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Facilitators and barriers to the adoption of active back-support exoskeletons in the construction industry

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A R T I C L E I N F O

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A B S T R A C T

Introduction: Active back-support exoskeletons are gaining more awareness as a solution to the prevalence of work-related musculoskeletal disorders in the construction industry. This study aims to understand the factors that influence the adoption of active back-support exoskeletons in the construction industry. *Method:* A literature review was conducted to gather relevant adoption factors related to exoskeleton implementation. Building on the TOE (Technology, Organization, and Environment) framework, two rounds of the survey via the Delphi technique were administered with 13 qualified industry professionals to determine the most important adoption factors using the relative importance index. Through semi-structured interviews, the professionals expressed their perspectives on the impact of active back-support exoskeletons on the construction industry. *Results:* Important factors included 18 facilitators and 21 barriers. The impact of the exoskeletons in the construction industry was categorized into expected benefits, barriers, solutions, adjustment to technology, implementation, and applicable tasks. *Conclusions:* This study identified the factors to be considered in the adoption and implementation of active back-support exoskeletons in the construction industry from the perspective of stakeholders. The study also elucidates the impact of active exoskeletons on construction organizations and the broader environment. *Practical Applications*: This study provides useful guidance to construction companies interested in adopting active back-support exoskeletons. Our results will also help manufacturers of active back-support exoskeletons to understand the functional requirements and adjustments required for utilization in the construction industry. Lastly, the study expands the application of the TOE framework to the adoption of active back-support exoskeletons in the construction industry.

1. Introduction

Exoskeletons are increasingly perceived as a solution to work-related musculoskeletal disorders (WMSDs) across various industrial sectors where the nature of work is physically demanding. Specifically, active back-support exoskeletons, a type of exoskeletons, relieve the spine of work stress by contributing the required torque for completing work tasks, thus reducing muscle contraction (Huysamen et al., 2018). Studies have demonstrated the potential of active exoskeletons for reducing muscle activity and the range of motion of the body parts during different physically demanding activities. For instance, Poliero et al. (2020) identified reduced muscle activity at the back, and range of motion at the hip and knee region by 12% and 10% respectively, from the use of active back-support exoskeleton for tasks involving carrying, pushing, and pulling. Walter, Stutzig, and Siebert (2023) observed an 8% to 22% reduction in back muscle activity from the use of an active exoskeleton for weight-lifting tasks. Moreover, Huysamen et al. (2018) revealed a 12% to 15% reduction in back muscle activity due to the use of an active back-support exoskeleton for manual material handling tasks involving lifting and lowering tasks. In addition, compared with other classes of exoskeletons (e.g., passive back-support exoskeletons), active back-support exoskeletons can provide more support to the back using actuators such as electrical motors (Gonsalves, Ogunseiju, Akanmu, & Nnaji, 2021). These benefits are motivating the construction industry to explore the feasibility of active back-support exoskeletons for construction work. This is significant given that workers in the

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construction industry are 1.23 times more likely to sustain back injuries than workers in other industry sectors (Bureau of Labor Statistics, 2020). However, little is known about the factors that influence the adoption of active back-support exoskeletons in the construction industry.

The introduction of new technologies (such as wearable devices) into the workplace could be influenced by various factors (Magni, Scuotto, Pezzi, & Guiduice, 2021). Understanding how specific factors affect the implementation of new technologies would inspire the development of strategies to improve the acceptance of the interventions. If workers accept an intervention, they will use it and derive the intended benefits (Gonsalves et al., 2023). Underpinned by adoption theories, extant studies have advocated for capturing the feedback of stakeholders regarding the facilitators of and barriers to the adoption of intervention or technology, and possible solutions to the barriers (Kim et al., 2018; Upasani, Franco, Niewolny, & Srinivasan, 2019; Pan & Pan, 2020; Elprama, Vanderborght, & Jacobs, 2022). Despite these efforts, similar factors have yet to be formalized for the use of active back-support exoskeletons in the construction industry. Studies that have attempted to explain some of the identified factors that can influence the adoption of technologies in workplaces have done so through the lens of several theories including the technology acceptance model (TAM) (Chen, Lou, & Cheng, 2023; Pacifico et al., 2023), socio-technical systems (STS) (Cimini, Pirola, Pinto, & Cavalieri, 2020) and technology, organization, and environment (TOE) (Pan & Pan, 2019; Pan & Pan, 2020). A key characteristic of these theories, particularly, the Technology, Organization, and Environment (TOE) framework, is that the adoption and implementation of new technologies should be studied from the perspectives of understanding how the technology would fit into the organizational context and the external environment in which the organization is situated. These theories can provide information on the strengths of these factors and their interaction with one another (Gangwar, Date, & Raoot, 2014). The decision-making process regarding the adoption of new technology could be complex in the construction industry (Samad et al., 2021), and the adoption of an active back-support exoskeleton could involve various factors considering the organization and its environment. Therefore, TOE theory was adopted because it provides more comprehensive and holistic frameworks that offer a flexible structure, allowing researchers to adjust and adapt factors based on the specific research context (Baker, 2011).

Thus, the objective of this study was to identify the facilitators and barriers influencing the adoption of active back-support exoskeletons in the construction industry, and possible solutions to the barriers. This was achieved through a formal literature review to understand existing factors impacting exoskeleton adoption, a Delphi survey to formalize facilitators and barriers applicable to the use of active back-support exoskeleton in the construction industry, and semi-structured interviews to understand how the factors impact the implementation of the exoskeletons and potential solutions in the construction industry. The adoption factors are explained through the lens of the TOE theory to understand the implications for construction organizations. Overall, the paper is structured as follows: the introduction section, a review of existing work on active back-support exoskeleton, factors influencing exoskeleton adoption, and the underpinning theory. Next, the methodology is presented to explain the approach employed to elicit feedback from stakeholders. This is followed by the results, a discussion of the results, and a conclusion of the paper. This paper contributes to the scarce literature on factors that would influence the adoption of active back-support exoskeletons in the construction industry. The study also contributes to option-related theories such as TOE by explaining the context in which active back-support exoskeletons fit into the construction industry.

2. Background

2.1. Potentials of the active exoskeletons

Active exoskeletons differ from other types of exoskeletons, in that active exoskeletons can deliver additional energy to the user by exploiting electrical motors or pneumatic actuators (Poliero et al., 2020). These active elements in active exoskeletons, rather than relying on the users' movement, are powered by batteries or external supplies. Therefore, active exoskeletons can support a much greater load than passive exoskeletons (Kong et al., 2023). Roveda et al. (2020) opined that active exoskeletons are generally preferred compared to their counterparts due to the possibility of actively assisting the human during the task execution. Active exoskeletons have the potential to adapt their action to varying conditions and user needs (Toxiri et al., 2018). Studies have examined the suitability of active exoskeletons for reducing WMSDs. Some of these studies have their roots in the medical field, where active exoskeletons are being used for rehabilitation and gait control (Hsu, Changcheng, Lee, & Chen, 2021; Archangeli, Ishmael, & Lenzi, 2022; Miller-Jackson et al., 2022). For example, Archangeli et al. (2022) evaluated the range of motion and completion time due to the use of an active hip exoskeleton to support participants with hemiparesis. The exoskeleton improved walking speed and range of motion at the hip of the affected side by 30% and 49%, respectively.

Active exoskeletons have also been explored for industry sectors that involve manual material handling tasks (Huysamen et al., 2018; Sado, Yap, Ghazilla, & Ahmad, 2019; von Glinski et al., 2019; Poliero et al., 2020; Walter et al., 2023). Huysamen et al. (2018) evaluated an active back-support exoskeleton for tasks involving dynamic lifting and lowering. The exoskeleton reduced muscle activity in the back region by 12–15%. Poliero et al. (2020) investigated an active back-support exoskeleton (XoTrunk) for carrying and lifting tasks. The study identified a reduction of 12% in muscle activity at the back and a 10% reduction in the range of motion at the hip and knee. The study also reported reduced discomfort in the lower back. von Glinski et al. (2019) evaluated an active back-support exoskeleton (HAL) for tasks involving repetitive lifting. The study reported a 10% reduction in muscle activity in the back region. Sado et al. (2019) developed and assessed a lower body hybrid (i.e., active and passive) exoskeleton for work that involved repetitive lower limb movements. The findings show a 30% reduction in muscle activity in the lower leg. Walter et al. (2023) evaluated the efficacy of an active back-support exoskeleton (CrayX) for sports tasks involving weight lifting. The study indicated that the exoskeleton reduced 8% to 22% of the muscle activity in the back, and a 50% reduction in the perceived rate of exertion. Studies have shown the usage and potential of active exoskeletons across different industry sectors. However, limited studies have examined the potential of active back-support exoskeletons in the construction industry.

2.2. Factors influencing exoskeleton adoption

Evidence of reduced ergonomic risks from exoskeleton use has triggered investigations into factors that could influence the adoption of the technology in different industry sectors. In the manufacturing industry, Schwerha, McNamara, Nussbaum, and Kim (2021) showed major benefits (e.g., aid in lifting, reduction in turnover, and ability to expand worker pool) as well as major barriers (e.g., use of EXO with PPE, safety issues, and quality issues) that can influence exoskeleton use. Moreover, in the healthcare industry, Cha, Monfared, Stefanidis, Nussbaum, and Yu (2020) classified the adoption factors influencing the implementation of exoskeletons for surgical teams as characteristics of individuals, perceived benefits, environmental/societal factors, and intervention characteristics. On the other hand, Upasani et al. (2019) investigated the adoption factors involved in exoskeleton use for the agriculture industry. Their study identified adoption factors (e.g., affordability, durability, compatibility, and versatility) and potential barriers (e.g., body stress, getting caught on equipment, unexpected failure, and fall risks) that can influence the adoption of exoskeletons. In a general use assessment, Elprama et al. (2022) classified the adoption factors (physiological factors, work-related factors, policy-related factors, psycho-social factors, and implementation-related factors) that can influence exoskeleton acceptance. Despite these efforts, scarce studies have explored similar adoption factors that influence exoskeleton use for the construction industry, especially active exoskeletons.

Previous studies (Kim et al., 2019; Mahmud et al., 2022) have explored some of these adoption factors in the construction industry. However, some of these studies have been laden with several limitations. For instance, Kim et al. (2019) used a qualitative approach to classify the perspective of construction industry stakeholders regarding adopting exoskeletons as expected benefits (e.g., productivity gains), exoskeleton technology adoption factors (e.g., initial investment cost and return on investment), and perceived barriers to use (e.g., safety concerns and usability). However, many of the participants had neither experienced the use of an exoskeleton before they participated in the studies nor were the findings of the study explained through the lens of grounded theories. In Mahmud et al. (2022), a quantitative Delphi approach was used to classify the facilitators, barriers, and potential solutions from the perspective of business, technology, organization, policy/regulation, ergonomics/safety, and end users. Again, a mixed-method approach could have been used to give further insight into the empirical perspective of the experts used. Also, most of these studies have focused on all exoskeletons without the factors being specific to active exoskeletons. Active back-support exoskeletons differ from passive back-support exoskeletons in terms of cost, weight, mode of operation, lifting capacity, and range of motion. These differences would spark diverse physical and psychological risks, which could impact the contextual use of exoskeletons, and organizational and user adoption considerations. Hence, the need to understand the facilitators and barriers specific to the adoption of active back-support exoskeletons in the construction industry.

2.3. Theoretical underpinning

This study is grounded in the Technology, Organization, and Environment (TOE) framework, which explains that factors influencing the adoption and implementation of new technologies within an organization can be categorized into technological, organizational, and environmental contexts (Tornatzky & Fleischer, 1990). The technological context in the TOE framework refers to the specific technological innovation being adopted and includes factors such as complexity, potential benefits, and compatibility with existing systems and practices (Tornatzky et al., 1990; Baker, 2011). The organizational context refers to the capability of the adopting organization and includes factors such as organizational structure, culture, resources, and readiness to change (Tornatzky & Fleischer, 1990; Baker, 2011). The environmental context refers to the external context in which the organization operates and includes factors such as market conditions, industry dynamics, competitive pressures, government regulations, and socioeconomic factors (Tornatzky et al., 1990; Baker, 2011; Chen, Yin, Browne, & Li, 2019).

Over the years, studies have utilized the TOE framework to understand the adoption of new technologies such as inter-organizational systems (Mishra, Konana, & Barua, 2007), robots (Pan & Pan, 2019; Pan & Pan, 2020), artificial intelligence (Fonseka, Jaharadak, & Raman, 2022) and other digital technologies (Eze et al., 2019). In each of these studies, slightly different factors have been used for the technological, organizational, and environmental contexts (Baker, 2011). This is a major feature of the TOE framework that makes it dynamic. In essence, researchers believe that the three TOE contexts influence adoption, however, these researchers have then assumed that for each specific technology, context, or organization that is being studied, there is a unique set of factors or measures that apply (Baker, 2011; Maroufkhani, Iranmanesh, & Ghobakhloo, 2022). By categorizing these adoption factors under the TOE framework, Nguyen, Le, and Vu (2022) argued that it increases the validity of the interpretation of the findings. Similar to previous studies that have used the TOE framework, this study examined the facilitators, barriers, and potential solutions to barriers (Chau & Tam, 1997; Baker, 2011; Pan & Pan, 2020; Nguyen et al., 2022) associated with active back-support exoskeleton adoption. Fig. 1 shows a TOE-based theoretical framework adapted for this study. In this study, the TOE framework is used to understand adoption factors, considering the interplay of technological, organizational, and environmental factors, that would influence the adoption of active back-support exoskeleton in the construction industry.

3. Methodology

This section describes the methods adopted to achieve the objective of this study. As shown in Fig. 2, this section begins by explaining the literature review conducted to identify existing facilitators of and barriers to the adoption of exoskeletons. This is followed by a description of the Delphi technique and semi-structured interviews adopted in this study. Previous studies (Omoniyi, Trask, Milosavljevic, & Thamsuwan, 2020; Mahmud et al., 2022) have used similar techniques in their research. Lastly, the methods employed for analyzing the research data are explained.

3.1. Literature review: Identification of facilitators and barriers

Facilitators of and barriers to the adoption of exoskeletons, established in previous studies, were identified through a review of existing studies. The authors targeted studies that focused on factors that influence the adoption and implementation of exoskeletons. The review was conducted across different industry sectors, such as manufacturing, healthcare, and construction. Multiple databases were used, including Google Scholar, Science Direct, and the American Society of Civil Engineers (ASCE) Library. Different combinations of keywords were used, including "exoskeletons and adoption factors," "exoskeletons and facilitators and barriers," "exoskeletons and implementations," and "exoskeletons and benefits," "exosuits and adoption factors," "assist suits and benefits and barriers," and "wearable robotics and adoption factors." The results of these searches are thematically organized and prepared for the Delphi study. This review resulted in the formalization of factors that have been identified as significant for the adoption of exoskeletons across different industry sectors.

3.2. Delphi technique

According to Hallowell and Gambatese (2010), the Delphi technique was developed by the RAND Corporation to examine the impacts of technology on warfare using the judgments of qualified experts. The Delphi technique involves surveying experts to establish consensus about a subject matter (Hallowell & Gambatese, 2010). Experts anonymously present their opinions regarding the subject matter through rounds of surveys (Alomari, Gambatese, & Tymvios, 2018). The rounds of surveys provide experts an opportunity to review their previous responses, thereby leading to consensus among the experts (Alomari et al., 2018; Karakhan, Gambatese, Simmons, & Al-Bayati, 2021). The Delphi technique is flexible and can be adapted to various research problems, especially studies that are sensitive and complex, such as safety, risk management, innovation, and technology forecasting (Hallowell & Gambatese, 2010). This study adopted a 2-round Delphi technique (Karakhan et al., 2020; Fathi et al., 2023) due to the incomplete knowledge and lack of clarity (Iqbal & Pipon-Young, 2009) about the use of active back-support exoskeletons. This study utilized a sample size of 13 industry practitioners, which is more than the minimum of seven experts recommended (Stone Fish & Busby, 2005).

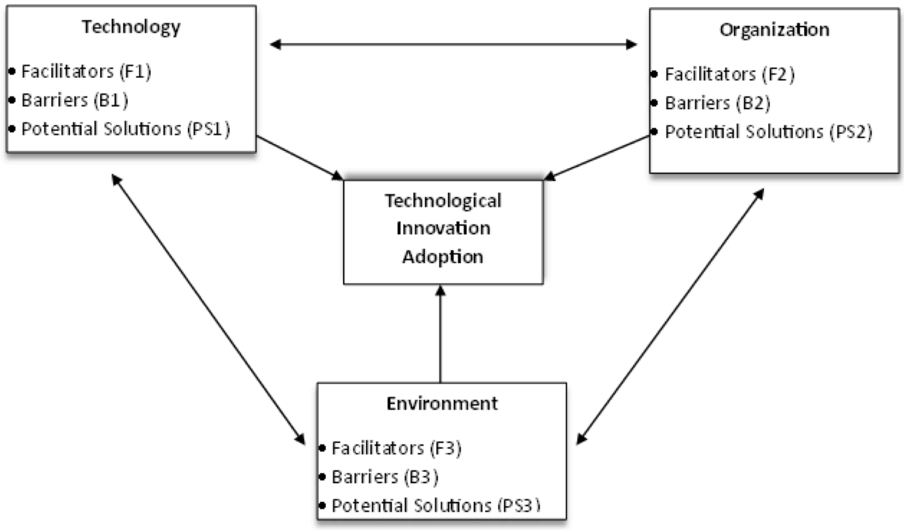

Fig. 1. TOE-based Theoretical Framework.

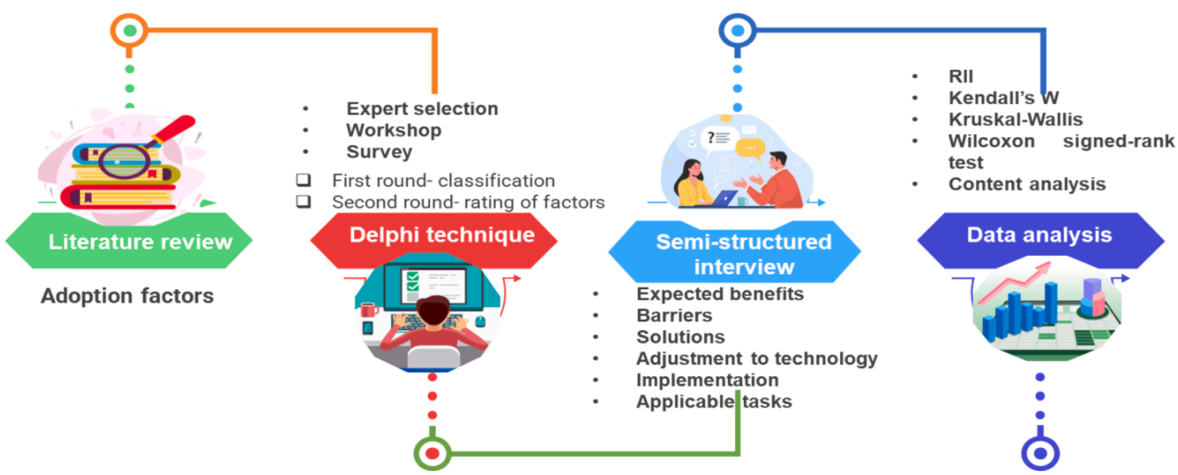

Fig. 2. Overview of Methodology.

3.3. *Expert panelist selection*

The success of Delphi studies hinged on the qualification of the participants (Karakhan et al., 2021). Purposive sampling guided by the criteria highlighted in Table 1 was used to identify and select potential participants who can provide valuable insights to the study (Yusoff, Hashim, Muhamad, & Hamat, 2021). A point system was used to identify the number of criteria met by the professionals. Equal points were apportioned to each criterion, with the maximum points of all the criteria amounting to 100% (Alomari et al., 2018; Okpala, Nnaji, & Gambatese, 2023). The professionals were expected to meet at least 50% of the criteria to be considered for the study (Hallowell & Gambatese, 2010; Alomari et al., 2018; Okpala et al., 2023).

Table 1
Expert Selection Criteria.

Criteria	C1	C2	C3	C4	C5	C6	Percentage of criteria
E-1	X	X	X	X	X	0	83.3%
E-2	X	X	X	X	X	0	83.3%
E-3	X	X	X	X	0	0	66.7%
E-4	X	X	X	X	X	0	83.3%
E-5	X	X	X	X	X	0	83.3%
E-6	X	X	X	X	X	0	83.3%
E-7	X	X	X	X	X	0	83.3%
E-8	X	X	X	X	X	0	83.3%
E-9	X	0	X	X	0	X	83.3%
E-10	X	0	X	X	0	X	83.3%
E-11	X	X	X	0	0	X	66.7%
E-12	X	X	X	X	X	X	100.0%
E-13	X	X	X	X	0	X	83.3%

Note C = criterion; and E = expert.

3.4. *Workshop*

Given that exoskeleton technology is relatively new in the construction industry, it was important to enhance the study participants' knowledge of the functionality and potential of active back-support exoskeletons. Therefore, a workshop was organized to demonstrate, train, and provide each participant with hands-on experience with an active back-support exoskeleton (Telford, Boote, & Cooper, 2004). During the workshop, the workings of a commercially available active back-support exoskeleton (CrayX) were described and shown to the participants as shown in Fig. 3. The participants had the opportunity to try out the exoskeleton and imagine task-specific applications and risks of the device on construction sites.

3.5. *Questionnaire development and survey administration*

Two rounds of questionnaires were developed to achieve the

Fig. 3. Sample of the active back-support exoskeleton (CrayX).

objective of the study. The questionnaires were reviewed by an external evaluator, with extensive experience in research evaluation, to ensure clarity of the questions and compliance with the objective of the study. The questionnaires were revised based on the feedback of the evaluator. Thereafter, the questionnaires were uploaded in Question Pro and administered to the participants via email. The first-round questionnaire has two sections. The first section captured the demographics of the participants, which is meant to determine the qualifications of the experts per the set criteria. The demographic questions include the participants' gender, race, qualifications, working experience, job title, professional certification, and familiarity with exoskeletons. The second section includes the factors identified from the literature review (i.e., the facilitators-of-and barriers to the adoption of exoskeletons). The participants were asked to classify each of the factors as a facilitator of or a barrier to the adoption of active back-support exoskeletons in construction. In addition, the participants were asked to provide additional facilitators and barriers that were not in the survey but are important to the adoption of active back-support exoskeletons in the construction industry. The second-round questionnaire was aimed at understanding the extent to which each of the facilitators and barriers from the first round would influence the adoption of active back-support exoskeletons in the construction industry. In this round, the participants were asked to rate the classified facilitators and barriers (from the first round) on a 5-point Likert scale, with 5 = Very high influence, 4 = high influence, 3 = moderate influence, 2 = minor influence, 1 = low influence, and 0 = I do not know.

3.6. Semi-structured interview

Semi-structured interviews were conducted with the participants of the Delphi study to understand how the facilitators and barriers identified from the second-round survey would impact the adoption of active back-support exoskeletons in the construction industry. The interview questions were structured to identify the following: (1) How the identified facilitators support the adoption of active back-support exoskeletons in the construction industry; (2) How the identified barriers hinder the adoption of active back-support exoskeletons in the construction industry, and solutions to the barriers; (3) The most suitable construction activities or tasks that would benefit from the use of active back-support exoskeletons; and (4) Additional information that could benefit researchers to better understand the adoption of active back-support exoskeletons in the construction industry. The semi-structured interviews were conducted over Zoom and recorded.

3.7. Data analysis

Different data analysis techniques were adopted to analyze the data types collected during the study. Data obtained from the first-round survey were analyzed by classifying the facilitators and barriers. The factors that were classified by at least one-third of the participants were considered facilitators or barriers. The proportion was selected to maximize the suitable factors given that most of the factors are safety-related. The ranking of the factors from the second-round survey was computed using the relative importance index (RII). RII (see equation (1) was employed to compare and rank the factors (i.e., to determine the factors that have the most level of influence based on the responses from the participants). A similar technique was employed by Fathi and Shrestha (2023) to identify and prioritize factors with the most influence and factors with RII of 0.8 to 1.0 were considered to be the most influential.

$$RII = \frac{\Sigma W}{(A^*N)} \tag{1}$$

where W is the weight given to each factor by the participants (ranging from 1 to 5), A is the highest weight (i.e., 5), and N is the total number of participants. Furthermore, to assess the level of agreement among the participants regarding the facilitators and barriers, Kendall's coefficient of concordance (W) Chi-square distribution test was conducted. The test was conducted to determine whether consensus existed among the participants. The values of Kendall's coefficient range from 0, indicating 'no agreement,' to 1, representing 'full agreement.' Typically, values between 0.23 and 0.60 are considered indicative of achieving consensus (Nnaji, Okpala, Gambatese, & Jin, 2023). Content analysis was adopted to analyze the qualitative data obtained from the semi-structured interview using QDA Miner Lite v3.0 (Lo, Stephenson, & Lockwood, 2020). Based on the semi-structured interview questions, codes were generated, and themes were further developed among the codes. To understand the trustworthiness of the coded data, an inter-coder reliability test was conducted using the Cohen-Kappa coefficient. The assessment showed 97% between the two coders. The resulting Cohen-kappa coefficient (κ) of 0.90 shows a strong level of agreement.

4. Results

This section presents the results of the analysis of the study conducted to identify the factors influencing the adoption of active back-support exoskeletons in the construction industry. The results include facilitators, barriers, and feedback from the semi-structured interviews.

4.1. Delphi technique

4.1.1. Demographic analysis

Fifteen (15) industry practitioners expressed interest in the study and were invited to the workshop, however, only 13 attended the workshop. After the workshop, the 13 industry practitioners were administered the first-round survey, and all 13 practitioners completed the survey and proceeded to the second round. In the second round, only 12 of the 13 participants completed the survey. As part of the demographic data obtained, the criteria for expert selection and qualification are shown in Table 1. All 13 participants met the first criteria (C1), that is, all of them are construction professionals and are currently working for various construction firms. Out of the 13 participants, 11 (85%) met the second criterion (C2), which is having a minimum of 3 years of construction-related experience. One hundred percent of the participants met the third criterion (C3), that is, having a minimum bachelor's degree in a construction-related program. Regarding the criteria of professional certification and affiliation (C4), 12 (92%) out of 13 participants possess a relevant professional certification related to either construction engineering or safety management. Eight (61%) out of the 13 participants possess a minimum of 3 years of construction safety experience, which is one of the criteria set (C5) for the participants to qualify as experts for this study. Lastly, on the awareness of the exoskeleton (C6), 6 (46%) participants are moderately aware of the exoskeletons, and at least 10

(77%) participants are slightly familiar with exoskeletons. The low level of familiarity with the exoskeletons is understandable, as the technology is new to the industry. Overall, all the participants met at least 67% of all the criteria set for qualification to participate in the study, which indicates that they are all qualified, as they were expected to meet at least 50% of the set criteria (Karakhan et al., 2020; Fathi et al., 2023).

4.1.2. First-round survey

As mentioned in the data analysis section, factors that were classified by at least one-third of the participants were considered facilitators or barriers. As such, 40 facilitators and 52 barriers were identified as shown in Table 2. This is inclusive of the suggestions from the participants. These factors were included in the second-round survey.

4.1.3. Second-round survey

The 40 facilitators and 52 barriers identified from the first-round survey were fed into the second-round questionnaire. The participants rated the level at which each of the facilitators and barriers would influence the adoption of active back-support exoskeletons in the construction industry. For the facilitators, the RII results in Table 3 show that 3 facilitators possessed the highest ranking of 0.91: 'understanding the costs and benefits for my organization – F39,' 'understanding the productivity gains – F40,' and 'having the ability to walk on uneven surfaces – F4.' The lowest RII result is 0.27, which represents 'cultural beliefs – F15′. To present the significant factors, RII values f 0.8 to 10 (0. $\geq RII \leq 1$ are considered to be the most important facilitators (Fathi & Shrestha, 2023).

Regarding the barriers, Table 4 shows the highest RII value is 0.93, with two factors occupying the first position: 'incompatibility with other devices – B23′ and 'purchasing an exoskeleton/affordability/investment – B4′ while 'inability to walk on uneven surfaces – B19′ ranked third. The lowest RII result is 0.25, representing 'cultural belief – (B9)'. In presenting the most important factors, similar criteria to those used for facilitators were adopted. RII values of 0.8 to 1.0 were considered the most significant. The experts reached a consensus, as indicated by Kendall's coefficient of concordance (W), which demonstrated a significant outcome ($p < 0.05$) with a value of 0.23 for the facilitators' rating and 0.27 for the barriers' rating.

4.1.4. Semi-structured interview

Six main categories emerged from the analysis of the semi-structured interview. These include desired benefits, barriers, solutions, adjustment to technology, implementation, and suitable construction activities. Fig. 4 presents an overview of the results, showing the categories and their associated themes.

4.1.4.1. Desired benefits. From the desired benefits category, five themes were generated: resilience of the exoskeleton, dynamic adaptability, ergonomics, derive satisfaction, and derive values from the use of the exoskeletons.

The resilience of the exoskeleton covers the participants' views on the ruggedness of exoskeletons, the resistance of exoskeletons to unfavorable weather conditions, and the ease of maintenance and durability of exoskeletons. Though exoskeleton usage is scarce in the construction industry, professionals recognized several benefits. For instance, one participant emphasized, "*I think it would have to be a very durable product, and it had to be a rugged product, because, you know, obviously depending on where we all are in construction. You know you're exposed to the elements, whether it's the UV from the sun, rainwater, snow, it could be water falling off a deck above.*"

Many of the participants agreed that one of the major benefits expected from the use of active back-support exoskeletons is the ease of maintenance, as indicated by one participant, who said that "*the easier the maintenance, the more intriguing it is for people to use and buy.*" Regarding the exoskeleton's dynamic adaptability, the desired benefits

Table 2
Identified Facilitators and Barriers by Domain Experts.

Code	Facilitators	Code	Barriers
F1	Ability to augment worker's physical strength throughout the working hours	B1	The added weight of the exoskeleton
F2	Ability to reduce or prevent back-related injuries	B2	Anthropometric fit
F3	Ability to sustain the aging workforce (i.e., helping older workers who are still working in construction)	B3	The bad appearance of Exo
F4	Ability to walk on uneven surfaces while wearing the exoskeleton	B4	Buy Exo / Affordability / Investment
F5	Ability to climb stairs	B5	Catch and snag risks
F6	Access to ergonomics training	B6	Comfort in hot/cold weather
F7	Alleviate labor shortages	B7	Convincing management to buy-in
F8	Amount of energy needed for use	B8	Cost justification of initial purchase
F9	Anthropometric fit (i.e., proper fit for each user)	B9	Cultural beliefs
F10	Awareness of a problem that exoskeletons can fix	B10	Difficulty in removing exo during hazards
F11	Benefits of posture corrections	B11	Drops in the performance of the exo
F12	Client-driven use of exoskeletons	B12	Duration of Maintenance
F13	Compatibility of exoskeleton with work tasks	B13	Errors and inefficient quality standards
F14	Create job opportunities for individuals with expertise in exoskeleton use, training, and certification	B14	False sense of safety
F15	Cultural beliefs (i.e., how workers' religion and/or tradition influences the use of exoskeletons)	B15	Inability to access confined workspaces
F16	Curiosity about exoskeletons (i.e., Openness to innovation)	B16	Inability to climb stairs
F17	Durability and ruggedness of exoskeleton	B17	Inability to maintain Exo in a dusty environment
F18	Ease of maintenance	B18	Inability to use the restroom
F19	Ease of using an exoskeleton / Ease of putting on and off / comfort	B19	Inability to walk on uneven surfaces
F20	Evidence of demonstration by others in similar fields and use case	B20	Inadequate suitable active exoskeleton options
F21	Existing champion in the workplace (i.e., willingness to lead the testing of exoskeletons)	B21	Incompatibility of exoskeleton with tasks
F22	Exoskeleton application for specific trades like concrete and steelwork	B22	Incompatibility with certain environments
F23	Exoskeletons to enable performance and attract other workers	B23	Incompatibility with other devices
F24	Few errors and efficiency for quality standards (i.e., limited impact on quality of construction)	B24	Lack of ability to try out an exo
F25	Immediate pain relief from using exoskeletons	B25	Lack of familiarity with exoskeletons
F26	Light cognitive workload (i.e., low mental demand in using the exoskeletons)	B26	Lack of peer acceptance for exo
F27	Adequate knowledge of exoskeletons	B27	Lack of professionals for proper training
F28	Lower time to training proficiency	B28	Lack of storage for exo on job site
F29	Minimum disturbances of the construction process	B29	Lack of team buy-in
F30	Ownership of exoskeleton by company (i.e., companies bear the cost of the exoskeleton)	B30	Lack of understanding of the cost-benefits
F31	Personal exoskeleton (i.e., each worker will have their exoskeleton)	B31	Lengthy-time to reach training proficiency
F32	The positive appearance of exoskeletons	B32	Limited knowledge about exoskeletons

(*continued on next page*)

Table 2 (*continued*)

Code	Facilitators	Code	Barriers
F33	Positive attitude towards exoskeletons	B33	Limited space
F34	Positive perceptions of the usefulness of exoskeletons	B34	Low technology literacy of the workers
F35	Reduced worker compensation costs as a result of the reduction in injury	B35	Mandatory use of exoskeleton
F36	Size of the construction firm	B36	Negative attitudes toward exoskeletons
F37	Support from exoskeleton manufacturers	B37	Negative impact on coworkers
F38	Understanding of long-term benefits	B38	The negative perception of exo by users and others
F39	Understanding the costs and benefits for my organization	B39	Ownership of exoskeleton by worker
F40	Understanding the productivity gains	B40	The perceived complexity of the exo
		B41	Perception of an increased fall risk
		B42	Perception of weakness
		B43	Personal history of complaints
		B44	Potential for equipment failure and injury
		B45	Reactions of the Exo to Common Chemicals
		B46	Reduced durability and ruggedness of the Exos
		B47	Resistance to change by workers
		B48	Sharing Exo with other employees
		B49	Size of the construction firm
		B50	Sterilization/Hygiene
		B51	Using the Exo on high-temperature tasks
		B52	Wear and tear of exo parts

were the ability to climb stairs and ladders, a full-day power supply, and a good fit of the exoskeleton for different body sizes.

Given the dynamic nature of the construction site, the participants expected that the exoskeleton would be able to cope and adapt to support smooth operations on site. As mentioned by one of the participants, *"You have got to be able to walk stairs."*

Another desired benefit was the ergonomics of the exoskeleton. Participants expected the exoskeleton to help maintain body balancing, ensure correct posture, provide long-term health benefits, flexibility in movement, skill improvement, reduce soft tissue injuries, and reduce fatigue. Many of the participants admitted that the most important consideration for the exoskeleton was the reduction of injuries. For instance, one of the participants said he signed up for the study because he expected the exoskeleton to reduce injuries. Another participant indicated that "*if we can show that we can save your back, then it is a great benefit.*"

The next theme generated under desired benefits was derived satisfaction. The participants hoped that the exoskeleton would be helpful and that workers would give good feedback, create positive perceptions, positive experiences, work-life balance, compatibility, comfortability, positive immediate consequences, and sustain the workforce. This is best captured by a participant saying, "*You want to make sure that they're doing their work healthily and safely. So exoskeletons will help with that.*"

The last desired benefit theme was derived values. Values expected to benefit the organization included: demonstration that exoskeletons save money ('*it has to be worth it*'), evidence from data, reducing labor costs, benefits to the organization and projects, improving productivity, and reducing claims. Under this theme, improving productivity and reducing the worker's compensation claim was emphasized. This was comprehensively detailed by a participant: *"I would say that the biggest cost benefit would be a reduction in workman's compensation claims and soft tissue industry injuries. Also, an increase in the productivity of workers who were doing repetitive work."*

Table 3
Facilitators of the adoption of active exoskeletons in the construction industry.

Code	Facilitators	RII	Rank
F39	Understanding the costs and benefits	0.909*	1
F40	Understanding the productivity gains	0.909*	1
F4	Ability to walk on uneven surfaces	0.909*	1
F17	Durability and ruggedness of exoskeletons	0.891*	4
F5	Ability to climb stairs	0.891*	4
F2	Ability to reduce back-related injuries	0.873*	6
F20	Evidence of demonstration	0.873*	6
F22	Exoskeleton application for specific trades	0.855*	8
F30	Ownership of exoskeletons by the company	0.855*	8
F35	Reduced worker compensation costs	0.836*	10
F13	Compatibility of exoskeletons with tasks	0.836*	10
F36	Size of the construction firm	0.836*	10
F8	Amount of energy needed for use	0.836*	10
F18	Ease of maintenance	0.818*	14
F9	Anthropometric fit	0.818*	14
F34	Positive perceptions of the usefulness	0.800*	16
F38	Understanding of long-term benefits	0.800*	16
F1	Ability to augment worker's strength	0.800*	16
F24	Few errors and efficiency for quality	0.782	19
F19	Ease of using an exoskeleton	0.782	19
F29	Lower time to training proficiency	0.782	19
F16	Curiosity about exoskeletons	0.764	22
F25	Immediate pain relief	0.745	23
F29	Minimum disturbances	0.745	23
F31	Personal exoskeletons	0.745	23
F10	Awareness of a problem that the exoskeleton can fix	0.727	26
F7	Alleviate labor shortages	0.727	26
F3	Ability to sustain the aging workforce	0.727	26
F26	Light cognitive workload	0.709	29
F32	The positive appearance of exoskeletons	0.709	29
F6	Access to ergonomics training	0.709	29
F33	Positive attitude towards exoskeletons	0.691	32
F14	Create job opportunities for expert	0.691	32
F11	Benefits of posture corrections	0.691	32
F21	Existing champion in the workplace	0.673	35
F37	Support from exoskeleton manufacturers	0.673	35
F12	Client-driven use of exoskeletons	0.655	37
F23	Exoskeletons to enable performance and attract other workers	0.636	38
F27	Adequate knowledge of exoskeletons	0.618	39
F15	Cultural beliefs	0.273	40

4.1.4.2. Barriers. Eight barrier themes were identified: associated cost, comfortability and compatibility issues, environmental barriers, durability and ruggedness, risks to the user, lack of awareness and demonstration, design compatibility, and resistance to technology.

The associated cost covers the affordability problem, maintenance costs, long-term investment, and unfavorability to small firms. Emphasis was placed on the affordability of the technology, especially the initial cost. As such, many of the participants believed that small firms would likely not be the early adopters because of the high cost of their initial purchase. As indicated by a participant, *"convincing management to buy in is quite difficult because it has to fit their budget."* Another participant also mentioned that: "*I see this as a barrier because of the high cost of investment.*"

The comfortability and compatibility issue theme covers the participants' concerns about how the exoskeleton will fit into some of the tasks carried out on the construction site. The theme encapsulates compatibility issues, unease, incompatibility with all tasks, being uncomfortable at height, not favorable in hot weather, difficulty for use in confined spaces, and inability to climb ladders and stairs. Given the dynamic nature of the construction site, many of the participants raised at least one compatibility issue between the exoskeleton and different construction tasks. For instance, a participant expressed that "*I don't see it being able to be worn by that personnel who are working at heights that*

Table 4
Barriers to the adoption of active exoskeletons in the construction industry.

Code	Barriers	RII	Rank
B23	Incompatibility with other devices	0.927*	1
B4	Buy Exoskeletons / Affordability / Investment	0.927*	1
B19	Inability to walk on uneven surfaces	0.909*	3
B5	Catch and snag risks	0.891*	4
B10	Difficulty in removing exoskeletons during hazards	0.891*	4
B20	Inadequate suitable active exoskeleton options	0.891*	4
B7	Convincing management to buy-in	0.891*	4
B2	Anthropometric fit	0.873*	8
B16	Inability to climb stairs	0.873*	8
B17	Inability to maintain exoskeletons in a dusty	0.873*	8
B47	Resistance to change by workers	0.855*	9
B32	Limited knowledge about exoskeletons	0.855*	9
B30	Lack of understanding of the cost-benefits	0.855*	9
B8	Cost justification	0.855*	9
B27	Lack of professionals for proper training	0.836*	15
B6	Comfort in hot/cold weather	0.836*	15
B21	Incompatibility of exoskeleton with tasks	0.818*	17
B1	The added weight of the exoskeleton	0.818*	17
B41	Perception of an increased fall risk	0.818*	17
B25	Lack of familiarity with exoskeletons	0.800*	20
B15	Inability to access confined workspaces	0.800*	20
B52	Wear and tear of exoskeleton parts	0.782	22
B14	False sense of safety	0.782	22
B45	Reactions of the exoskeletons to common chemicals	0.782	22
B44	Potential for equipment failure and injury	0.782	22
B24	Lack of ability to try out an exoskeleton	0.764	26
B29	Lack of team buy-in	0.764	26
B46	Reduced durability and ruggedness of the exoskeletons	0.764	26
B40	The perceived complexity of the exoskeletons	0.764	26
B39	Ownership of exoskeleton by worker	0.764	26
B33	Limited space	0.709	31
B11	Drops in the performance of the exoskeletons	0.709	31
B31	Lengthy-time to reach training proficiency	0.709	31
B18	Inability to use the restroom	0.691	34
B51	Using the exoskeletons on high-temperature tasks	0.691	34
B35	Mandatory use of exoskeleton	0.691	34
B49	Size of the construction firm	0.691	34
B28	Lack of storage for exoskeletons on the job site	0.673	38
B22	Incompatibility with certain environments	0.673	38
B13	Errors and inefficient quality standards	0.673	38
B36	Negative attitudes toward exoskeletons	0.636	41
B34	Low technology literacy of the workers	0.636	41
B12	Duration of Maintenance	0.618	43
B38	The negative perception of exoskeletons by users and others	0.582	44
B26	Lack of peer acceptance for exoskeletons	0.582	44
B42	Perception of weakness	0.582	44
B37	Negative impact on coworkers	0.564	47
B48	Sharing exoskeletons with other employees	0.564	47
B3	The bad appearance of exoskeletons	0.527	49
B50	Sterilization/Hygiene	0.473	50
B43	Personal history of complaints	0.418	51
B9	Cultural beliefs	0.255	52

require fall protection."

Environmental barriers included the dynamic and unstructured nature of the construction site. Unlike the manufacturing industry, the participants believed that the nature of the construction site would be a setback in the adoption of exoskeletons in the construction industry. A good caption was expressed by a participant: "*Like if you're working in a warehouse, you're in a relatively static environment all the time you're on an even surface, and you're doing very repetitive things. On a construction site, we don't always have that. It's never really until you get to the tail end of a project, you don't always have a conducive environment for a lot of things. It has a lot of wear on products."*

Many of the participants believed exoskeletons were not ready for construction as they were still in the early stages of development. They believed that the exoskeleton was not durable and rugged enough to withstand the rigors of construction. Participants' concerns included the wear and tear of the exoskeleton, catch and snag risks, not being durable and rugged enough, and difficulty in maintenance. A good example cited by a participant is that: "*You are in a trench like laying pipe, and there's like some gravel or stuff that's kind of like hitting part of the exoskeleton, or some dirt that's kind of just flying up against it. You want to make sure if you're spending potentially hundreds, maybe for the bigger systems, thousands of dollars on something that if hit by a small rock like it's part of the machine, won't just break completely."*

Another barrier was the risk to the user. Participants were concerned about the inadequate range of motion, overexertion of the body, stress and strain, overwork due to less fatigue, negative experiences, difficulty in removal, injury proneness, an increase in fall risk, a shift in the center of gravity, and a lot of unknowns.

Despite some of the anticipated barriers, many of the participants were very curious and inclined to see how the desired benefits could be demonstrated on the construction site. Given the environmental barrier of the construction, as stated previously, many of the participants believed that benefits experienced in other industries may not be realized in construction. A good example was when a participant mentioned that "*it sounds to me like the technology seems like it could be mighty delicate or a rough job site, but if it can be shown that the exoskeletons are made for that environment."*

Concerning the bulkiness and weight of the exoskeleton, one of the most concerning risks is the fear of falling, as a result of imbalance, especially for those working at height. A good instance was when a participant said that "*But if they're a lot of uneven surfaces and people are wearing this device and trying to carry heavy things on not even surfaces that could lead to a risk for injury because they're wearing this."*

The last theme in the barriers category is resistance to technology. Many of the participants believed there would be resistance from the experienced workers. For instance, a participant expressed that: "*They were locked in by some experienced workers, and apart from traditional methods, that's a very polite way of saying there's no way out there. They don't want to change and have been doing it their way for 35 years."*

4.1.4.3. Possible solutions. Eight themes were suggested as possible solutions to some of the barriers identified. The themes are practical evaluation, integration into construction, safety considerations, training, affordability, more exoskeleton products, awareness, and target users. Given the barriers identified, many of the participants believed there is a need for practical evaluation of the exoskeleton on the construction site. They believed that practical demonstration with construction tasks to identify justifiable benefits, and regular feedback to the designers could be a way to resolve the identified problems. For instance, a participant responding to the compatibility of the exoskeleton with other devices responded that "*Put it on somebody, and then go get a tool belt with actual tools, load it up with screws, nails, a screw gun hammer, and try to figure out the best way to incorporate the tool belt with it."* Another participant believed that "*if the industry isn't demonstrating it, nobody is going to buy it. I would not buy today with videos.*"

The construction industry is known for being injury-prone, so participants were concerned about the safety considerations of the device. They believed that the device should be built with the utmost safety in mind, be easy to carry due to its bulkiness and weight, have weight distribution across the body, and have an extra break in the summer for users for thermal comfort. An instance was when a participant said it would be better if the weight of the device was "*distributed across the body."*

Many of the participants reported that training and education would be of great importance in the process of combating the identified barriers. They believe that the industry will adapt to the use of the exoskeleton with time, just as it has adapted to other technologies in the past. Most importantly, they believed that the exoskeleton has to be used for the right tasks. In response to the compatibility of the exoskeleton, a participant reported that "*they are limited in what they can do, so you have to pick the right task.*"

Another solution was affordability. Given that cost is the major

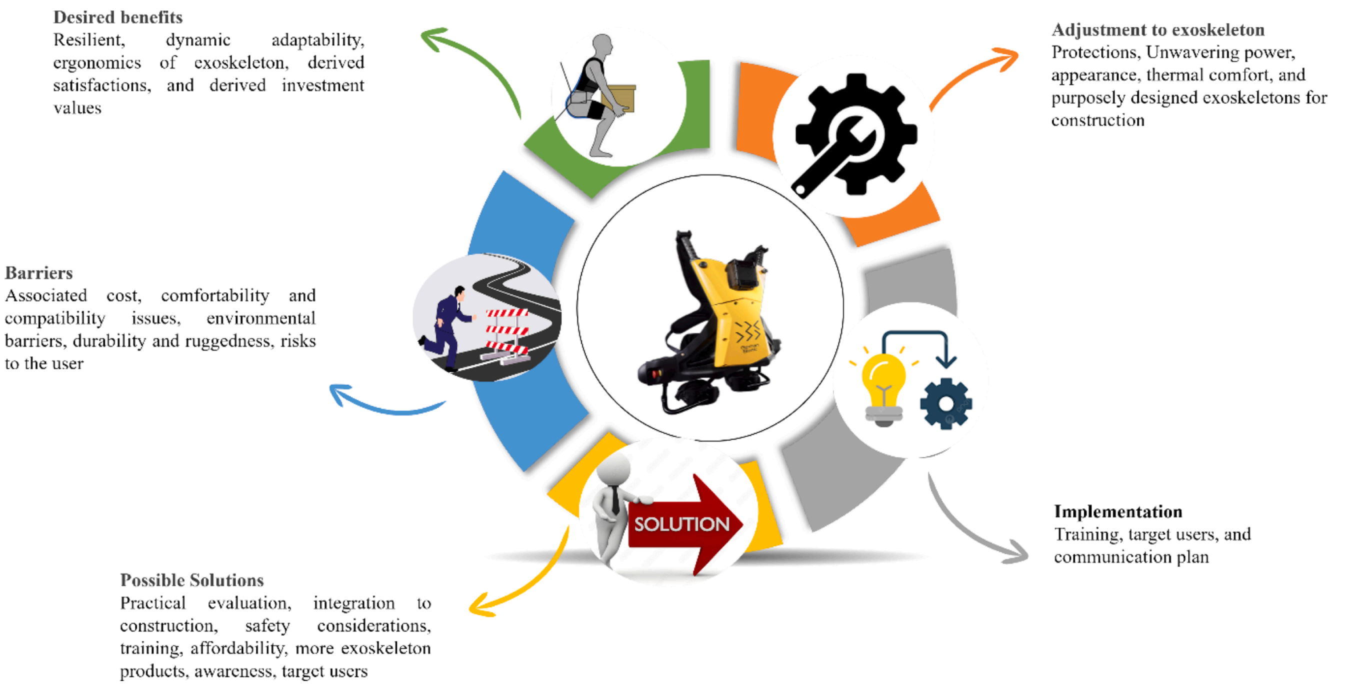

Fig. 4. Categories and themes showing the impact of adopting factors.

barrier to the adoption of the technology, as indicated in the survey results, the participants suggested that reducing the cost and leasing instead of buying could be a good idea. This was best captured by a participant who said, "*Convince manufacturers that they've got to come up with cost-effective solutions.*" The participants believed that it would be nice to convince the manufacturer to produce more products to resolve the issue of the few available options for exoskeletons.

Lastly, creating more awareness by spreading success stories, and most importantly, through young professionals was important.

4.1.4.4. Adjustment to technology. This category suggests possible adjustments that could be made to the technology to suit the construction industry. The themes gathered were protection, power, appearance, thermal comfort, and purposely designed exoskeleton for construction.

Given the dynamic and unstructured nature of the construction site, as indicated by the participants, it is important to make significant adjustments to the exoskeleton. The first theme identified was the protection of the device. The participants suggested that the device must be dust resistant, able to withstand mishandling, have a rugged back case, consider protecting the sensitive parts of the device, and be manufactured with easy-to-maintain materials. A good caption from one of the participants: "*They're going to take it off, run their hands through it, and then they're going to let it hit, drop that one foot to the ground, maybe even a foot and a half to the ground. So, all sides of it have to be able to handle that, even the weaker parts that are sticking out.*" The majority of the participants expected the battery of the device to be able to work for 8 to 10 h a day. Many of the participants discussed the appearance of the exoskeleton, and they suggested that it must be sleek, fit different body sizes, be manufactured with lightweight materials, and have pouches. This was best captured by one of the participants, who said, *"If they protrude too much. it's not going to fly, so they have to be sleek. They have to be as close to a second skin."*

For the thermal comfort of the users, the participants suggested that the manufacturer should consider the comfort of the users who are going to be working in high temperatures. They suggested there could be a kind of cooling system built into the exoskeleton. The last theme generated on adjustment to technology was that the exoskeleton must be purposely built for the construction environment. The participants suggested that the exoskeleton must be customized for construction tasks and consider the integration of safety equipment. This was indicated by a participant, who suggested that *"maybe a product that is suitable for a manufacturing facility is different from one for a construction site. It's got to be fit for purpose. It's got to be designed to work on construction."*

4.1.4.5. Implementation. Possible implementation strategies included training, targeted users, and communication plans. The participants agreed that many of the problems identified could be solved through simplified training procedures and education during the implementation process. This was indicated by one of the participants who said, "*I think you would need to educate and train management and the work crews. So they understood what the benefits were, you know, especially long term on the human body.*" For a successful implementation, the participants believed that it would be better to start by targeting some groups that would promote the benefits of the technology. Some participants believed that targeting the young professionals would be better, as the technology would be too weird for the old professionals. The participants also believed that it would be good to start the implementation with large firms. Lastly, a good communication plan was suggested for the implementation process to communicate the benefits. An example was sighted by a participant, "*You have to bring people in, you have to demonstrate to them, and again, you have to let individuals try it, and then, gaining experience, use that to communicate both through word of mouth and through official communication.*"

4.1.4.6. Suitable construction tasks. Participants proposed various construction tasks that are prone to back-related disorders and could benefit from active back-support exoskeletons. As indicated by the word cloud in Fig. 5, the top prioritized tasks, i.e., the most frequent tasks are "concrete work" and "steelwork." Other tasks, such as general labor work, plumbing work, rebar work, carpentry work, and drywall also appear relatively frequently. The lowest frequency tasks identified by the participants include scaffolding work, electrical work, flooring work, mason, and ceiling work.

Fig. 5. Word cloud showing suitable construction tasks.

5. Theoretical implications

This study was conducted to identify the facilitators and barriers to the adoption of active back-support exoskeletons in the construction industry. Through the Delphi technique and semi-structured interviews of construction industry practitioners, the study identified facilitators, barriers, and solutions to the adoption of active back-support exoskeletons in the construction industry. The findings of this study are explained through the lens of the Technology, Organization, and Environment (TOE) framework.

5.1. Technology

The technology context in the TOE framework relates to existing and non-existing technologies that are relevant to the organization (Baker, 2011). Since this study focused on a technology that had not been used by the firms of the participants, the technology context explains the limit of what is possible to implement such innovative technology. Facilitators, barriers, and possible solutions in the technology contexts are explained in this section.

5.1.1. Facilitators

The study showed that 'understanding the costs and benefits for my organization' was the major facilitator in the adoption of active back-support exoskeletons in the construction industry. Similar studies (Pan & Pan, 2020) referred to this variable as the relative advantage of the technology in the TOE framework. Even though the participants were aware of the technology after the workshop, their major concern was the cost and the benefits. This is not surprising as it has been emphasized in previous studies (Kim et al., 2019; Upasani et al., 2019; Mahmud et al., 2022; Gutierrez et al., 2023). Because the market prices of most exoskeletons range between $2,000 to $100,000, the current costs are still out of reach for those who need them. This cost is more than the total cost it would require to purchase other construction personal protective equipment (PPE) for a single worker (Gutierrez et al., 2023). Besides, there are additional costs associated with the maintenance of exoskeletons, determining the job-specific requirement for exoskeletons, and training the construction workers (Mahmud et al., 2022). Beyond the unit cost, participants considered the multiplier effect of purchasing for all workers within a firm. Another dimension the facilitator identified regarding the active back-support exoskeleton is that participants were concerned about the benefits. Exoskeletons have been touted as a solution to the increasing WMSDs, however, the economic implication of adopting them trumps the benefits (Kim et al., 2019). For the adoption of active back-support exoskeletons to increase, the cost needs to be revised (Cumplido-Trasmonte et al., 2023).

Further insight was provided from the semi-structured interview. The study shows that for the adoption of the exoskeleton technology to increase, desired benefits must be met. Four themes from the desired benefits such as resilience of the exoskeleton, dynamic adaptability, and ergonomics align with the characteristics of the technology context in the TOE framework. This is similar to the technological context factors found in Chau and Tam (1997), Kuan and Chau (2001), and Lee and Shim (2007). As revealed in the results of the semi-structured interview, the benefits associated with technology can endear users towards adopting the technology with little cognizance of the cost. This means that researchers and manufacturers need to continue emphasizing and publicizing the benefits of exoskeletons in the construction industry to influence adoption. Past studies have shown that active back-support exoskeletons can provide better support during construction tasks than their counterparts (Roveda et al., 2020; Kong et al., 2023). The dynamic adaptability of active back-support exoskeletons has also been highlighted by Toxiri et al. (2018). In terms of reducing construction ergonomic risks, studies have shown that active back-support exoskeletons performed excellently during various construction activities (Sado et al., 2019; Poliero et al., 2020; Walter et al., 2023).

5.1.2. Barriers

The major barrier to the adoption of active back-support exoskeleton is the 'incompatibility with other devices.' This is a vital attribute of the characteristics of the technology that cannot be overlooked. Huysamen et al. (2018) opined that if perceptions of positive effects are outweighed by perceptions of negative effects, perceptions of usability can be low among potential users. The integration or compatibility of exoskeleton attachments with standard work attire may play a major role in their success in field applications (Toxiri et al., 2018). This is similar to the findings of Gonsalves et al. (2023) where workers raised concerns regarding the compatibility of exoskeletons with the safety harnesses. Similarly, in the agricultural sector, Upasani et al. (2019) and Omoniyi et al. (2020) showed that incompatibility with the farming environment and equipment was one of the major barriers to farmers adopting exoskeletons. This could be a problem because the compatibility of exoskeletons with on-site tools has been identified as an important factor for the adoption of exoskeletons in the construction industry (Kim et al., 2019). Construction workers usually wear different personal protective equipment and use several tools while they are performing their duties. However, the incompatibility of active back-support exoskeletons with other devices may create new safety risks for the construction worker (Nnaji et al., 2023). Gonsalves et al. (2023) tried to ensure that their participants used harnesses with the exoskeleton they tested, but this resulted in discomfort and high temperatures for the participants. In the technology context of the TOE framework, this may require an overhaul of the exoskeleton design to incorporate other devices needed for each sector. Similar suggestions have been made for design changes where different PPEs are integrated into exoskeletons so that construction workers do not have to put on several pieces of equipment at a time (Kim et al., 2019; Gonsalves et al., 2023).

A review of some themes from the semi-structured interview corroborates the major barrier to the adoption of active back-support exoskeletons in the technology context. Themes such as comfortability and compatibility issues, durability and ruggedness, and design compatibility point to the need to re-evaluate exoskeleton designs for optimum acceptance by users. As indicated in the results of the semi-structured interview, the participants envisage compatibility issues while using exoskeleton and fall protection. This showcases a design flaw that needs to be addressed and raises security and safety concerns. Apart from the compatibility, previous studies (De Looze, Bosch, Krause, Stadler, & O'Sullivan, 2016; Gonsalves et al., 2021) have raised concerns about the comfort level perceived from the use of exoskeletons. Similar to active back-support exoskeletons, Gonsalves et al. (2021) reported perceived discomfort in the lower back when using a passive back-support exoskeleton for manual repetitive handling and rebar work, respectively. Baltrusch, Houdijk, Van Dieën, and de Kruif (2021) noted that this could impact usability, self-efficacy, and safety. Sustained pressure on any part of the body when using active back-support exoskeletons could be perceived negatively (Toxiri et al., 2018). Therefore, the material used to construct an exoskeleton should ensure appropriate breathability to avoid excessive heat and sweating during extended use (Toxiri et al., 2018). Active back-support exoskeleton needs to have reduced unintended consequences such as discomfort to any body parts (De Looze et al., 2016).

5.1.3. Potential solutions

All eight themes (practical evaluation, integration to construction, safety considerations, training, affordability, more exoskeleton products, awareness, and target users) identified through the semi-structured interview can be explained from the technology context lens. For instance, given that the adoption of an active back-support exoskeleton is new to the construction industry, a practical demonstration of using the device over a reasonable period would resolve many of the identified barriers by providing justifiable benefits. This is similar to the suggestion of Kim et al. (2018) where the trialability of exoskeletons was considered a positive way to promote the use of exoskeletons in the construction industry. This could mean translating the exoskeleton use from the laboratories to real-life scenarios. Since real-life experiences are scarce in exoskeleton use in the construction industry, practical demonstrations on construction sites could help increase adoption (Dahmen & Constantinescu, 2020). Toxiri et al. (2018) argued that comfort and usability during extended use will be affected by numerous factors, likely beyond the simplified laboratory scenarios in which the devices are often evaluated for biomechanical effectiveness. Another impact of practical demonstrations is social influence. Previous studies (Kim et al., 2019; Elprama et al., 2020) have highlighted how the social influence of individuals could influence the formation of reactions around the acceptance and usage of technologies.

Another aspect worth discussing in the technology context in the TOE framework is the safety consideration as a potential solution to the barriers that could influence the adoption of active back-support exoskeletons. Despite the positives of exoskeletons, studies (Kim et al., 2018; Nnaji et al., 2023) have shown how human-exoskeleton interactions can introduce new hazards to construction sites. ISO EN 13482 and ASTM F48 have highlighted some hazards that may pertain to exoskeleton use. Risk reduction strategies need to be put in place to prevent or reduce the impact of safety and health risks such as fall risks, catch and snag risks, body discomfort, hygiene concerns, false sense of safety (De Looze et al., 2016; Kim et al., 2019; Zhu, Dutta, & Dai, 2021). Peters and Wischniewski (2022) opined that the identification of risk reduction strategies associated with exoskeletons will enable the prioritization of established control measures in the workplace. One of the risk reduction strategies that have been suggested in previous studies (Gorgey, 2018) is the need for periodic training of construction workers. This would help construction workers to be accustomed to the force output before using them actively in the workplace (Nnaji et al., 2023).

5.2. Organization

The organizational context in the TOE framework explains the characteristics and resources of the firm (Baker, 2011). This includes variables that may be intrinsic or extrinsic to the organization. In this study, facilitators, barriers, and potential solutions associated with the organizational context in the TOE framework are explained in this section.

5.2.1. Facilitators

Awa, Ukoha, and Igwe (2017) noted that organizations are always trying to proficiently use their available resources. One way to achieve this is by using new innovative technologies. In the study by Gonsalves, Khalid, Akinniyi, Ogunseiju, and Akanmu (2022), workers felt that wearing the back-support exoskeleton could help them work for longer hours, which would increase their productivity. This is similar to the findings of this study in the organizational context. The study showed that one of the major facilitators to the adoption of active back-support exoskeleton is 'understanding the productivity gains.' This is in contrast to the organizational context variables (e.g., top management, human resources, interconnectedness, and firm size) provided by Pan and Pan (2020) as the major determinants of construction robot adopters. In this study, the findings point to the organizational resources and processes. Most organizations want to measure and monitor their productivity performance. This is because the construction industry has been struggling with low productivity (Pan et al., 2018). By using exoskeletons, the positive side effect is the productivity gains in the work process (Pan et al., 2018; Gutierrez et al., 2023). Exoskeletons are predominantly used preemptively in production to enhance the actual ergonomic work situation of the workers (Dahmen & Constantinescu, 2020). Kramer et al. (2010) opined that exoskeletons are more likely to be adopted if they demonstrate a higher impact on quality and productivity. In the same light, Gutierrez et al. (2023) reported that users were hesitant to use exoskeletons which hindered their productivity.

'Understanding the productivity gains' construct here aligns with the insight provided in the semi-structured interview. The desired benefit theme of 'derived values from the use of exoskeleton' encapsulates this. The statement of one of the participants gave the bottom line to the adoption of exoskeletons from the organizational perspective: '*It has to be worth it.*' The use of exoskeletons has to be able to provide real-life evidence and data that it can reduce labor costs, benefit the organization and projects, improve productivity, and reduce workers' compensation claims due to WMSDs.

5.2.2. Barriers

The barrier 'buying exoskeleton/affordability/investment' was indicated as one of the major barriers that organizations consider in the adoption of active back-support exoskeleton. Studies (Kim et al., 2019) show that it is a major exoskeleton adoption concern. Similarly, the semi-structured interviews revealed that associated costs can be a major concern within the organization. In contrast, a study (Wang, Wang, & Yang, 2010) identified firm size as the key variable in the organizational context of the TOE framework that can influence adoption. The assumption is that large firms are more likely to adopt new technologies than small ones, as they have more flexibility, resources, and risk tolerance. Pan and Pan (2020) argued that expensive robotics such as exoskeletons are unaffordable to many small and medium-scale firms. However, studies (Baker, 2011; Pan & Pan, 2020) have shown that firm size is not a significant influence, rather, there is a need to view the underlying factor of resources available to the firm. This means that the availability of financial resources is a major key to the successful implementation of exoskeletons. Mahmud et al. (2022) reported that construction companies are hesitant to adopt exoskeletons due to the costs of acquiring and implementing exoskeletons. This is similar to the findings of Kim et al. (2019), who noted that organizations are less likely to adopt exoskeletons if they are too expensive and have a low return on investment. There is a need for more research to highlight the economic implications of exoskeleton adoption by organizations as there is scarce evidence on this line (Baldassarre et al., 2022).

5.2.3. Potential solutions

To resolve the potential barrier of affordability or return on investment that exists within the organizational context of adopting new innovative technology, the semi-structured interview provided some insight. The theme "affordability" was highlighted as a potential solution to increasing the adoption of active back-support exoskeletons. Sadly, very little consideration has been given to the minimization of active exoskeleton costs (Palazzi et al., 2022). Studies (van Dijsseldonk et al., 2023) have shown that there have been several calls to manufacturers to reduce costs. Some researchers (Toxiri et al., 2018; Palazzi et al., 2022) have started designing low-cost solutions, however, most of them are still in the development stage. A few participants in a previous study (van Dijsseldonk et al., 2023) pointed out that the exoskeleton should have fewer functionalities so that it could be marketed cheaper and become accessible to a larger group. However, affordability should not be marketed above functionality and safety (Wolff, Parker, Borisoff, Mortenson, & Mattie, 2014; van Dijsseldonk et al., 2023). To reduce the cost impacts of adopting new technologies, Thiesse, Staake, Schmitt, and Fleisch (2011) suggested cooperation with partners (i.e., exoskeleton manufacturers) via cost-sharing agreements.

5.3. Environment

The environmental context in the TOE framework includes the structure of the industry, the presence or absence of technology service providers, and the regulatory environment (Baker, 2011). The environmental context is dynamic and can be synthesized to the characteristics of the industry (Awa et al., 2017). The environmental context concerns factors that are external to the organization. This can present challenges or opportunities to the adoption of innovative technologies (Tornatzky & Fleischer, 1990; Thiesse et al., 2011). For this study, the facilitators, barriers, and potential solutions in the environmental context are presented.

5.3.1. Facilitators and barriers

In an environmental context, one of the major facilitators to the adoption of an active back-support exoskeleton is the 'ability to walk on uneven surfaces.' Similarly, the barrier identified was the 'inability to walk on uneven surfaces.' This is in contrast to the environmental context variables (e.g., market competitive pressure) used in the TOE framework in previous studies (Pan & Pan, 2020) on the adoption of construction robots. Kim et al. (2019) noted that construction sites are unstructured and pose several safety and usability challenges to construction workers. For instance, workers are concerned that the added weight of the active back-support exoskeleton would cause an imbalance when walking on uneven surfaces. Identifying these factors in opposite directions means that construction workers are concerned about it. On one hand, the participants opined that active back support should be able to allow users to walk on uneven surfaces. While on the other hand, they are concerned that it may not. Gonsalves et al. (2022) showed that back-support exoskeletons can allow workers to walk on uneven terrains while performing construction-related tasks. This is important because if the workers feel unsafe while working with the exoskeleton, it will affect their willingness to use the device (Kim et al., 2019).

5.3.2. Potential solutions

In the environmental context, there is a need for training and increased awareness about the use of active back-support exoskeletons. These themes were identified during the semi-structured interview and can be categorized under the environmental context in the TOE framework. Based on the facilitator and barrier identified under this section, training, and awareness would ensure that users and firms are up-to-date on the benefits and functionalities of the device. To reduce WMSDs, previous training on ergonomic risks has been on postural training (Antwi-Afari et al., 2019; Akanmu, Olayiwola, Ogunseiju, & Mcfeeters, 2020). Despite this postural training, WMSDs in the construction industry continue to remain high. With advancements in exoskeleton technology, there is a need to explore alternative training methods to reduce WMSDs in the construction industry. Gonsalves et al. (2021) suggested using training to influence the perception of other workers to promote the implementation of exoskeletons on construction sites. Similarly, Elprama et al. (2020) noted that construction companies can adopt a training strategy to gain support for exoskeletons among their workers. Witnessing what exoskeletons can achieve may influence their intention to use. Previous studies (Hensel & Keil, 2019) have shown that users' intention to use an exoskeleton was influenced by their perception of the exoskeleton's usability. Through training, Gonsalves et al. (2021) noted that the correlation between workers' intention to use and usability parameters (e.g., comfort, performance, and safety) increased as the week progressed.

6. Conclusion, limitation, and future work

Active exoskeletons are potential technological solutions for construction tasks, due to their advanced powered features. Studies have examined the facilitators and barriers of exoskeletons across different industry sectors, including manufacturing. However, understanding the facilitators and barriers of active back-support exoskeletons in the construction industry context has been overlooked. Therefore, this study's Delphi results showed the facilitators and barriers recognized as the most important adoption factors to consider. Semi-structured interviews revealed the impact of the factors on exoskeletons' adoption in the construction environment and were categorized under desired benefits, barriers, solutions, adjustments, and implementation and applicable construction tasks. Building on the TOE framework, this study discussed the implication of facilitators, barriers, and potential solutions under the technology, organization, and environment context. While this study reveals the facilitators, barriers, and possible solutions to the adoption of exoskeletons in the construction industry, future studies should examine the suitability of available exoskeletons for the construction industry. Findings could help the construction industry understand the factors to be considered in the implementation process of exoskeletons. Also, results help designers understand the requirements and adjustments for active back-support exoskeletons to be fitted in the construction industry. This study also contributes to the body of knowledge on exoskeleton adoption utilizing the existing TOE framework.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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