

BRIEF REPORT



Manufacturing Industry Stakeholder Perspectives on Occupational Exoskeletons: Changes after a Brief Exposure to Exoskeletons

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OCCUPATIONAL APPLICATIONS

Multiple occupational exoskeletons have been developed recently with potential to reduce physical demands, muscle fatigue, and risk of over-exertion injuries in manufacturing, yet there are currently challenges in practical, large-scale deployment. We explored how stakeholder perceptions of exoskeletons were affected by exposure to passive arm- and back-support exoskeletons. Our outcomes indicate that even brief exposure to exoskeletons can positively influence worker and stakeholder perceptions on the usefulness and safety of exoskeletons. However, worker concerns about device usability and acceptability in the field were not mitigated by such brief exposure. This work may help manufacturing industry stakeholders understand what technology-adoption factors need further consideration when planning for exoskeleton deployment.

TECHNICAL ABSTRACT

Background: Despite evidence from several laboratory studies on the effectiveness of passive exoskeletons to support specific industrial jobs, barriers to adoption still exist. Contextual factors underlying exoskeleton adoption need further understanding. **Purpose:** We aimed to document how stakeholder perceptions of exoskeleton technologies could be affected by physical exposure to a wide variety of exoskeletons, by providing an opportunity to wear them and perform standardized tasks. **Methods:** We recorded the opinions of 22 participants from different manufacturing industries, both before and after trying seven different passive arm-support and back-support occupational EXOs. EXO expectations, adoption factors/barriers in their work settings, and perceived next steps for implementing such technologies were captured. Participants also completed usability questionnaires after each EXO trial. **Results:** Even brief exposure to EXOs positively influenced both worker and stakeholder perceptions on exoskeleton usefulness and safety; in contrast, worker concerns about usability and acceptability remained unchanged. Participants indicated stronger preferences for some specific EXO technologies, in terms of ease of use, performance improvements, and applicability. **Conclusions:** Actual exposure to occupational exoskeletons, even if brief, was found to alter worker and stakeholder perceptions of exoskeleton usefulness and safety. Future work on technology perceptions and intention to use exoskeletons may need to consider physical exposure to devices before soliciting perceptions, especially for novel technologies like exoskeletons.

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Work-related musculoskeletal disorders; exoskeleton adoption; passive exoskeleton; intervention; wearable technology

1. Introduction

In the context of ergonomic interventions, EXOs are wearable mechanical structures that can augment, physically assist, and reduce exposure to physical demands, thereby having the potential to alleviate muscle fatigue, pain from long working hours, and help maintain performance (Theurel & Desbrosses, 2019). EXOs have received increasing attention in

recent years for occupational use, as evidence for EXO effectiveness has been obtained through several controlled laboratory simulations of industrially relevant tasks (Bär et al., 2021; Kermavnar et al., 2021). While such lab-based studies have shown the potential for EXOs to be useful for specific use-cases, such as those involving repetitive lifting and overhead work, the contextual factors affecting EXO adoption and subsequent use may be different across industrial sectors.

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In the automotive sector, Hensel and Keil (2019) reported decreased physical discomfort in low back and increased physical discomfort in the chest region as a result of load redistribution using a passive back support exoskeleton. Kim et al. (2022) recently completed an 18-month longitudinal study in the automotive sector, and reported that arm support exoskeletons were perceived to be effective in reducing physical demands on the shoulder. Moreover, they found that perceived job performance, overall fit, and comfort were the key determinants of workers' intention to use exoskeletons. In sectors, such as construction or agriculture, where tasks are less standardized, durability, compatibility with other equipment, and ability to operate in diverse conditions (including indoor and outdoor) have been identified as key considerations (Kim et al., 2019; Moore et al., 2021; Schwerha et al., 2021; Upasani et al., 2019).

With the exception of Schwerha et al. (2021), prior work involving stakeholder perceptions have included introductory material in the form of demonstrations, video presentations, and/or brief "show and tell" sessions about what EXOs are and how they work. It is reasonable to expect that actual experience with and use of the EXO technologies may help ground expectations and clarify the initial perceptions of stakeholders and end-users about the adoption potential of EXOs in operational settings. Hence, we aimed to understand manufacturing stakeholder perceptions of EXO adoption factors at baseline (pre-EXO exposure) and understand how these perceptions change following exposure to several currently available passive arm-support and back-support occupational EXOs. As a secondary outcome, participant responses to usability of each exoskeleton device they tried were also gathered. A brief abstract of our work was reported earlier (Narasimhan Raghuraman et al., 2022), and the current manuscript provides a more comprehensive summary and interpretation of our findings.

2. Methods

2.1. Study Population

Twenty-two volunteers (2 females and 20 males) from 12 different manufacturing companies in the state of South Carolina participated in this study. The participants represented a broad range of manufacturing and logistics operations, from companies including manufacturing of automotive systems, high-performance machine tools, electronics components, skylights and daylight, pool equipment, ceramics, and logistics. All participants were attending a manufacturing

conference that was being conducted in the state of South Carolina. They volunteered to participate in the EXO Expo event, during which they trialed multiple passive occupational EXOs and responded to questions in the form of surveys and interviews. Forty percent of the participants were from environmental health and safety, 18% were directors/vice presidents, 23% were managers, and 19% were from research and development. Overall, 77% of the participants self-reported being decision makers in their respective organizations. Although the other 23% of the participants were also stakeholders, and their inputs may be critical for implementing new ergonomic interventions in their organizations, they did not self-identify as decision makers within their organization. The study protocol was approved by the Clemson University Institutional Review Board, and all participants signed informed consent prior to data collection.

2.2. Experimental Task and Procedures

Figure 1 summarizes the study protocol. At the beginning, participants watched a brief (<3 min) video presentation, containing an introduction to what exoskeletons are, how they work, and their benefits and applications as known from contemporary studies. Then, pre-EXO interviews were conducted, in which we asked questions regarding specific concerns/pain-points in their operations that had encouraged them to reach out to learn more about EXOs; what measures (if any) had already been tried in their organizations to address those concerns; their expectations for what impact EXOs could have; and any factors (opportunities or barriers) they could foresee affecting EXO adoption. Note that all interview questions are included in Appendix 1. Participants then had the opportunity to try on four different arm-support EXOs: Ekso EVO™ (Ekso Bionics, Inc., San Rafael, CA, USA), AIRFRAME® (Levitte Technologies, Inc., San Diego, CA, USA), Paexo Shoulder (Ottobock SE & Co. KGaA, Duderstadt, Germany), and SuitX ShoulderX™ (V3, Ottobock SE & Co. KGaA, Duderstadt, Germany). Three different back-support EXOs were included: SuitX BackX™ (V3, Ottobock SE & Co. KGaA, Duderstadt, Germany), Laevo V2.5™ (Laevo BV, Delft, Nederland), and Paexo Back (Ottobock SE & Co. KGaA, Duderstadt, Germany). These EXOs were set up in separate booths and fitted on the participants by representatives from the respective EXO manufacturers. Additionally, the booths were set up such that participants performed the same standardized tasks, both with and without EXOs.

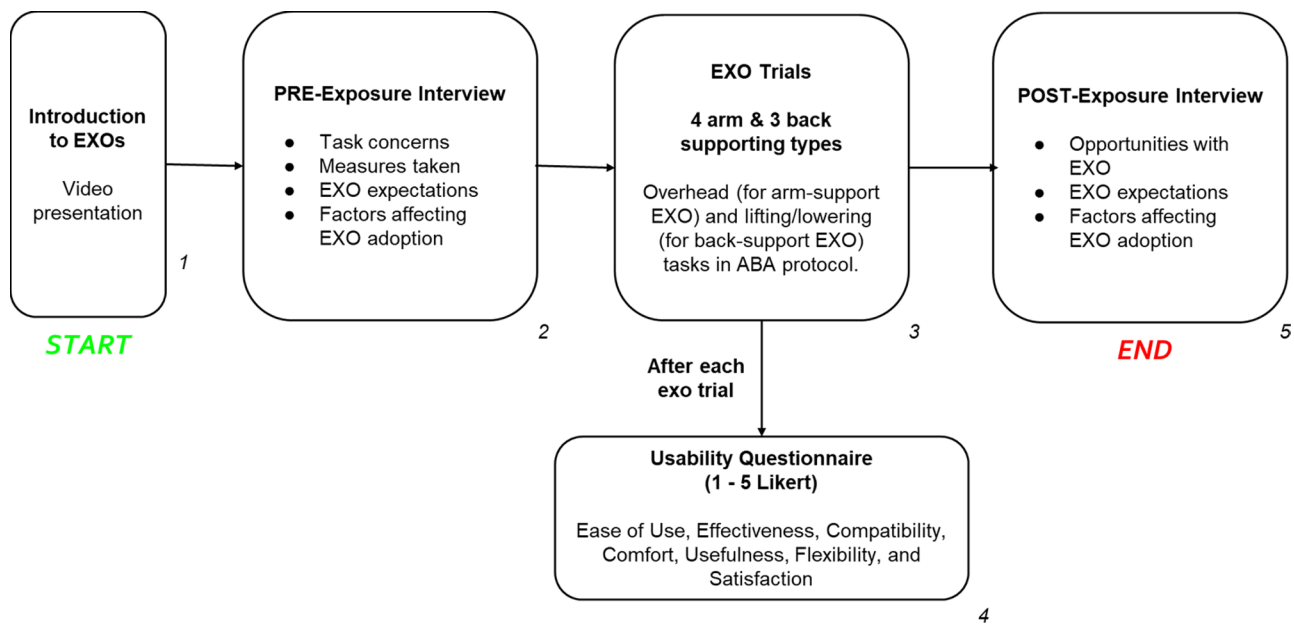


Figure 1. Study protocol, showing the sequential steps of introduction to EXOs, pre-exposure interviews, EXO exposure protocol, and post-exposure interview.

In booths with arm-support EXOs, participants completed a battery of simple bimanual and unimanual static and dynamic tasks: they completed three trials of lifting and lowering loads (4kg) between waist and head height, in front of their bodies (at arm's length) using both arms; and repeated the tasks thrice with only their dominant arm, when the load was held laterally to the dominant side of their bodies. They also held the same load statically, at head height, for a 10-s duration. In booths with back-support EXOs, participants completed five trials of repetitive lifting of boxes loaded with sandbags having mass = 7.25kg, between floor and waist levels. After fitting each exoskeleton device, each task (overhead/repetitive lifting) with the EXO took ~12–15 min, following an ABA experiment design protocol: The participants first completed the tasks without an EXO (A), completed the same tasks with the EXO (B), and then repeated the task without an EXO again (A). We did not control order of EXO exposures, which instead was left to the convenience of the participants. Participants responded to a usability survey (adapted from EUI Model, APHC, 2020) immediately after each EXO trial. The survey included questions about ease of use, effectiveness, compatibility, comfort, usefulness, flexibility, and satisfaction, and participants provided responses using Likert scales from 1 to 5 (see [Appendix 2](#)). Each participant experienced at least five different EXOs. After completing the EXO exposures, participants completed a post-EXO exit interview. Participants were asked to identify any

specific design features of individual EXOs that stood out from the trials and were asked about EXO expectations, perceived opportunities, and barriers for EXO implementation in their organizations (similar to pre-exposure questions).

2.3. Data Collection and Analysis

The interviews were conducted by a team of six pairs of researchers, with each pair including of one of the six current coauthors and a member of the local student chapter of the Human Factors and Ergonomics Society. As one researcher asked the questions, the other researcher took notes and recorded the interview. Interview data were recorded using smartphone devices and transcribed to text using Otter.ai (Otter.ai, Los Altos, CA). ATLAS.ti 22 (ATLAS.ti Scientific Software, Berlin, Germany) was used to code all interviews.

We used the Grounded Theory Method of qualitative research for this work (Muller & Kogan, 2010). Commonly used in the social sciences, this method is used to generate theories directly from qualitative data, rather than testing existing theories/hypotheses. The method involves qualitative content analysis that was performed using an inductive coding process that was used to combine codes with similar meanings into clusters (Hsieh & Shannon, 2005). This inductive process avoids using preconceived categories, and instead allows categories to emerge from the data. As part of the process, an initial codebook was

developed, and two coauthors (RNR and SU) worked individually on two random transcripts. Inter-rater agreement was determined by comparing the codebooks, and a minimum agreement of 70% was used to generate each code. When such agreement was not reached initially, differences were discussed until 70% agreement was reached, and a single codebook was generated using this process iteratively. One author (RNR) then coded all the other transcripts from the interviews. Responses from participants during the pre- and post-EXO use interviews were analyzed separately. The themes that emerged, and their frequency of mention, were compared from pre- to post-exposure, to understand how user-perspectives to exoskeletons changed with exposure.

3. Results

The workplace intervention measures that were already in place to address shoulder and back MSD risks, as reported by our participants, and the specific task-related concerns in their manufacturing operations, are reported in [Appendix 3](#).

3.1. Factors Influencing Adoption of EXOs (pre-EXO Use)

Pre-exposure interview data from the participants yielded six main themes with 14 subthemes. The six main themes were *effectiveness*, *usability*, *environmental concerns*, *unintended impacts*, *individual factors*, and *expectations to get support from management*. [Figure 2\(a\)](#) illustrates these main themes, along with their specific subthemes, organized as a thematic map. Among the six themes, the two with the highest frequency of responses were *effectiveness* and *usability*. Subthemes such as *appropriate assistance levels* (sample quote: “Will the device provide enough support to alleviate risks involved in the job”), *task applicability* (“Will it work with the different tasks in day-to-day work”), and *weight & ease of use* (“Should not have too many settings and be easy to play with”) were mentioned most frequently.

3.2. Factors Influencing Adoption of EXOs (post-EXO Use)

Post-exposure interview data from participants yielded five main themes and 13 subthemes. The five themes were *effectiveness*, *usability*, *environmental concerns*, *individual factors*, and *expectations to get support from management*. These five themes were the same as those

that emerged in pre-EXO use interviews. However, during pre-EXO interviews, there was a sixth theme called *unintended impacts*, which did not emerge in the post-EXO use interview. [Figure 2\(b\)](#) illustrates these themes, along with their specific subthemes, again organized as a thematic map. Of the five themes, the three most frequently mentioned were *effectiveness*, *usability*, and *individual factors*. For these main themes, subthemes, such as *task applicability* (e.g., “It really comes down to whether you target EXOs to the right jobs where it’s the only thing that can work”), *increase in safety & reduction of risk* by usage of EXOs (e.g., “Better than having an injury and company pay out”) and *worker acceptance* (“Workers have been doing the same thing for a long time”) were reiterated in the post-EXO use interviews, based on frequency of response. While the main themes were largely similar between pre- and post-EXO use, a few concerns that were initially noted by the participants at baseline (i.e., pre-EXO-exposure) did not arise during post-EXO use. For instance, participants did not mention *evidence for effectiveness*, *heat/humidity concerns*, or *potential injury due to failure* as factors after they had tried on the EXOs. However, some new subthemes emerged in the post-EXO use interviews, such as the desire for a *single device with shoulder and back support* to increase the generalizability of application in a variety of task contexts; concern for *quick don/doff*; and whether *sharing devices to reduce cost* and other ideas could be viable strategies to reduce the cost of implementation. Finally, some subthemes such as *worker acceptance* and *task applicability* that were mentioned in the pre-EXO use interviews were more frequently highlighted and emphasized in the post-EXO use interviews.

When asked about the next steps needed to adopt EXO(s) in their operations, many participants expressed a wish to have EXO trials conducted at their sites so that they could demonstrate the benefits of EXOs for their specific tasks to both workers and senior management. Many participants also found the exposure to the broad variety of EXOs very useful and expressed concern that it was otherwise difficult and/or expensive to trial multiple devices simultaneously, especially for small businesses.

3.3. Responses to Usability Questions

Responses to the usability questionnaire are summarized in [Figure 3](#). Overall, participants perceived all EXOs to be comfortable, flexible, useful, and easy to use, and with only relatively small differences across specific EXOs for each factor examined.

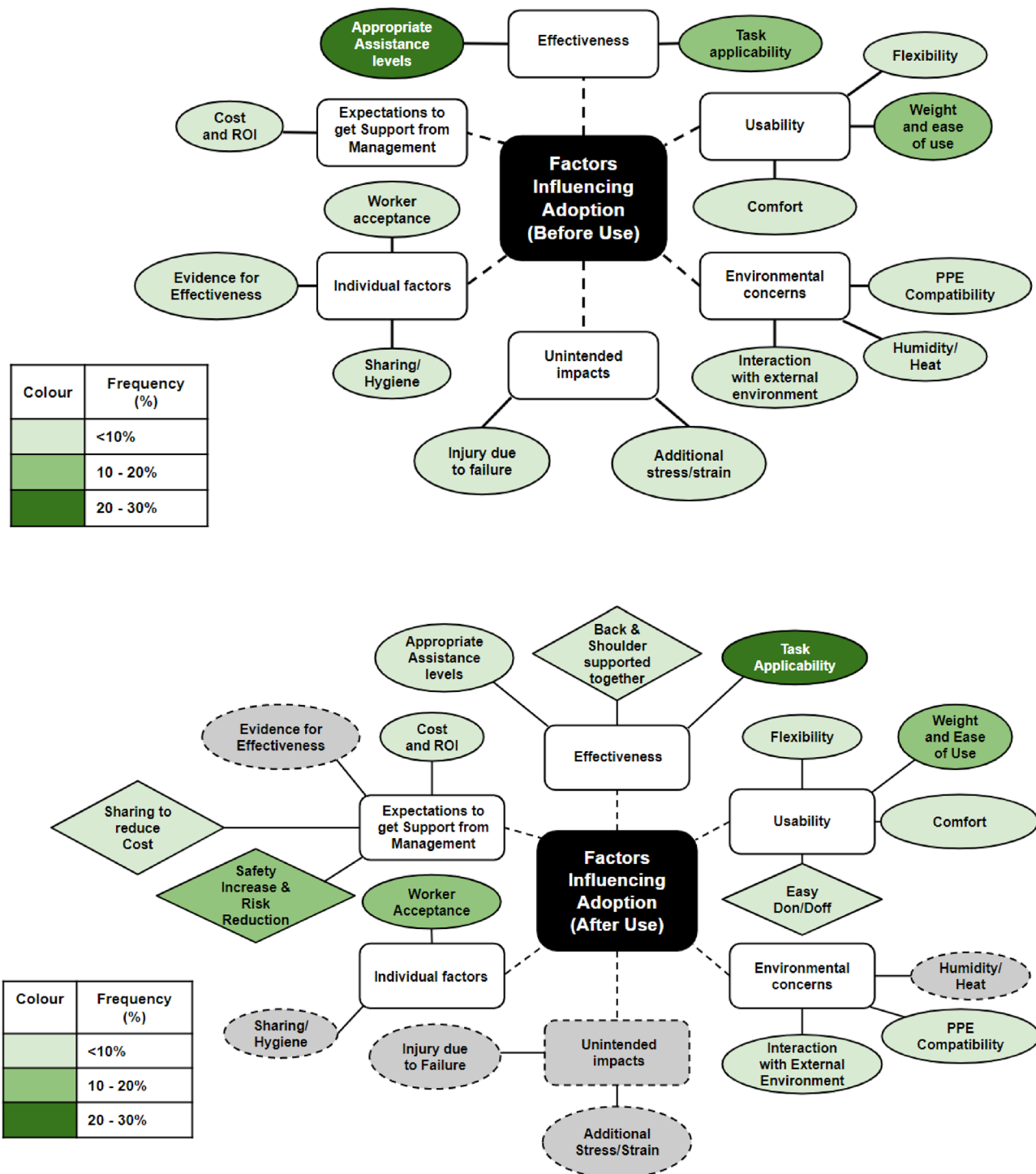


Figure 2. (a) Top panel: a thematic map of adoption factors described by participants before trying EXOs. Six main themes are shown as white boxes, and subthemes within each theme are represented as ovals. (b) Bottom panel: a thematic map of influencing adoption factors mentioned by participants after trying EXOs. Five main themes are shown as white boxes, and subthemes within each theme are represented as ovals/diamonds. The gray box with dashed borders for “unintended impacts” indicates that this theme was not mentioned during post-EXO use (although it was originally mentioned during pre-EXO use). The dash-bordered gray ovals indicate subthemes that were mentioned during pre-EXO use interviews but not during subsequent post-EXO use interviews; and the diamonds indicate new subthemes that emerged during post-EXO use interviews. All subthemes (ovals) are color coded to represent the frequency of mention (as a percentage of all participant responses), with increasing gradient of green representing higher frequency of occurrence among participants.

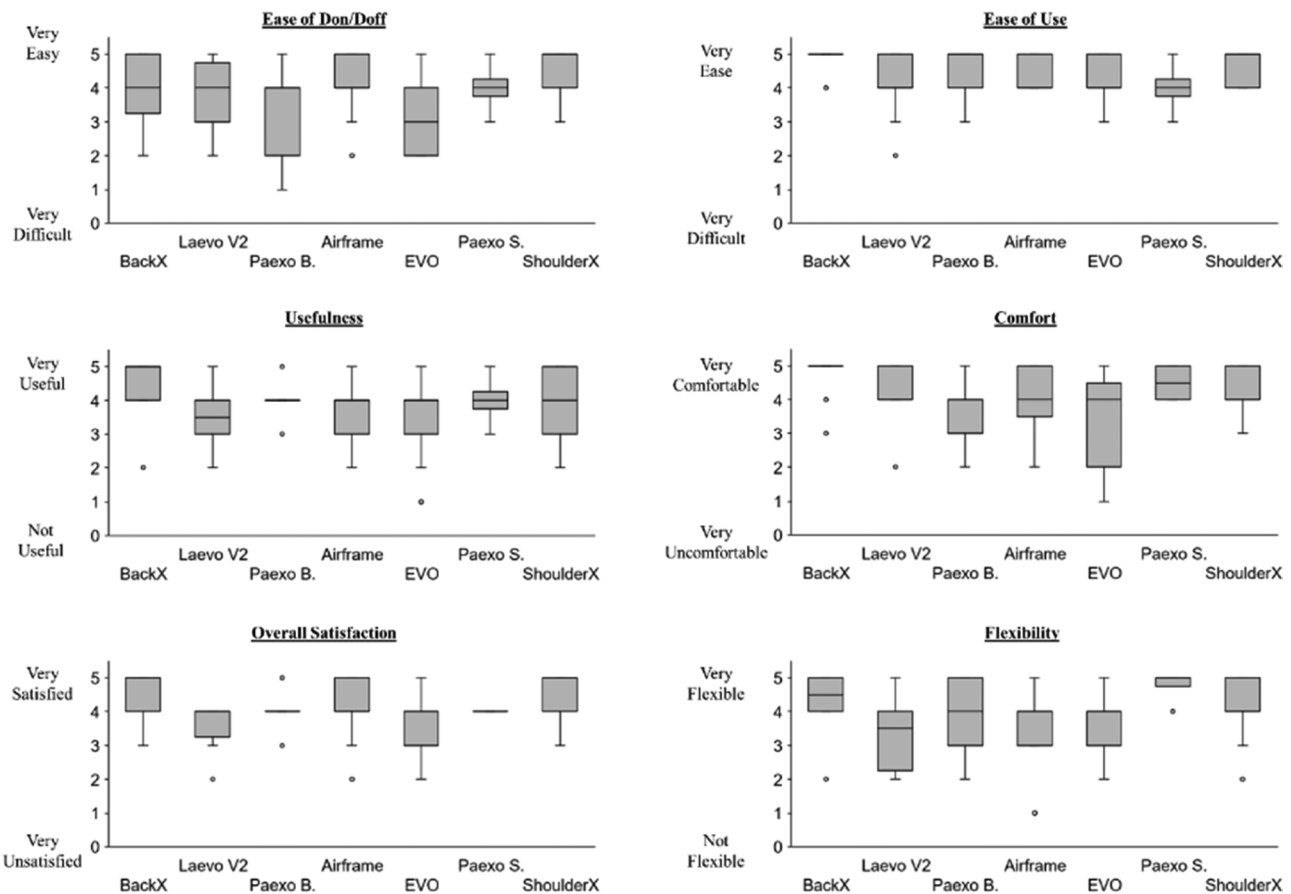


Figure 3. Box plots of responses for usability ratings for the EXOs.

4. Discussion

4.1. Application of EXOs in Manufacturing Industries

Many studies conducted in laboratory and industrial settings have demonstrated the effectiveness of EXOs for specific tasks (e.g., see Nussbaum et al., 2019; Theurel & Desbrosses, 2019), but the factors affecting adoption/implementation of them in manufacturing industries are not yet completely understood. Although previous studies have sought stakeholder perceptions of EXO technologies, most of these studies have captured the opinions of stakeholders that have only “seen” such EXOs demonstrated. In this context, the current report contributes to understanding how initial perceptions of exoskeletons by novice users change after physical introduction to a range of exoskeletons, even if the exposures are just brief.

4.2. Perceptions of Technology Effectiveness and Safety Improved after EXO Use

Evidence for EXO effectiveness (i.e., whether the device would provide appropriate levels of assistance

for their tasks) was mentioned by several respondents at pre-EXO use. However, after trying the EXOs, these concerns seemed to have alleviated to the extent that effectiveness was not even mentioned, and the mentions of appropriate support settings were largely reduced in the post-EXO use interview. The reduction in concern about EXO effectiveness post exposure suggests that people may find it rather easy to perceive EXO effectiveness for specific tasks; however, this needs to be confirmed in future work. Similarly, while participants were initially concerned about additional stress/strain from using EXOs and possible injuries due to device failure, these concerns were also reduced after EXO use, supporting the idea that exposure to the technology may alleviate immediate safety concerns. It should be noted, though, that the tasks that participants completed were designed specifically to be one that EXOs are typically designed to assist. These initial impressions may change if multiple industry relevant tasks were included since the EXOs may not ideally assist a wider variety of tasks.

4.3. Perceptions of Usability and Acceptance Were Unchanged after EXO Use

In general, usability concerns such as comfort and flexibility continued to be important even after EXO exposure. This was the case despite the fact that most EXOs were rated as being comfortable, flexible, and easy to use in the usability surveys. This outcome is in line with results from prior evidence that a key factor contributing to worker adoption (as measured by intention to use) is comfort (e.g., see de Looze et al., 2016; Moyon et al., 2019; Siedl & Mara, 2021). Post-exposure, specific usability-related concerns increased, whether the EXOs would be compatible for tasks relevant to their operations and if they are easy and quick to don/doff. Additionally, concern about worker acceptance as an adoption barrier also remained post exposure. Worker acceptance of EXOs may be linked to factors like sharing, hygiene, general resistance to change, and perception of weakness (Schwerha et al., 2021). Our findings agree with this earlier work, with the number of mentions of worker acceptance doubling after trying out the EXOs.

4.4. Specificity of Expectations and Concerns Increased following EXO Use

In general, participants articulated their expectations of EXOs in more specific terms following exposure to a wide variety of devices. Notably, participants noted a desire for an EXO that supported the back and arms together, that increased the range of postures supported by specific EXOs, and that allowed for quicker donning and doffing. Participants also explored cost optimization through device sharing, and showing Return on Investment (ROI) of EXOs through reduction in MSD risk to the senior management.

4.5. Limitations

Our study sample represented a group of people that voluntarily attended an exoskeleton Expo event, as they were curious to learn more about exoskeletons and whether they could be deployed in their organizations. This method of (non-probabilistic) sampling may have introduced a degree of selection bias in our findings. Yet, our findings in the pre-EXO-exposure interviews seem to be rather consistent with prior literature. Although participants spent approximately 3 h in the study, participant exposure time to each EXO device was brief (~15 min), and the order of EXOs was not counterbalanced due to practical time constraints. Instead, participants went through the trials

according to convenience, preference, and device/booth availability. Participants performed simple simulated tasks (overhead/repetitive lifting) under controlled settings to perceive the benefits of the EXOs. As such, actual exposure to tasks relevant to real industrial work was not captured in these brief trials, which may have affected their perception of the EXOs.

5. Conclusions

There is an ongoing concern about worker acceptance of exoskeletons: how to introduce these technologies to workers, what technology expectations to create and manage among workers and stakeholders, and the best training methods for creating a positive physical, psycho-social, and cultural experience are topics that are being actively explored in the field of exoskeleton implementation. In this context, our work demonstrated that even brief exposure to EXOs can positively influence both worker and stakeholder perceptions on technology usefulness and safety. However, stakeholder concerns about technology usability and acceptability were evident (and unchanged) even with brief exposures to EXO use. Finally, manufacturing industry stakeholders, especially those representing small businesses, also expressed concern that while comparative evaluations of multiple devices were needed for selecting the best technology to fit their users and use-cases, obtaining such data and trials is currently infeasible or too expensive. Future work is recommended to: (1) Understand how physical exposure to EXOs in actual industrial settings affect subjective feedback on device usability in the short- and long-term; (2) Conduct longer investigations of changes in technology perception, social attitudes, and intention-to-use (compared to only brief exposures); and (3) Diversify the user-base from whom evaluation metrics are obtained, to be more representative of users of different age, gender, and physical ability.

Conflict of interest

No potential conflict of interest was reported by the author(s).

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Appendix 1

Entry Interview/Pre-EXO Use Questions:

1. What is your role within your company? To what degree are you involved in the decision-making related to adoption of technology such as EXOs?
2. What are your concerns or "pain points" because of which you're here?
 - a. Probe 1: What are the consequences of these issues (e.g. loss in productivity)?
 - b. Probe 2: Are there specific tasks associated with these concerns?
 - i. How frequently are these tasks performed?
 - c. Probe 3: How widespread is the concern (e.g., is this specific to one site or across several locations?)
3. What measures have you tried so far, to solve these issues? (E.g., automation, specialized equipment, job rotation, job modification...)
 - a. Probe 1: To what extent have they been effective? Why did/didn't they work?
4. How do you think EXOs potentially solve these issues? (This question can reveal their prior exposure to, and expectations of, EXOs)
 - a. Probe 1: (If their response does not indicate how familiar they are with exos, ask these questions): What have you heard/do you know about EXOs? Have you ever tried one on?...
5. What factors do you think are important to consider, if you were to implement EXOs in your facility today?
 - a. Probe 1: Do you have any hesitations/reservations?
 - b. Probe 2: What are you hoping to learn from today's event that would help you make such decisions?

Exit Interview/Post EXO Use Questions:

1. Which EXO device stood out to? Why?
2. Based on what you've seen today, would you implement EXOs in your company?
 - a. Probe 1: Why/Why not?
 - b. Probe 2: Could some further information/validation address the concern(s)?
 - c. Probe 3: (If the answer is said yes, or probably yes): What are the next steps? What more would you like to know and/or how would you like to proceed?
3. What are your most immediate concerns on EXOs that you need answers to?
 - a. Probe 1: Effectiveness?
 - b. Probe 2: Usability/appropriateness for the use-cases they have in mind?
 - c. Worker acceptance? Management support? d. ROI?

4. Did you find the answers you were seeking in the conference today? Any new questions or concerns that you didn't have before which may or may not have been answered?

Appendix 2

Usability Ratings

Please circle a rating for each of the following questions.

1. How easy was the exoskeleton to don/doff (put on and take off)?

1	2	3	4	5
Very Difficult	Somewhat Difficult	Neutral	Somewhat Easy	Very Easy

2. How easy was it to do the tasks using the exoskeleton?

1	2	3	4	5
Very Difficult	Somewhat Difficult	Neutral	Somewhat Easy	Very Easy

3. How easy was it to perform the task with the exoskeleton compared to *WITHOUT*?

1	2	3	4	5
Much worse	Slightly worse	The same	Slightly easier	Much easier

4. How comfortable was the exoskeleton during use? If there were any noticeable points of discomfort, where were they located (e.g., lower back, thighs, shoulders...)

1	2	3	4	5
Very Uncomfortable	Somewhat Uncomfortable	Neutral	Somewhat Comfortable	Very Comfortable

5. Would this exoskeleton be useful in your job? (*Or in the jobs in question, for which you're considering exoskeletons*)

1	2	3	4	5
Not Useful	Somewhat Not Useful	Neutral	Somewhat Useful	Very Useful

6. How flexible do you think this exoskeleton would be, for performing the different subtasks in a routine shift?

1	2	3	4	5
Not Flexible	Somewhat Not Flexible	Neutral	Somewhat Flexible	Very Flexible

7. What was your overall satisfaction with this exoskeleton device?

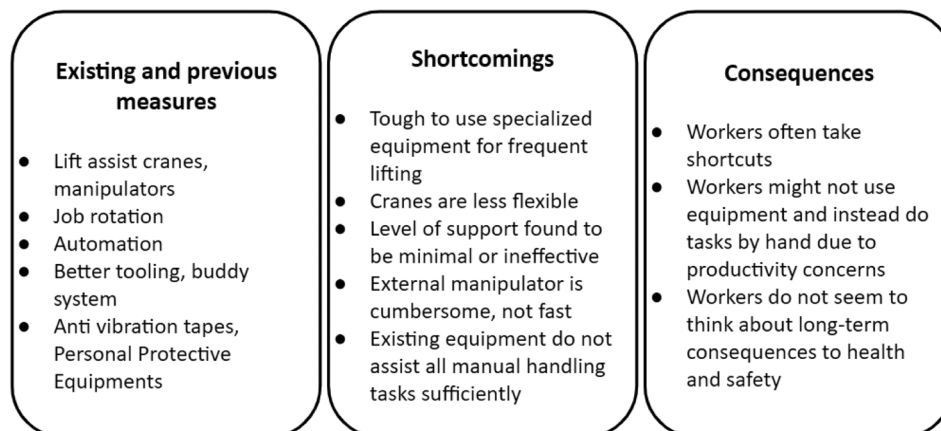
1	2	3	4	5
Very Unsatisfied	Somewhat Unsatisfied	Neutral	Somewhat Satisfied	Very Satisfied

8. If given the choice, would you use/recommend use of this exoskeleton for your job tasks?

1	2	3	4	5
Definitely not	Probably not	Unsure	Probably, yes	Definitely, yes

Appendix 3

Workplace intervention measures in place to address shoulder and back MSD risk



Task related concerns

