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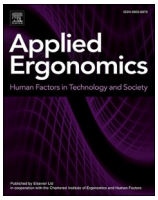

Perceived benefits, barriers, perceptions, and readiness to use exoskeletons in the construction industry: Differences by demographic characteristics

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ABSTRACT

Exoskeletons (EXOs) are a promising wearable intervention to reduce work-related musculoskeletal disorder risks among construction workers. However, the adoption of EXOs may differ with demographic characteristics. Survey data (n = 361) were collected from construction industry stakeholders and a summation score method was used to summarize respondent's benefits and barriers to EXO use, along with perceptions and readiness to use. Responses were stratified by race (White vs. non-White), sex (male vs. female), and age (<47 years vs. ≥47 years). Both a higher Benefits score and a higher Perceptions score were significantly and positively associated with a higher Readiness to Use score. There were also significant differences in perceived barriers to EXO use by race and sex. These results demonstrate substantial interest in EXO use but also emphasize the need to ensure proportionate access to the potential benefits of EXO technology.

1. Introduction

Construction workers continue to experience high rates of work-related musculoskeletal disorders (WMSDs), predominantly attributed to exposure to physically demanding tasks, including lifting, carrying, over-shoulder work, and non-neutral/prolonged static postures (Umer et al., 2018). The back and the shoulder are the two body regions most often impacted, respectively accounting for 39% and 16% of all cases and with medians of 9 and 25 lost workdays (BLS, 2020a; BLS, 2020b). However, controlling exposures to physical hazards has been a substantial challenge in the construction industry due in part to the physically demanding nature of the work, substantial task variability, fast work pace, and dynamic and often unstructured environments (Dasgupta et al., 2015; Forde and Buchholz, 2004; Ringen and Stafford, 1996). In contrast to work being performed in a warehouse or on an assembly line, wherein job design can often mitigate physical hazards that increase the risks of back and shoulder WMSDs, construction work often involves highly variable environments and tasks and therefore mitigation is more challenging through job design. Thus, there is a critical need for a different approach to balancing the demand of construction work with the physical capacity of construction workers to reduce risk of WMSDs.

A promising new approach to addressing this need is by augmenting worker physical capacity using exoskeleton (EXO) technologies (Kim et al., 2019). EXOs are wearable, assistive devices that function by passively or actively providing external forces/moments about joints (ASTM, 2020). Given the high prevalence of back and shoulder WMSDs across all industry sectors, most EXOs developed for the workplace are designed to reduce physical demands on these body regions. Occupational EXOs have been pilot-tested in several manufacturing settings (Butler and Wisner, 2017; Hetzner, 2016; Kim, 2018; Krok, 2017; Selko, 2019; Wren, 2018), typically situations wherein the environment is consistent and the tasks are repetitive. However, very limited evidence is available to inform end-users on the selection of a suitable EXO for construction work, in which both the environment and task often change regularly.

We are unaware of any comparative evaluations of different EXOs during construction tasks. Extensive earlier work, though, has demonstrated that using an arm-support EXO or back-support EXO can respectively reduce physical demands on the shoulders or the back as

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evident in reduced muscle activity and physical discomfort during simulated overhead work (Huysamen et al., 2018; Kim et al., 2021; Spada et al., 2018; Van Engelhoven et al., 2019) and stooped/lifting work (Bosch et al., 2016; Madinei et al., 2020). The magnitude of beneficial effects was dependent upon specific EXO designs, task conditions, and user characteristics (e.g., males vs. females). While results from these studies are promising, other results have indicated that an EXO can impact body parts in an unexpected or potentially adverse way. For example, one arm-support EXO – a tool support type with a zero gravity mechanical arm – was found to increase low back demands during a simulated drilling (Rashedi et al., 2014) while a different ASE (Kim et al., 2018) decreased low back demands. This divergence of findings suggest that EXO benefits and limitations may be dependent on multiple factors such as EXO design, their fit on the user, the duration of use, and the type of work demands involved. As suggested in a field study with plasterers that examined behavior and acceptance, EXOs must be both applicable in real work situations and accepted by users to have a meaningful impact on the health and well-being of workers (de Vries et al., 2022). Hence, it may be premature to promote the adoption and use of EXOs in construction, since critical knowledge gaps remain regarding effectiveness, efficacy, and safety.

Construction industry labor projection models identified a shortage of 650,000 workers to meet the increase in critical infrastructure across the United States in 2022 alone ("ABC: Construction Industry Faces Workforce Shortage of 650,000 in 2022," 2022). Between 2020 and 2030, the highest number of projected job openings are expected to be construction laborers (1.4 million), carpenters, (893,000), and electricians (847,000) (Simpson, 2023). Attracting more people to construction, and retaining them, necessitates a deeper understanding of how to shape construction work that is acceptable for a large and diverse population of workers (Simpson, 2023). For example, although female workers currently comprise a small percentage of construction workers (10%), with approximately 25% of those being in managerial roles (CPWR, Women in Construction, 2023), there are widespread efforts to increase their inclusion in the trades (Simpson, 2023), including via specialized training programs and conferences geared toward women. Additionally, workers above the age of 65 years tend to leave the trades due to the physical requirements of the work (Sokas et al., 2019). In general, EXOs may be beneficial for both experienced and novice construction workers of varying demographic characteristics, allowing them to complete tasks that they might not otherwise be able to perform, perform the same tasks more easily with less WMSD risk, and/or enhance retention (Andrade and Nathan-Roberts, 2022). Facilitating the widespread implementation of EXOs in construction requires an approach that promotes the inclusion of workers from various backgrounds who likely have different experiences in their work. Therefore, the aim of this study was to understand the initial opinions of relevant construction industry stakeholders across the United States, regarding the potential benefits, barriers, perceptions, and readiness to use EXOs in construction, with a focus on how these opinions differed by age, sex, and race. Awareness of a new technology is required before a decision is made to explore it. The exploration of a new technology determines whether it is accepted which is followed by identifying how to integrate the technology before it can be used regularly. This study includes initial perceptions of EXOs among those who were newly aware of the technology as well as some who had explored its use. Further, this study investigated differences in the barriers to and facilitators of EXO use in different user groups to inform a tailored approach to their introduction and implementation. Understanding the users' needs has been identified as a critical first step in the large scale adoption of EXOs (Crea et al., 2021).

It was hypothesized that female, younger, and White workers would have fewer identified barriers, more benefits, positive perceptions, and a higher readiness to use than their counterparts, primarily because: 1) females work at a higher relative workload for a given task and may be more open to the augmentation provided by an EXO; 2) younger workers are typically more apt to accept new technology; and 3) White workers typically experience fewer occupational health and safety disparities and may be more likely to trust new technology.

2. Materials and methods

2.1. Participants and study design

This was a cross-sectional survey of construction stakeholders. Individuals were eligible to participate if they had current or prior experience working in construction, supervising construction workers, and/or managing a construction company. There were no exclusion criteria, and prior EXO experience was not required. Participants were recruited primarily through an email containing a flyer with the survey link, which was sent to construction companies, labor unions, and training centers with working relationships with two research groups and The Center for Construction Research and Training. Additional recruitment was done through a short video advertisement on social media platforms and presentations at various national conferences. All forms of recruitment were primarily from the United States of America. All participants gave informed consent before any data collection. The study protocol was approved by the Institutional Review Boards of Virginia Tech and the University of California, San Francisco.

2.2. Survey design

The survey was a mix of 65 open- and closed-ended questions (Appendix A) and was designed to elicit information and opinions about prior EXO knowledge, work history, personal factors, task characteristics, perceived benefits, perceived barriers (e.g., health and safety concerns), facilitators for adoption, and readiness to use EXOs in construction. The survey included a mixture of questions typical to physical workload studies and new ones specific to the aims of this study. For example, questions on ratings of perceived exertion and discomfort were asked using validated scales (Borg Rating of Perceived Exertion Scale and Numerical Pain Rating Scale). The survey also included items from existing scales on perceived usefulness, perceived ease of use, and user acceptance of information technology (Davis, 1989) and questions from a prior usability survey (Kim et al., 2019). Based on the four domains of interest in this study (benefits, barriers, perceptions, and readiness to use), we identified items from existing scales and developed additional items to address each construct. Ultimately, the survey was developed iterative, during which feedback was addressed from numerous stakeholders who varied by trade, age, sex, and race.

Responses to the online self-administered survey were collected between July 31, 2020, and January 9, 2021, using an online survey platform (Qualtrics, Seattle, WA, USA). Participants were encouraged to watch a 5-min introductory video that presented current applications of EXOs, demonstrated the donning and possible applications of both an arm-support EXO and a back-support EXO in overhead and stooped construction work, and verbally presented a wearer's perspective of how EXOs provide physical support to specific body regions. Both the survey and introductory video were made available in English and Spanish.

All responses were anonymous, and participants had the option to skip all but one question that asked them to specify their role in construction. Questions were split into eight sections (Fig. 1). *Prior Knowledge* addressed their prior knowledge and use of EXOs; *Physical Demand & Task Suggestions* addressed the physically demanding aspects of their work and provided participants the opportunity to suggest work tasks for which EXO use may be helpful; *Demographic and Work History* contained questions about years worked in construction, experience in different trades, the size of their company, and their age, sex, and race; *Adoption of Technology* addressed their willingness to use an EXO, as well as their perceptions on use and cost; *Health & Safety* asked questions about potential health and safety concerns they had about EXO use;

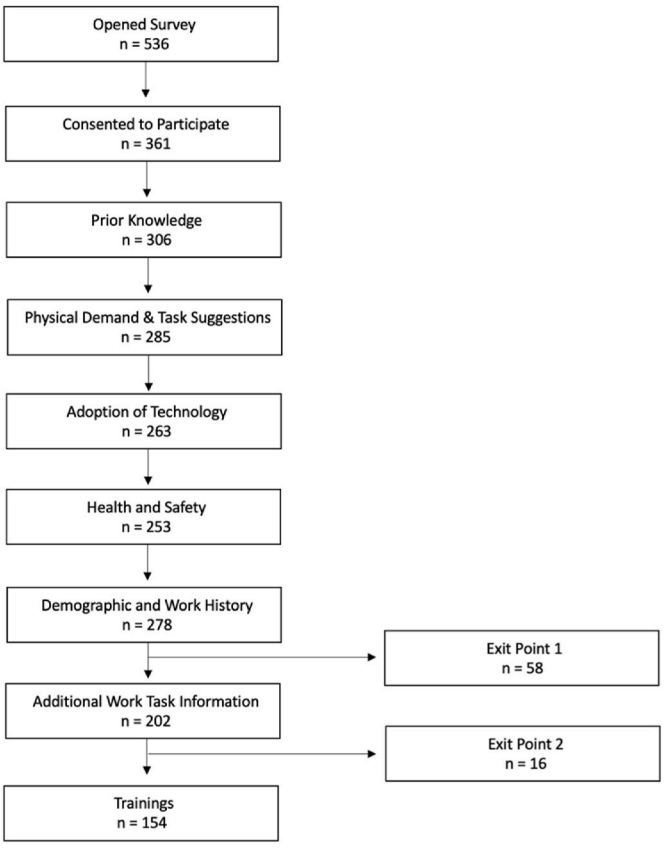

Fig. 1. Subject Flowchart. Each box on the left represents a subset of survey questions, in which *n* is the number of participants who answered at least one question in that section. Exit Points 1 and 2 represent the two formal exit points in the survey, in which *n* indicates the number of participants who chose to opt out of completing the remaining, optional, sections of the survey.

Additional Work Task Information asked about work-related heat and cold discomfort, how productivity is measured by their employer, and what PPE and equipment they commonly use; lastly, *Trainings* contained questions regarding how language, age, and gender barriers may have made it challenging for them to learn and fully benefit from health and safety training. Questionnaire skip logic was used to present job title or trade specific questions to appropriate respondents. Due to the length of the overall survey, it was designed to allow participants to formally exit after the 43rd and 55th questions and to opt out of completing sections that asked about additional work task information and health and safety trainings (Fig. 1).

The scope of this paper is limited to analyzing a subset of the responses from the survey, and forthcoming papers will cover additional aspects of the data, including responses by trade and self-reported fatigue and exertion.

2.3. Sex-based analysis

Sex primarily refers to biological differences between females and males, typically assigned to a newborn based on their external reproductive organs. Gender identity refers to one's innermost concept of self as a girl, woman, boy, man, or a blend of both or neither (Sexual Orientation and Gender Identity Definitions, 2022). Our approach to using a sex-based analysis was to collect information regarding how the physical features that are associated with biological attributes might impact the efficacy of EXOs. However, we acknowledge the importance of integrating both sex and gender in implementation research.

2.4. Summation scoring

A summation score technique (Sullivan and Artino, 2013) using participant responses to key questions was used to characterize multiple questions designed to investigate the four primary domains – 1) perceived benefits of EXO use in construction (Benefits score); 2) perceived barriers to EXO use in construction (Barriers score); 3) perceptions of the use of EXOs to complete a task (Perceptions score); and 4) readiness to use EXOs at work (Readiness to Use score). The initial selection of key questions was based on our judgment and prior evidence (Kim et al., 2019); See Table A1 for questions. Questions with low response rates (<75%) were omitted. Although some questions were not included when calculating summation scores due to missing data, these results remain relevant and are summarized accordingly. Additionally, direct quotes from respondents to three open-ended questions are summarized in italics.

For 14 of the 15 questions used to calculate summation scores, Likert scales ranging from strongly agree to strongly disagree were used. For these questions, response choices were assigned a numeric value ranging from 1 to 5, based on the directionality of the statement. Higher values were assigned to responses that implied a higher perceived benefit, larger perceived barrier, more favorable perception of EXOs, and a higher readiness to use. For example, strongly agree was assigned a value of 1 when asked about sharing an EXO, but it was assigned a value of 5 when asked about storage concerns. The remaining question also used a Likert scale; participants were asked to rate how useful they thought EXOs would be, by selecting a response ranging from 0 (extremely unuseful) to 5 (extremely useful). For this question, the value that equaled the number they selected was assigned to their overall score.

Participant Benefits, Barriers, Perceptions, and Readiness to Use scores were calculated by summing the participants' values for each respective set of questions (Table A1). Raw summation scores were then normalized to a scale of 0–10 to obtain final summation scores.

Questions used in calculating summation scores were summarized into two response categories depending on the specific response options: 1) agree (including agree and strongly agree) and disagree (including disagree and strongly disagree); or 2) not useful (including Likert scores ranging 0–2) and useful (including Likert scores ranging 3–5). To maintain statistical power, we retained all data, including responses from individuals who identified as neutral about each statement. We grouped neutral responses with either agree or disagree, based on our judgement of which grouping would be perceived as a barrier to achieving optimal and widespread use of EXOs in construction (see Table A2). This approach was used under the assumption that those who responded neutrally were less convinced of the benefits of using EXOs in

Table 1
Respondent demographics and work-related information.

	n (%)		*n* (%)
Race (*n* = 224)		**Job Types (*n* = 330)**	
White	140 (63)	Tools & Equipment	182 (55)
Hispanic/Latino	54 (24)	Tools & Equipment (Past)	38 (12)
Black	14 (6)	Primarily Office Worker	110 (33)
Other	16 (7)	**Years in Construction (*n* = 271)**	
Sex (*n* = 231)		0-14	95 (35)
Male	177 (77)	15-27	90 (33)
Female	54 (23)	28+	86 (32)
Age (*n* = 195)		**Company Size (*n* = 270)**	
<47 years	97 (50)	<50 people	96 (36)
≥47 years	98 (50)	50–199 people	60 (22)
Education (*n* = 232)		≥200 people	114 (42)
High school or less	62 (27)	**Top Trades**	
Vocational degree	24 (10)	Laborer	149 (47)
Some college	76 (33)	Carpenter	51 (16)
Associate degree	24 (10)	General Contractor	38 (12)
Bachelor's degree or more	46 (20)	Electrician	35 (11)

Table 2
Mean Benefits, Barriers, Perceptions, and Readiness to Use scores by race (White vs. non-White), sex (Male vs. Female), and age (<47 years vs. ≥47 years). Results from unpaired *t* tests are shown for differences in mean values with Cohen's *d* indicating effect size of difference in mean values. *p-value <0.05.

Summary Score	*n*	Mean	SD	*t* (*p*)	Cohen's *d*	95% CI
Benefits						
White	118	7.0	2.2	−2.3 (0.024*)	−0.34	[-0.63, −0.05]
Non-White	74	7.7	2.0			
Male	150	7.4	2.0	1.8 (0.078)	0.32	[-0.03, 0.66]
Female	47	6.7	2.5			
<47 years	83	7.7	2.1	2.2 (0.028*)	0.34	[0.04, 0.65]
≥47 years	84	7.0	2.1			
Barriers						
White	120	6.8	1.9	−1.3 (0.19)	−0.19	[-0.48, 0.09]
Non-White	75	7.2	1.8			
Male	154	6.7	1.7	−3.7 (0.00*)	−0.63	[-0.97, −0.28]
Female	47	7.8	1.8			
<47 years	85	6.7	1.8	2.1 (0.033*)	−0.33	[-0.63, −0.02]
≥47 years	85	7.3	1.8			
Perceptions						
White	136	5.8	1.9	0.21 (0.83)	0.03	[-0.24, 0.30]
Non-White	76	5.8	1.6			
Male	167	5.9	1.8	0.78 (0.44)	0.13	[-0.19, 0.45]
Female	51	5.7	1.9			
<47 years	94	6.2	1.8	2.4 (0.018*)	0.35	[0.06, 0.63]
≥47 years	96	5.6	1.7			
Readiness to Use						
White	119	6.7	2.1	−3.1 (0.00*)	−0.45	[-0.74, −0.17]
Non-White	78	7.7	2.0			
Male	156	7.3	2.0	1.7 (0.096)	0.30	[-0.05, 0.64]
Female	47	6.6	2.3			
<47 years	86	7.5	1.9	2.5 (0.015*)	0.38	[0.07, 0.68]
≥47 years	84	6.7	2.2			

construction.

2.5. Statistical analysis

If ≤5% of participant responses were missing for at least one question required to calculate a given summation score, those participants were dropped from further analysis. Otherwise, if 5–25% of participant responses were missing for at least one question, participants who answered more than half of the questions, but had a missing value for any of the remaining questions, were assigned the mean of values for the unanswered question(s).

Data were stratified by and compared across binary variables of race, sex, and age. Race was categorized as White and non-White. Sex was categorized as male and female, with respondents who selected other (n = 1) included in the female strata for analysis based on our judgement that they more closely related to the experiences and challenges of female respondents. Age categories of <47 years and ≥47 years were determined based on the median age of all participants. High and low categorization of the four summation scores were similarly assigned based on median scores, with labels of low high.

Data normality was evaluated using the Shapiro-Wilk test and visual inspection of histograms. Scatter plots and Pearson product-moment correlation coefficients were used to assess correlations between domains. Unpaired *t*-tests were used to compare mean values of summation scores by race, sex, and age, with Cohen's *d* used to quantify effect sizes. Separate Pearson's chi-square tests for independence were used to compare between scores (high vs. low), by race, sex, and age. Separate Chi-square tests were also used to assess differences between individual questions used to calculate summation scores, again by race, sex, and age. For all statistical tests, an alpha level of 0.05 was used as the criterion for statistical significance, and R software Version 4.0.0 (R Core Team, 2020) was used for analysis. Finally, open-ended questions were not formally analyzed and were collected only to provide context to respondent's answers.

3. Results

The survey was at least partially completed by 361 participants (Table 1). Most respondents were White males (46%) and over 40 years of age (65%). A plurality were current workers who primarily used tools and equipment (56%), with about one-third having that experience in the past and 12% being primarily office workers. The median number of years of work experience in construction was 20 (IQR = 20). Most participants worked at larger companies with 200 people or more. While laborers, carpenters, general contractors, and electricians were among the top trades represented, we received responses from a variety of trades, including bricklayers, plumbers, and flooring installers. Nearly all (96.8%) respondents worked in the United States (n = 158), with 48% in California, and 13% in Ohio, followed by 6% in New York. Only 71 participants had previously heard about workers using EXOs in construction, with 10 having tried on an EXO in the past.

While all summation scores failed the Shapiro-Wilk test for normality, inspection of score distributions (histograms) indicated near-normal distributions for Benefits (mean 7.3, SD 2.1, IQR 3.4), Barriers (mean 6.9, SD 1.8, IQR 2.5), Perceptions (mean 5.8, SD 1.8, IQR 2.5), Readiness to Use (mean 7.1, SD 2.0, IQR 2.3) scores. Therefore, parametric models were used for further analysis.

3.1. Benefits of EXO use

Roughly 84% indicated that EXOs would be beneficial for construction workers (n = 240), with half of those who responded predicting it would become standard equipment (n = 255). About three-quarters of respondents indicated that EXOs would reduce fatigue (n = 219), 70% of those who responded (n = 221) noted that it would make their work easier and 62% that it could make them more productive (n = 221). When asked to comment about the potential benefits of an EXO, one participant wrote that it might make work easier and so people with prior injuries might benefit. Five participants mentioned concerns, included increasing demands on other body regions and increasing injuries in those regions, losing muscle mass, and workers doing more, thereby negating the intended benefit of the EXO: *"The use of EXOs will be a tremendous benefit for the person's health over their career. My only concern will be [the wearer] lifting more than what they can or doing more than what they should since it is making it slightly easier for them."*

3.2. Barriers to EXO use

About 43% of the respondents would be willing to share an EXO (n = 223), with 82% indicating concerned about cleanliness (n = 223) and 80% that sharing an EXO would make it hard to refit or reuse (n = 222). About two-thirds (65%) would be concerned about storing the EXO (n = 222).

Heat discomfort while working was a common concern, with 36% of workers who primarily use tools and equipment experiencing heat discomfort more than half of the time during a typical workday (n = 174). When asked to specify what contributed the most to their heat discomfort, 83% reported working directly under the sun, 50% heat exposures due to personal protective equipment (PPE), 42% working inside hot rooms or buildings, 27% from hot work (such as welding or grinding), and another 26% from working in small spaces (n = 169).

Regarding the purchase price that would appeal to both employers

and laborers, 85% of workers thought that laborers would only purchase the EXO if it cost less than $US500 ($n = 212$), with respondents overall indicating that employers would pay more for an EXO, up to $US1,000. Specific comments regarding cost included: "*affordability is key here. This needs to be something a worker purchases, maintains, and sees as essential to their work … just like work boots.*"; "*The cost-effective benefits need to be stressed over the cost itself.*"

When asked to comment on perceived barriers to the use of EXOs in construction, many safety concerns were reported, such as increased slips/trips/falls, interference with tool belts, hindered movement when climbing poles or ladders, and EXOs being conductive/dangerous when performing electrical work. Some representative comments were: "*The EXOs would be difficult to wear with our tool belts and the fall protection harnesses we are required to wear.*"; "*is the equipment conductive or cause there to be an increased exposure to energized equipment?*"

Many respondents also shared concerns that the EXO would get caught or stuck on things or trap them in a trench or a piece of equipment that tipped over. For example: "*I work around moving equipment and on ever-changing job sites. The current design you guys have for this would be extremely unsafe to wear in any sort of plant or on a new construction site … We work around moving parts and with dangerous tools. Wearing a gadget like that could lead to a fatal accident.*" Overall, there was concern that the EXO would reduce mobility, agility, and the ability to get out of harm's way when necessary.

Other usability concerns included pressure points on the skin and the excess weight due to wearing the EXO together with other equipment such as tool belts. The durability of the EXO was also a concern noted, with questions on how it would perform in environments that have dust, water, dirt, and debris. Some indicated that the EXO would be a hassle to deal with because it is an extra piece of equipment, and others indicated that it would limit workers to just one task and may reduce task rotation: *"Too much extra equipment to haul around"; "The idea is cool, but the extra equipment is a hassle. Another thing to adjust and have get in the way"; "Bulky, tasks always change."*

3.3. Perceptions of EXOs

When asked what their reaction would be if they saw a co-worker using an EXO, 51% reported wondering why they don't have one ($n = 253$). About 70% had the reaction that it was really cool and would want to know more about what it did ($n = 255$). About half reported thinking the person was injured ($n = 250$), 24% would think the person is old ($n = 250$), and 22% would think the worker is physically weak ($n = 253$). One participant noted that "*construction workers like to think they are very strong and don't need any* support."

3.4. Readiness to use an EXO

When asked about the adoption of EXOs in the construction industry, approximately 75% responded they would try an EXO ($n = 171$), with 83% indicating they would use it voluntarily at work if provided ($n = 187$). Half noted they would wear the EXO for an entire workday ($n = 112$). Comments regarding the adoption of EXOs included: "*as long it doesn't interfere with your job"; "They would be helpful in some tasks and a hindrance/not practical in others.*"

3.5. Correlations among response domains

Significant, positive correlations were found among several pairs of summations scores: Benefits and Readiness to Use (Pearson's $r = 0.83$, $p < 0.001$); Perceptions and Readiness to Use (Pearson's $r = 0.51$, $p < 0.001$); and Perceptions and Benefits (Pearson's $r = 0.58$, $p < 0.001$). Barriers s and Readiness to Use scores, though, were not significantly correlated (Pearson's $r = -0.13$, $p = 0.06$).

3.6. Race (white vs. non-white)

There was a significant difference in mean Benefits and Readiness to Use scores among White participants (7 and 6.7, respectively) compared to non-White participants (7.7 for both), with the latter having higher scores in both cases (Table 2). There was also a significant difference in high vs low Barriers score among those who identified as White (Table 3). The two survey questions that yielded significant differences between Racial groups was one that asked if they would wear an EXO for an entire workday and one that asked if they would have concerns about storing an EXO; in both cases, Non-white participants were more likely to agree (Table A2).

3.7. Sex (male vs. female)

Females had a significantly higher mean Barriers score (7.8 vs. 6.7 for men) (Table 2). Comments included how EXOs are typically designed for males: "*I foresee my breasts being a problem in how the back EXO will fit. Will it consider our hips? Smaller shoulders …*"; "*assumptions that 'one size fits all' means women as well*".

3.8. Age (<47 years vs. ≥47 years)

There was a significant difference in mean Benefits, Barriers, Perceptions, and Readiness to Use scores among those who were <47 years vs. ≥47 years of age (Table 2). Mean Benefits, Perceptions, and Readiness to Use scores were each higher for those <47 years (7.7 vs. 7.0, 6.2 vs. 5.6, and 7.5 vs. 6.7, respectively), while mean Barriers score was lower (6.7 vs. 7.3). For individual questions, those <47 years of age were more likely to agree that EXOs are both useful and that they would be open to sharing an EXO and were less likely to indicate concerns about storing an EXO (Table A2). Those ≥47 years of age were more likely to report that a worker is physically weak or old for using an EXO (Table A2).

4. Discussion

Overall, this study explored construction workers initial perceptions and concerns about using a passive arm support exoskeleton during their work. A strength of this study was that the cohort was large and varied in its representation demographically. This allowed the exploration of differing opinions by key demographic characteristics, something that could not be done in a small focus group or on a small number of participants in a laboratory study. Both race and sex influenced responses related to perceived barriers, an important finding when introducing ASEs to female and older construction workers. Additionally, since a higher Benefits score and a higher Perceptions score were significantly and positively associated with a higher Readiness to Use score, introductions to ASEs should be sure to highlight the benefits of wearing ASEs and proactively ensure that ASEs are not introduced as a way to support weaker or injured workers, rather a tool, like choosing the right drill, to make the work feel easier.

It should be noted that there are recommendations on the safe implementation of EXOs such as the ASTM F48 technical committee that states that such standards would enhance the adoption and use of EXOs across industries. Although industry wide standards would likely be helpful in EXO implementation, construction work is unique and varied in tasks, environments, and workers. Therefore, having additional construction specific guidance may be critically important; the results of this study provide insight as to what should be included in such material.

4.1. Sample representativeness

2020 national construction industry data (BLS, 2020a) shows that women accounted for approximately 11% of the construction workforce, compared to 23% female respondents for our survey. We note that

Table 3
Chi-square results for associations between high vs. low Benefits, Barriers, Perceptions, and Readiness to Use scores. Results are stratified by race (White vs. non-White), sex (male vs. female), and age (<47 years vs. ≥47 years).

	Race					Sex					Age				
	n	White (*n* = 140)	Non-White (*n* = 84)	χ^2	*p*	*n*	Male (*n* = 177)	Female (*n* = 54)	χ^2	*p*	*n*	<47 years (*n* = 97)	≥47 years (*n* = 98)	χ^2	*p*
Overall Benefits Score	192	**$n = 118$**	**$n = 74$**	1.1	0.30	197	**$n = 150$**	**$n = 47$**	1.4	0.24	167	**$n = 83$**	**$n = 84$**	0.17	0.68
High (≥7.5)		66	47				91	24				51	49		
Low (<7.5)		52	27				59	23				32	35		
Overall Barriers Score	195	**$n = 120$**	**$n = 75$**	4.6	0.03*	201	**$n = 154$**	**$n = 47$**	8.5	0.00*	170	**$n = 85$**	**$n = 85$**	2.4	0.12
High (≥6.9)		63	51				81	36				45	55		
Low (<6.9)		57	24				73	11				40	30		
Overall Perceptions Score	212	**$n = 136$**	**$n = 76$**	0.22	0.64	218	**$n = 167$**	**$n = 51$**	0.13	0.71	190	**$n = 94$**	**$n = 96$**	2.9	0.088
High (≥5.5)		85	45				103	30				66	56		
Low (<5.5)		51	31				64	21				28	40		
Overall Readiness to Use Score	197	**$n = 119$**	**$n = 78$**	2.1	0.15	203	**$n = 156$**	**$n = 47$**	1.2	0.28	170	**$n = 86$**	**$n = 84$**	1.6	0.21
High (≥6.9)		72	55				103	27				61	52		
Low (<6.9)		47	23				53	20				25	32		

the BLS uses woman to categorize sex, instead of female. The BLS data also show that 30% identified as Hispanic, 61% as White, and 5% as Black. In our survey, the corresponding values were 24%, 63%, and 6% as Black. Regarding age, 4% of our survey respondents were between 16 and 24, 70% between 25 and 54, and 30% were 55 years or older, compared to respective national percentages of 9%, 68% and 23%. Overall, we thus conclude that our sample was reasonably representative of the U.S. construction workforce.

4.2. Benefits of EXO use

A mix of laborers, management, and union workers indicated potential benefits of EXOs, including reducing fatigue and increasing productivity. Additionally, some respondents considered EXOs a potential opportunity to expand the pool of construction workers, either for those whose aging or musculoskeletal injuries resulted in their reduced work assignments or leaving of the workforce entirely. In both cases, our results are consistent with previous findings that suggest EXOs as an intervention to meet physical requirements of a job could contribute to a larger, healthier population of construction workers (de Looze et al., 2016; Mahmud et al., 2022; Theurel and Desbrosses, 2019). By promoting long-term retention, employers may avoid both losing valuable, experienced workers and the costs that come with recruiting and training new workers (Schwatka et al., 2012).

4.3. Barriers to EXO use

While our results were consistent with expected benefits of EXO use (Andrade and Nathan-Roberts, 2022; Okpala et al., 2022), there were many concerns regarding barriers that need to be addressed prior to EXOs being implemented as standard equipment in construction. Concerns about limited mobility emphasize the importance of conducting further laboratory studies to address how EXOs might affect climbing, balance, or movement through tight spaces, both when performing work tasks and in the event of an emergency response. Heat-related illness has been identified as a severe hazard for the safety and wellbeing of both indoor and outdoor construction workers. As an added layer for the user, EXOs without additional interventions may increase the risk for heat-related illness. In fact, thermal discomfort resulting from EXO use was often of concern even in indoor manufacturing environments (Gilotta et al., 2019; Kim et al., 2022; Smets, 2019). Future work is recommended to identify how EXOs can be paired with cooling clothing, or water, rest, and shade, and be adapted into heat illness prevention plans and employee training. These results are consistent with previous findings that have identified limited mobility and adverse indoor and outdoor climate among the ten critical safety and health hazards associated with EXO use (Nnaji et al., 2023).

The price of available occupational EXOs ranges from approximately $US500 to $US5,000 (based on recent quotes from manufacturers received by the authors). The cost of an EXO, which is generally designed for a single user, is much higher compared to typical face shields, gloves, and fall or respiratory protection ($US10-$US200), all common PPE in construction. Concerns about the cost of EXOs indicate that their wide-spread adoption may depend on an employer's ability and willingness to purchase them. Employers will likely want to purchase multiple EXOs to avoid workflow disruptions that come from deciding who gets to use one and constantly readjusting it once it has been used by someone else.

4.4. Perceptions of EXO

There was notable interest among respondents to learn more about what EXOs are, how they work, and why they can be an important intervention for WMSD's in construction. While there is this growing popularity and marketing of EXOs, responses here suggested that EXOs were at least partly perceived as intended for workers who are physically weak (50%) or already injured (22%). It is therefore important to be intentional about the messaging of EXOs, as intended for use as PPE or tool rather than a rehabilitative device. In December of 2020, ASTM International Exo Technology Center of Excellence hosted a panel discussion on considerations to make when deciding to categorize EXOs as PPE (ET CoE PPE Webinar, n.d.). As described in a publicly-available, written Q&A follow-up for this event, PPE that is mandated by the Occupational Safety and Health Administration (OSHA) has standards that provide formal guidance on the measurable risks that a PPE reduces (ET CoE PPE Webinar, n.d.). In addition to helping employers and/or employees avoid making biased judgements based on their perceptions of EXOs, making it clear the EXOs are PPE may help with changing the perception from workers who are injured to workers being safer wearing their PPE.

4.5. Readiness to use an EXO

There was clear interest among respondents, with 83% of workers expressing that they would use an EXO if provided by their employer. Understandably, however, accompanying comments implied a level of

hesitancy towards using EXOs in situations that might hinder safety or productivity. This hesitancy highlights a need for researchers, manufacturers, companies, and regulating committees to first address the type of work for which EXO use can be implemented effectively as well as the safety elements that will need to be addressed in conjunction with EXOs. This agrees with many earlier studies that reported task specificity (Alabdulkarim et al., 2019; de Vries et al., 2022). Results from laboratory studies in a controlled environment that simulate select construction tasks could help in targeting EXO applications.

4.6. Differences between demographic characteristics

As expected, workers who perceived the benefits of EXOs felt more strongly about being ready to use one during work. Similarly expected, those who viewed EXOs as an opportunity to prevent injury instead of a sign of weakness felt more strongly about being ready to use one during work. These results align with earlier research that found worker perceptions of how useful EXOs are (performance expectancy), and whether others think workers should use EXOs (social influence), play a role in predicting their intention to use an EXO (Elprama et al., 2020). As such, education on the benefits and intended use of EXOs may be an important component of achieving wide-spread adoption. Given that Barriers and Readiness to Use scores were not significantly correlated, it appears that the number of barriers that someone perceives to the adoption of EXOs might not necessarily influence their perceived readiness to use one. This result leaves the impression that even after addressing barriers, a worker's perception and understanding of EXO benefits might have a greater influence on their adoption of EXOs. Lastly, workers with a more positive perception of EXO use also identified EXOs as having greater benefits, once again emphasizing the importance of how EXOs are promoted within the construction industry.

4.7. Race (white vs. non-white)

Non-White participants identified more barriers to the implementation of EXOs, consistent with existing literature on occupational health and safety disparities across various industries (Steege et al., 2014). Concerns about heat stress (Rinehart, 2021) and access to appropriate training (Cunningham et al., 2018), both of which are documented, disproportionate vulnerabilities among non-White workers, may be contributing factors. Despite these barriers, non-White participants having higher scores for both Benefits and Readiness to Use may also be indicative of a strong drive to counteract longstanding occupational health disparities and advance towards a more equitable workplace.

4.8. Sex (male vs. female)

While there were no statistically significant differences in reported concerns about adjusting EXOs, it is worth noting that a properly fitted EXO was an important consideration for both males and females (see section 3.7), even if for potentially distinct reasons. Females may require EXOs tailored to their body proportions, which may require additional or specific EXO design considerations. In contrast, concerns from male respondents highlighted concerns about the practicality of sharing a single EXO among multiple individuals or adjusting it to accommodate different job tasks.

With the objective that EXOs will be introduced as PPE, it will be the employer's responsibility, as with all PPE, to ensure both that it is appropriate for a given task and that it is the right fit for the worker. Earlier work among female construction workers found that they continued to have difficulty accessing properly fitting PPE, including safety harnesses, gloves, and safety glasses (Onyebeke et al., 2016). Similarly, a 2016 survey conducted by the Trades Union Congress that found that just 29% of female respondents were using PPE designed for women, and 57% said their PPE hampered their work (Personal protective equipment and women, 2017). The latter authors noted that work equipment tends to be designed for the average-sized male worker, which can lead to an increased risk of musculoskeletal disorders among those who are smaller, taller, or otherwise have different body proportions. A more recent study found that standard face masks recommended by the Centers for Disease Control and Prevention (CDC) to reduce airborne transmission of the SARS-CoV-2 during the COVID-19 were more susceptible to perimeter leakage, and therefore were not as effective against aerosols, for thin, feminine, or young faces (Solano et al., 2021). Our results are consistent with these findings, indicating the importance of designing EXOs that fit workers of varying body proportions, including those with breasts and wider hips (Alemi et al., 2020).

4.9. Age (< 47 years vs. ≥47 years)

A study on building a sustainable construction workforce lists pension plans, retiree health care benefits, and increasing age eligibility requirements for full Social Security retirement benefits as financial pressures for continue to work (Sokas et al., 2019). The authors also noted that while age discrimination is hard to prove, increased workers' compensation costs may lead contractors to hire younger workers and lay off older ones (Sokas et al., 2019). Following this rationale, we expected that older respondents would be more drawn to EXOs, which could help with the physical demands experienced by an aging workforce. However, with a more positive perception of EXOs and their benefits, younger respondents appeared more ready to implement EXOs in their work. Older respondents, on the other hand, tended to view EXOs as less useful. Possible explanations include younger workers being more familiar and receptive of new technologies, more experienced workers believing they do not need to adapt their working methods or being concerned about how negative attitudes towards aging workers or their need for what may be perceived as assistive devices.

4.10. Limitations

While respondents had the option to watch an introductory video on EXOs, due to the COVID-19 pandemic, there were no opportunities for hands-on EXO demonstrations in tandem with the survey. Given that EXOs are still uncommon, respondents may not have had a sufficient and accurate depiction of what to expect from this technology. However, this approach emulates what the majority of workers will initially experience – awareness about an EXO before deciding whether to explore or pilot it further. Therefore, this study represents workers initial perceptions as they decide whether or not to even try an EXO. Secondly, treating responses from survey questions that use a Likert scale as parametric data is both supported and discouraged in the literature, as is the approach of creating a summation score from multiple responses (Sullivan and Artino, 2013). However, the assumption of normality was evaluated before applying parametric statistical approaches and a chi-square test was chosen to analyze differences in summation scores between groups; therefore a factor analysis of clustered items was not included in these results. As a third potential limitation, a survey question regarding whether participants would wear an EXO for an entire workday was included in the Readiness to Use score. However, there is no generalized expectation that EXOs need to be worn for an entire workday, and guidance on use will likely vary by work trade and/or specific work task. Additionally, when addressing missingness in calculating summation score, we gave participants a value that was the mean value among participants who answered a given question. While this approach was only used for a portion of Readiness to Use scores, this approach may have led to results that are biased towards the null.

One participant identified their sex as other. Without any information on whether this person's physical characteristics were more comparable to a male or female body, we arbitrarily added them to a category to include their perspective. After qualitatively examining this individual's feedback, we included them as part of the female category

for the purposes of statistical analysis. Additionally, we completed a sensitivity analysis excluding the person who identified as other and found that there were no meaningful changes in effect estimates or levels of statistical significance.

5. Conclusions

The use of EXOs has the potential to be accepted as an intervention to reduce WMSD risks, expand accessibility to construction jobs, and even enhance performance. Most respondents expressed interest in learning more about EXO use in construction and how this technology could be applied in their own work. These findings can be used to facilitate successful future adoption and implementation of EXOs in construction and other industries. EXO implementation efforts should focus on the reduction of fatigue and related increases in productivity. Communication efforts should also describe how EXOs, through physical augmentation, could increase the number of workers who can perform a task and help retain experienced workers. The primary barriers that must be addressed in communications include EXO impacts on mobility and safety. Guidelines on how to implement EXOs effectively and safely should be devised and shared widely. Further, to address cost concerns, vendors should consider additional strategies to make EXO use affordable, such as through rentals or interest free payment plans.

We also found some differences in perceived barriers, benefits, perceptions, and readiness for EXO adoption by race, sex, and age, which should also be taken into consideration when communicating about EXOs with workers from these demographic groups. For instance, non-White and female workers identified the potential for increased risk of injury from safety hazards as a significant barrier. Targeted training should address how to identify tasks suitable for EXO use as well as safety-based contraindications to EXO use. Given these concerns, it will be imperative that EXO trainings are offered in languages and with cultural considerations appropriate to the worker population. Additionally, we found that older workers ($\geq$47 years) identified fewer benefits from EXOs. Targeted sensitive messaging for this age group may help improve their perceptions and readiness to adopt EXOs.

Variable work conditions and construction site hazards are aspects of construction work that make EXO adoption distinctive from other industries such as in manufacturing. However, findings from this study and industry sector can be used to facilitate widespread adoption of EXOs across industries that will similarly depend on clear, consistent, and compelling messages about how the technology can be safely used to support the worker when performing physically demanding tasks.

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Declaration of competing interest

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

Appendix A

Table A1
Raw Benefits, Barriers, Perceptions, and Readiness to Use score calculations. A participant's score was calculated by summing values based on their responses to the questions below.

Benefits Score Calculation		
Survey Question	Participant's Response	Assigned Value
1) It would make my work easier.	Strongly agree	5
	Agree	4
	Neither agree nor disagree	3
	Disagree	2
	Strongly disagree	1
2) It would reduce fatigue.	Strongly agree	5
	Agree	4
	Neither agree nor disagree	3
	Disagree	2
	Strongly disagree	1
3) It could make me more productive.	Strongly agree	5
	Agree	4
	Neither agree nor disagree	3
	Disagree	2
	Strongly disagree	1
	Participant's Benefits Score =	
Barriers Score Calculation		
Survey Question	**Participant's Response**	**Assigned Value**
1) I would share an EXO.	Strongly agree	1
	Agree	2
	Neither agree nor disagree	3
	Disagree	4
	Strongly disagree	5
2) I would be concerned about storage.	Strongly agree	5
	Agree	4
	Neither agree nor disagree	3
	Disagree	2
	Strongly disagree	1
3) I would be concerned about cleaning it.	Strongly agree	5
	Agree	4
	Neither agree nor disagree	3

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Table A1 (*continued*)

Benefits Score Calculation		
Survey Question	Participant's Response	Assigned Value
	Disagree	2
	Strongly disagree	1
4) I would be concerned about readjusting it.	Strongly agree	5
	Agree	4
	Neither agree nor disagree	3
	Disagree	2
	Strongly disagree	1
	Participant's Barriers Score =	
Perceptions Score Calculation		
Survey Question	**Participant's Response**	**Assigned Value**
1) Why don't I have one?	Strongly agree	5
	Agree	4
	Neither agree nor disagree	3
	Disagree	2
	Strongly disagree	1
2) They're physically weak.	Strongly agree	1
	Agree	2
	Neither agree nor disagree	3
	Disagree	4
	Strongly disagree	5
3) They're old.	Strongly agree	1
	Agree	2
	Neither agree nor disagree	3
	Disagree	4
	Strongly disagree	5
4) How cool!	Strongly agree	5
	Agree	4
	Neither agree nor disagree	3
	Disagree	2
	Strongly disagree	1
5) They're injured.	Strongly agree	1
	Agree	2
	Neither agree nor disagree	3
	Disagree	4
	Strongly disagree	5
	Participant's Perceptions Score =	
Readiness to Use Score Calculation		
Survey Question	**Participant's Response**	**Assigned Value**
1) I would use it voluntarily if provided	Strongly agree	5
	Agree	4
	Neither agree nor disagree	3
	Disagree	2
	Strongly disagree	1
2) I would wear it for an entire workday.	Strongly agree	5
	Agree	4
	Neither agree nor disagree	3
	Disagree	2
	Strongly disagree	1
3) How useful do you think an EXO will be?	0 (extremely unuseful)	0
	1	1
	2	2
	3	3
	4	4
	5 (extremely useful)	5
	Participant's Readiness to Use Score =	

Table A2
Expanded version of Table 3 to include Chi-square results to test for association between binary categorizations of survey questions used to calculate Benefits, Barriers, Perceptions, and Readiness to Use. Also included are chi-square results to test for associations between high vs. low Benefits, Barriers, Perceptions, and Readiness to Use scores. Results are stratified by race (White vs. non-White), sex (male vs. female), and age (<47 years vs. ≥47 years). *Includes agree and strongly agree. ** Includes disagree and strongly disagree.

	Race					Sex					Age				
	n	White (*n* = 140)	Non-White (*n* = 84)	χ^2	*p*	*n*	Male (*n* = 177)	Female (*n* = 54)	χ^2	*p*	*n*	<47 years (*n* = 97)	≥47 years (*n* = 98)	χ^2	*p*
Benefits															

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Table A2 (*continued*)

	Race					Sex					Age				
	n	White (*n* = 140)	Non-White (*n* = 84)	χ^2	*p*	*n*	Male (*n* = 177)	Female (*n* = 54)	χ^2	*p*	*n*	<47 years (*n* = 97)	≥47 years (*n* = 98)	χ^2	*p*
It would make my work easier.	195	***n* = 120**	***n* = 75**	0.18	0.67	201	***n* = 153**	***n* = 48**	3.8	0.05*	169	***n* = 84**	***n* = 85**	0.00	0.96
Agree*		83	54				112	28				59	60		
Disagree**/ Neutral		37	21				41	20				25	25		
It would reduce fatigue.	194	***n* = 119**	***n* = 75**	0.00	1.0	199	***n* = 152**	***n* = 47**	2.7	0.10	169	***n* = 84**	***n* = 85**	1.6	0.21
Agree*		92	58				121	32				69	63		
Disagree**/ Neutral		27	17				31	15				15	22		
It could make me more productive.	195	***n* = 119**	***n* = 76**	0.26	0.61	201	***n* = 153**	***n* = 48**	0.21	0.65	169	***n* = 85**	***n* = 84**	1.1	0.30
Agree*		74	50				98	29				59	52		
Disagree**/ Neutral		45	26				55	19				26	32		
Overall Benefits Score	192	***n* = 118**	***n* = 74**	1.1	0.30	197	***n* = 150**	***n* = 47**	1.4	0.24	167	***n* = 83**	***n* = 84**	0.17	0.68
High (≥7.5)		66	47				91	24				51	49		
Low (<7.5)		52	27				59	23				32	35		
Barriers															
I would share an EXO.	197	***n* = 120**	***n* = 77**	0.57	0.45	203	***n* = 155**	***n* = 48**	2.9	0.09	171	***n* = 86**	***n* = 85**	3.9	0.05*
Agree*		48	35				70	15				41	28		
Disagree**/ Neutral		72	42				85	33				45	57		
I would be concerned about storage.	196	***n* = 120**	***n* = 76**	4.6	0.03*	202	***n* = 154**	***n* = 48**	0.03	0.86	170	***n* = 85**	***n* = 85**	3.6	0.05*
Agree*/Neutral		95	69				130	40				67	76		
Disagree**		25	7				24	8				18	9		
I would be concerned about cleaning it.	197	***n* = 120**	***n* = 77**	0.70	0.40	203	***n* = 155**	***n* = 48**	2.3	0.13	171	***n* = 86**	***n* = 85**	0.00	0.98
Agree*/Neutral		110	73				142	47				81	80		
Disagree**		10	4				13	1				5	5		
I would be concerned about readjusting it.	196	***n* = 120**	***n* = 76**	0.12	0.73	202	***n* = 155**	***n* = 47**	0.78	0.38	171	***n* = 86**	***n* = 85**	0.55	0.46
Agree*/Neutral		114	73				147	46				83	80		
Disagree**		6	3				8	1				3	5		
Overall Barriers Score	195	***n* = 120**	***n* = 75**	4.6	0.03*	201	***n* = 154**	***n* = 47**	8.5	0.00*	170	***n* = 85**	***n* = 85**	2.4	0.12
High (≥6.9)		63	51				81	36				45	55		
Low (<6.9)		57	24				73	11				40	30		
Perceptions															
Why don't I have one?	217	***n* = 138**	***n* = 79**	0.70	0.40	224	***n* = 171**	***n* = 53**	0.14	0.71	191	***n* = 95**	***n* = 96**	0.44	0.51
Agree*		74	47				95	31				55	51		
Disagree**/ Neutral		64	32				76	22				40	45		
They're physically weak.	219	***n* = 139**	***n* = 80**	0.48	0.49	225	***n* = 172**	***n* = 53**	0.15	0.70	197	***n* = 97**	***n* = 96**	0.92	0.34
Agree*/Neutral		82	51				102	33				53	59		
Disagree**		57	29				70	20				44	37		
They're old.	216	***n* = 139**	***n* = 77**	0.14	0.71	222	***n* = 170**	***n* = 52**	0.72	0.40	191	***n* = 95**	***n* = 96**	3.9	0.05
Agree*/Neutral		83	48				100	34				49	63		
Disagree**		56	29				70	18				46	33		
How cool!	219	***n* = 138**	***n* = 81**	1.9	0.17	226	***n* = 173**	***n* = 53**	0.047	0.83	193	***n* = 97**	***n* = 96**	3.7	0.06
Agree*		88	59				117	35				73	60		
Disagree**/ Neutral		50	22				56	18				24	36		
They're injured.	216	***n* = 137**	***n* = 79**	1.5	0.22	222	***n* = 171**	***n* = 51**	0.05	0.82	191	***n* = 95**	***n* = 96**	0.92	0.34
Agree*/Neutral		101	64				130	38				74	69		
Disagree**		36	15				41	13				21	27		
Overall Perceptions Score	212	***n* = 136**	***n* = 76**	0.22	0.64	218	***n* = 167**	***n* = 51**	0.13	0.71	190	***n* = 94**	***n* = 96**	2.9	0.088
High (≥5.5)		85	45				103	30				66	56		

(*continued on next page*)

Table A2 (*continued*)

	Race					Sex					Age				
	n	White (*n* = 140)	Non-White (*n* = 84)	χ^2	*p*	*n*	Male (*n* = 177)	Female (*n* = 54)	χ^2	*p*	*n*	<47 years (*n* = 97)	≥47 years (*n* = 98)	χ^2	*p*
Low (<5.5)		51	31				64	21				28	40		
Readiness to Use															
I would use it voluntarily if provided.	197	***n* = 119**	***n* = 78**	1.2	0.28	203	***n* = 156**	***n* = 47**	0.70	0.40	170	***n* = 86**	***n* = 84**	1.2	0.26
Agree*		95	67				131	37				75	68		
Disagree**/ Neutral		24	11				25	10				11	16		
I would wear it for an entire workday.	196	***n* = 120**	***n* = 76**	5.0	0.03*	202	***n* = 155**	***n* = 47**	2.2	0.13	171	***n* = 86**	***n* = 85**	0.05	0.82
Agree*		53	46				82	19				43	44		
Disagree**/ Neutral		67	30				73	28				43	41		
How useful do you think an EXO will be?	222	***n* = 139**	***n* = 83**	2.9	0.09	229	***n* = 176**	***n* = 53**	0.37	0.54	193	***n* = 97**	***n* = 96**	3.8	0.05*
Not Useful (0–2)		25	8				24	9				8	17		
Useful (3–5)		114	75				152	44				89	79		
Overall Readiness to Use Score	197	***n* = 119**	***n* = 78**	2.1	0.15	203	***n* = 156**	***n* = 47**	1.2	0.28	170	***n* = 86**	***n* = 84**	1.6	0.21
High (≥6.9)		72	55				103	27				61	52		
Low (<6.9)		47	23				53	20				25	32		

References

Alabdulkarim, S., Kim, S., Nussbaum, M.A., 2019. Effects of exoskeleton design and precision requirements on physical demands and quality in a simulated overhead drilling task. Appl. Ergon. 80, 136–145. https://doi.org/10.1016/j.apergo.2019.05.014.

Alemi, M.M., Madinei, S., Kim, S., Srinivasan, D., Nussbaum, M.A., 2020. Effects of two passive back-support exoskeletons on muscle activity, energy expenditure, and subjective assessments during repetitive lifting. Hum. Factors 62 (3), 458–474. https://doi.org/10.1177/0018720819897669.

Andrade, C., Nathan-Roberts, D., 2022. Occupational exoskeleton adoption and acceptance in construction and industrial work: a scoping review. Proc. Hum. Factors Ergon. Soc. Annu. Meet. 66 (1), 1325–1329. https://doi.org/10.1177/1071181322661415.

ASTM, 2020. ASTM International—ASTM F3323-20—Standard Terminology for Exoskeletons and Exosuits. https://standards.globalspec.com/std/14137488/ASTM%20F3323-20.

BLS, 2020a. The Construction Industry: Characteristics of the Employed, 2003–20 : Spotlight on Statistics. U.S. Bureau of Labor Statistics. https://www.bls.gov/spotlight/2022/the-construction-industry-labor-force-2003-to-2020/home.htm.

BLS, 2020b. U.S. Bureau of Labor Statistics: Survey of Occupational Injuries and Illnesses Data. https://www.bls.gov/iif/nonfatal-injuries-and-illnesses-tables.htm#dafw.

Bosch, T., van Eck, J., Knitel, K., de Looze, M., 2016. The effects of a passive exoskeleton on muscle activity, discomfort and endurance time in forward bending work. Appl. Ergon. 54, 212–217. https://doi.org/10.1016/j.apergo.2015.12.003.

Butler, T., Wisner, D., 2017. Exoskeleton Technology: Making Workers Safer and More Productive | Professional Safety | OnePetro. https://onepetro.org/PS/article-abstract/61/09/32/33392/Exoskeleton-Technology-Making-Workers-Safer-and?redirectedFrom=fulltext.

CPWR, 2023. Women in Construction. CPWR |. https://www.cpwr.com/research/data-center/data-dashboards/women-in-construction/.

Crea, S., Beckerle, P., Looze, M.D., Pauw, K.D., Grazi, L., Kermavnar, T., Masood, J., O'Sullivan, L.W., Pacifico, I., Rodriguez-Guerrero, C., Vitiello, N., Ristić-Durrant, D., Veneman, J., 2021. Occupational exoskeletons: a roadmap toward large-scale adoption. Methodology and challenges of bringing exoskeletons to workplaces. Wearab. Tech. 2, e11. https://doi.org/10.1017/wtc.2021.11.

Cunningham, T.R., Guerin, R.J., Keller, B.M., Flynn, M.A., Salgado, C., Hudson, D., 2018. Differences in safety training among smaller and larger construction firms with non-native workers: evidence of overlapping vulnerabilities. Saf. Sci. 103, 62–69. https://doi.org/10.1016/j.ssci.2017.11.011.

Dasgupta, P., Punnett, L., Moir, S., Kuhn, S., Buchholz, B., 2015. Interventions to reduce the ergonomic exposures of drywall installation. Procedia Manuf. 3, 4173–4180. https://doi.org/10.1016/j.promfg.2015.07.392.

de Looze, M.P., Bosch, T., Krause, F., Stadler, K.S., O'Sullivan, L.W., 2016. Exoskeletons for industrial application and their potential effects on physical work load. Ergonomics 59 (5), 671–681. https://doi.org/10.1080/00140139.2015.1081988.

de Vries, A.W., Baltrusch, S.J., de Looze, M.P., 2022. Field study on the use and acceptance of an arm support exoskeleton in plastering. Ergonomics 0 (0), 1–11. https://doi.org/10.1080/00140139.2022.2159067.

Elprama, S., Vannieuwenhuyze, J., De Bock, S., Vanderborght, B., De Pauw, K., Meeusen, R., Jacobs, A., 2020. Social processes: what determines industrial workers' intention to use exoskeletons? Hum. Factors: J. Human Factor. Ergon. Soci. 62, 001872081988953 https://doi.org/10.1177/0018720819889534.

ET CoE PPE Webinar. Retrieved January 4, 2023, from. https://static1.squarespace.com/static/5dc4665416995d66930da7f5/t/600f23380e5fca6c1c1d0ad2/1611604792671/ET+CoE+PPE+Webinar+Questions+/281/29.pdf.

Forde, M.S., Buchholz, B., 2004. Task content and physical ergonomic risk factors in construction ironwork. Int. J. Ind. Ergon. 34 (4), 319–333. https://doi.org/10.1016/j.ergon.2004.04.011.

Gilotta, S., Spada, S., Ghibaudo, L., Isoardi, M., Mosso, C.O., 2019. Accept. Beyond Usabil.: Manufact. Case Study 824, 922–934. https://doi.org/10.1007/978-3-319-96071-5_95.

Hetzner, C., 2016. BMW Workers Don "Iron Man" Suit | Automotive News. https://www.autonews.com/article/20160626/OEM01/306279965/bmw-workers-don-iron-man-suit.

Huysamen, K., Bosch, T., Looze, M., Stadler, K., Graf, E., O'Sullivan, L., 2018. Evaluation of a passive exoskeleton for static upper limb activities. Appl. Ergon. 70, 148–155. https://doi.org/10.1016/j.apergo.2018.02.009.

Kim, J.-H., 2018. Hyundai Brings Wearable Robotics to Factories. https://koreajoongangdaily.joins.com/news/article/article.aspx?aid=3054561&cloc=joongangdaily%7Chome%7Cnewslist1.

Kim, S., Moore, A., Srinivasan, D., Akanmu, A., Barr, A., Harris-Adamson, C., Rempel, D. M., Nussbaum, M.A., 2019. Potential of exoskeleton technologies to enhance safety, health, and performance in construction: industry perspectives and future research directions. IISE Transact. Occupat. Ergon. Human Factor. 0 (0), 1–7. https://doi.org/10.1080/24725838.2018.1561557.

Kim, S., Nussbaum, M.A., Mokhlespour Esfahani, M.I., Alemi, M.M., Jia, B., Rashedi, E., 2018. Assessing the influence of a passive, upper extremity exoskeletal vest for tasks requiring arm elevation: Part II - "Unexpected" effects on shoulder motion, balance, and spine loading. Appl. Ergon. 70, 323–330. https://doi.org/10.1016/j.apergo.2018.02.024.

Kim, S., Nussbaum, M.A., Smets, M.., 2021. Effects of an arm-support exoskelton on perceived work intensity and musculoskeletal discomfort: An 18-month field study in automotive assembly. American Journal of Industrial Medicine. 64 (11), 905–914. https://doi.org/10.1002/ajim.23282.

Kim, S., Nussbaum, M.A., Smets, M., 2022. Usability, user acceptance, and health outcomes of arm-support exoskeleton use in automotive assembly: an 18-month field study. J. Occup. Environ. Med. 64 (3), 202–211. https://doi.org/10.1097/JOM.0000000000002438.

Krok, A., 2017. Ford's Exoskeleton Could Help Factory Workers in a Big Way—CNET. https://www.cnet.com/roadshow/news/fords-exoskeleton-could-help-factory-workers-in-a-big-way/.

Madinei, S., Alemi, M.M., Kim, S., Srinivasan, D., Nussbaum, M.A., 2020. Biomechanical evaluation of passive back-support exoskeletons in a precision manual assembly task: "expected" effects on trunk muscle activity, perceived exertion, and task performance. Hum. Factors 62 (3), 441–457. https://doi.org/10.1177/0018720819890966.

Mahmud, D., Bennett, S.T., Zhu, Z., Adamczyk, P.G., Wehner, M., Veeramani, D., Dai, F., 2022. Identifying facilitators, barriers, and potential solutions of adopting exoskeletons and exosuits in construction workplaces. Sensors 22 (24), 9987. https://doi.org/10.3390/s22249987.

Nnaji, C., Okpala, I., Gambatese, J., Jin, Z., 2023. Controlling safety and health challenges intrinsic in exoskeleton use in construction. Saf. Sci. 157, 105943 https://doi.org/10.1016/j.ssci.2022.105943.

Okpala, I., Nnaji, C., Ogunseiju, O., Akanmu, A., 2022. Assessing the role of wearable robotics in the construction industry: potential safety benefits, opportunities, and implementation barriers. In: Jebelli, H., Habibnezhad, M., Shayesteh, S., Asadi, S., Lee, S. (Eds.), Automation and Robotics in the Architecture, Engineering, and Construction Industry. Springer International Publishing, pp. 165–180. https://doi.org/10.1007/978-3-030-77163-8_8.

Onyebeke, L.C., Papazaharias, D.M., Freund, A., Dropkin, J., McCann, M., Sanchez, S.H., Hashim, D., Meyer, J.D., Lucchini, R.G., Zuckerman, N.C., 2016. Access to properly fitting personal protective equipment for female construction workers. Am. J. Ind. Med. 59 (11), 1032–1040. https://doi.org/10.1002/ajim.22624.

Personal protective equipment and women, 2017. Trades Union Congress. https://www.tuc.org.uk/sites/default/files/PPEandwomenguidance.pdf.

R Core Team, 2020. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing [Computer software]. https://www.R-project.org.

Rashedi, E., Kim, S., Nussbaum, M.A., Agnew, M.J., 2014. Ergonomic evaluation of a wearable assistive device for overhead work. Ergonomics 57 (12), 1864–1874. https://doi.org/10.1080/00140139.2014.952682.

Rinehart, R., 2021. *Heat-related Illness & Death In Construction.* CPWR. June 29.

Ringen, K., Stafford, E.J., 1996. Intervention research in occupational safety and health: examples from construction. Am. J. Ind. Med. 29 (4), 314–320. https://doi.org/10.1002/(SICI)1097-0274(199604)29:4<314::AID-AJIM7>3.0.CO;2-O.

Schwatka, N.V., Butler, L.M., Rosecrance, J.R., 2012. An aging workforce and injury in the construction industry. Epidemiol. Rev. 34 (1), 156–167. https://doi.org/10.1093/epirev/mxr020.

Selko, A.M., 2019. SLC: 2019 Toyota's Finding Success with Exoskeletons | EHS Today. https://www.ehstoday.com/safety-leadership-conference/article/21920474/slc-2019-toyotas-finding-success-with-exoskeletons.

Sexual Orientation and Gender Identity Definitions, 2022. Human Rights Campaign. https://www.hrc.org/resources/sexual-orientation-and-gender-identity-terminology-and-definitions.

Simpson, T., 2023. *CPWR | Women In the Trades*. CPWR |. https://www.cpwr.com/research/research-to-practice-r2p/r2p-partnerships/r2p-p2r-at-work-reaching-vulnerable-workers/women-in-the-trades/.

Smets, M., 2019. A field evaluation of arm-support exoskeletons for overhead work applications in automotive assembly. IISE Transact. Occupat. Ergon. Human Factor. 7 (3–4), 192–198. https://doi.org/10.1080/24725838.2018.1563010.

Sokas, R.K., Dong, X.S., Cain, C.T., 2019. Building a sustainable construction workforce. Int. J. Environ. Res. Publ. Health 16 (21). https://doi.org/10.3390/ijerph16214202. Article 21.

Solano, T., Mittal, R., Shoele, K., 2021. One size fits all?: a simulation framework for face-mask fit on population-based faces. PLoS One 16 (6), e0252143. https://doi.org/10.1371/journal.pone.0252143.

Spada, S., Ghibaudo, L., Gilotta, S., Gastaldi, L., Cavatorta, M.P., 2018. Analysis of exoskeleton introduction in industrial reality: main issues and EAWS risk assessment. In: Goonetilleke, R.S., Karwowski, W. (Eds.), Advances in Physical Ergonomics and Human Factors. Springer International Publishing, pp. 236–244. https://doi.org/10.1007/978-3-319-60825-9_26.

Steege, A.L., Baron, S.L., Marsh, S.M., Menéndez, C.C., Myers, J.R., 2014. Examining occupational health and safety disparities using national data: a cause for continuing concern. Am. J. Ind. Med. 57 (5), 527–538. https://doi.org/10.1002/ajim.22297.

Sullivan, G.M., Artino, A.R., 2013. Analyzing and interpreting data from likert-type scales. J. Grad. Med. Educat. 5 (4), 541–542. https://doi.org/10.4300/JGME-5-4-18.

Theurel, J., Desbrosses, K., 2019. Occupational exoskeletons: overview of their benefits and limitations in preventing work-related musculoskeletal disorders. IISE Transact. Occupat. Ergon. Human Factor. 7 (3–4), 264–280. https://doi.org/10.1080/24725838.2019.1638331.

Umer, W., Antwi-Afari, M.F., Li, H., Szeto, G.P.Y., Wong, A.Y.L., 2018. The prevalence of musculoskeletal symptoms in the construction industry: a systematic review and meta-analysis. Int. Arch. Occup. Environ. Health 91 (2), 125–144. https://doi.org/10.1007/s00420-017-1273-4.

Van Engelhoven, L., Poon, N., Kazerooni, H., Rempel, D., Barr, A., Harris-Adamson, C., 2019. Experimental evaluation of a shoulder-support exoskeleton for overhead work: influences of peak torque amplitude, task, and tool mass. IISE Transact. Occupat. Ergon. Human Factor. 7 (3–4), 250–263. https://doi.org/10.1080/24725838.2019.1637799.

Wren, D., 2018. Boeing Co. Studying Wearable Exoskeletons that Can Reduce Workplace Injuries | Business | postandcourier.Com. https://www.postandcourier.com/business/boeing-co-studying-wearable-exoskeletons-that-can-reduce-workplace-injuries/article_efc6bbe0-a15d-11e8-a8c4-737ba6ec5b2e.html.