing requirements at construction jobsites. There are also decisions involved to determine the best uses of EXOs for construction tasks that could lead to more administrative work for the organization. Moreover, if companies decide to use EXOs at their jobsites, they need to ensure that effective training programs are available to train workers on the proper use of EXOs. Additionally, construction companies could face increased liability from improper use of EXOs by workers, and this risk can discourage construction companies from adopting EXOs.

Construction companies follow standards and best practices for using materials, tools, and equipment to achieve efficiency and quality of work at jobsites. When new technologies are introduced in a workplace, standards and best practices for the use of the technologies are needed to ensure that the project performance is maintained or improved. Unfortunately, such standards and best practices for EXO use in the construction industry are yet to be established and thereby reducing organizational decision-makers' confidence towards EXO adoption.

Corporate culture plays an important role in the successful adoption of new technologies. Many organizations become tied to performing their operations in an established way and are reluctant to change. The adoption of new technologies will result in a series of changes in areas such as work practices, policies, staffing, organizational structure, administration and employee responsibilities. When a company's culture is resistant to change, it can be exceedingly challenging to influence their beliefs, opinions, and attitudes toward EXO use.

According to the Center for Construction Research and Training (CPWR), about 91% of U.S. construction businesses have fewer than 20 employees. For these small businesses with low annual revenues, the adoption of EXOs with high initial costs would be difficult.

4.3.4 Potential Solutions to Barriers

Currently, EXOs are not commonly used in construction sites, and hence there is inadequate real-world data on EXO use in construction. Extant assessments of the impacts of EXOs are primarily based on experiments conducted in a laboratory setting. To promote adoption of EXOs in the construction industry, there is a need for more research studies performed at construction jobsites to gather data regarding the usability and performance of EXOs.

Systematic scientific studies can be supplemented by the pilot implementation of EXOs to examine their feasibility in the construction industry. Evidence-based findings from such studies will reduce the knowledge gap regarding the applicability and benefits of EXO use in the construction industry and encourage companies to consider the adoption of EXOs.

If an accident occurs while using EXOs in construction workplaces, a standard procedure is necessary to analyze the event and determine the root causes for the accident as well as the responsible parties, including the worker, the construction company, the EXO manufacturer, and the insurance company. Having an established process for addressing EXO-related accidents and injuries will help ensure that appropriate interventions are taken and that the impacted workers are adequately compensated.

Increased awareness and education in the construction industry regarding the benefits, potentials, and proper use of EXOs can be impactful in driving the adoption of EXOs. Such education can be done at industry events where EXO producers can demonstrate the products firsthand. Also, reaching out to community leaders who may influence big corporations can help in this adoption process.

4.3.5 Mapping Solutions to Barriers

Experts identified probable solutions to all the identified barriers in the organization category as indicated in **Figure 4.3**.

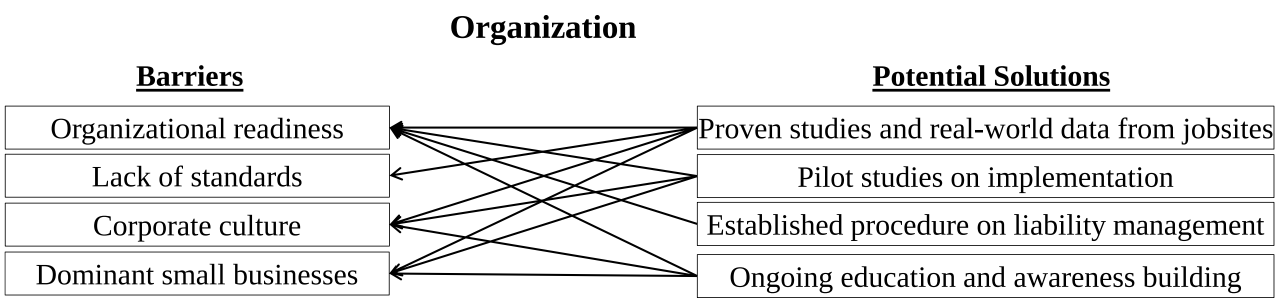

Figure 4.3: Mapping of potential solutions to identified barriers in the organization category.

4.4 Policy/Regulation

While new technologies hold the promises for improved performance of the production, it is necessary to ensure their implementation is responsible and support for a prosperous industry. Policy attention is focused on the adverse effects of technological adoption, which is also necessary for decision making of adopting EXOs in the construction industry.

4.4.1 Results

Table 4.4 presents the compiled outcomes from the discussion of the expert panel regarding the facilitators, barriers, and potential solutions to solve these barriers of the policy/regulation category.

Table 4.4: Summary of policy/regulation category outcomes.

	Policy/Regulation

Facilitators	• Third-party promotion • SBIR and STTR programs
Barriers	• No policies/regulations, standards (e.g., ASTM F48), or union rules • Difficulty and slowness in development of regulations at the state/national level • Policy differences (e.g., US vs. Europe) • Lack of authoritative references to incorporate EXOs with PPE in elevated conditions • Unclarity about whether EXOs are PPE? If so, there will be a need for regulation
Potential Solutions to Solve Barriers	• Scientific data to drive regulation and policy development • Work with unions and organizations (e.g., CAWP) • Education • Dissemination through word of mouth • Form industry standard practices • ANSI A10-standardization • Regulation for use in elevated conditions

*SBIR: Small Business Innovation Research; STTR: Small Business Technology Transfer; ASTM: American Society for Testing and Materials; CAWP: Constructors Association of Western PA; ANSI: American National Standards Institute; PPE: Personal Protective Equipment.

4.4.2 Facilitators

Third-party organizations such as unions, industry associations, and public agencies can help initiate discussions on policies, standards, and regulation development for EXOs, which is vital to the adoption and implementation of EXOs in construction workplaces.

The US government's Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) funding programs encourage domestic small businesses to engage in Federal Research/Research and Development (R/R&D) with the potential for commercialization. The goal of these programs is to encourage technological innovation to meet the nation's research and development needs and can help drive EXO use by small businesses.

4.4.3 Barriers

There are currently no established standards for EXOs, though some initiatives are underway, such as ASTM F48 on Exoskeletons and Exosuits (Lowe et al. 2019), to provide guidelines for testing or assessing the performance and use of EXOs. EXOs are equipment that are susceptible to wear and tear from use. If an EXO breaks or malfunctions while performing a task, it can result in severe injuries and even fatalities. Therefore, regular inspections are essential to ensure that the EXOs work properly. Any minor issue needs to be fixed immediately so that these incidents can be avoided while workers use the equipment at the jobsite. Regulations or policies are needed to govern or guide the maintenance of EXOs in a timely manner to ensure worker safety. Currently, such regulations or policies have not been established. Unions strive to ensure worker safety and new or updated union rules may be needed to help the trades implement this new technology at construction workplaces.

Relevant regulations made at the state/government level would accelerate EXO adoption. Nevertheless, the development of such regulations is difficult and painstakingly slow.

Differences in EXO-related policies across countries and regions would be a hurdle. Such differences may lead to confusion in understanding the procedures and protocols of EXO use and pose challenges to EXO manufacturers and vendors to standardize their products.

Workers who use PPE while working in elevated conditions can face challenges with using EXOs. As a result, if workers need to use EXOs in an elevated condition in construction workplaces, it would be desirable to incorporate the PPE with such EXOs.

This also raises the question of whether EXOs should be considered PPE. The general duty clause states that all workers have a right to a safe and healthy workplace. Accordingly, PPE has specific regulations that all workers must follow on-site. If EXOs are considered PPE, then EXOs need to be regulated.

4.4.4 Potential Solutions to Barriers

The availability of more scientific data will provide stronger evidence regarding EXOs' benefits and risks. The data will assist in identifying opportunities for improvement of EXOs and provide the bases for regulation and policy development, which thereby will drive the adoption of the technology in the construction industry.

Unions work relentlessly to protect the rights of workers. They can play a significant role in policy formulation by voicing demands for regulation of EXOs to the authorities to ensure workers' safety in construction workplaces. Other organizations, such as the Constructors Association of Western Pennsylvania (CAWP), can also play a vital role in this regard as they interact with Occupational Safety and Health Administration (OSHA) and can significantly influence policymaking.

To support EXO use by construction workers, training and education are essential for all associated roles, such as general contractors, project managers, superintendents, and trades workers. Training should include not only the proper use of EXOs but also all the policies and regulations (if any) regarding the safe use of EXOs and prevent any violation of regulations.

If there are businesses implementing EXOs in their workplaces, dissemination of such endeavors may encourage other businesses to consider the use of EXOs. If their experience is satisfactory, these businesses can expand their use of EXOs and thereby encourage more businesses to adopt EXOs. As such, a positive perception regarding EXOs will grow within the industry, which will foster the formulation of relevant regulations and policies for EXO implementation.

The development of industry standards and best practices for EXOs by industrial associations as well as relevant agencies will encourage the adoption of EXOs.

The ANSI A10 is a series of American national standards published by the American Society of Safety Professionals (ASSP) that covers the safety requirements for activities related to construction and demolition operations. It provides safety regulations for every activity, from erecting scaffolding to handling explosives to pouring concrete. ANSI A10 drives OSHA regulations for construction. Therefore, it is plausible to develop a series of national standards for activities concerning the use of EXOs in the construction industry that ensure the safety of construction workers while using EXOs on jobsite.

There are strict regulations regarding work performed at elevated conditions by construction workers, such as wearing personal fall arrest systems. Regulations for the use of EXOs at elevated conditions will aid their adoption.

4.4.5 Mapping Solutions to Barriers

Figure 4.4 shows the mapping of potential solutions to the barriers identified in the policy/regulation category by the expert panel. The barrier "Policy differences (e.g., USA vs. Europe)" requires further investigation as no feasible solution was immediately evident from the workshop discussion.

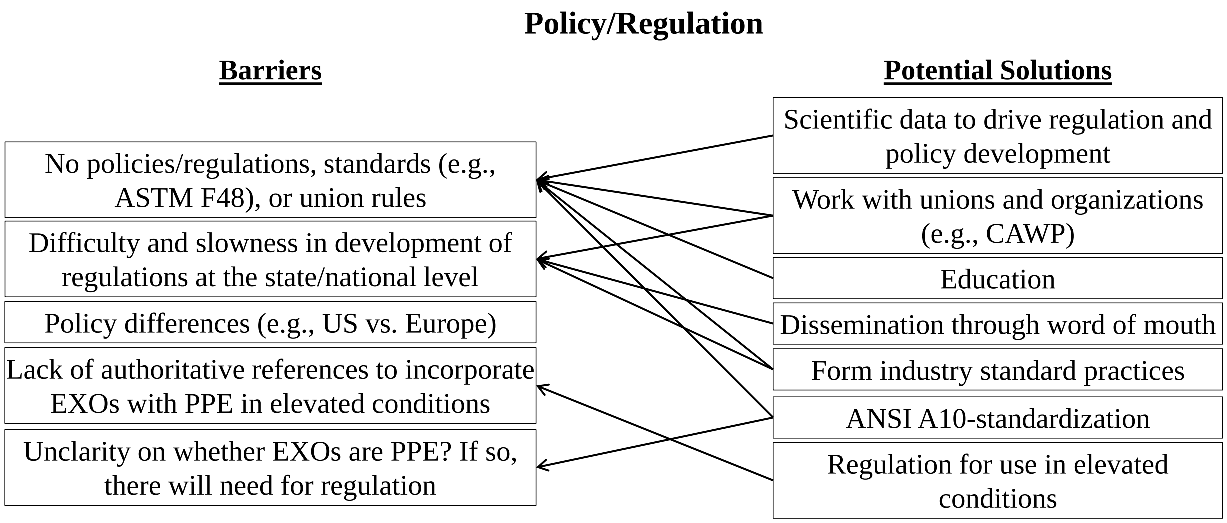

Figure 4.4: Mapping of potential solutions to identified barriers in the policy/regulation category.

4.5 Ergonomics/Safety

EXOs are wearable technologies that have direct contact with the human body. The protection provided, as well as potential ergonomic injury risks and safety hazards induced by the use of the EXOs during work, will be a decisive factor in the adoption of the EXO technology in the workplaces of the construction industry.

4.5.1 Results

The outcomes from the expert panel’s discussion regarding facilitators, barriers, and potential solutions to solve these barriers in the ergonomics/safety category are compiled in **Table 4.5**.

Table 4.5: Summary of ergonomics/safety category outcomes.

	Ergonomics/Safety
Facilitators	• Prevention of musculoskeletal disorders (MSDs)
Barriers	• Safety risk of EXOs ○ Device failure ○ Misconception about the augmented capability ○ Residual injury risks ○ Muscle atrophy ○ Pre-existing conditions/injuries • Additional safety hazards ○ Loss of balance ○ Different weather conditions ○ Different work conditions • Comfort ○ Movement restraints ○ Device weight ○ Over-exertion like back belts ○ Pain, soreness, and discomfort • Objective measurement with respect to benefits and risks ○ No reliable methods or literature ○ Still many unknowns in real-life use
Potential Solutions to	• Use only for intended tasks • Provide strong evidence

Solve Barriers	• Develop inspection protocols • Establish best practices to avoid atrophy and ensure safety • Examples to show impacts, even if negative • Regulations for safe EXO use

4.5.2 Facilitators

A significant number of workers in the construction industry suffer from musculoskeletal disorders (MSDs) (Wang et al. 2015). Construction companies also incur immense losses due to days away from work and compensation payments to the impacted workers. EXOs have the potential to reduce the risk of MSDs among workers by providing additional means of protection while the workers are performing physically demanding tasks. Such benefits can encourage both workers and employers to adopt EXOs in construction workplaces.

4.5.3 Barriers

Several safety concerns exist involving the use of EXOs. First, there are no safety inspection protocols that exist for EXOs to ensure the safety of using the devices. If a device fails while performing the task, it might lead to severe safety consequences. For example, suppose a worker is carrying a load that exceeds his physical capacity, and the EXO fails while holding the load overhead or over the shoulder. In that case, the total load can fall and cause severe injuries to the worker. Second, active EXOs are powered by external sources that give a worker strength significantly higher than his own physical strength. When a worker is constantly performing heavy-duty work while wearing EXOs, s/he might develop a misconception regarding his/her capability. This misconception about personal augmented capability might lead to the worker intuitively performing heavy work when not wearing EXOs, which can result in injuries. Third, passive EXOs use other body muscles to counterbalance forces by redistribution of loads. This may cause residual injuries to other body parts. Fourth, due to continuous support from EXOs, the supported parts of the body might get weaker leading to muscle atrophy. Finally, workers may have pre-existing conditions that may deteriorate due to the use of EXOs. There are currently no methods to definitively ascertain that EXOs would not negatively affect the workers under these conditions.

There are several additional safety hazards associated with EXOs. For example, active EXOs are typically heavy and not very flexible for movement. Therefore, while working in an elevated condition, the worker might lose balance and fall, causing severe injuries. Also, different weather conditions like rain or snow can be the reason for accidents due to slipping, as the movement with EXOs can be unnatural. Many active EXOs are powered by an electric source and are required to be connected to the source with wires. There is a possibility of electrocution of the worker while connected to the source, and the wires may get tangled with the worker and result in an accident.

EXOs need to be comfortable to wear for the workers as they may spend a long-time during shifts in these suits. If the EXOs are not comfortable, there might be a risk of introducing MSDs, and this would defy the whole purpose of using EXOs in the first place. Moreover, suits need to be tailor-fit for each worker so that the mechanism can work perfectly. Otherwise, it might exert pressure on unintended body parts, thereby increasing the risk of MSDs. Heavy and bulky EXOs, together with PPE in construction sites, are harder to carry and create constraints for movement for a worker. If the worker wears the EXOs, like back belts, for many hours, it might cause over-exertion of the muscles involved. Furthermore, wearing EXOs for long durations can cause pain, soreness, and discomfort for workers.

For EXOs to be adopted in the construction industry, objective measurements related to ergonomics and safety in terms of benefits and risks are necessary. However, reliable methods or research literature for performing such measurements are currently unavailable. EXOs are new to the construction industry, and studies with EXOs have primarily been done in laboratory settings; hence, there are still many unknowns regarding the use of this technology in real-world construction tasks. These knowledge gaps also hinder the development of confidence in the industry regarding the use of EXOs.

4.5.4 Potential Solutions to Barriers

Most of the EXOs in use are task-oriented. So, ensuring the proper selection of EXO products for the right task is important. If an EXO is used to perform tasks for which it was not designed, it might exert undesired pressure on body parts, increasing further risks of MSDs.

If real-life case studies of EXO use can be conducted with construction workers at actual jobsites, then the performance data generated from these studies will provide research-based evidence to encourage the adoption of EXOs. These data can also facilitate further improvement of the EXOs to better satisfy the actual task and workplace requirements and constraints.

Inspection protocols are essential to ensure the safety of EXO devices and to prevent any accidents while performing tasks with EXOs. A specific inspection and maintenance schedule might be desirable to identify wear and tear and malfunction in a timely manner and perform necessary repair and replacement activities so as to ensure EXO safety. Policies or regulations might be needed to enforce implementation of the protocols so that all organizations will be obliged to follow them.

Muscle atrophy caused by continual use of EXOs can be minimized by establishing best practices on the safe use of EXOs. Training programs on such best practices for those who wear EXOs in construction workplaces can be beneficial to reduce muscle atrophy.

Implementation of EXOs in construction jobsites has great potential to reduce MSDs and increase productivity. More examples as evidence and encouragement are needed for prospective users to adopt EXOs, even if the results are not always positive. The negative results (if any) can also be valuable in helping the EXO manufacturers improve their products, ensuring that future products are safer for use in construction workplaces.

Regulations are required to ensure safety while using EXOs. Safety guidelines are essential, and the supervisors must ensure that the guidelines are accordingly followed by workers so that the risks of MSDs or injuries from improper use of EXOs are minimized.

4.5.5 Mapping Solutions to Barriers

Figure 4.5 portrays the mapping of potential solutions to the barriers identified in the ergonomics/ safety category by the expert panel during the workshop.

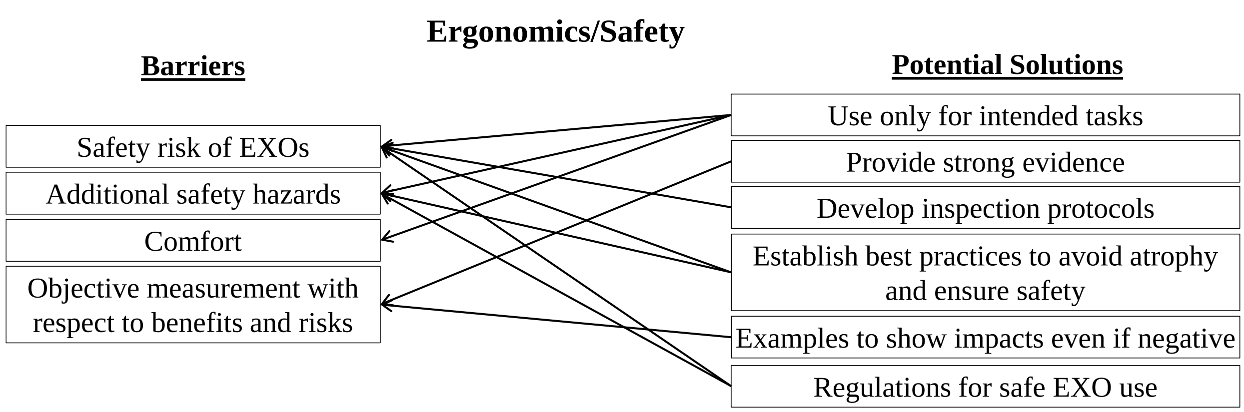

Figure 4.5: Mapping of potential solutions to identified barriers in the ergonomics/safety category.

4.6 End Users (Trades Professionals)

The success of any technology adoption hinges on end users' (trades professionals in this case) acceptance and confidence to implement a new behavior for such adoption. Understanding the trades professionals' readiness components, such as skills learning requirements, physical and psychological safety, and perceivable value, is critical to the adoption of EXO use in construction workplaces.

4.6.1 Results

The outcomes regarding the facilitators, barriers, and potential solutions to these barriers in the end users (trades professionals) category resulting from the expert panel discussion are compiled in **Table 4.6**.

Table 4.6: Summary of end users (trades professionals) category outcomes.

	End Users (Trades Professionals)
Facilitators	• Retention of aged workers • Self-efficacy of workers • Increased ease of use • Reduced costs • Positive product perception • Tangible results (physical and productivity-related) • Training • Support from EXO manufacturers
Barriers	• Difficult to use o Steep learning curve

	• Reluctance to use
	• Workers' concerns about being tracked
	• Workers' satisfaction
	  ○ Workers not consulted
	  ○ Perception about tangible benefits (e.g., percentage reduction in injuries)
	• Impacts on employment
	  ○ Does this impact employment number?
	  ○ Do workers have the right to refuse?
	  ○ Does this impact workers' ability to maintain employment based on health/ability to use?
	• Concerns regarding injuries due to EXOs
	  ○ Will equipment failure result in injuries?
	• Stigma
	• Incompatibility with certain working environments

Potential Solutions to Solve Barriers	• Simple enough to try • Research, education, and training • Leadership and campaigns • Increase worker satisfaction • Make the EXOs invisible or visually appealing • Perceivable and measurable benefits

4.6.2 Facilitators

Construction workers are required to perform physically demanding work that is impractical for aged workers and, consequently, are often forced to leave this industry. EXOs offer the potential to help aged workers to perform heavy-duty work by providing additional support and protection to relevant body parts and thereby enabling this population to keep their employment for an extended period of time. The benefits of retaining aged workers through the use of EXOs may be an impetus for the adoption of EXOs in the construction industry.

Building self-efficacy of the workers with the use of EXOs may facilitate their adoption. Self-efficacy refers to an individual's belief in their capacity to act in the ways necessary to reach specific goals. If workers have hands-on experience with EXOs, they can develop a greater appreciation for the benefits of EXOs, such as augmented capacity, reduced pressure on vulnerable body parts, as well as reduced exhaustion or fatigue over time. Such self-efficacy can motivate workers to adopt EXOs and increase productivity while reducing the risk of MSDs.

Enhancing the ease of use of EXOs would facilitate their adoption. Workers often have concerns regarding complex products and hence are unwilling to try them, which eventually impedes the adoption process. If EXOs can be made easy to use for workers, it would be more likely that they would be willing to try EXOs in construction jobsites and drive adoption.

Reduced cost is an important factor for the adoption of the EXO products. Affordable EXOs will make it possible for independent workers and small contractors to procure the products and use them for their businesses. General contractors and large corporates would also benefit from lower-priced EXOs for large-scale deployment of EXOs in the industry.

It would be beneficial if the worker population has a positive perception of EXOs so that they can encourage union leaders, industry associations and employers to EXO adoption.

Tangible results in terms of physical benefits and productivity would be strong evidence to encourage workers to try EXOs. If such tangible results can be presented to workers showing that they can benefit from the use of EXOs in terms of improved safety, enhanced capabilities, or increased productivity, the workers are likely to get motivated about adopting EXOs at jobsites.

Training can provide workers firsthand experience with the proper use of EXOs, which would allow them to formulate personal opinions based on their own experience and might encourage them to adopt EXOs.

Manufacturers can play a significant role in the adoption process of EXOs in the construction industry through activities such as demonstrations at exhibitions, providing training in apprentice programs and trade schools, publication of short manuals tailored to this industry, and provision of technical support to contractors, all of which would increase the opportunities for worker-EXO interactions within the industry and thereby facilitate their adoption. Manufacturers can also help in developing case studies by collaborating with the construction industry and the academic research community, which in turn will increase their products' visibility and encourage adoption.

4.6.3 Barriers

From the perspective of end users (workers), EXOs currently are considered as being difficult to use and becoming proficient with EXOs involves a steep learning curve. This barrier can discourage trades professionals from attempting the use of these products and therefore hinder EXO adoption in the construction industry.

During the course of their work experience, workers would have cultivated their preferred methods and habits for doing routine daily jobs and hence would be reluctant and resistant to change and try out new technologies.

EXOs can be equipped with sensors for collecting real-time or asynchronous data for performance monitoring and safety inspection. However, this can raise a concern among the end users (i.e., the workers) that they will be tracked and lose their privacy. Such concerns can pose barriers to the use and adoption of EXOs by the end users.

Workers' satisfaction plays a vital role in the adoption of EXOs as they are the end users of the products. Nevertheless, in practice, workers are often not fully consulted in the process of adoption and implementation. For this reason, workers may not be well informed and thereby have misperceptions regarding the effects, functions, benefits, and potential risks of using EXOs. As such, the workers may become less enthusiastic about using EXOs. The workers need to develop a personal appreciation for the benefits of using EXOS in order to facilitate their adoption in the workplace.

EXOs are designed to make workers more efficient and productive. However, this raises the concern that the increased productivity with EXOs could translate into a lower need for labor. Workers may thereby perceive the adoption of EXOs in the industry as increasing the risk of their unemployment. Also, there is a concern about workers' rights, i.e., whether workers have the right to refuse using EXOs if they do not want to. Additionally, some workers may have chronic health issues that prevent them from wearing EXOs. If a company requires its workers to use EXOs, then those who are unwilling or unable to wear EXOs can become concerned about their employment.

Being construction devices or equipment, EXOs are subject to wear and tear, deterioration, and unexpected breakdown. As the workers will rely on functional support from EXOs while they wear them at work, unexpected malfunction of EXOs during usage would potentially cause harm. As a result, workers can be concerned about the injuries that may result from EXO failure while in use.

Workers may disapprove of new technologies due to the potential stigma associated with the use of EXOs. Workers may fear that construction automation may make them redundant and result in unemployment.

Active EXOs are usually bulky in size and require a power source that sometimes requires an electrical connection. This requirement can cause incidents such as entanglement with connecting wires, if any. Furthermore, for certain types of EXOs, working near electromagnetic fields can be risky.

4.6.4 Potential Solutions to Barriers

Providing hands-on experience with easy to use EXOs (including easy donning, doffing, adjusting and operation) will promote their adoption among workers. Such experiences will help workers build their own unbiased perception of the usability and comfort of the devices that would facilitate the acceptance and adoption of EXOs among the worker population.

As many unknowns exist regarding the use of EXOs in construction settings, continued research is essential for the growing adoption of this technology in the construction industry. Education and training in different ways at various stages are also necessary to grow awareness and use of the technology among current workers and future workers. Higher awareness regarding the benefits of EXOs may also trigger the workers' interest in seeking education and training.

Proper training would allow for more interactions of the workers with EXOs and provide them with the needed skills for the use of EXOs, both of which would be positive for the adoption of EXOs in the construction industry.

Leadership from both employers and unions can play an important role in the adoption process of EXOs through influence on and sharing value with their employees, members, and followers, among whom many are workers. Workers would be further informed about the potential benefits of EXOs through campaigns, where they can get more information, opinions, experience, and, therefore, ideas about possible EXO use in construction.

As the end users, workers' satisfaction is a key factor for acceptance of any new technology in their workplaces. Worker feedback needs to be sought and incorporated while designing EXOs intended for construction use. Bidirectional communications would benefit both the workers (end users) and the EXO manufacturers. Growing satisfaction with EXOs among workers will drive the adoption of this technology in construction.

The visual appearance and appeal of new technologies can also affect their adoption by users. Construction workers wear different safety gear for performing their tasks. If EXOs can be designed in a way that their appearance seems "invisible" (i.e., not noticeable) or appealing (e.g., fashionable like superhero outfits), they might be attractive for workers, especially future young workers, and encourage adoption at jobsites.

Identifying ways to generate, collect, and disseminate perceivable and measurable benefits of EXOs for workers to comprehend and is vital to the adoption process. This may be achieved through case studies and examples of applications and dissemination of the benefits through campaigns, visual presentations, training programs, workshops, and word of mouth.

4.6.5 Mapping Solutions to Barriers

Figure 4.6 shows the mapping of potential solutions to the barriers identified in the end users (trades professionals) category discussed by the expert panel. The barrier "Impacts on employment" requires further investigation before potential solutions can be proposed.

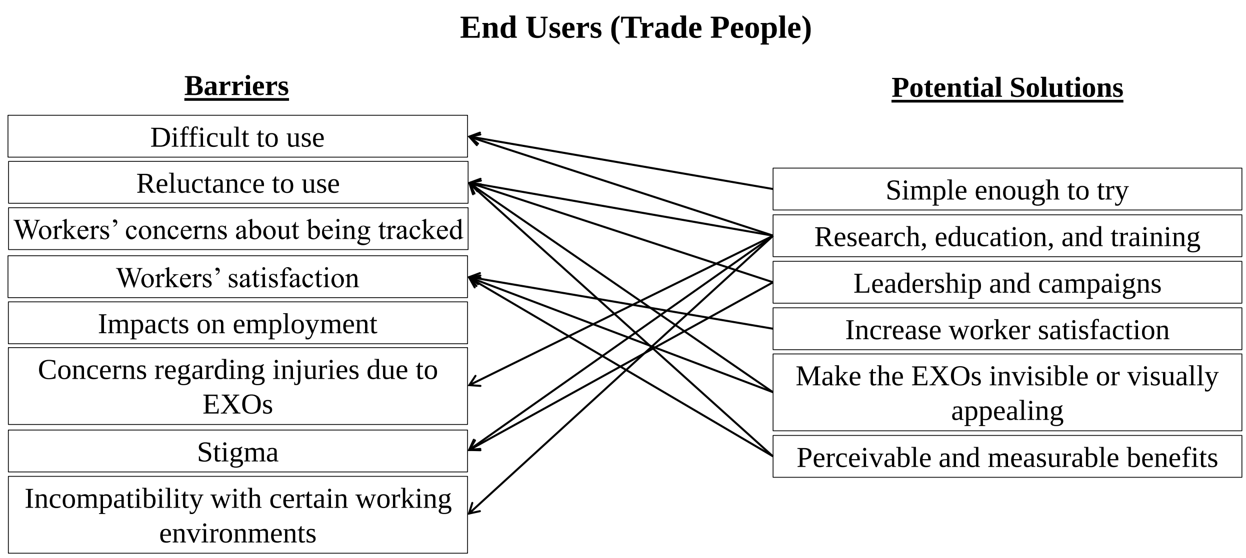

Figure 4.6: Mapping of potential solutions to identified barriers in the end users (trades professionals) category.

4.7 Top barriers to EXO adoption

The expert panel reached a consensus on the top barriers to EXO adoption, which are listed in **Table 4.7**: with their associated categories. These barriers and their potential solutions are discussed in the prior subsections. The panel particularly emphasized the importance of education, including educating contractors, workers, engineers, and even future generations of engineers and workers. Human-centric design and development of EXOs is another factor prioritized by the panel as being critical for industry adoption of the technology.

Table 4.7: Top barriers identified by the expert panel with associated categories.

Top Barriers	**Associated Categories**

Lack of education	Business, Organization, Policy/regulation, End Users (Trade People)
Lack of worker engagement from the beginning (e.g., trade school)	End Users (Trade People)
Lack of trust in the devices	Business
Lack of subjective user experience (short-term vs. long-term)	Business, Organization, Ergonomics/Safety, End Users (Trade People)
Lack of comprehensive evaluations (worker responses, short-term vs. long-term, long way to validation)	Business, Organization, Ergonomics/ Safety, End Users (Trade People)
Limited applications	Business, Technology, Ergonomics/ Safety, End Users (Trade People)
Lack of easy access to EXOs (including quick trials, onsite demonstrations, and resources for troubleshooting)	Business, End Users (Trade People)
Few devices designed for construction work (need to wear multiple devices at the same time, as they are not integrated with PPE)	Business, Technology, Policy/Regulation

Chapter 5. Discussion

EXOs are a new technology for the construction industry with the potential to improve the industry by reducing WMSDs and improving productivity. Several research works have highlighted the potential benefits of using EXOs in construction workplaces, but the adoption of EXOs in the industry has been very limited. This study attempted to identify the reasons underlying the limited implementation of EXOs in construction by gaining input and consensus through a Delphi process from a panel of experts representing academia, industry, and a government agency to obtain a holistic understanding of the facilitators, barriers, and potential solutions to those barriers. Although the experts involved in this study are all from the U.S., the outcomes still shed light on the development of EXOs for construction adoption and implementation in many other countries and regions, considering aspects such as the nature of construction tasks and work settings being alike worldwide, the lens through which the potential of EXO adoption was viewed, and the positioning of the present study based on the state of research in assessments of EXO use in construction. The present study determined that a wide range of issues remain to be addressed for using EXOs in construction workplaces, and the implications for different stakeholders are presented below.

5.1 Implications for the Academic/Research Community

Researchers have been performing experiments and analyses on EXOs to gain insights into the potential uses of EXOs in construction and their benefits. This study provides the research community with additional information to guide future efforts. The complete list of barriers with prioritized ones identified by the experts for EXO use in real-life construction settings may set the stage for future research efforts in finding solutions to solve the barriers and thereby facilitate the adoption process.

5.2 Implications for Government & Public Agencies

Adoption of EXOs in construction workplaces will require new policies and regulations for ensuring the safety of workers while wearing EXOs and supporting them if any injuries or accidents occur due to EXO use. Specific policies are also required to determine which party is liable for training arrangements and possible injuries (if any) due to continuous EXO use. The findings regarding desirable policies and regulations discussed earlier in this paper can aid appropriate government and public agencies in the formulation of policies and regulations for EXO users, businesses, and manufacturers.

5.3 Implications for EXO Manufacturers

EXOs are rapidly evolving technologies. While EXO usage is more prevalent in several other sectors, the technology needs further development and need modifications/improvements to adapt to construction applications. This study has identified several critical requirements which highlight the necessary modifications for EXOs to work in construction workplaces. For example, this study determined that EXOs need to be integrated with PPE to work in construction environments. It also emphasized that EXOs need to be lightweight and tailor-fit for ease of use by construction workers. The findings and recommendations from this study can help EXO manufacturers in improving EXOs to meet the requirements of the construction industry. The availability of EXOs that are well-suited for construction tasks will encourage construction firms to invest in them, thereby benefiting both EXO manufacturers and the construction industry overall.

5.4 Implications for Construction Firms

At present, most construction businesses and organizations remain unconvinced about the benefits of EXO use in construction workplaces in terms of cost, safety, and efficacy. While several studies have been conducted to assess the usability of extant EXOs in construction, feasibility studies and real-world case studies of EXO applications in construction are still required to influence organizations toward the adoption of this new technology. This study portrays a comprehensive view of the barriers that construction organizations are facing and also identifies key factors that can encourage businesses to adopt EXOs.

5.5 Implications for Trades Professionals (End Users)

Wide adoption of EXOs in the construction industry will strongly depend on the acceptance of trades professionals (end users). The variety of barriers that can cause the rejection of EXO products among workers or slow down the process of EXO adoption in construction workplaces has been identified in this study. The potential solutions to those barriers are discussed. The identified barriers will help inform the end users regarding the potential risks given the status quo of the EXO products and enable the worker community to understand the steps needed for the adoption of EXOs to be successful. Some of the technological modifications required to meet the needs of construction environments are also identified from the end users' perspective. Manufacturers and researchers are encouraged to leverage these findings to continually improve EXOs in collaboration with workers.

5.6 Implications for Other Industries

Many other industries, such as manufacturing (Graham et al. 2009), agriculture (Omoniyi et al. 2020; Wang et al. 2021), baggage handling (Baltrusch et al. 2019), logistics (De Bock et al. 2020; Motmans et al. 2018), medical care (Settembre et al. 2020), automotive (Hefferle et al. 2020;

Iranzo et al. 2020; Smets 2019), and ship maintenance (Moyon et al. 2018) are exploring potential uses for EXOs. As of now, the rate of EXO use in these industries is also limited. The outcomes resulting from this study may shed light on the pros, cons, opportunities, and challenges of EXO development for adoption and use in these industries. For instance, the facilitators, barriers, and potential solutions to those barriers identified for the business and organization categories in this paper are likely to be relevant to other industries. While considering technological modifications of EXO products necessary for a certain industry, the outcomes in the technology category might provide useful insights regarding the factors that need to be scrutinized. The outcomes with respect to policies and regulations from this paper may also be thought-provoking for other industries, as worker safety concerns are quite similar. The ergonomics/safety category in this paper elaborated on the safety concerns to be addressed for adopting EXOs pertinent to many of the workers in other industries as they are susceptible to WMSDs. Finally, the workers' concerns identified in the end user category represent the concerns of workers, regardless of which industry they belong to. As a result, the findings of this paper are beneficial not only to construction but also to many other industries that are actively evaluating the potential use of EXOs and working toward their adoption.

Chapter 6. Conclusions

6.1 Conclusions

Using a three-phase Delphi approach, this study identified the facilitators, barriers, and potential solutions to those barriers to the adoption of EXOs in the construction industry, considering the substantial benefits that this new technology can potentially offer to the industry. A panel of experts from academia, industry, and government with relevant knowledge and experience gathered in a workshop to provide input, perform discussions, and reach a consensus. The outcomes will help provide a better understanding of the benefits, risks, and opportunities of EXO use in the construction industry while shedding light on ongoing development and endeavors needed to study the envisioned future of technology, workers, and work in construction workplaces.

6.2 Contributions of the Research

This research highlighted the potential benefits of employing EXOs in the construction industry and identified the reasons for their limited adoption. The most significant contribution of this research lies in the knowledge revealed with respect to the potential facilitators, barriers, and solutions to the barriers of using EXOs in construction workplaces from a holistic perspective of stakeholders, including EXO manufacturers, contractors, robotic and mechanical experts, psychologists, insurance companies, economic specialists, and government agencies. This knowledge is useful in support of developing a roadmap for EXO development and adoption in the construction industry. The identified barriers, in a categorized manner, provide a basis on which subsequent EXO studies can build. For instance, one of the key barriers in the business category is the lack of tangible data in real construction settings, which may motivate researchers to conduct more collaborative studies with trade people on the effects of EXOs on construction workers in real jobsites. Experts identified that the currently available EXO products require modifications and improvements to meet construction workplace requirements, such as reduction in size and weight, provisions for free movement, and the addition of user-friendly donning and doffing mechanisms. Integrating EXOs with PPE without compromising the functional use of PPE that protects the safety and health of workers is a crucial aspect. These identified barriers may provide EXO manufacturers with the knowledge necessary to adapt their current products to future construction workplaces that will accommodate the use of EXOs. Also, the barriers identified in the ergonomics category highlighted several safety concerns regarding the use of EXOs, including sudden device failure, possible injuries due to misunderstanding of personal augmented capability, residual injuries, muscle atrophy, and pre-existing conditions, among others. These barriers may provide EXO users with a better understanding of the risks associated with using EXOs and the aspects to be aware of, but also manufacturers with the opportunity to enhance their products, if necessary, to mitigate these risks. In conclusion, it can be stated that the identified facilitators, barriers, and potential solutions to those barriers provide new perspectives to various stakeholders to research, modify, and improve EXOs to emulate construction workplaces and to facilitate the adoption process of EXOs for the future workforce.

6.3 Recommendations for Future Research

EXOs are a new technology with numerous research opportunities on the product and its use in construction workplaces. This study sought to discover the reasons behind the limited adoption of EXOs in construction by soliciting the input and consensus of a panel of experts, so paving the way for an extensive range of future research possibilities. Future research endeavors may attempt to solve the challenges mentioned in this study. The effectiveness of EXOs is typically tested in laboratory settings. Future research works may identify ways of testing EXOs in real-life settings in collaboration with the construction industry. Researchers may also work towards the development of viable policies and regulations for EXO users, businesses, and manufacturers appropriate for use by government and public agencies. Commercially available EXOs are not made for construction workplaces that may conflict with PPE. This calls for further investigation into the incorporation of EXOs with PPE, which is necessary to overcome the conflict and determine an optimal solution.

Publications from This Research

Journals:

Mahmud, D., Bennett, S. T., Zhu, Z., Adamczyk, P. G., Wehner, M., Veeramani, D., & Dai, F. (2022). "Identifying Facilitators, Barriers, and Potential Solutions of Adopting Exoskeletons and Exosuits in Construction Workplaces." *Sensors*, 22(24), 9987.

Conference Proceedings:

Mahmud, D., Bennett, S. T., Zhu, Z., Adamczyk, P. G., Wehner, M., Veeramani, D., & Dai, F. (2022). "Potential of Adopting Occupational Exoskeletons in Construction: A Synergistic Perspective." *Proc., Computing in Civil Engineering 2023* (Under review).

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Appendix

Survey for Expert Panel Selection

NSF FW-HTP WORKSHOP
Questionnaire for Experts

1. Level of education:

   01 – High school degree or equivalent

   02 – Bachelor's degree

   03 – Master's degree

   04 – Doctorate degree

   05 – Other advanced professional degree; please specify ______________________________

   06 – Prefer not to answer

2. Years of working experience: ___________ years

3. Current position: ____________________________

4. Level of familiarity with the use of Exoskeletons and Exosuits:

   01 – Not familiar at all

   02 – Slightly familiar

   03 – Moderately familiar

   04 – Very familiar

   05 – Extremely familiar

5. Do you have work/research/study experience with EXOs? Please select any of the following that is applicable.

   01 – Work   02 – Research   03 – Study   04 – Not applicable

Follow-up Survey

NSF FW-HTP WORKSHOP
Follow-up Survey

1. What is your point of interest in attending this workshop?

____

____

____

____

2. What questions are you seeking for answers from this workshop?

____

____

____

____

Exit Survey at the End of the Workshop

NSF FW-HTP WORKSHOP
Exit Survey

6. Name: ____

7. How satisfied are you with the workshop?

   01 – Extremely satisfied

   02 – Somewhat satisfied

   03 – Neither satisfied nor dissatisfied

   04 – Somewhat dissatisfied

   05 – Extremely dissatisfied

8. Do you have additional comments to the discussed items:

   ____

   ____

   ____

   ____

9. Do you have any suggestions for improvements if another workshop is organized in the future:

   ____

   ____

   ____

   ____

10. If we report for posting this event on our university as a piece of eNews, is it okay to include photos that may contain you?

    01 – Yes　　　　　　　　02 – No

11. Additional comments:

    ____

    ____

    ____

    ____