Understanding the Drivers of and Barriers to Adopting Passive Back- and Arm-Support Exoskeletons in Construction: Results from Interviews and Short-term Field Testing

[a]Mohamad Behjati Ashtiani, https://orcid.org/0009-0004-5607-3409

[a]Wallace Morris, https://orcid.org/0000-0001-5174-1763

[b]Aanuoluwapo Ojelade, https://orcid.org/0000-0001-9715-3254

[a]Sunwook Kim, https://orcid.org/0000-0003-3624-1781

[a]Feyisayo Akinwande, https://orcid.org/0000-0003-0858-885X

[c]Alan Barr, https://orcid.org/0000-0001-6275-0358

[c & d]Carisa Harris-Adamson, https://orcid.org/0000-0003-4031-5034

[e]Abiola Akanmu, https://orcid.org/0000-0001-9145-4865

[a]Maury A. Nussbaum, https://orcid.org/0000-0002-1887-8431

[a] Department of Industrial and Systems Engineering, Virginia Tech, Blacksburg, VA 24061, USA

[b] Department of Industrial and Systems Engineering, University at Buffalo, Buffalo, NY 14226, USA

[c] Department of Medicine, University of California at San Francisco, CA, USA

[d] School of Public Health, University of California at Berkeley, CA, USA

[e] Construction Engineering and Management, Myers Lawson School of Construction, Virginia Tech, Blacksburg, VA, USA

Corresponding address: Maury A Nussbaum

Department of Industrial and Systems Engineering,

Blacksburg, Virginia, United States.

Email: nussbaum@vt.edu

Phone: (540) 231-6053

Abstract

Construction workers experience high rates of work-related musculoskeletal disorders (WMSDs), particularly affecting the back and shoulders. Exoskeletons (EXOs), including arm-support (ASEs) and back-support (BSEs) devices, have clear potential as ergonomic interventions for reducing WMSD risks, yet the specific benefits and limitations in the construction industry remain largely unclear. We aimed to identify drivers and barriers to adopting EXOs in construction, which was done using a two-phase approach: an interview study involving 24 construction stakeholders, followed by a field study with 22 construction workers. Participants in the interview study had hands-on experiences with diverse EXOs, then provided feedback on initial impressions, perceived barriers, and potential benefits of EXO use. Interview recordings were analyzed for sentiment, systematically categorizing responses as positive, neutral, and negative. During the field study, workers wore EXOs while performing their job tasks for up to one hour, then completed structured exit surveys that assessed usability, comfort, safety, and overall satisfaction. We found a generally positive view of EXO technology in construction, with stakeholders open to adoption for enhancing productivity and reducing physical demands. However, usability, safety, and social acceptance concerns indicated a need for design improvements focused on comfort and compatibility. Notably, safety concerns expressed by interviewees contrasted with positive field study responses, suggesting that the input obtained can vary between assessment conditions. Future research should include longitudinal studies to track shifts in perception and assess diverse designs. These findings highlight the need for refined EXOs to meet construction demands and support broader industry adoption.

Keywords: Exoskeletons, Work-related musculoskeletal disorders, Sentiment analysis, construction, ChatGPT, Usability, Safety

1. Introduction

The construction industry continues to be characterized by challenging work environments wherein workers are often exposed to risks of work-related musculoskeletal disorders (WMSDs). Such exposures are primarily related to tasks requiring heavy lifting, non-neutral postures, repetitive motions, and prolonged postures (Umer et al., 2018). In 2021 alone, 164,700 non-fatal injuries were reported in the construction sector (BLS, 2022), with over 20% attributed to WMSDs (CPWR, 2023). The most commonly affected body areas were the back and shoulder, which respectively accounted for 42% and 12% of lost workday cases in the construction sector in 2017 (Dong et al., 2019). In addition to the health consequences, WMSDs cause considerable financial burdens due to medical expenses (Bhattacharya, 2014) and productivity loss (Bevan, 2015). In recent years, occupational exoskeletons (EXOs)—and soft devices or exosuits—have emerged as promising ergonomic interventions to help reduce or prevent WMSD risks (de Bock et al., 2022; De Looze et al., 2016; Torricelli et al., 2020). Given the prevalence of back and shoulder injuries in construction, we focused on EXOs that provide support to the shoulder, referred to as arm-support exoskeletons (ASEs), and the back, referred to as back-support exoskeletons (BSEs). We also focused on passive EXOs, which do not require actuators or a power supply. These devices were of particular interest due to their lighter, simpler, and more cost-effective design, making them more likely to gain widespread adoption in the construction sector in the near future (Voilqué et al., 2019).

Earlier research on EXO use in construction has focused primarily on understanding construction stakeholders' perspectives regarding the adoption and implementation of these devices, as well as their efficacy in reducing physical demands during construction-relevant tasks. For example, investigators have explored factors that facilitate or hinder EXO adoption, such as user intention, potential applications, and barriers to widespread implementation, often employing interviews and questionnaires as research methods (Gonsalves et al., 2024; Gutierrez et al., 2024; Kim et al., 2019; Mahmud et al., 2022). Such studies demonstrated that wearing EXOs can reduce perceived physical demands and muscle activity, especially in the back and shoulders, during construction-related tasks like lifting, carrying, block-laying, plastering, and ceiling construction (Alemi et al., 2020; Baltrusch et al., 2024; de Vries et al., 2021; Mänttäri et al., 2024; Musso et al., 2024; Song et al., 2024; Zheng et al., 2024). As highlighted in recent reviews (Gagnon et al., 2023; Nnaji & Karakhan, 2020), EXOs have clear potential for mitigating WMSD risks in the construction industry.

However, current knowledge regarding EXO adoption and use in construction is primarily derived from responses to interviews and questionnaires, often without providing hands-on experience with different types of EXOs. Hand-on experience with EXOs may be important because such exposure could influence stakeholders' opinions and perceptions considerably. For example, Schwerha et al. (2022) found that manufacturing stakeholders with experience using EXOs during their jobs raised more practical concerns (e.g., related to work quality and fit). Similarly, Raghuraman et al. (2023) demonstrated that even short-term exposure to EXOs can alter perceptions of the usefulness and safety of these devices. These findings suggest that hands-on experience with EXOs is essential to ensure more complete and valid assessments of practicality and effectiveness. As mentioned in a recent review (Al-Khiami et al., In Press), an existing research gap is that earlier reports focused on a limited set of tasks, overlooking the broader range of construction activities. To better assess EXO effectiveness in real-world

conditions, there is a need to examine a more diverse set of tasks. Additionally, existing research predominantly investigated the effects of a single EXO (de Vries et al., 2023; Lindhard et al., 2023), further highlighting the need for assessing potential differences between EXO types.

The current study consisted of two phases, with a central research question of helping to determine what are the expected benefits of and barriers to adopting EXO technology in construction. We did so by providing construction stakeholders with hands-on experience with different EXOs, either through simulated tasks or in their actual work environments for a short use period. The first phase was an Interview Study conducted with construction stakeholders after they tried various EXOs. The second phase was a Field Study, which used a mixed-methods approach and had construction workers use different EXOs for up to two hours during their job tasks. We anticipated that the findings from this study could promote the effective adoption and use of EXOs in construction and offer recommendations for their broader implementation across the industry.

2. Methods

2.1. Interview study

2.1.1. Participants

A total of 24 participants completed one-on-one semi-structured interviews. The mean age of the participants was 37.6 years (SD = 12.8; range = 22–61 years). Their job titles included construction laborer instructor (n = 4), superintendent or assistant superintendent (n = 4), project/business/safety/field manager (n = 5), field representative (n = 2), assistant safety director (n = 1), masonry worker (n = 3), pipe worker (n = 1), electrician (n = 1), supervisor (n = 1), and resident quantity surveyor (n = 1). Job experience ranged from 1 to 35 years, with a mean (SD) of 14.6 (10.8) years and data missing for one participant. The biological sex reported by the interviewees included 22 males and two females. Prior to data collection, participants provided informed consent following procedures approved by the Virginia Tech Institutional Review Board.

2.1.2. Interview processes and materials

We visited construction sites in Virginia and South Carolina, and a labor training center in Ohio, to familiarize construction stakeholders with various EXOs. Familiarization included providing hands-on experiences through performing tasks in non-work settings. We included three BSEs (Paexo Back [Ottobock], backX Type S [suitX], HeroWear Apex V1 and three ASEs (Paexo Shoulder [Ottobock], shoulderX [suitX], EVO [EksoBionics]). These EXOs were selected to represent a range of design characteristics and were commercially available at the time of the interviews. We explained the basic mechanisms of EXO operation and demonstrated procedures for donning, doffing, and fitting the devices. Participants then had the opportunity to try whichever EXOs they desired. Familiarization and hands-on experience typically lasted 2–3 hours. Subsequently, most interviews were conducted on-site; however, some participants opted to complete their interviews via an online conferencing tool (Zoom) due to time constraints. All interviews were audio-recorded.

Interview questions were designed to elicit in-depth discussions on interviewee impressions and perceptions of ASEs and BSEs. Specific questions addressed readiness, necessary training resources, perceived challenges, peer acceptance, physical effects, safety concerns, work performance, potential tasks that could benefit most from the use of ASEs and BSEs, reasonable pricing, and the party responsible for covering the cost. Interviewees were also asked to provide anthropometric and demographic information. The complete interview script is available in Appendix A and was adopted from Kim et al. (2019). Compensation was provided to interviewees at a rate of $50/hour.

2.1.3. Sentiment analysis of interviews

Recorded interviews were first transcribed verbatim using a speech-to-text model (Radford et al., 2023) through the Whisper library from OpenAI in Python (Version 3.10.12). We then proofread the transcriptions to correct any errors, and we organized the answers to each question by separating the responses from all interviewees according to specific interview questions. We divided the questions into different categories and subcategories adopted from our earlier studies (Gutierrez et al., 2024; Kim et al., 2019). The five categories and the corresponding questions are summarized in Table 1.

Table 1. Categories and subcategories for content analysis of interview study

Category	Subcategories	Question
First impressions	Arm-support Exoskeletons	What are your first impressions of arm-support exoskeletons?
	Back-support Exoskeletons	What are your first impressions of back-support exoskeletons?
Readiness for use	-	Do you think exoskeletons are ready to be used in your work?
Perceived Barriers	Peer acceptance	How do you think other workers will respond, either positively or negatively, when exoskeletons are introduced at construction sites?
	Safety impacts	Do you think using an exoskeleton could affect safety?
Expected Benefits	Productivity	Do you think using an exoskeleton could affect work performance such as in terms of productivity, efficiency, or quality?
	Physical impact	Do you think using an exoskeleton could affect workers physically, either in a good way or a bad way (e.g., fatigue, discomfort, effort, injuries, etc.)?
Technology Adoption	Training material	If you were going to try out an exoskeleton at your workplace, what would you want or like to know? What resources would you want or like to have?
	ASEs task examples	What do you think are examples of tasks that could most benefit from using arm-support exoskeletons?
	BSEs task examples	What are some examples of tasks that could most benefit from using back-support exoskeletons?
	Price	What would be a reasonable price for an exoskeleton?
	Responsibility for cost	Who do you think should pay for exoskeletons?

To assess the emotional tone of the responses, we employed sentiment analysis, a natural language processing method that classifies text as positive, neutral, or negative (Mohammad, 2016). Sentiment analysis was not performed for Technology Adoption, as the questions were intended to gather factual information rather than emotions or impressions. This technique provided a systematic framework for quantifying subjective viewpoints and analyzing the emotional context of the data. We used the GPT-4 model to conduct sentiment analysis, a large language model (LLM) based on OpenAI's GPT-4 architecture, accessed via OpenAI's Python

library (Brown, 2020). LLMs such as GPT-4, which are built on transformer-based architectures, excel at understanding the context, syntax, and semantics of complex language inputs (Yadav, 2024). The model's attention mechanism enables it to process long-range dependencies in text, making it highly effective in capturing nuanced sentiment, even in complex or ambiguous responses (Ralambomihanta et al., 2024; Yadav, 2024).

To conduct the sentiment analysis, we employed a so-called *zero-shot* prompting approach inspired by a previous study (Fatouros et al., 2023). This approach leverages GPT-4's extensive language training and understanding of patterns to generate responses without requiring task-specific fine-tuning or additional training. Zero-shot learning is a machine learning technique wherein a model can recognize or make predictions about new, unseen classes without any prior training data for those specific classes (Lampert et al., 2013). This technique relies on transferring knowledge from previously learned classes to infer information about new ones, using high-level features or attributes that link known and unknown classes. Previous studies have demonstrated the effectiveness of this model (GPT-4) for zero-shot sentiment classification across various fields, including the financial domain and customer feedback analysis (Fatouros et al., 2023; Krugmann & Hartmann, 2024).

For our study, we set the model "temperature" parameter to zero, ensuring outputs were near deterministic (Krugmann & Hartmann, 2024). This parameter typically ranges between 0 and 1 and controls the level of randomness in the model's responses, with lower values producing more predictable and repetitive behavior and with higher values increasing randomness (OpenAI., 2024). Then, we created a specific prompt that established context by identifying the respondents as construction industry experts and clearly stating the question posed. We instructed the model to classify the sentiment of each response as positive, neutral, or negative. The prompt we used is provided below, in which 'question' and 'response' placeholders were replaced for each specific inquiry:

Prompt*: "The following is a response from a construction industry expert to the question:* ***'question'****. Please classify the sentiment of the response as either 'positive', 'neutral', or 'negative'. Response:* ***'response'****."*

The process of sentiment analysis involved dynamically replacing 'question' with the actual interview question, and 'response' with the participant's verbatim response. The formatted prompt was sent to the GPT-4 API, which analyzed the linguistic features, word choices, and overall tone to determine the appropriate sentiment category. Leveraging a pre-trained understanding of language patterns, emotional cues, and contextual semantics, GPT-4 classified each response as positive, neutral, or negative. Specifically, the model assessed sentiment based on sentiment-related words, phrases, and syntactic structures. For instance, responses containing words such as "beneficial," "helpful," or "effective," were typically classified as positive, while those including "problematic," "ineffective," or "difficult" were classified as negative. Descriptive or factual responses without strong emotional connotations were labeled as neutral. The API then returned a single sentiment label ("positive," "neutral," or "negative") as a text output, which was extracted and stored in our dataset for further analysis.

We also extracted frequent comments and key points from the responses to all questions, using an AI-powered tool (ChatGPT by OpenAI) that recent studies confirmed provides reasonably

reliable results (Bijker et al., 2024; Morgan, 2023). One of us then verified the final interpretations. Representative direct quotes are provided below, though some have been lightly edited to enhance clarity.

2.2. Field study

2.2.1 Participants and study design

We conducted short-term field testing of EXOs at local construction sites in southwestern Virginia and the California Bay area. Both local Institutional Review Boards approved the study protocol, and all participants provided informed consent before data collection. Participation was limited to volunteers who were aged 18 to 65 years and with no significant musculoskeletal disorders that would limit their work activities; who were currently employed in construction with at least one year of experience; and who had a waist size between 26 and 46 inches (to ensure proper EXO fit). A total of 22 participants (21 male and 1 female) completed the study. Their job titles included: electrician (n = 4), sheet metal worker (n = 5), plumber (n = 4), laborer (n = 2), flooring installer (n = 2), concrete worker (n = 2), painter (n = 1), and rebar worker (n = 2). Participants had a mean age of 33.3 years (SD = 12.5; range = 18 - 60 years); they also reported mean (SD) body mass as 85.6 (15.7) kg and stature as (SD) 1.76 (0.1) m. Job experience varied from 1 to 35 years (mean = 9.2, SD = 10). We provided access to seven commercially available EXOs. Specifically, three BSEs that included suit X backX Type S (suitX), HeroWear Apex V1 (HeroWear), and Laevo Flex; and four ASEs that included suitX shoulderX V2, Ottobock Paexo Shoulder, EksoBionics, and Levitate Airframe Flex. These EXOs were selected to represent diverse design characteristics and because each had been used in reported pilot testing in several industries prior to our study.

2.2.2. Field study procedures data collection

We recruited participants after an introductory session in which EXOs were introduced and informal feedback was gathered. Workers were selected based on their trades, with a limit of five participants per specialty. We allowed all participants to try on the EXOs, provided time for practice, obtained consent, and fitted the devices. Additionally, all participants completed an entry survey that included questions about demographics, anthropometry, job title, and work experience. Participants were instructed to select the device they felt would most support their work based on their job requirements and comfort level with the device. As they evaluated each EXO, we provided them with instructions on how the device offers physical support (e.g., to the back or shoulder regions), how to adjust the fit and support, and how to engage and disengage the support if relevant. We also addressed any questions that arose regarding using the device. Participants were then fitted with their chosen EXOs and then worked for an hour using the EXO (Figure 1) with the option to discontinue use at any time. They subsequently completed a usability exit survey, which used 1-10 scales to assess comfort, ease of use, balance, range of motion, safety, performance, and perceptions of environmental temperature, as well as items on usefulness, acceptance, and open-ended questions (see Appendix B). Participants then had the option to try a different EXO for one additional hour, following the same procedures. The EXOs that were selected are summarized in Table C1 of Appendix C. Compensation was provided to participants at a rate of $50/hour.

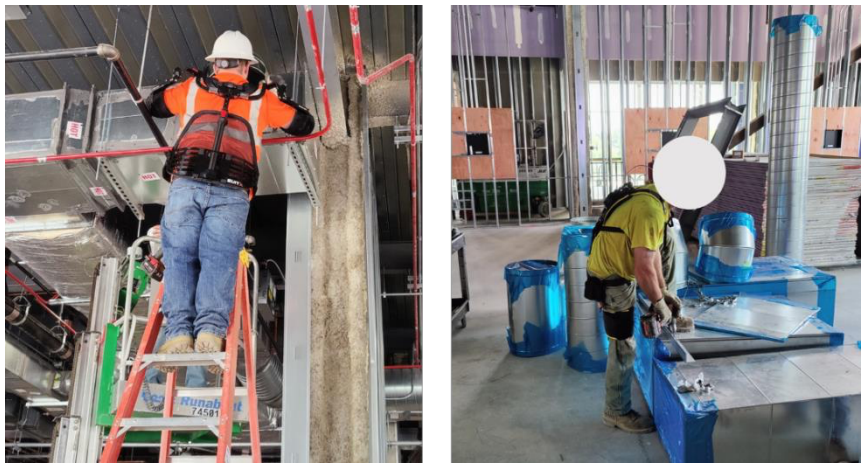

Figure 1. Photographs of two participants wearing an exoskeleton while performing their construction tasks (left: suitX shoulderX arm-support exoskeleton; right: HeroWear Apex V1 back-support exosuit).

2.2.3. Field study data analysis

Descriptive statistics were derived for the 1-10 responses to thermal perception and usefulness questions (questions 1, 2, and 5 in Appendix B), treating these responses as interval data (Wu & Leung, 2017). Responses for each Likert scale item (questions 3, 4, 6, and 7 in Appendix B) were categorized as follows: scores of 1 and 2 were classified as strongly disagree or extremely unlikely; 3 and 4 as disagree or unlikely; 5 and 6 as neutral; 7 and 8 as agree or likely; and 9 and 10 as strongly agree or extremely likely. We then categorized the exit survey questions into the aforementioned categories. Note that the subcategories for the interview questions were not identical; Table 2 presents the categories and subcategories related to the exit survey used for field testing. One of the categories also differed; in the field study, we assessed whether participants were ready to use EXOs, while in the interviews, we asked whether the EXOs were ready for use in construction. To analyze responses to the open-ended questions in the exit survey, we applied the same approach used for the interview data, employing an AI-powered tool (ChatGPT by OpenAI).

Table 2. Categories and subcategories of responses to questions in the field study exit survey

Category	Subcategories	Question	Scale
First impressions	-	Overall, I am satisfied with it (Q1)	Strongly Disagree, Disagree, Neutral, Agree, and Strongly Agree
		The exoskeleton's capabilities meet my requirements (Q2)	
Readiness to use	-	It should be a standard work device that is available for my job (Q3)	Strongly Disagree, Disagree, Neutral, Agree, and Strongly Agree
		I would recommend it to coworkers (Q4)	
		If your employer provided this exoskeleton to you, how likely would you be to use it? (Q5)	Extremely unlikely, Unlikely, Neutral, Likely, Extremely Likely
		How likely would you be to use this exoskeleton if you had to purchase it? (Q6)	
Perceived Barriers	Peer acceptance	Wearing it will be socially accepted in construction work (Q7)	Strongly Disagree, Disagree, Neutral, Agree, and Strongly Agree
	Safety impacts	It negatively affects work safety (Q8)	Strongly Disagree, Disagree, Neutral, Agree, and Strongly Agree
		It positively affects work safety (Q9)	
		It negatively affects my balance during work (Q10)	
	Usability	It is comfortable to wear during my work (Q11)	
		It is easy to use during my work (Q12)	
		It limits my movement (Q13)	
		I have to spend too much time correcting things with it, such as adjusting the fit (Q14)	
		Using it is a frustrating experience (Q15)	
		I have concerns about maintaining it (e.g., cleaning, repairing) (Q16)	
		What was your perception of thermal comfort and/or feelings of sweatiness when using the exoskeleton during your work? (Q17)	Interval (1 very cold - 10 very hot)
Expected Benefits	Productivity	Compared to working without it, how did the exoskeleton affect the following characteristics of your work? (Speed, quality, fatigue) (Q18)	Interval (1 slower-10 faster)
	Physical impact	It reduces discomfort or pain in my body during my work, such as in the back or shoulders (Q19)	Strongly Disagree, Disagree, Neutral, Agree, and Strongly Agree
		It reduces my level of physical effort during my work (Q20)	

3. Results

3.1. First impressions and readiness to/for use

3.1.1. Interview responses

Sentiment analysis indicated that most interviewees held positive impressions of ASEs (67%), BSEs (75%), and the readiness of EXOs for use in construction (60%). However, a non-trivial subset of participants expressed neutral or even negative impressions (Figure 2).

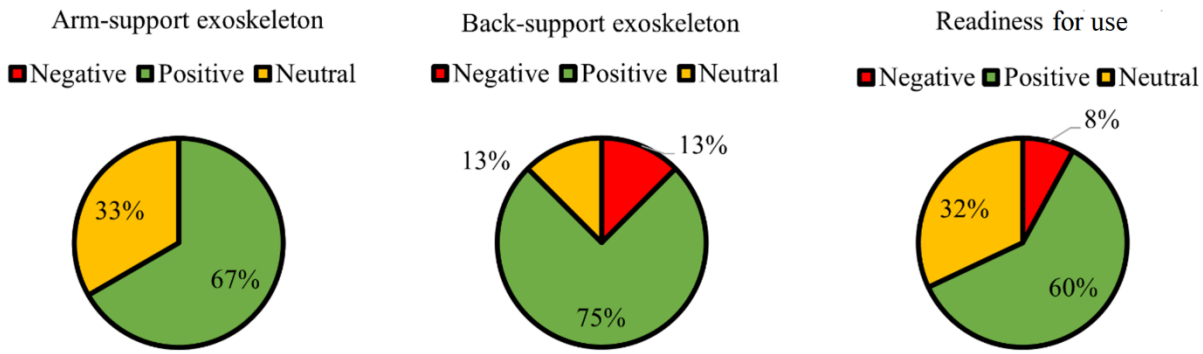

Figure 2. Results of sentiment analysis for responses to questions regarding impressions of exoskeletons and readiness for use in construction.

Regarding ASEs, nearly half (~46%) of the interviewees expressed liking how the ASEs provided support for overhead work and helped reduce strain. For example, one stated: *But I think if you're in a factory, ..., shooting bolts over your head, I thought that would be fantastic*. However, approximately a fifth (~21%) raised concerns about the ASEs being bulky or uncomfortable. As one noted: *... just I guess how bulky it is, and sometimes it feels like it helps your movement when picking things up, but it also kind of restricts you in certain areas, too*. A similar portion (~21%) noted that an ASE would be more beneficial for specific tasks, such as overhead work, than for general use. One interviewee elaborated: *In masonry, it wouldn't be too beneficial. I mean, if you're doing stuff overhead, but for a laborer throwing block up on six-foot frames, it would be good, but other than that, not too beneficial.*

For BSEs, nearly half (~46%) of interviewees appreciated the support provided by BSEs during lifting and bending. One interviewee mentioned: *When you bend down, the back exoskeleton helps you come back to a standing position.* Additionally, several (~21%) mentioned that BSEs would be particularly useful for specific tasks, such as in masonry and asphalt work. A similar percentage highlighted that BSEs helped with posture and made lifting easier. As one interviewee explained: *The back support one [device], I liked it the most. Because when you're bending over and lifting stuff up, it kind of springs you back up. In a sense, it's like somebody grabbing the back of your shirt and pulling you up.* However, similar to the ASEs, one-third expressed concerns about the BSEs being bulky or uncomfortable, particularly in confined spaces. For instance, one noted: *but my worry is how viable the usage will be in a confined space, where you don't have a lot of room to move around*.

Regarding readiness of EXOs for use, a third (~33%) indicated that the EXOs were nearly ready for implementation, requiring only minor modifications. For example, one interviewee noted: *They're pretty close. Just a few little tweaks are needed. The only concern I have is, will they get damaged if I bump up against something or if I'm pouring concrete and it dries on them? I might not get it washed quickly enough.* Yet, a smaller portion (~12%) raised concerns that exoskeletons might interfere with other equipment, such as fall arrest harnesses. As one interviewee elaborated: *The confined space concerns are about job sites where you have to wear harnesses, and I haven't tried that yet. I'm curious if the harness goes on the outside or the inside of these and how it will work with a harness.* Additionally, nearly a third (~29%) expressed concerns about the need for further adjustments, particularly related to bulkiness and comfort.

3.1.2. Field study responses

The responses to the open-ended questions indicated that participants reported discomfort that stemmed from wearing the EXO, primarily in body regions such as the shoulders/armpits, upper arms, lower back/hips, and where leg straps made contact, although half indicated they experienced no discomfort. Negative feedback that was provided included bulkiness hindering movement, heat buildup, and interference with harnesses or tool belts. On the positive side, participants valued the support provided by EXOs during overhead tasks, the ability of EXOs to alleviate back pain and reduce physical strain, as well as the ease of use.

Table C2 summarizes the exit survey responses regarding participants' impressions and readiness to use the EXO (Appendix C). For first impressions, the majority expressed satisfaction, with many participants agreeing (~41%) and a notable number strongly agreeing (~34%) that they were satisfied with the EXO (Q1). Regarding EXO capabilities, some participants were neutral (35%), while a smaller group strongly agreed (~29%) that the device met their job requirements (~Q2). In terms of participant readiness to use the EXO, a portion was neutral (36%) about whether it should become a standard work device (Q3), while some participants agreed (~24%). However, a similar proportion agreed (~31%) and strongly agreed (~31%) that they would recommend a given EXO to coworkers (Q4). When asked about the likelihood of using the EXO if provided by their employer (Q5), some indicated they would likely use it (~34%), while a comparable group was extremely likely to use it (~31%). However, when considering purchasing the EXO personally (Q6), a portion were neutral (~31%), while some were extremely likely to do so (~25%).

3.2. Perceived barriers

3.2.1 Interview responses

A majority of interviewees expressed neutral impressions regarding peer acceptance of EXOs (50%) and the potential impact of EXOs on safety (58%). A noteworthy subset of participants expressed positive impressions regarding peer acceptance and negative impressions concerning safety impact (Figure 3).

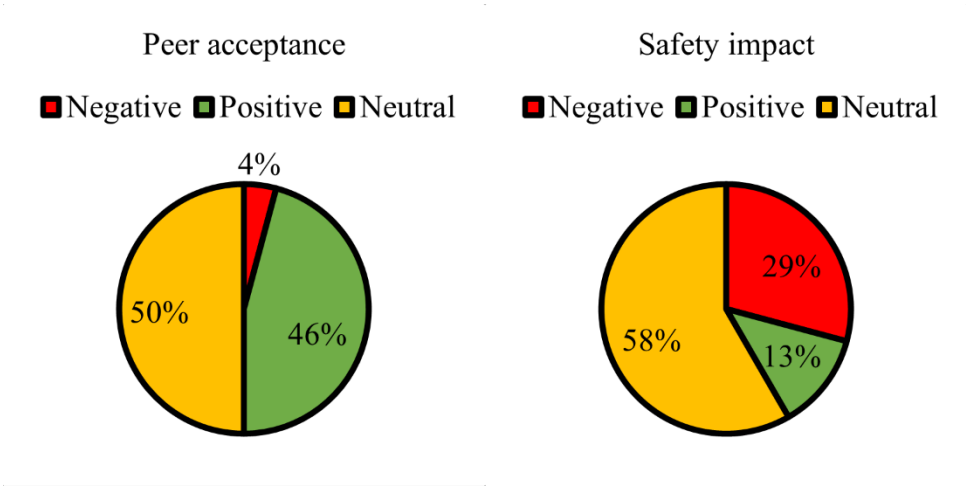

Figure 3. Results of sentiment analysis for responses to questions regarding peer acceptance and the safety impact of EXOs in the construction workplace.

Concerning peer acceptance, two-thirds (~67%) of interviewees mentioned that they anticipated initial skepticism, but they believed that over time workers would respond positively once they experienced the benefits of EXOs, such as reduced fatigue and injury prevention. For example, one interviewee remarked: *I think they will be apprehensive at first, because they might tell each other this is another safety measure or another restriction. ..., but if they realize it's going to help them with injuries and longevity in the trade, I think they might come around*. Additionally, a quarter (~25%) mentioned that some workers might be curious and willing to try exoskeletons out of interest in new technology. As one interviewee explained: *So you're saying at both levels, it's just curiosity about why they're being used. You need to know what it is, what it's doing.* However, several (~21%) suggested that workers might initially mock or tease others who use EXOs. One interviewer noted: *Well, if only one guy was wearing it at first, he'd probably get made fun of a little bit…* Additionally, ~17% mentioned that younger workers are more likely to embrace the technology, while older workers may resist. For instance, one interviewee shared: *Some of the old timers are going to make fun of you and think you're, you know, you're going into the future.*

Regarding the safety impact of EXOs, many (~79%) interviewees had concerns about the exoskeleton getting snagged or caught on objects, potentially leading to safety risks. Relevant quotes include: *... especially in a confined space. If it gets caught on the stairs, usually you don't want two people in a manhole, and sometimes you can only fit one person in a manhole. So how are you going to save someone down there who might be trapped? You know what I mean?* and *the only part about safety is getting snagged on something just because it is away from your body. Maybe climbing drop-side ladders and stuff like that, getting hung up on something.*

Additionally, about one-fifth (~21%) expressed concerns about ensuring that EXOs integrate with other safety equipment, like fall arrest harnesses, to avoid interfering with current safety practices. For example, one interviewee noted: *When needed, a harness of some sort. I'm trying to figure out a way to use a harness or make these harnesses compatible.* Another interviewee mentioned that it might create a false sense of security: *My only question is, will it give them a*

false sense of security about how much they can actually do? Will it make them feel like, well, I'm Superman. I can do anything I want to and pick up something I normally wouldn't when wearing the exoskeleton, and then they go, oh, wait. On the other hand, ~33% mentioned that exoskeletons could help prevent injuries, particularly those caused by repetitive strain or improper lifting. One interviewee said: *I can see it preventing some of the chronic exposures, especially from repetitive tasks. If you have a drywaller, for example, he's going to be doing that for eight hours a day, 40 hours a week, 50 weeks of the year. That's a real chronic exposure over time, and that can really affect someone working with their hands above them. If you reduce some of the fatigue they're experiencing, it can help.*

3.2.2 Field study responses

Participants offered diverse suggestions for improving the EXO in open-ended questions, including enhancing fit and comfort, reducing bulk, adding cooling features to the padding, and improving compatibility with tool belts. Maneuverability in tight spaces was another concern. Some challenges that were expressed related to daily use included the inconvenience of donning and doffing the device, discomfort over prolonged use, and difficulties in navigating confined spaces. However, many suggested that these challenges would be manageable.

In terms of peer acceptance (Q7), over half of participants (~54%) responded that the EXO would gain social acceptance in construction work. Regarding safety, most participants (~63%) disagreed that the EXO had a negative impact on work safety (Q8), with nearly half (~47%) perceiving it as positively impacting safety (Q9). Balance concerns were minimal (Q10), as a substantial majority (~69%) indicated that the EXO did not negatively affect their balance.

Regarding usability, over half of participants (~53%) indicated that wearing the EXO was comfortable (Q11), and nearly two-thirds (~65%) agreed it was easy to use (Q12). Some concerns were noted, with about half (~51%) indicating it restricted movement (Q13). Maintenance was also a concern (Q16) for nearly half (~44%) of participants, though a majority (~78%) disagreed that adjusting the EXO was time-consuming (Q14), and most (~82%) did not find using it to be a frustrating experience (Q15) (Table C3, Appendix C). Participants rated thermal comfort while using the EXO (Q17) as "just comfortable" as "just comfortable," with a mean (SD) of 4.8 (1.9).

3.3. Expected benefits

3.3.1. Interview responses

Most interviewees expressed positive impressions regarding the effect of EXOs on productivity (~75%) and a positive perspective on the physical effect (~63%). However, some participants expressed neutral or even negative impressions (Figure 4).

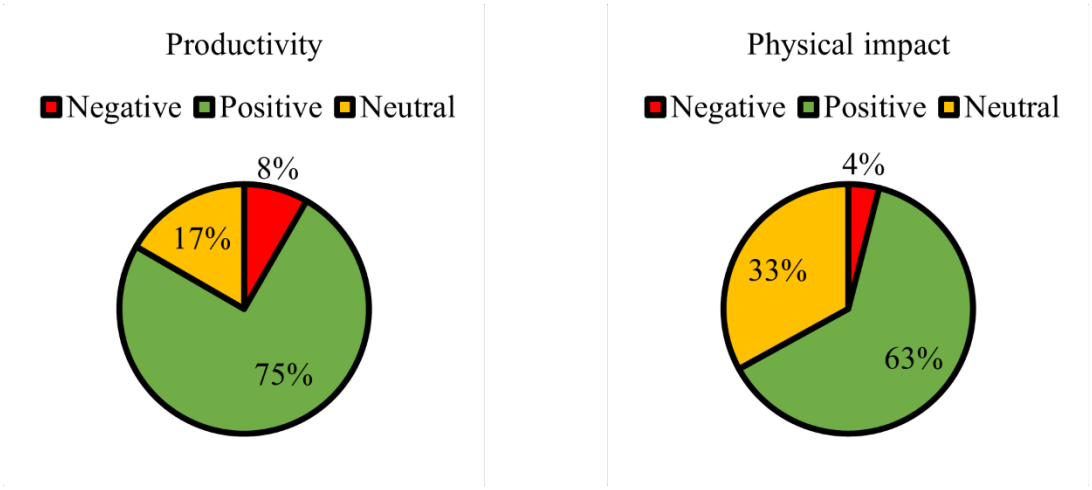

Figure 4. Results of sentiment analysis for responses to questions regarding interviewees' perspective on peer acceptance and safety impact of exoskeletons.

Roughly 42% of interviewees mentioned that the exoskeleton could reduce fatigue or help conserve energy, leading to increased productivity. For example, one interviewee stated: *So, if I could have one of those, you know, a type of form of a back brace or the back exoskeleton, like the light one. I think it takes a lot of strain off your back. So, at the end of the day, you will feel a lot better*. On the other hand, several (~17%) noted an initial adjustment or learning curve when using the exoskeleton, which could negatively affect productivity. One interviewee explained: *It just, yeah, the time it takes to put it on and take it off. So, on that note, for the most part, we see after you spend a considerable amount of time, you need to adjust it to your body the first time. After that, you can more or less put it on and off yourself relatively easily, you know, within a minute.* On the other hand, some interviewees (~9%) expressed concerns about the exoskeleton slowing down work due to the need for adjustments or discomfort. One interviewee noted: *I wouldn't say better… put things on while you walk, then, you know, you just think just a little bit of, oh, let me adjust this while you're doing something, and make a mistake. So, yeah, it's going to affect productivity and some aspects of the work*. Moreover, one interviewee mentioned that older workers might have more difficulty adjusting to EXO use compared to younger workers: *Probably the older generation. I mean, if we're being honest, then they're not going to take to it the same way that the younger generation will.*

Concerning the physical impact of EXOs, most (~67%) interviewees mentioned that exoskeletons would reduce fatigue, particularly in the shoulders and back. One interviewee stated: *So, using these things to help you lift things easier, not put stress on your body and stuff like that, it's going to save trips to the chiropractor. It's going to save trips to the doctor. You're going to go home. You're not going to be as tired.* On the other hand, 25% of interviewees mentioned potential discomfort, such as chafing, rubbing, or the bulkiness of the exoskeleton. One interviewee noted: *But the rubbing and sweating would be the only other issues I'd probably see with it. Yeah, because I don't wear overalls in the winter just for the fact I hate being restricted when I'm moving and bending over.* Additionally, some (~13%) expressed concern about potential over-reliance on the exoskeleton, which could lead to other problems or injuries. One interviewee explained: *But I do think there could be some over-reliance. And I don't know if*

we're going to have concomitant overuse injuries if you start over-relying on the exoskeleton. ... Because whenever you over-rely on a strength, you create another weakness. Lastly, some (~13%) interviewees indicated that exoskeletons could restrict movement, particularly when bending or performing specific tasks. One interviewee remarked: *I think it's going to restrict you bending over, trying to walk and put the screws in while you're bent over.*

3.3.1. Field study responses

For productivity (Q18), mean ratings of EXO effects were 5.5 for speed, 6.2 for quality, and 6.9 for fatigue, suggesting moderate to slightly positive overall effects compared to working without the EXO. Regarding physical impact (Q19), many (~60%) participants agreed or strongly agreed that the EXO reduced discomfort or pain in areas like the back or shoulders, while some (~19%) were neutral. Additionally, the majority (~61%) agreed or strongly agreed that it reduced their physical effort (Q20), with only ~16% expressing disagreement.

3.4. Adoption of exoskeleton technology

Two-thirds of the interviewees expressed the need for training sessions, educational materials, and instructions on the proper use of the exoskeletons. One interviewee stated: *I'd say training sessions. If you implement a training session, show it to the guys. I can see a lot of guys, they'll take that, put it on, and then be able to go out and use that out on the field.* Additionally, a smaller group (~9%) emphasized the importance of providing information on return on investment and productivity benefits. One interviewee explained: *Well, if you want to get a contractor to buy into it, showing them the costs of injuries versus saving benefits, but then you have to have a track record.* Furthermore, a quarter of interviewees highlighted the importance of safety instructions, especially concerning fitting, electrical hazards, and handling the EXO in various environments. Relevant quotes include: *Definitely want to know the materials. Do they conduct electricity, those things? We have guys on lifts, things of that nature. It could be closer to power lines, transformers. When I walk around in a plant, are they conductive?* and *yeah, it would definitely help informing them and then getting them on board as far as using them would be making sure that the tasks they're using them for are the proper tasks they're designed for.*

Several tasks were identified where ASEs could be beneficial. Around half (~54%) of participants highlighted drywalling, particularly for overhead tasks. Ceiling work, including screwing, drilling, and other overhead activities, was mentioned by about a third (~37%). Additionally, tasks performed by electricians and pipe installers were noted by roughly 30%. Concrete work and jackhammering were identified by ~25%, with masonry and bricklaying indicated by approximately 21%. Framing and carpentry were also mentioned by several interviewees (~21%), and painting and welding were highlighted by about 13%.

Interviewees also identified several tasks for which BSEs could be beneficial. Approximately 38% noted concrete work, including setting forms, cutting, screeding, and using jackhammers. About 33% indicated masonry and bricklaying as tasks where BSEs would be useful, while another 33% highlighted general construction tasks involving bending and lifting, such as carpentry and laying out materials. Other tasks mentioned included pipe laying and installation (around 13%), landscaping tasks—such as moving trees and planting (approximately 13%)—

flooring work like laying tiles or working on flooring (about 13%), and roofing and general labor (also around 13%).

Interviewees noted a wide range of what they considered reasonable prices for an EXO, specifically between $100 and $5,000. All indicated that employers should bear responsibility for covering the costs.

4. Discussion

We examined the perceptions and concerns of construction stakeholders—such as managers, instructors, superintendents, safety directors, and onsite workers—regarding the use of ASEs and BSEs. These inputs were obtained after the participants had hands-on experience with EXOs, either through performing tasks in non-work settings or over a short duration (up to one hour) of actual work on site. We used a qualitative approach to obtain a reasonably broad understanding of the readiness to/for use, barriers, expected benefits, and technology adoption aspects of EXO technology within the construction industry. Overall, the results of both the interview and field studies suggested that there is optimism regarding the applications of EXOs in construction, but that there are also important and prevalent concerns about EXO safety and usability.

4.1. First impressions and readiness for/to use exoskeletons

Results from the interviews (Figure 2) and the field study (Table C2) indicated that stakeholders had a positive impression of both ASEs and BSEs, highlighting the readiness of this technology for use, while workers also stated a willingness to use EXOs in their workplace. While interviewees and participants appreciated the support provided by EXOs, they also emphasized the need for design improvements, particularly in reducing bulkiness and enhancing comfort. These findings align with earlier studies, highlighting the importance of addressing comfort and functionality to promote broader acceptance and integration of EXOs within the construction industry (Bennett et al., 2023; Gutierrez et al., 2024). Specifically, Gutierrez et al. (2024) reported that 83% of workers expressed a willingness to use EXOs after completing an online survey. However, they also indicated that improvements in design are needed to address discomfort. Similarly, Bennett et al. (2023) found mixed opinions during a field assessment of construction workers using EXOs, with some participants expressing willingness to use the devices, while others reported discomfort during use.

4.2. Perceived barriers

The interview results revealed concerns about the social acceptance of EXOs in the workplace, with most interviewees expressing neutral or negative sentiments about peer acceptance (Figure 3). In contrast, the field study participants generally expressed that EXOs would be socially accepted during their tasks (Table C3). While earlier research (Elprama et al., 2020; Kim et al., 2019) identified social acceptance as a potential obstacle, the differences we found between the interviews and field study suggest that acceptance may be context-dependent and influenced by direct experience with EXOs in the workplace. This divergence suggests that social acceptance may not be a static barrier but rather one that varies based on exposure and work setting. Additionally, both of our current studies suggested that social acceptance could vary with age. Gutierrez et al. (2024) similarly found that generational differences may influence the readiness to embrace EXO technology in the construction industry.

Usability was a common concern in both the interviews and the field study. Interviewees raised concerns about the compatibility of EXOs with other equipment, as well as their comfort and range of motion. Similarly, field study participants reported having challenges related to limited movement and experiencing discomfort, and they shared concerns about how to store and maintain the EXOs. Other researchers have identified similar concerns about EXOs being uncomfortable and limiting range of motion (Maurice et al., 2018; Nnaji et al., 2023; Schwerha et al., 2022; Schwerha et al., 2021). These practical aspects of EXO use highlight the need for design improvements to enhance the usability and compatibility of EXOs for various construction tasks, environments, and integration with other equipment.

There were mixed findings between the interviews and the field study regarding safety implications. Most (~79%) interviewees raised concerns about the potential for EXOs to get snagged or caught on objects, particularly in confined spaces, which could pose safety risks. Other concerns included integrating EXOs with existing safety equipment, such as harnesses, and the possibility of creating a false sense of security. These concerns were also reported in earlier studies (Kim et al., 2019; Raghuraman et al., 2023; Schwerha et al., 2021). Some interviewees (~33%) here, though, pointed out that EXOs could help prevent injuries, especially those resulting from repetitive strain or improper lifting.

In contrast, our field study participants did not express notable safety concerns, possibly because their tasks did not involve risks of snagging or getting caught. The discrepancy in safety concerns between the interviewees and field study participants suggests the importance of context in evaluating EXO safety practices. These concerns may have been task-specific and influenced by differing views on technology. Further, the tasks tested in the field study were not performed in tight spaces and did not require safety equipment, which may not have fully reflected the concerns raised in the interviews. The difference in outcomes could also have stemmed from differing perspectives on safety between workers or between experience levels and types (Namian et al., 2022). Maurice et al. (2018) found similar differences between groups, with non-workers expressing more concern about user safety, while workers tended to trust EXOs regarding safety.

4.3. Expected Benefits

Both the interview and field studies revealed a generally positive perception of EXOs regarding productivity among construction stakeholders and workers. Interviewees noted the potential of EXOs to reduce fatigue and conserve energy, although some indicated that an initial adjustment period could temporarily decrease productivity. Overall, while EXOs show potential to enhance productivity in construction tasks, addressing usability concerns seems essential to maximizing their effectiveness to increase productivity. Previous reports have presented mixed findings regarding the impact of EXOs on productivity. In two laboratory studies that assessed productivity based on task completion time, one found a decrease when using a BSE (Madinei et al., 2020) while another reported an increase with ASE use (Kim et al., 2018); both studies, though, found relatively small effects. Results from a recent field study indicated either no impact on work rate or perceived quality (de Vries et al., 2023), while another longitudinal study found lowered expectations regarding productivity and health benefits (Dufraissse et al., 2025). In our current work, interviews and field testing both provided only short-term, hands-on experience, rather than longitudinal assessments, suggesting that productivity outcomes may

require further evaluation over extended periods and could vary depending on the specific tasks performed.

Interview responses indicated a favorable perspective on the effects of EXOs on physical well-being. Participants mentioned that EXOs could help reduce fatigue, particularly in the shoulders and back. However, concerns were also expressed about discomfort, such as chafing or bulkiness. Some participants feared that over-reliance on EXOs might lead to other injuries, while others worried about movement restrictions during specific tasks. Similar concerns were expressed during field testing, though participants generally indicated that using an EXO alleviated discomfort and reduced physical effort. These results highlight the potential benefits of EXOs in reducing physical demands while also emphasizing the importance of addressing discomfort and movement restrictions for effective integration into construction work, which aligns with findings from previous studies (De Looze et al., 2016; Gutierrez et al., 2024; Mahmud et al., 2022; Theurel & Desbrosses, 2019).

4.4. Adoption of exoskeleton technology

We found general agreement among interviewees regarding the need for training and educational materials for using EXOs. Most interviewees (~67%) emphasized the necessity of training sessions to ensure proper usage, highlighting that hands-on instruction would enhance understanding and effectiveness in the field. Safety instructions were also deemed crucial, particularly concerning proper fitting, electrical hazards, and handling protocols in various work environments. These findings, also highlighted in prior work (Gorgey, 2018; Gutierrez et al., 2024; Mahmud et al., 2022), suggest that comprehensive training and educational resources are vital for the successful adoption of EXOs in construction.

Return-on-investment was also a key theme in the responses, highlighting that the initial costs of EXOs still need to be justified for stakeholders to consider adoption. Similar concerns about the cost-benefit balance of EXOs were reported by Kim et al. (2019). The decision to invest in EXOs appears to be driven not only by the potential to reduce injury-related costs but also by the expectation of tangible financial returns. This evidence may imply that justifying an EXO investment based solely on the potential for injury prevention will be ineffective without stronger evidence of actual injury reduction and associated cost savings, as well as potential productivity benefits. These findings underscore the need for more robust data on the long-term health outcomes and economic impacts of EXO use to support broader adoption.

4.5. Limitations and future needs

We acknowledge three important limitations in these two studies. First, the hands-on experience with exoskeletons in both phases was brief. Dufraissse et al. (2025) noted that operator perceptions of EXOs can shift over the course of a longitudinal study. For future research, we recommend assessing stakeholder perceptions after a more extended evaluation period. Second, while we aimed to diversify the types of EXOs used and the tasks tested in the field study, the number of participants and tasks was limited due to challenges in recruiting. This limitation prevented us from comparing outcomes quantitatively across different EXO designs or tasks. We recommend a more comprehensive evaluation of different EXO designs across a variety of

construction tasks. Third, the stakeholders and construction workers in our study may not fully represent the broader construction industry, potentially introducing bias into the results. Future studies should include a more diverse sample to enhance the generalizability of our findings.

5. Conclusions

We examined the perceptions and concerns of construction stakeholders regarding the use of ASEs and BSEs, finding a generally positive outlook on the applicability of this technology. Stakeholders expressed a readiness for/to use EXOs, recognizing the potential to enhance productivity and mitigate physical strain. However, critical concerns about usability, safety, and social acceptance emerged, indicating a need for design improvements to address issues such as comfort and compatibility with other equipment. Our finding aligns with earlier studies, suggesting that similar results may be achieved across various study designs, contexts, and populations, and supporting the validity and generalizability of these findings. Our current work also highlighted a discrepancy between the concerns expressed by interviewees regarding EXO safety and the generally positive responses from field study participants, suggesting that perceptions of safety may vary depending on the context of use and the user. The short duration of field testing, however, might have limited the ability of workers to fully understand/experience certain EXO benefits or concerns. Future research should involve longitudinal studies to capture shifts in stakeholder perceptions of EXO technology and to include more diverse populations, EXO designs, and construction tasks. Our findings also underscore the need for future refinement of EXOs to address safety concerns and enhance usability, ensuring the technology meets the specific demands of construction work and supports broader adoption across the industry.

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7. Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, we used ChatGPT to refine some sentences and improve the clarity of the text. After using this tool/service, we reviewed and edited the content as needed, and we take full responsibility for the content of this publication.

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We sincerely thank the reviewers for the constructive comments. Based on these comments, we have made several changes that we believe have enhanced the quality of our paper. Our responses here to each comment are provided in blue font. Specific changes made to the manuscript are indicated here in blue font with yellow background, and their locations in the manuscript are provided. These changes are also highlighted in yellow background with black font in the manuscript itself.

Editor and Reviewer comments:
I have now received reviews from experts in areas particularly relevant to your manuscript. The recommendations range from major to minor revisions. Their reviews are appended to this letter for your review. Reviewer #1 recommends clarifying the methodology for GPT-based sentiment analysis and articulating the study's novelty compared to existing research. Reviewer #2 suggests adding research questions, clarifying the exoskeleton selection process, and expanding the discussion on return-on-investment considerations, particularly regarding productivity improvements. Both reviewers agree that incorporating recent literature and addressing these points would enhance the manuscript's clarity, rigor, and practical relevance, making it a strong candidate for publication.

1. Are the objectives and the rationale of the study clearly stated?

Reviewer #1: To strengthen the introduction and research motivation, the authors should incorporate references to recent studies published in prominent journals such as IJIE and Ergonomics.

We have incorporated additional references (Al-Khiami et al., In Press; Song et al., 2024; Zheng et al., 2024; de Vries et al., 2023; Lindhard et al., 2023; de Vries et al., 2021) into the Introduction (Page 3, lines 29, 30, 42, and Page 4, line 5). Additionally, we have updated the introduction to improve the clarity of the objectives.

Page 3, lines 26–30:
"… Such studies demonstrated that wearing EXOs can reduce perceived physical demands and muscle activity, especially in the back and shoulders, during construction-related tasks like lifting, carrying, block-laying, plastering, and ceiling construction (Alemi et al., 2020; Baltrusch et al., 2024; de Vries et al., 2021; Mänttäri et al., 2024; Musso et al., 2024; Song et al., 2024; Zheng et al., 2024)."

Page 3, line 40 to page 4, line 3:
"… These findings suggest that hands-on experience with EXOs is essential to ensure more complete and valid assessments of practicality and effectiveness. As mentioned in a recent review (Al-Khiami et al., In Press), an existing research gap is that earlier reports focused on a limited set of tasks, overlooking the broader range of construction activities. To better assess EXO effectiveness in real-world conditions, there is a need to examine a more diverse set of tasks. Additionally, existing research predominantly investigated the effects of a single EXO (de Vries et al., 2023; Lindhard et al., 2023), further highlighting the need for assessing potential differences between EXO types."

Reviewer #2: Yes.

2. If applicable, is the application/theory/method/study reported in sufficient detail to allow for its replicability and/or reproducibility?

Please provide suggestions to the author(s) on how to improve the replicability/reproducibility of their study. Please number each suggestion so that the author(s) can more easily respond.

Reviewer #1: Mark as appropriate with an X:
Yes [X] No [] N/A []
Provide further comments here:

Reviewer #2: Mark as appropriate with an X:
Yes [X] No [] N/A []
Provide further comments here:

3. If applicable, are statistical analyses, controls, sampling mechanism, and statistical reporting (e.g., P-values, CIs, effect sizes) appropriate and well described?

Please clearly indicate if the manuscript requires additional peer review by a statistician. Kindly provide suggestions to the author(s) on how to improve the statistical analyses, controls, sampling mechanism, or statistical reporting. Please number each suggestion so that the author(s) can more easily respond.
Reviewer #1: Mark as appropriate with an X:
Yes [] No [] N/A [X]
Provide further comments here:

Reviewer #2: Mark as appropriate with an X:
Yes [X] No [] N/A []
Provide further comments here:

4. Could the manuscript benefit from additional tables or figures, or from improving or removing (some of the) existing ones?

Please provide specific suggestions for improvements, removals, or additions of figures or tables. Please number each suggestion so that author(s) can more easily respond.

Reviewer #1: The figures and tables currently included are satisfactory.

Reviewer #2: No.

5. If applicable, are the interpretation of results and study conclusions supported by the data?

Please provide suggestions (if needed) to the author(s) on how to improve, tone down, or expand the study interpretations/conclusions. Please number each suggestion so that the author(s) can more easily respond.

Reviewer #1: Mark as appropriate with an X:
Yes [X] No [] N/A []
Provide further comments here:

Reviewer #2: Mark as appropriate with an X:
Yes [X] No [] N/A []
Provide further comments here:

6. Have the authors clearly emphasized the strengths of their study/theory/methods/argument?

Please provide suggestions to the author(s) on how to better emphasize the strengths of their study. Please number each suggestion so that the author(s) can more easily respond.

Reviewer #1: The article presents several general conclusions derived from the interviews and field study. However, it is unclear what new insights or unique perspectives this research offers. For example, were any novel viewpoints discovered? There are already numerous studies on the acceptance of exoskeletons in the construction industry. What distinguishes the findings of this study from previous research?

In our research, we aimed to address the question of what the expected benefits of and barriers to adopting EXO technology in construction are. We did this by examining various types of EXOs and tasks, based on what we considered to be a substantial research gap that we tried to identify in the Introduction. While prior studies have investigated EXO acceptance, they have often focused on a limited range of tasks and EXO types, overlooking the potential variability in adoption across different work contexts.

Methodologically, our study incorporated sentiment analysis of interview data using a large language model, allowing for both a quantitative assessment and an in-depth qualitative interpretation of stakeholder perspectives. Additionally, we conducted a field study in which participants were provided with a broader range of EXOs compared to prior field studies and could select and use up to two devices of their choice during their work. This approach enabled us to capture real-world perceptions and usability considerations under more representative conditions.

Regarding our findings, some were indeed consistent with existing research. The consistency of our findings with earlier studies suggests that similar results may be replicated across different study designs, contexts, and populations. This alignment reinforces the reliability of existing research on EXO acceptance while also strengthening the validity and generalizability of our findings. By combining sentiment analysis with field observations and providing participants with direct EXO experience, our study offers a more comprehensive understanding of the factors influencing EXO adoption and use in construction. We also suggest that there is an important role for confirmatory evidence, since such evidence is very much lacking given the novelty of exoskeleton research.

We also believe that we have provided insights that may differ from previous studies. To emphasize this point, we have updated the manuscript (page 17, lines 34 to 38):

"While earlier research (Elprama et al., 2020; Kim et al., 2019) identified social acceptance as a potential obstacle, the differences we found between the interviews and field study suggest that acceptance may be context-dependent and influenced by direct experience with EXOs in the workplace. This divergence suggests that social acceptance may not be a static barrier but rather one that varies based on exposure and work setting."

Additionally, we observed differences in safety perceptions between the interview and field study phases. Interviewees expressed concerns about safety, but workers did not raise similar concerns when using the devices in practice. This discrepancy may be due to differing perspectives on safety between workers (participants in the field study) and non-workers (most interviewees) or task-dependent factors. We discussed these findings in Section 4.2 of the Discussion (page 18, lines 10–28). Evidence from the literature supports this hypothesis, as Maurice et al. (2018) also identified discrepancies in EXO safety concerns between workers and non-workers.

Reviewer #2: Yes.

7. Have the authors clearly stated the limitations of their study/theory/methods/argument?

Please list the limitations that the author(s) need to add or emphasize. Please number each limitation so that author(s) can more easily respond.

Reviewer #1:
Beyond the limited sample size, the representativeness of the stakeholders and construction workers may pose a concern, potentially introducing bias into the results.

Thank you for your constructive comment. We have updated our discussion of study limitations to include this point as follows (page 19, Section 4.5):

Page 19, Section 4.5:
"We acknowledge three important limitations in these two studies. First, … Second, … Third, the stakeholders and construction workers in our study may not fully represent the broader construction industry, potentially introducing bias into the results. Future studies should include a more diverse sample to enhance the generalizability of our findings."

Reviewer #2: Yes.

8. Does the manuscript structure, flow or writing need improving (e.g., the addition of subheadings, shortening of text, reorganization of sections, or moving details from one section to another)?

Please provide suggestions to the author(s) on how to improve the manuscript structure and flow. Please number each suggestion so that author(s) can more easily respond.

Reviewer #1: The manuscript structure is fine.

Reviewer #2: No.

9. Could the manuscript benefit from language editing?

Reviewer #1: Yes

Reviewer #2: No

Reviewer #1: This article aims to examine the drivers and barriers to adopting exoskeletons in construction. The methodology is well-structured, incorporating both an interview study and a field study. Notably, the field study included rigorous hands-on trials where participants actively wore and used exoskeletons, enhancing the credibility of the findings. The paper could be considered for acceptance after addressing the following issues:

1. Title Revision: As the study focuses exclusively on certain types of exoskeletons (e.g., passive, back, and shoulder exoskeletons), the title should be revised to more accurately reflect the specific scope of the research.

We agree and have updated the title, which now reads as follows:

"Understanding the Drivers of and Barriers to Adopting Passive Back- and Arm-Support Exoskeletons in Construction: Results from Interviews and Short-term Field Testing"

2. Details on Sentiment Analysis Using GPT: The authors should clarify the methodology for employing GPT in sentiment analysis. Providing detailed information about the process and

implementation would significantly enhance the transparency and reproducibility of this aspect of the study.

We have added the following paragraph to the manuscript (page 7, lines 29 to 40) to clarify our methodology for sentiment analysis using GPT-4:

"The process of sentiment analysis involved dynamically replacing 'question' with the actual interview question, and 'response' with the participant's verbatim response. The formatted prompt was sent to the GPT-4 API, which analyzed the linguistic features, word choices, and overall tone to determine the appropriate sentiment category. Leveraging a pre-trained understanding of language patterns, emotional cues, and contextual semantics, GPT-4 classified each response as positive, neutral, or negative. Specifically, the model assessed sentiment based on sentiment-related words, phrases, and syntactic structures. For instance, responses containing words such as "beneficial," "helpful," or "effective," were typically classified as positive, while those including "problematic," "ineffective," or "difficult" were classified as negative. Descriptive or factual responses without strong emotional connotations were labeled as neutral. The API then returned a single sentiment label ("positive," "neutral," or "negative") as a text output, which was extracted and stored in our dataset for further analysis."

3. Novelty of Findings: While the article presents general conclusions from the interviews and field study, the novelty and unique contributions of the research remain unclear. For instance, were any distinct or innovative insights uncovered? Given the abundance of studies on the acceptance of exoskeletons in the construction industry, it is essential to articulate what sets this study apart from existing research.

We have tried to address this comment in our response to the comment related to Question 6 above.

4. Inclusion of Recent Literature: To strengthen the introduction and discussion sections, the authors should incorporate references to recent studies published in prominent journals such as IJIE and Ergonomics.

We have tried to address this comment in our response to the comment related to Question 1 above.

Reviewer #2: General Comments to the Authors

The objective of this paper was to "identify drivers and barriers to adopting EXOs in construction". This general topic is appropriate for this journal. The manuscript is well written with a clear objective that is relevant to current challenges in musculoskeletal disorder prevention. I have just a few comments that I would like the authors to consider/address before publication.

Specific Comments to the Authors

1. Introduction. The Introduction does a nice job of motivating the current work. Please conclude the Introduction with stated research question(s) and testable hypotheses.

Thank you for your feedback. We appreciate this suggestion. Due to the qualitative nature of our study, though, we did not formulate testable hypotheses. Instead, our research was guided by more exploratory questions to understand stakeholder and worker perceptions, as well as the barriers to and facilitators of EXO adoption in construction. We have updated the manuscript as follows (page 4, lines 4–6) to explicitly state our research question.

Page 4, lines 4–6:

"The current study consisted of two phases, with a central research question of helping to determine what are the expected benefits of and barriers to adopting EXO technology in construction."

2. Section 2.2.2. The authors note that the "Participants were then fitted with their chosen EXOs" how were these chosen? Was any guidance (particularly ASE vs. BSE) given?

Thank you for your constructive comment. We have revised our manuscript based on your feedback, which now reads as follows (page 8, lines 29-33).

Page 8, lines 29-33:

"Participants were instructed to select the device they felt would most support their work based on their job requirements and comfort level with the device. As they evaluated each EXO, we provided them with instructions on how the device offers physical support (e.g., to the back or shoulder regions), how to adjust the fit and support, and how to engage and disengage the support if relevant. We also addressed any questions that arose regarding using the device."

3. Section 3.4. I am glad that you raised the question of Exo cost. My own experience in this sector is that if an intervention does not improve productivity - regardless of how much reduction in back/shoulder stress - it is dead in the water. Are you able to expand at all this critically important "return on investment" aspect of this work?

Thank you for your constructive comment. We have revised our manuscript expand on this aspect, which now reads as follows (page 19, line 23 to line 31).

"Return-on-investment was also a key theme in the responses, highlighting that the initial costs of EXOs still need to be justified for stakeholders to consider adoption. Similar concerns about the cost-benefit balance of EXOs were reported by Kim et al. (2019). The decision to invest in EXOs appears to be driven not only by the potential to reduce injury-related costs but also by the expectation of tangible financial returns. This evidence may imply that justifying an EXO investment based solely on the potential for injury prevention will be ineffective without stronger evidence of actual injury reduction and associated cost savings, as well as potential productivity benefits. These findings underscore the need for more robust data on the long-term health outcomes and economic impacts of EXO use to support broader adoption."

Highlights

- Explored facilitators of and barriers to exoskeleton (EXO) adoption in construction
- Interview responses were analyzed for sentiment: positive, neutral, or negative
- Field study had workers use EXOs, followed by queries on usability and comfort
- Stakeholders viewed EXOs positively, highlighting productivity and demand reduction
- Usability, safety, and acceptance concerns emphasize need for design improvements

Understanding the Drivers of and Barriers to Adopting Passive Back- and Arm-Support Exoskeletons in Construction: Results from Interviews and Short-term Field Testing

[a]Mohamad Behjati Ashtiani, https://orcid.org/0009-0004-5607-3409

[a]Wallace Morris, https://orcid.org/0000-0001-5174-1763

[b]Aanuoluwapo Ojelade, https://orcid.org/0000-0001-9715-3254

[a]Sunwook Kim, https://orcid.org/0000-0003-3624-1781

[a]Feyisayo Akinwande, https://orcid.org/0000-0003-0858-885X

[c]Alan Barr, https://orcid.org/0000-0001-6275-0358

[c & d]Carisa Harris-Adamson, https://orcid.org/0000-0003-4031-5034

[e]Abiola Akanmu, https://orcid.org/0000-0001-9145-4865

[a]Maury A. Nussbaum, https://orcid.org/0000-0002-1887-8431

[a] Department of Industrial and Systems Engineering, Virginia Tech, Blacksburg, VA 24061, USA

[b] Department of Industrial and Systems Engineering, University at Buffalo, Buffalo, NY 14226, USA

[c] Department of Medicine, University of California at San Francisco, CA, USA

[d] School of Public Health, University of California at Berkeley, CA, USA

[e] Construction Engineering and Management, Myers Lawson School of Construction, Virginia Tech, Blacksburg, VA, USA

Corresponding address: Maury A Nussbaum

Department of Industrial and Systems Engineering,

Blacksburg, Virginia, United States.

Email: nussbaum@vt.edu

Phone: (540) 231-6053

Abstract

Construction workers experience high rates of work-related musculoskeletal disorders (WMSDs), particularly affecting the back and shoulders. Exoskeletons (EXOs), including arm-support (ASEs) and back-support (BSEs) devices, have clear potential as ergonomic interventions for reducing WMSD risks, yet the specific benefits and limitations in the construction industry remain largely unclear. We aimed to identify drivers and barriers to adopting EXOs in construction, which was done using a two-phase approach: an interview study involving 24 construction stakeholders, followed by a field study with 22 construction workers. Participants in the interview study had hands-on experiences with diverse EXOs, then provided feedback on initial impressions, perceived barriers, and potential benefits of EXO use. Interview recordings were analyzed for sentiment, systematically categorizing responses as positive, neutral, and negative. During the field study, workers wore EXOs while performing their job tasks for up to one hour, then completed structured exit surveys that assessed usability, comfort, safety, and overall satisfaction. We found a generally positive view of EXO technology in construction, with stakeholders open to adoption for enhancing productivity and reducing physical demands. However, usability, safety, and social acceptance concerns indicated a need for design improvements focused on comfort and compatibility. Notably, safety concerns expressed by interviewees contrasted with positive field study responses, suggesting that the input obtained can vary between assessment conditions. Future research should include longitudinal studies to track shifts in perception and assess diverse designs. These findings highlight the need for refined EXOs to meet construction demands and support broader industry adoption.

Keywords: Exoskeletons, Work-related musculoskeletal disorders, Sentiment analysis, construction, ChatGPT, Usability, Safety

1. Introduction

The construction industry continues to be characterized by challenging work environments wherein workers are often exposed to risks of work-related musculoskeletal disorders (WMSDs). Such exposures are primarily related to tasks requiring heavy lifting, non-neutral postures, repetitive motions, and prolonged postures (Umer et al., 2018). In 2021 alone, 164,700 non-fatal injuries were reported in the construction sector (BLS, 2022), with over 20% attributed to WMSDs (CPWR, 2023). The most commonly affected body areas were the back and shoulder, which respectively accounted for 42% and 12% of lost workday cases in the construction sector in 2017 (Dong et al., 2019). In addition to the health consequences, WMSDs cause considerable financial burdens due to medical expenses (Bhattacharya, 2014) and productivity loss (Bevan, 2015). In recent years, occupational exoskeletons (EXOs)—and soft devices or exosuits—have emerged as promising ergonomic interventions to help reduce or prevent WMSD risks (de Bock et al., 2022; De Looze et al., 2016; Torricelli et al., 2020). Given the prevalence of back and shoulder injuries in construction, we focused on EXOs that provide support to the shoulder, referred to as arm-support exoskeletons (ASEs), and the back, referred to as back-support exoskeletons (BSEs). We also focused on passive EXOs, which do not require actuators or a power supply. These devices were of particular interest due to their lighter, simpler, and more cost-effective design, making them more likely to gain widespread adoption in the construction sector in the near future (Voilqué et al., 2019).

Earlier research on EXO use in construction has focused primarily on understanding construction stakeholders' perspectives regarding the adoption and implementation of these devices, as well as their efficacy in reducing physical demands during construction-relevant tasks. For example, investigators have explored factors that facilitate or hinder EXO adoption, such as user intention, potential applications, and barriers to widespread implementation, often employing interviews and questionnaires as research methods (Gonsalves et al., 2024; Gutierrez et al., 2024; Kim et al., 2019; Mahmud et al., 2022). Such studies demonstrated that wearing EXOs can reduce perceived physical demands and muscle activity, especially in the back and shoulders, during construction-related tasks like lifting, carrying, block-laying, plastering, and ceiling construction (Alemi et al., 2020; Baltrusch et al., 2024; de Vries et al., 2021; Mänttäri et al., 2024; Musso et al., 2024; Song et al., 2024; Zheng et al., 2024). As highlighted in recent reviews (Gagnon et al., 2023; Nnaji & Karakhan, 2020), EXOs have clear potential for mitigating WMSD risks in the construction industry.

However, current knowledge regarding EXO adoption and use in construction is primarily derived from responses to interviews and questionnaires, often without providing hands-on experience with different types of EXOs. Hand-on experience with EXOs may be important because such exposure could influence stakeholders' opinions and perceptions considerably. For example, Schwerha et al. (2022) found that manufacturing stakeholders with experience using EXOs during their jobs raised more practical concerns (e.g., related to work quality and fit). Similarly, Raghuraman et al. (2023) demonstrated that even short-term exposure to EXOs can alter perceptions of the usefulness and safety of these devices. These findings suggest that hands-on experience with EXOs is essential to ensure more complete and valid assessments of practicality and effectiveness. As mentioned in a recent review (Al-Khiami et al., In Press), an existing research gap is that earlier reports focused on a limited set of tasks, overlooking the broader range of construction activities. To better assess EXO effectiveness in real-world

conditions, there is a need to examine a more diverse set of tasks. Additionally, existing research predominantly investigated the effects of a single EXO (de Vries et al., 2023; Lindhard et al., 2023), further highlighting the need for assessing potential differences between EXO types.

The current study consisted of two phases, with a central research question of helping to determine what are the expected benefits of and barriers to adopting EXO technology in construction. We did so by providing construction stakeholders with hands-on experience with different EXOs, either through simulated tasks or in their actual work environments for a short use period. The first phase was an Interview Study conducted with construction stakeholders after they tried various EXOs. The second phase was a Field Study, which used a mixed-methods approach and had construction workers use different EXOs for up to two hours during their job tasks. We anticipated that the findings from this study could promote the effective adoption and use of EXOs in construction and offer recommendations for their broader implementation across the industry.

2. Methods

2.1. Interview study

2.1.1. Participants

A total of 24 participants completed one-on-one semi-structured interviews. The mean age of the participants was 37.6 years (SD = 12.8; range = 22–61 years). Their job titles included construction laborer instructor (n = 4), superintendent or assistant superintendent (n = 4), project/business/safety/field manager (n = 5), field representative (n = 2), assistant safety director (n = 1), masonry worker (n = 3), pipe worker (n = 1), electrician (n = 1), supervisor (n = 1), and resident quantity surveyor (n = 1). Job experience ranged from 1 to 35 years, with a mean (SD) of 14.6 (10.8) years and data missing for one participant. The biological sex reported by the interviewees included 22 males and two females. Prior to data collection, participants provided informed consent following procedures approved by the Virginia Tech Institutional Review Board.

2.1.2. Interview processes and materials

We visited construction sites in Virginia and South Carolina, and a labor training center in Ohio, to familiarize construction stakeholders with various EXOs. Familiarization included providing hands-on experiences through performing tasks in non-work settings. We included three BSEs (Paexo Back [Ottobock], backX Type S [suitX], HeroWear Apex V1 and three ASEs (Paexo Shoulder [Ottobock], shoulderX [suitX], EVO [EksoBionics]). These EXOs were selected to represent a range of design characteristics and were commercially available at the time of the interviews. We explained the basic mechanisms of EXO operation and demonstrated procedures for donning, doffing, and fitting the devices. Participants then had the opportunity to try whichever EXOs they desired. Familiarization and hands-on experience typically lasted 2–3 hours. Subsequently, most interviews were conducted on-site; however, some participants opted to complete their interviews via an online conferencing tool (Zoom) due to time constraints. All interviews were audio-recorded.

Interview questions were designed to elicit in-depth discussions on interviewee impressions and perceptions of ASEs and BSEs. Specific questions addressed readiness, necessary training resources, perceived challenges, peer acceptance, physical effects, safety concerns, work performance, potential tasks that could benefit most from the use of ASEs and BSEs, reasonable pricing, and the party responsible for covering the cost. Interviewees were also asked to provide anthropometric and demographic information. The complete interview script is available in Appendix A and was adopted from Kim et al. (2019). Compensation was provided to interviewees at a rate of $50/hour.

2.1.3. Sentiment analysis of interviews

Recorded interviews were first transcribed verbatim using a speech-to-text model (Radford et al., 2023) through the Whisper library from OpenAI in Python (Version 3.10.12). We then proofread the transcriptions to correct any errors, and we organized the answers to each question by separating the responses from all interviewees according to specific interview questions. We divided the questions into different categories and subcategories adopted from our earlier studies (Gutierrez et al., 2024; Kim et al., 2019). The five categories and the corresponding questions are summarized in Table 1.

Table 1. Categories and subcategories for content analysis of interview study

Category	Subcategories	Question
First impressions	Arm-support Exoskeletons	What are your first impressions of arm-support exoskeletons?
	Back-support Exoskeletons	What are your first impressions of back-support exoskeletons?
Readiness for use	-	Do you think exoskeletons are ready to be used in your work?
Perceived Barriers	Peer acceptance	How do you think other workers will respond, either positively or negatively, when exoskeletons are introduced at construction sites?
	Safety impacts	Do you think using an exoskeleton could affect safety?
Expected Benefits	Productivity	Do you think using an exoskeleton could affect work performance such as in terms of productivity, efficiency, or quality?
	Physical impact	Do you think using an exoskeleton could affect workers physically, either in a good way or a bad way (e.g., fatigue, discomfort, effort, injuries, etc.)?
Technology Adoption	Training material	If you were going to try out an exoskeleton at your workplace, what would you want or like to know? What resources would you want or like to have?
	ASEs task examples	What do you think are examples of tasks that could most benefit from using arm-support exoskeletons?
	BSEs task examples	What are some examples of tasks that could most benefit from using back-support exoskeletons?
	Price	What would be a reasonable price for an exoskeleton?
	Responsibility for cost	Who do you think should pay for exoskeletons?

To assess the emotional tone of the responses, we employed sentiment analysis, a natural language processing method that classifies text as positive, neutral, or negative (Mohammad, 2016). Sentiment analysis was not performed for Technology Adoption, as the questions were intended to gather factual information rather than emotions or impressions. This technique provided a systematic framework for quantifying subjective viewpoints and analyzing the emotional context of the data. We used the GPT-4 model to conduct sentiment analysis, a large language model (LLM) based on OpenAI's GPT-4 architecture, accessed via OpenAI's Python

library (Brown, 2020). LLMs such as GPT-4, which are built on transformer-based architectures, excel at understanding the context, syntax, and semantics of complex language inputs (Yadav, 2024). The model's attention mechanism enables it to process long-range dependencies in text, making it highly effective in capturing nuanced sentiment, even in complex or ambiguous responses (Ralambomihanta et al., 2024; Yadav, 2024).

To conduct the sentiment analysis, we employed a so-called *zero-shot* prompting approach inspired by a previous study (Fatouros et al., 2023). This approach leverages GPT-4's extensive language training and understanding of patterns to generate responses without requiring task-specific fine-tuning or additional training. Zero-shot learning is a machine learning technique wherein a model can recognize or make predictions about new, unseen classes without any prior training data for those specific classes (Lampert et al., 2013). This technique relies on transferring knowledge from previously learned classes to infer information about new ones, using high-level features or attributes that link known and unknown classes. Previous studies have demonstrated the effectiveness of this model (GPT-4) for zero-shot sentiment classification across various fields, including the financial domain and customer feedback analysis (Fatouros et al., 2023; Krugmann & Hartmann, 2024).

For our study, we set the model "temperature" parameter to zero, ensuring outputs were near deterministic (Krugmann & Hartmann, 2024). This parameter typically ranges between 0 and 1 and controls the level of randomness in the model's responses, with lower values producing more predictable and repetitive behavior and with higher values increasing randomness (OpenAI., 2024). Then, we created a specific prompt that established context by identifying the respondents as construction industry experts and clearly stating the question posed. We instructed the model to classify the sentiment of each response as positive, neutral, or negative. The prompt we used is provided below, in which 'question' and 'response' placeholders were replaced for each specific inquiry:

Prompt*: "The following is a response from a construction industry expert to the question:* ***'question'****. Please classify the sentiment of the response as either 'positive', 'neutral', or 'negative'. Response:* ***'response'****."*

The process of sentiment analysis involved dynamically replacing 'question' with the actual interview question, and 'response' with the participant's verbatim response. The formatted prompt was sent to the GPT-4 API, which analyzed the linguistic features, word choices, and overall tone to determine the appropriate sentiment category. Leveraging a pre-trained understanding of language patterns, emotional cues, and contextual semantics, GPT-4 classified each response as positive, neutral, or negative. Specifically, the model assessed sentiment based on sentiment-related words, phrases, and syntactic structures. For instance, responses containing words such as "beneficial," "helpful," or "effective," were typically classified as positive, while those including "problematic," "ineffective," or "difficult" were classified as negative. Descriptive or factual responses without strong emotional connotations were labeled as neutral. The API then returned a single sentiment label ("positive," "neutral," or "negative") as a text output, which was extracted and stored in our dataset for further analysis.

We also extracted frequent comments and key points from the responses to all questions, using an AI-powered tool (ChatGPT by OpenAI) that recent studies confirmed provides reasonably

reliable results (Bijker et al., 2024; Morgan, 2023). One of us then verified the final interpretations. Representative direct quotes are provided below, though some have been lightly edited to enhance clarity.

2.2. Field study

2.2.1 Participants and study design

We conducted short-term field testing of EXOs at local construction sites in southwestern Virginia and the California Bay area. Both local Institutional Review Boards approved the study protocol, and all participants provided informed consent before data collection. Participation was limited to volunteers who were aged 18 to 65 years and with no significant musculoskeletal disorders that would limit their work activities; who were currently employed in construction with at least one year of experience; and who had a waist size between 26 and 46 inches (to ensure proper EXO fit). A total of 22 participants (21 male and 1 female) completed the study. Their job titles included: electrician (n = 4), sheet metal worker (n = 5), plumber (n = 4), laborer (n = 2), flooring installer (n = 2), concrete worker (n = 2), painter (n = 1), and rebar worker (n = 2). Participants had a mean age of 33.3 years (SD = 12.5; range = 18 - 60 years); they also reported mean (SD) body mass as 85.6 (15.7) kg and stature as (SD) 1.76 (0.1) m. Job experience varied from 1 to 35 years (mean = 9.2, SD = 10). We provided access to seven commercially available EXOs. Specifically, three BSEs that included suit X backX Type S (suitX), HeroWear Apex V1 (HeroWear), and Laevo Flex; and four ASEs that included suitX shoulderX V2, Ottobock Paexo Shoulder, EksoBionics, and Levitate Airframe Flex. These EXOs were selected to represent diverse design characteristics and because each had been used in reported pilot testing in several industries prior to our study.

2.2.2. Field study procedures data collection

We recruited participants after an introductory session in which EXOs were introduced and informal feedback was gathered. Workers were selected based on their trades, with a limit of five participants per specialty. We allowed all participants to try on the EXOs, provided time for practice, obtained consent, and fitted the devices. Additionally, all participants completed an entry survey that included questions about demographics, anthropometry, job title, and work experience. Participants were instructed to select the device they felt would most support their work based on their job requirements and comfort level with the device. As they evaluated each EXO, we provided them with instructions on how the device offers physical support (e.g., to the back or shoulder regions), how to adjust the fit and support, and how to engage and disengage the support if relevant. We also addressed any questions that arose regarding using the device. Participants were then fitted with their chosen EXOs and then worked for an hour using the EXO (Figure 1) with the option to discontinue use at any time. They subsequently completed a usability exit survey, which used 1-10 scales to assess comfort, ease of use, balance, range of motion, safety, performance, and perceptions of environmental temperature, as well as items on usefulness, acceptance, and open-ended questions (see Appendix B). Participants then had the option to try a different EXO for one additional hour, following the same procedures. The EXOs that were selected are summarized in Table C1 of Appendix C. Compensation was provided to participants at a rate of $50/hour.

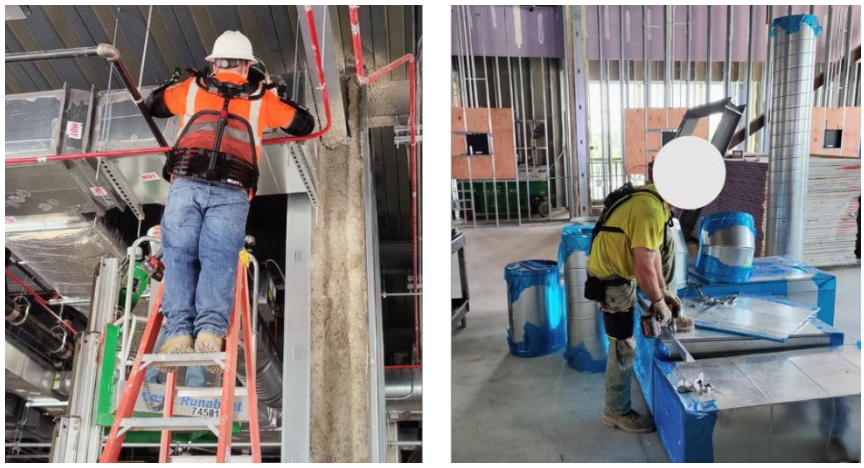

Figure 1. Photographs of two participants wearing an exoskeleton while performing their construction tasks (left: suitX shoulderX arm-support exoskeleton; right: HeroWear Apex V1 back-support exosuit).

2.2.3. Field study data analysis

Descriptive statistics were derived for the 1-10 responses to thermal perception and usefulness questions (questions 1, 2, and 5 in Appendix B), treating these responses as interval data (Wu & Leung, 2017). Responses for each Likert scale item (questions 3, 4, 6, and 7 in Appendix B) were categorized as follows: scores of 1 and 2 were classified as strongly disagree or extremely unlikely; 3 and 4 as disagree or unlikely; 5 and 6 as neutral; 7 and 8 as agree or likely; and 9 and 10 as strongly agree or extremely likely. We then categorized the exit survey questions into the aforementioned categories. Note that the subcategories for the interview questions were not identical; Table 2 presents the categories and subcategories related to the exit survey used for field testing. One of the categories also differed; in the field study, we assessed whether participants were ready to use EXOs, while in the interviews, we asked whether the EXOs were ready for use in construction. To analyze responses to the open-ended questions in the exit survey, we applied the same approach used for the interview data, employing an AI-powered tool (ChatGPT by OpenAI).

Table 2. Categories and subcategories of responses to questions in the field study exit survey

Category	Subcategories	Question	Scale
First impressions	-	Overall, I am satisfied with it (Q1)	Strongly Disagree, Disagree, Neutral, Agree, and Strongly Agree
		The exoskeleton's capabilities meet my requirements (Q2)	
Readiness to use	-	It should be a standard work device that is available for my job (Q3)	Strongly Disagree, Disagree, Neutral, Agree, and Strongly Agree
		I would recommend it to coworkers (Q4)	
		If your employer provided this exoskeleton to you, how likely would you be to use it? (Q5)	Extremely unlikely, Unlikely, Neutral, Likely, Extremely Likely
		How likely would you be to use this exoskeleton if you had to purchase it? (Q6)	
Perceived Barriers	Peer acceptance	Wearing it will be socially accepted in construction work (Q7)	Strongly Disagree, Disagree, Neutral, Agree, and Strongly Agree
	Safety impacts	It negatively affects work safety (Q8)	Strongly Disagree, Disagree, Neutral, Agree, and Strongly Agree
		It positively affects work safety (Q9)	
		It negatively affects my balance during work (Q10)	
	Usability	It is comfortable to wear during my work (Q11)	
		It is easy to use during my work (Q12)	
		It limits my movement (Q13)	
		I have to spend too much time correcting things with it, such as adjusting the fit (Q14)	
		Using it is a frustrating experience (Q15)	
		I have concerns about maintaining it (e.g., cleaning, repairing) (Q16)	
		What was your perception of thermal comfort and/or feelings of sweatiness when using the exoskeleton during your work? (Q17)	Interval (1 very cold - 10 very hot)
Expected Benefits	Productivity	Compared to working without it, how did the exoskeleton affect the following characteristics of your work? (Speed, quality, fatigue) (Q18)	Interval (1 slower-10 faster)
	Physical impact	It reduces discomfort or pain in my body during my work, such as in the back or shoulders (Q19)	Strongly Disagree, Disagree, Neutral, Agree, and Strongly Agree
		It reduces my level of physical effort during my work (Q20)	

3. Results

3.1. First impressions and readiness to/for use

3.1.1. Interview responses

Sentiment analysis indicated that most interviewees held positive impressions of ASEs (67%), BSEs (75%), and the readiness of EXOs for use in construction (60%). However, a non-trivial subset of participants expressed neutral or even negative impressions (Figure 2).

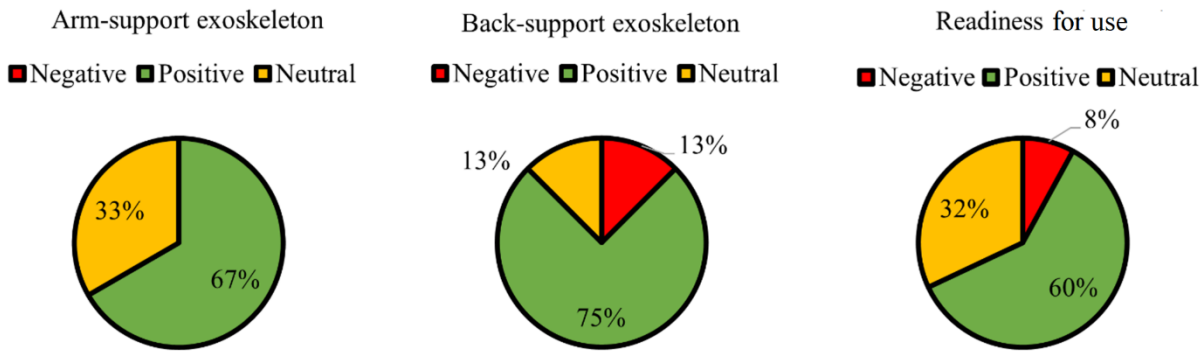

Figure 2. Results of sentiment analysis for responses to questions regarding impressions of exoskeletons and readiness for use in construction.

Regarding ASEs, nearly half (~46%) of the interviewees expressed liking how the ASEs provided support for overhead work and helped reduce strain. For example, one stated: *But I think if you're in a factory, ..., shooting bolts over your head, I thought that would be fantastic*. However, approximately a fifth (~21%) raised concerns about the ASEs being bulky or uncomfortable. As one noted: *... just I guess how bulky it is, and sometimes it feels like it helps your movement when picking things up, but it also kind of restricts you in certain areas, too*. A similar portion (~21%) noted that an ASE would be more beneficial for specific tasks, such as overhead work, than for general use. One interviewee elaborated: *In masonry, it wouldn't be too beneficial. I mean, if you're doing stuff overhead, but for a laborer throwing block up on six-foot frames, it would be good, but other than that, not too beneficial.*

For BSEs, nearly half (~46%) of interviewees appreciated the support provided by BSEs during lifting and bending. One interviewee mentioned: *When you bend down, the back exoskeleton helps you come back to a standing position.* Additionally, several (~21%) mentioned that BSEs would be particularly useful for specific tasks, such as in masonry and asphalt work. A similar percentage highlighted that BSEs helped with posture and made lifting easier. As one interviewee explained: *The back support one [device], I liked it the most. Because when you're bending over and lifting stuff up, it kind of springs you back up. In a sense, it's like somebody grabbing the back of your shirt and pulling you up.* However, similar to the ASEs, one-third expressed concerns about the BSEs being bulky or uncomfortable, particularly in confined spaces. For instance, one noted: *but my worry is how viable the usage will be in a confined space, where you don't have a lot of room to move around*.

Regarding readiness of EXOs for use, a third (~33%) indicated that the EXOs were nearly ready for implementation, requiring only minor modifications. For example, one interviewee noted: *They're pretty close. Just a few little tweaks are needed. The only concern I have is, will they get damaged if I bump up against something or if I'm pouring concrete and it dries on them? I might not get it washed quickly enough.* Yet, a smaller portion (~12%) raised concerns that exoskeletons might interfere with other equipment, such as fall arrest harnesses. As one interviewee elaborated: *The confined space concerns are about job sites where you have to wear harnesses, and I haven't tried that yet. I'm curious if the harness goes on the outside or the inside of these and how it will work with a harness.* Additionally, nearly a third (~29%) expressed concerns about the need for further adjustments, particularly related to bulkiness and comfort.

3.1.2. Field study responses

The responses to the open-ended questions indicated that participants reported discomfort that stemmed from wearing the EXO, primarily in body regions such as the shoulders/armpits, upper arms, lower back/hips, and where leg straps made contact, although half indicated they experienced no discomfort. Negative feedback that was provided included bulkiness hindering movement, heat buildup, and interference with harnesses or tool belts. On the positive side, participants valued the support provided by EXOs during overhead tasks, the ability of EXOs to alleviate back pain and reduce physical strain, as well as the ease of use.

Table C2 summarizes the exit survey responses regarding participants' impressions and readiness to use the EXO (Appendix C). For first impressions, the majority expressed satisfaction, with many participants agreeing (~41%) and a notable number strongly agreeing (~34%) that they were satisfied with the EXO (Q1). Regarding EXO capabilities, some participants were neutral (35%), while a smaller group strongly agreed (~29%) that the device met their job requirements (~Q2). In terms of participant readiness to use the EXO, a portion was neutral (36%) about whether it should become a standard work device (Q3), while some participants agreed (~24%). However, a similar proportion agreed (~31%) and strongly agreed (~31%) that they would recommend a given EXO to coworkers (Q4). When asked about the likelihood of using the EXO if provided by their employer (Q5), some indicated they would likely use it (~34%), while a comparable group was extremely likely to use it (~31%). However, when considering purchasing the EXO personally (Q6), a portion were neutral (~31%), while some were extremely likely to do so (~25%).

3.2. Perceived barriers

3.2.1 Interview responses

A majority of interviewees expressed neutral impressions regarding peer acceptance of EXOs (50%) and the potential impact of EXOs on safety (58%). A noteworthy subset of participants expressed positive impressions regarding peer acceptance and negative impressions concerning safety impact (Figure 3).

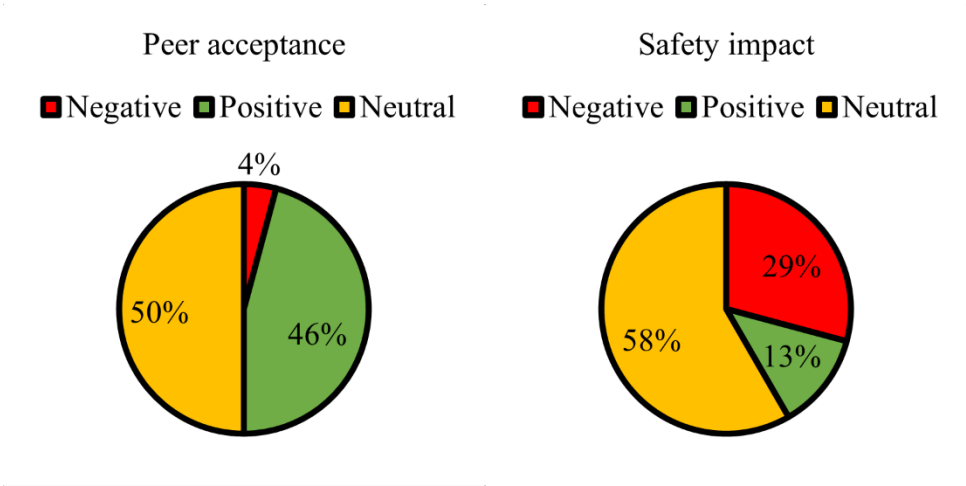

Figure 3. Results of sentiment analysis for responses to questions regarding peer acceptance and the safety impact of EXOs in the construction workplace.

Concerning peer acceptance, two-thirds (~67%) of interviewees mentioned that they anticipated initial skepticism, but they believed that over time workers would respond positively once they experienced the benefits of EXOs, such as reduced fatigue and injury prevention. For example, one interviewee remarked: *I think they will be apprehensive at first, because they might tell each other this is another safety measure or another restriction. ..., but if they realize it's going to help them with injuries and longevity in the trade, I think they might come around*. Additionally, a quarter (~25%) mentioned that some workers might be curious and willing to try exoskeletons out of interest in new technology. As one interviewee explained: *So you're saying at both levels, it's just curiosity about why they're being used. You need to know what it is, what it's doing.* However, several (~21%) suggested that workers might initially mock or tease others who use EXOs. One interviewer noted: *Well, if only one guy was wearing it at first, he'd probably get made fun of a little bit…* Additionally, ~17% mentioned that younger workers are more likely to embrace the technology, while older workers may resist. For instance, one interviewee shared: *Some of the old timers are going to make fun of you and think you're, you know, you're going into the future.*

Regarding the safety impact of EXOs, many (~79%) interviewees had concerns about the exoskeleton getting snagged or caught on objects, potentially leading to safety risks. Relevant quotes include: *... especially in a confined space. If it gets caught on the stairs, usually you don't want two people in a manhole, and sometimes you can only fit one person in a manhole. So how are you going to save someone down there who might be trapped? You know what I mean?* and *the only part about safety is getting snagged on something just because it is away from your body. Maybe climbing drop-side ladders and stuff like that, getting hung up on something.*

Additionally, about one-fifth (~21%) expressed concerns about ensuring that EXOs integrate with other safety equipment, like fall arrest harnesses, to avoid interfering with current safety practices. For example, one interviewee noted: *When needed, a harness of some sort. I'm trying to figure out a way to use a harness or make these harnesses compatible.* Another interviewee mentioned that it might create a false sense of security: *My only question is, will it give them a*

false sense of security about how much they can actually do? Will it make them feel like, well, I'm Superman. I can do anything I want to and pick up something I normally wouldn't when wearing the exoskeleton, and then they go, oh, wait. On the other hand, ~33% mentioned that exoskeletons could help prevent injuries, particularly those caused by repetitive strain or improper lifting. One interviewee said: *I can see it preventing some of the chronic exposures, especially from repetitive tasks. If you have a drywaller, for example, he's going to be doing that for eight hours a day, 40 hours a week, 50 weeks of the year. That's a real chronic exposure over time, and that can really affect someone working with their hands above them. If you reduce some of the fatigue they're experiencing, it can help.*

3.2.2 Field study responses

Participants offered diverse suggestions for improving the EXO in open-ended questions, including enhancing fit and comfort, reducing bulk, adding cooling features to the padding, and improving compatibility with tool belts. Maneuverability in tight spaces was another concern. Some challenges that were expressed related to daily use included the inconvenience of donning and doffing the device, discomfort over prolonged use, and difficulties in navigating confined spaces. However, many suggested that these challenges would be manageable.

In terms of peer acceptance (Q7), over half of participants (~54%) responded that the EXO would gain social acceptance in construction work. Regarding safety, most participants (~63%) disagreed that the EXO had a negative impact on work safety (Q8), with nearly half (~47%) perceiving it as positively impacting safety (Q9). Balance concerns were minimal (Q10), as a substantial majority (~69%) indicated that the EXO did not negatively affect their balance.

Regarding usability, over half of participants (~53%) indicated that wearing the EXO was comfortable (Q11), and nearly two-thirds (~65%) agreed it was easy to use (Q12). Some concerns were noted, with about half (~51%) indicating it restricted movement (Q13). Maintenance was also a concern (Q16) for nearly half (~44%) of participants, though a majority (~78%) disagreed that adjusting the EXO was time-consuming (Q14), and most (~82%) did not find using it to be a frustrating experience (Q15) (Table C3, Appendix C). Participants rated thermal comfort while using the EXO (Q17) as "just comfortable" as "just comfortable," with a mean (SD) of 4.8 (1.9).

3.3. Expected benefits

3.3.1. Interview responses

Most interviewees expressed positive impressions regarding the effect of EXOs on productivity (~75%) and a positive perspective on the physical effect (~63%). However, some participants expressed neutral or even negative impressions (Figure 4).

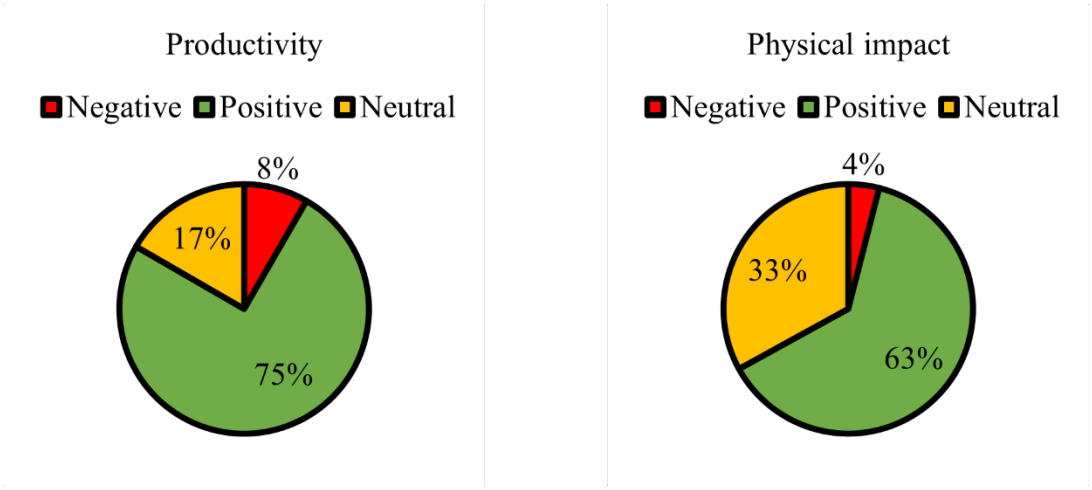

Figure 4. Results of sentiment analysis for responses to questions regarding interviewees' perspective on peer acceptance and safety impact of exoskeletons.

Roughly 42% of interviewees mentioned that the exoskeleton could reduce fatigue or help conserve energy, leading to increased productivity. For example, one interviewee stated: *So, if I could have one of those, you know, a type of form of a back brace or the back exoskeleton, like the light one. I think it takes a lot of strain off your back. So, at the end of the day, you will feel a lot better*. On the other hand, several (~17%) noted an initial adjustment or learning curve when using the exoskeleton, which could negatively affect productivity. One interviewee explained: *It just, yeah, the time it takes to put it on and take it off. So, on that note, for the most part, we see after you spend a considerable amount of time, you need to adjust it to your body the first time. After that, you can more or less put it on and off yourself relatively easily, you know, within a minute.* On the other hand, some interviewees (~9%) expressed concerns about the exoskeleton slowing down work due to the need for adjustments or discomfort. One interviewee noted: *I wouldn't say better… put things on while you walk, then, you know, you just think just a little bit of, oh, let me adjust this while you're doing something, and make a mistake. So, yeah, it's going to affect productivity and some aspects of the work*. Moreover, one interviewee mentioned that older workers might have more difficulty adjusting to EXO use compared to younger workers: *Probably the older generation. I mean, if we're being honest, then they're not going to take to it the same way that the younger generation will.*

Concerning the physical impact of EXOs, most (~67%) interviewees mentioned that exoskeletons would reduce fatigue, particularly in the shoulders and back. One interviewee stated: *So, using these things to help you lift things easier, not put stress on your body and stuff like that, it's going to save trips to the chiropractor. It's going to save trips to the doctor. You're going to go home. You're not going to be as tired.* On the other hand, 25% of interviewees mentioned potential discomfort, such as chafing, rubbing, or the bulkiness of the exoskeleton. One interviewee noted: *But the rubbing and sweating would be the only other issues I'd probably see with it. Yeah, because I don't wear overalls in the winter just for the fact I hate being restricted when I'm moving and bending over.* Additionally, some (~13%) expressed concern about potential over-reliance on the exoskeleton, which could lead to other problems or injuries. One interviewee explained: *But I do think there could be some over-reliance. And I don't know if*

we're going to have concomitant overuse injuries if you start over-relying on the exoskeleton. ... Because whenever you over-rely on a strength, you create another weakness. Lastly, some (~13%) interviewees indicated that exoskeletons could restrict movement, particularly when bending or performing specific tasks. One interviewee remarked: *I think it's going to restrict you bending over, trying to walk and put the screws in while you're bent over.*

3.3.1. Field study responses

For productivity (Q18), mean ratings of EXO effects were 5.5 for speed, 6.2 for quality, and 6.9 for fatigue, suggesting moderate to slightly positive overall effects compared to working without the EXO. Regarding physical impact (Q19), many (~60%) participants agreed or strongly agreed that the EXO reduced discomfort or pain in areas like the back or shoulders, while some (~19%) were neutral. Additionally, the majority (~61%) agreed or strongly agreed that it reduced their physical effort (Q20), with only ~16% expressing disagreement.

3.4. Adoption of exoskeleton technology

Two-thirds of the interviewees expressed the need for training sessions, educational materials, and instructions on the proper use of the exoskeletons. One interviewee stated: *I'd say training sessions. If you implement a training session, show it to the guys. I can see a lot of guys, they'll take that, put it on, and then be able to go out and use that out on the field.* Additionally, a smaller group (~9%) emphasized the importance of providing information on return on investment and productivity benefits. One interviewee explained: *Well, if you want to get a contractor to buy into it, showing them the costs of injuries versus saving benefits, but then you have to have a track record.* Furthermore, a quarter of interviewees highlighted the importance of safety instructions, especially concerning fitting, electrical hazards, and handling the EXO in various environments. Relevant quotes include: *Definitely want to know the materials. Do they conduct electricity, those things? We have guys on lifts, things of that nature. It could be closer to power lines, transformers. When I walk around in a plant, are they conductive?* and *yeah, it would definitely help informing them and then getting them on board as far as using them would be making sure that the tasks they're using them for are the proper tasks they're designed for.*

Several tasks were identified where ASEs could be beneficial. Around half (~54%) of participants highlighted drywalling, particularly for overhead tasks. Ceiling work, including screwing, drilling, and other overhead activities, was mentioned by about a third (~37%). Additionally, tasks performed by electricians and pipe installers were noted by roughly 30%. Concrete work and jackhammering were identified by ~25%, with masonry and bricklaying indicated by approximately 21%. Framing and carpentry were also mentioned by several interviewees (~21%), and painting and welding were highlighted by about 13%.

Interviewees also identified several tasks for which BSEs could be beneficial. Approximately 38% noted concrete work, including setting forms, cutting, screeding, and using jackhammers. About 33% indicated masonry and bricklaying as tasks where BSEs would be useful, while another 33% highlighted general construction tasks involving bending and lifting, such as carpentry and laying out materials. Other tasks mentioned included pipe laying and installation (around 13%), landscaping tasks—such as moving trees and planting (approximately 13%)—

flooring work like laying tiles or working on flooring (about 13%), and roofing and general labor (also around 13%).

Interviewees noted a wide range of what they considered reasonable prices for an EXO, specifically between $100 and $5,000. All indicated that employers should bear responsibility for covering the costs.

4. Discussion

We examined the perceptions and concerns of construction stakeholders—such as managers, instructors, superintendents, safety directors, and onsite workers—regarding the use of ASEs and BSEs. These inputs were obtained after the participants had hands-on experience with EXOs, either through performing tasks in non-work settings or over a short duration (up to one hour) of actual work on site. We used a qualitative approach to obtain a reasonably broad understanding of the readiness to/for use, barriers, expected benefits, and technology adoption aspects of EXO technology within the construction industry. Overall, the results of both the interview and field studies suggested that there is optimism regarding the applications of EXOs in construction, but that there are also important and prevalent concerns about EXO safety and usability.

4.1. First impressions and readiness for/to use exoskeletons

Results from the interviews (Figure 2) and the field study (Table C2) indicated that stakeholders had a positive impression of both ASEs and BSEs, highlighting the readiness of this technology for use, while workers also stated a willingness to use EXOs in their workplace. While interviewees and participants appreciated the support provided by EXOs, they also emphasized the need for design improvements, particularly in reducing bulkiness and enhancing comfort. These findings align with earlier studies, highlighting the importance of addressing comfort and functionality to promote broader acceptance and integration of EXOs within the construction industry (Bennett et al., 2023; Gutierrez et al., 2024). Specifically, Gutierrez et al. (2024) reported that 83% of workers expressed a willingness to use EXOs after completing an online survey. However, they also indicated that improvements in design are needed to address discomfort. Similarly, Bennett et al. (2023) found mixed opinions during a field assessment of construction workers using EXOs, with some participants expressing willingness to use the devices, while others reported discomfort during use.

4.2. Perceived barriers

The interview results revealed concerns about the social acceptance of EXOs in the workplace, with most interviewees expressing neutral or negative sentiments about peer acceptance (Figure 3). In contrast, the field study participants generally expressed that EXOs would be socially accepted during their tasks (Table C3). While earlier research (Elprama et al., 2020; Kim et al., 2019) identified social acceptance as a potential obstacle, the differences we found between the interviews and field study suggest that acceptance may be context-dependent and influenced by direct experience with EXOs in the workplace. This divergence suggests that social acceptance may not be a static barrier but rather one that varies based on exposure and work setting. Additionally, both of our current studies suggested that social acceptance could vary with age. Gutierrez et al. (2024) similarly found that generational differences may influence the readiness to embrace EXO technology in the construction industry.

Usability was a common concern in both the interviews and the field study. Interviewees raised concerns about the compatibility of EXOs with other equipment, as well as their comfort and range of motion. Similarly, field study participants reported having challenges related to limited movement and experiencing discomfort, and they shared concerns about how to store and maintain the EXOs. Other researchers have identified similar concerns about EXOs being uncomfortable and limiting range of motion (Maurice et al., 2018; Nnaji et al., 2023; Schwerha et al., 2022; Schwerha et al., 2021). These practical aspects of EXO use highlight the need for design improvements to enhance the usability and compatibility of EXOs for various construction tasks, environments, and integration with other equipment.

There were mixed findings between the interviews and the field study regarding safety implications. Most (~79%) interviewees raised concerns about the potential for EXOs to get snagged or caught on objects, particularly in confined spaces, which could pose safety risks. Other concerns included integrating EXOs with existing safety equipment, such as harnesses, and the possibility of creating a false sense of security. These concerns were also reported in earlier studies (Kim et al., 2019; Raghuraman et al., 2023; Schwerha et al., 2021). Some interviewees (~33%) here, though, pointed out that EXOs could help prevent injuries, especially those resulting from repetitive strain or improper lifting.

In contrast, our field study participants did not express notable safety concerns, possibly because their tasks did not involve risks of snagging or getting caught. The discrepancy in safety concerns between the interviewees and field study participants suggests the importance of context in evaluating EXO safety practices. These concerns may have been task-specific and influenced by differing views on technology. Further, the tasks tested in the field study were not performed in tight spaces and did not require safety equipment, which may not have fully reflected the concerns raised in the interviews. The difference in outcomes could also have stemmed from differing perspectives on safety between workers or between experience levels and types (Namian et al., 2022). Maurice et al. (2018) found similar differences between groups, with non-workers expressing more concern about user safety, while workers tended to trust EXOs regarding safety.

4.3. Expected Benefits

Both the interview and field studies revealed a generally positive perception of EXOs regarding productivity among construction stakeholders and workers. Interviewees noted the potential of EXOs to reduce fatigue and conserve energy, although some indicated that an initial adjustment period could temporarily decrease productivity. Overall, while EXOs show potential to enhance productivity in construction tasks, addressing usability concerns seems essential to maximizing their effectiveness to increase productivity. Previous reports have presented mixed findings regarding the impact of EXOs on productivity. In two laboratory studies that assessed productivity based on task completion time, one found a decrease when using a BSE (Madinei et al., 2020) while another reported an increase with ASE use (Kim et al., 2018); both studies, though, found relatively small effects. Results from a recent field study indicated either no impact on work rate or perceived quality (de Vries et al., 2023), while another longitudinal study found lowered expectations regarding productivity and health benefits (Dufraissse et al., 2025). In our current work, interviews and field testing both provided only short-term, hands-on experience, rather than longitudinal assessments, suggesting that productivity outcomes may

require further evaluation over extended periods and could vary depending on the specific tasks performed.

Interview responses indicated a favorable perspective on the effects of EXOs on physical well-being. Participants mentioned that EXOs could help reduce fatigue, particularly in the shoulders and back. However, concerns were also expressed about discomfort, such as chafing or bulkiness. Some participants feared that over-reliance on EXOs might lead to other injuries, while others worried about movement restrictions during specific tasks. Similar concerns were expressed during field testing, though participants generally indicated that using an EXO alleviated discomfort and reduced physical effort. These results highlight the potential benefits of EXOs in reducing physical demands while also emphasizing the importance of addressing discomfort and movement restrictions for effective integration into construction work, which aligns with findings from previous studies (De Looze et al., 2016; Gutierrez et al., 2024; Mahmud et al., 2022; Theurel & Desbrosses, 2019).

4.4. Adoption of exoskeleton technology

We found general agreement among interviewees regarding the need for training and educational materials for using EXOs. Most interviewees (~67%) emphasized the necessity of training sessions to ensure proper usage, highlighting that hands-on instruction would enhance understanding and effectiveness in the field. Safety instructions were also deemed crucial, particularly concerning proper fitting, electrical hazards, and handling protocols in various work environments. These findings, also highlighted in prior work (Gorgey, 2018; Gutierrez et al., 2024; Mahmud et al., 2022), suggest that comprehensive training and educational resources are vital for the successful adoption of EXOs in construction.

Return-on-investment was also a key theme in the responses, highlighting that the initial costs of EXOs still need to be justified for stakeholders to consider adoption. Similar concerns about the cost-benefit balance of EXOs were reported by Kim et al. (2019). The decision to invest in EXOs appears to be driven not only by the potential to reduce injury-related costs but also by the expectation of tangible financial returns. This evidence may imply that justifying an EXO investment based solely on the potential for injury prevention will be ineffective without stronger evidence of actual injury reduction and associated cost savings, as well as potential productivity benefits. These findings underscore the need for more robust data on the long-term health outcomes and economic impacts of EXO use to support broader adoption.

4.5. Limitations and future needs

We acknowledge three important limitations in these two studies. First, the hands-on experience with exoskeletons in both phases was brief. Dufraissse et al. (2025) noted that operator perceptions of EXOs can shift over the course of a longitudinal study. For future research, we recommend assessing stakeholder perceptions after a more extended evaluation period. Second, while we aimed to diversify the types of EXOs used and the tasks tested in the field study, the number of participants and tasks was limited due to challenges in recruiting. This limitation prevented us from comparing outcomes quantitatively across different EXO designs or tasks. We recommend a more comprehensive evaluation of different EXO designs across a variety of

construction tasks. Third, the stakeholders and construction workers in our study may not fully represent the broader construction industry, potentially introducing bias into the results. Future studies should include a more diverse sample to enhance the generalizability of our findings.

5. Conclusions

We examined the perceptions and concerns of construction stakeholders regarding the use of ASEs and BSEs, finding a generally positive outlook on the applicability of this technology. Stakeholders expressed a readiness for/to use EXOs, recognizing the potential to enhance productivity and mitigate physical strain. However, critical concerns about usability, safety, and social acceptance emerged, indicating a need for design improvements to address issues such as comfort and compatibility with other equipment. Our finding aligns with earlier studies, suggesting that similar results may be achieved across various study designs, contexts, and populations, and supporting the validity and generalizability of these findings. Our current work also highlighted a discrepancy between the concerns expressed by interviewees regarding EXO safety and the generally positive responses from field study participants, suggesting that perceptions of safety may vary depending on the context of use and the user. The short duration of field testing, however, might have limited the ability of workers to fully understand/experience certain EXO benefits or concerns. Future research should involve longitudinal studies to capture shifts in stakeholder perceptions of EXO technology and to include more diverse populations, EXO designs, and construction tasks. Our findings also underscore the need for future refinement of EXOs to address safety concerns and enhance usability, ensuring the technology meets the specific demands of construction work and supports broader adoption across the industry.

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7. Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, we used ChatGPT to refine some sentences and improve the clarity of the text. After using this tool/service, we reviewed and edited the content as needed, and we take full responsibility for the content of this publication.

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Author Contribution Statement:

Mohamad Behjati Ashtiani: Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review and editing, Software

Wallace Morris: Conceptualization, Writing – review and editing, Investigation, Methodology

Aanuoluwapo Ojelade: Conceptualization, Writing – original draft, Formal analysis, Investigation

Sunwook Kim: Formal analysis, Validation, writing – original draft, writing – review and editing, Funding acquisition, Methodology

Feyisayo Akinwande: Writing – review and editing

Alan Barr: Funding acquisition, Formal analysis, Validation, Writing – review and editing

Carisa Harris-Adamson: Project administration, Funding acquisition, Investigation, Validation, Writing – review and editing

Abiola Akanmu: Funding acquisition, Investigation, Validation, Writing – review and editing

Maury A. Nussbaum: Project administration, Funding acquisition, Investigation, Validation, Writing – review and editing