

## **Exploratory field testing of passive exoskeletons in several manufacturing environments: perceived usability and user acceptance**

### **OCCUPATIONAL APPLICATIONS**

Results of the current exploratory study suggest that use of an exoskeleton (EXO) has the potential to be accepted by workers as an intervention in diverse manufacturing environments. Also evident were that the major factors contributing to EXO-use-intention are perceived comfort, task-technology fit, perceived safety, and perceived usefulness. A user's perception of perceived usability may be established by using an exoskeleton during actual job tasks, yet some aspects of perceived usability likely require multiple exposures to an EXO for an accurate assessment. Many negative comments regarding EXO use were related to physical constraints (e.g., restricted movements, bulkiness), and to the EXO interface (e.g., straps, cuff designs), suggesting a need for further research on EXO design to minimize discomfort. In practice, there is likely value in having workers use and explore candidate EXOs during their actual job, both to accurately assess the usefulness of an EXO and to find the most effective EXO.

### **TECHNICAL ABSTRACT**

**Background:** There lacks an understanding of using an exoskeleton (EXO) in diverse manufacturing environments.

**Purpose:** Goals of this study were to: 1) gather worker feedback on different EXOs after using them during their actual jobs; 2) understand what contributes to EXO-use-intention in manufacturing companies; and 3) develop a decision tree model to explore which task characteristics and user perceptions might aid in determining how to implement an EXO effectively.

**Methods:** A field study was completed in five manufacturing companies in the state of Ohio. Fifteen participants used preferred EXOs selected from among two arm-support and two back-support devices during their regular jobs for  $\leq 30$  minutes in each of two separate sessions. After using an EXO, participants completed a questionnaire addressing several aspects of usability, comfort, safety, and EXO-

1 use-intention. Open-ended comments on these aspects were coded into emerging themes. A decision tree  
2 analysis was performed on participants' responses to the EXO-use-intention question to explore the  
3 predictive value of task characteristics, user characteristics, and questionnaire responses.

4 **Results:** Responses to usability-related questions were rather consistent between the two sessions, yet  
5 some responses were more positive in the 2<sup>nd</sup> session (perceived balance, overall comfort and fit, and  
6 range-of-motion). We identified four themes regarding EXO use – utility for work, wearability, working  
7 metrics, and ease of using; and negative comments on these themes were largely related to physical  
8 constraints from wearing an EXO, and EXO interface. The decision tree analysis suggested that perceived  
9 comfort, task-technology fit, perceived safety, and perceived usefulness are each associated with EXO-  
10 use-intention.

11 **Conclusions:** EXO use has the potential to be accepted by workers as an intervention in manufacturing  
12 environments. However, further work is needed for enhanced comfort, EXO-task fit, user acceptance, and  
13 to develop EXO introduction processes to create best practices for effective implementation and  
14 sustainable use of EXOs in practice.

15  
16 **KEYWORDS:** assistive device; intervention; technology adoption; field study; work-related  
17 musculoskeletal disorders

## 1. Introduction

Advances in exoskeleton (EXO) technologies have presented a new opportunity to control the continued problem of work-related musculoskeletal disorders (de Looze, Bosch, Krause, Stadler, & O'Sullivan, 2016; Nussbaum, Lowe, de Looze, Harris-Adamson, & Smets, 2019). EXOs are wearable systems that can augment and assist motion, posture, or physical activity by providing active and/or passive supports (Lowe, Billotte, & Peterson, 2019), and thereby reduce the physical demands imposed on the user. Given the prevalence of back and shoulder injuries in the workplace, and the market maturity of passive EXOs (requiring no actuators or power supply), passive arm- and back-support EXOs are increasingly being deployed in practice (e.g., Hensel & Keil, 2019; Selko, 2019; Smets, 2019).

Existing lab-based studies have demonstrated that using a passive EXO has the beneficial effect of reducing physical demands, as reflected in decreases in, for example, perceived exertion/discomfort and muscle activation levels. Such benefits have been reported for several activities, including manual lifting (e.g., Alemi, Madinei, Kim, Srinivasan, & Nussbaum, 2020; Kazerooni, Tung, & Pillai, 2019; Koopman, Kingma, de Looze, & van Dieën, 2020), and assembly-related tasks (Bosch, van Eck, Knitel, & de Looze, 2016; Madinei, Kim, Alemi, Srinivasan, & Nussbaum, 2019). Using an arm-support EXO led to better job quality with improved arm steadiness during painting and welding (Butler, 2016), and during overhead line tracing (Spada, Ghibaud, Gilotta, Gastaldi, & Cavatorta, 2017). More generally, a recent review highlighted that EXO use can reduce acute physical stress and strain in the exoskeleton target area during occupational tasks (Bär, Steinhilber, Rieger, & Luger, 2021). Overall, current evidence suggests that EXO use may be an attractive solution, particularly for tasks that would be otherwise challenging to address (e.g., those tasks performed in environments where modifications cannot be made easily).

Though limited in number and scope, some field-based studies have been completed, the results of which have identified potential EXO usage concerns that may not be evident in lab-based studies. For example, using an EXO may substantially reduce physical demands in controlled (lab-based) tests, yet in some

1 cases such beneficial effects were smaller in practice (Amandels, Eyndt, Daenen, & Hermans, 2019; De  
2 Bock et al., 2021; Kim, Nussbaum, Smets, & Ranganathan, 2021). A longitudinal study reported by Kim  
3 et al. (2021) examined the use of an arm-support exoskeleton during overhead work in automotive  
4 assembly facilities, finding that beneficial effects were only modest and differed across facilities.  
5 Schwerha et al. (2021) investigated the use of EXOs in small-, medium-, and large-sized enterprises and  
6 reported industry-specific concerns, such as not being able to have exposed Velcro<sup>TM</sup> in a food  
7 manufacturing facility, decontamination from lead exposures, and operation of EXOs in extreme cold  
8 temperatures (e.g., <0°C). In a 3-month field test of an ASE, thermal comfort was reported as the most  
9 common reason for not wearing an ASE in automotive assembly environments (Smets, 2019), which may  
10 be due to high ambient facility temperatures especially during summer months. Additional concerns with  
11 the field use of EXOs include that discomfort from wearing an EXO may be not immediately obvious, the  
12 level of discomfort could substantially increase with a longer duration of use (Hensel & Keil, 2019), and  
13 users may have difficulty in perceiving loads immediately after doffing the EXO (Marino, 2019).

14  
15 To promote the effective adoption and use of EXOs in the field, it is important to understand factors  
16 contributing to a user's intention to use an EXO. Theoretical frameworks for EXO-use-intention were  
17 developed in recent studies (Moyon, Poirson, & Petiot, 2019; Purcell, 2020), based on the predictive  
18 theories such as the Technology Acceptance Model (TAM; Davis, 1985) and the Unified Theory of  
19 Acceptance and Use of Technology (UTAUT; Venkatesh, Morris, Davis, & Davis, 2003). Moyon et al.  
20 (2019) and Purcell (2020) discussed several constructs that are associated with individual, social,  
21 physical, occupational, perceptual, and affective factors in relation to behavioral changes (i.e., EXO-use-  
22 intention). A few field-based studies have shown that perceived usefulness and comfort are key  
23 determinants of EXO-use-intention (Elprama et al., 2020; Hensel & Keil, 2019; Moyon et al., 2019; Siedl,  
24 Wolf, & Mara, 2021). However, given that the work environment and task requirements affect EXO-use-  
25 intention (Moyon et al., 2019; Purcell, 2020), there remains a clear need for more information in  
26 occupational environments particularly in various manufacturing environments.

1  
2 The purpose of the current study was therefore to: 1) gather worker feedback on different EXOs after  
3 using them during their actual jobs, to explore the consistency in their feedback; 2) understand what  
4 contributes to EXO-use-intention in manufacturing companies; and 3) explore a decision tree model that  
5 can help practitioners determine where to implement an EXO based on task characteristics and user  
6 perceptions. Specifically, a field study was performed to assess worker opinions related to EXO usage,  
7 involving volunteers at several manufacturing facilities who were provided with a short-term experience  
8 of using up to four different, commercially available EXOs during their actual work on two separate days.  
9 The results of this study were intended to help advance the effective adoption and use of EXO  
10 technologies in diverse manufacturing environments.

## 11 12 **2. Methods**

### 13 **2.1. Participants**

14 Participants were recruited using convenience sampling from among 10 manufacturing companies in the  
15 state of Ohio that had earlier been involved in a focus-group study (Schwerha et al., 2021). Fifteen  
16 workers (14 males, 1 female) from five of those companies voluntarily participated in the current study,  
17 and they had no self-reported current musculoskeletal disorders or injuries limiting their physical  
18 activities during their jobs. Though there were no gender exclusions, only one of the volunteers was  
19 female. Respective means (SD; range) of age, stature, and body mass were 35.7 (8.8; 24–54), 1.8 (0.11;  
20 1.6–2.1) m, and 92.8 (19.4; 52.2–129.4) kg. Further, participants had 6.2 (4.9; 2–20) years of work  
21 experience. All participants provided informed consent prior to data collection, and the study procedures  
22 were approved by the Institutional Review Boards of Ohio University and Virginia Tech.

### 23 24 **2.2. Task Selection**

25 Specific tasks were selected through discussions with participants at each company, considering that the  
26 benefits and limitations of an EXO are likely to depend on the task characteristics (e.g., Alabdulkarim,

Kim, & Nussbaum, 2019; Madinei et al., 2019). Potential tasks were initially identified that involved either transferring, assembling, or handling products. The final tasks included were chosen because they: 1) were known to be physically demanding, according to both management and relevant workers; 2) had been associated with prior musculoskeletal injuries; 3) were difficult to staff with other than physically strong employees due to high physical demands; and 4) might benefit from the use of an EXO, specifically requiring moderate-high physical efforts in the arms/shoulders and/or the low back.

A total of 17 tasks were identified across the five companies. Diverse activities were included, such as packing, lifting, moving, vacuuming, sanding, sewing, spraying, and other manufacturing activities. A task analysis was completed for each task to characterize the associated physical demands (Table 1). These analyses included whether the task was relatively static or involved more dynamic aspects, the mass of any object lifted, cycles per hour, and worker posture. Workers were video recorded, and joint angles were estimated from the digital recordings. Note that we attempted to obtain joint shoulder and torso angles, but we were unable to determine these with sufficient accuracy from the video recordings. Among the 17 tasks, 14 involved primarily shoulder efforts and three involved primarily back (extensor) efforts. Qualitatively, vibration was not present to a substantial level in any of the tasks.

Table 1 Variables used to characterize the tasks included in the study.

Variable	Continuous or Categorical	Description
Body Region	Categorical (shoulder, back, mixed)	Is the task more demanding of the shoulders or back, or involving mixed demands?
Task Type	Categorical (static, dynamic)	Static if posture is the same >50% of the time, dynamic otherwise
Object Mass	Continuous	Mass of object lifted in task (kg)
Cycles/Hour	Continuous	Number of cycles completed in one hour
Mass Lifted/Hour	Continuous	Cycles per hour multiplied by object mass (kg/hr)

## 2.2. Experimental Procedures

Participants completed two data collection sessions, typically on consecutive days. Two data collection sessions were used to assess the between-day repeatability of several subjective responses (see below). Data were collected during warmer months (July–September, 2019). The specific time of day for data collection was determined considering participant shift schedules and onsite circumstances such as production schedules (e.g., production demands, additional worker availability). All participants completed data collection between late morning and midafternoon.

In both sessions, four passive EXOs were made available to the participants. Two of these were arm-support EXOs (ASEs): the EksoBionics EksoVest™ (unit mass = 4.3 kg) and the Levitate Airframe™ v2.0 (unit mass = 2.7 kg). The other two were back-support EXOs (BSEs); the Laevo™ v2.5 (unit mass = 2.8 kg) and the SuitX™ backX™ AC (unit mass = 4.5 kg). These EXOs were selected based on availability at the time of the study and to represent some diversity in EXO designs.

Choice of EXO type was determined by the investigators based on the task requirements of each participant. Specifically, participants whose tasks required shoulder elevation that was primarily at the waist or higher were offered the ASEs, while participants whose tasks required mainly lifting from close to the floor to above the waist were offered the BSEs. Some tasks contained activities that could have benefit from either an ASE or a BSE. In these cases, participants were offered both ASEs and BSEs. If a participant felt uncomfortable (e.g., if they experienced rubbing against parts or straps), they were not required to wear a given EXO. In both sessions, EXOs were fitted to participants following instructions provided by the respective manufacturers. Almost all participants used more than one EXO, and several participants used EXO(s) during more than one task. Table 2 indicates the EXOs that were used in each session.

Table 2 Summary of EXOs used in Sessions 1 and 2. The “X” indicates which of the four EXOs were used in each session, and letters indicate specific exoskeletons (A1 & A2 were ASEs; B1 & B2 were BSEs).

Participant	Task	Task Type (Static or Dynamic)	Session 1				Session 2			
			A1	A2	B1	B2	A1	A2	B1	B2
1	1	D	X	X	X		X	X		
2	2	S	X	X			X	X		
3	3	D	X	X	X		X	X	X	
4	4, 5	D, S	X	X	X		X	X		
5	6, 7, 8	D, D, S	X	X			X	X		
6	6, 7, 8	D, D, S	X	X				X		
7	4, 5	D, S	X	X			X	X		
8	9	D			X	X			X	X
9	9	D			X	X			X	X
10	10	S	X	X			X	X		
11	11, 12	S, D		X	X	X		X	X	
12	13	S		X				X		
13	14, 15	D		X	X			X	X	
14	16	D			X	X			X	X
15	17	S	X	X				X		

In Session 1, participants were asked to use each of the selected EXOs while performing their normal job, and this continued until either they felt comfortable with the EXO or 30 minutes had elapsed. This duration was chosen arbitrarily, as one that would allow the employee to become familiarized with an EXO but that would not impinge on ongoing production. The duration of use selected by participants ranged from 5 to 30 min. Most participants tried at least two EXOs in this first session, and the specific EXOs were presented in a random order. After using each of the selected EXOs, participants were asked to complete a questionnaire that included items related to perceived safety, usability, and comfort (see 2.3 Questionnaire below).



1 In Session 2, participants again performed their tasks with each of the EXOs that were determined to have  
2 a benefit from the first session. If a participant did not feel comfortable wearing a given EXO in the first  
3 session, that EXO was not used in the second session. After working with the EXO, participants  
4 completed a questionnaire.

### 6 **2.3 Questionnaire**

7 Questionnaire items were modified from Kim et. al (2019), and a listing of all questions is provided in  
8 Appendix A. We included questions to assess aspects of perceived usability that could inform design and  
9 an individual's EXO-use-intention. The questionnaire used in Session 1 had 14 questions, 11 of which  
10 used an 11-point Likert scale and five of which were open ended. The questionnaire for Session 2 had 12  
11 questions, 10 of which used an 11-point Likert scale and two of which were open-ended. Scores of 0 on  
12 the Likert scale meant none, and scores  $> 0$  were negative, except for two questions. Eleven of the Likert-  
13 scale questions were repeated from the first to second sessions. The other questions were slightly different  
14 because of our intention to collect data specific to either Session 1 or Session 2. Specifically, in Session 1  
15 we asked participants how long it took them to get comfortable with wearing a given EXO, while in  
16 Session 2 we asked them about their ability to perform the job smoothly, since we believed that they  
17 would provide a more informed response after the second session. Participants were encouraged to  
18 provide comments in addition to their Likert scores.

19  
20 Participants completed the questionnaire after using each of the selected EXOs (Table 1), yielding  
21 respective totals of 33 and 28 completed questionnaire responses in Sessions 1 and 2. Note that fewer  
22 questionnaires were completed in Session 2 since some EXOs from Session 1 were not reused. For the  
23 question regarding the EXO-use-intention ("If the exoskeleton were available to you, would you use it?"),  
24 31 and 28 responses were obtained in Sessions 1 and 2, respectively.

## 2.4 Data Analysis

Questionnaire responses were analyzed using descriptive statistics, and two-sided Wilcoxon signed-rank tests were used to examine if significant ( $p \leq 0.05$ ) differences existed in the responses between the two sessions. Qualitative data (open-ended responses) were coded by the lead researchers (SD and NM) and were then discussed by the entire research team. Data analysis included a process of Content Analysis (Seale & Silverman, 1997), where themes were developed from the comments provided by participants. These themes were similar to those previously reported (Hensel & Keil, 2019), and were related to EXO usability, comfort, and use within an occupational setting, and to what was expressed commonly by participants over the course of the study. Themes were also coded as either positive or negative perceptions that were loosely related to the barriers and benefits that we had identified earlier (Schwerha et al., 2021).

## 2.5 Decision Tree

To gain information that may help with successfully implementing an EXO, a decision tree analysis was used to explore what factors influence EXO-use-intention. A decision tree is a commonly used data mining method that provides a graphical representation of hierarchical decision sequences (Myles, Feudale, Liu, Woody, & Brown, 2004; Song & Lu, 2015). Specifically, this method splits the data set into several subsets (that are relatively homogeneous) to describe the variable of interest, yielding a tree-like diagram with nodes and branches. Here, we considered 17 variables as predictors of EXO-use-intention – five task characteristics (Table 1), three user characteristics (age, stature, and body mass), and eight responses regarding usability. The latter were user perceptions regarding overall comfort, range-of-motion, thermal comfort, balance, change in working posture, safety, EXO weight, and job performance (see Appendix A). In each session, participants gave their responses to these questions, answered “yes” or “no” to the EXO-use-intention question, and then provided the number of hours that they were likely to use an EXO (i.e., 0–8 hours). For the current analysis, we coded a participant’s response either as

Negative (“no” or usage hour  $\leq 2.66$  hrs, corresponding to 1/3 of an 8 hr work shift) or Positive (usage hour  $> 2.66$  hrs).

We conducted a decision tree analysis with EXO-use-intention responses from both sessions, using the conditional interference tree (*ctree*) function of the *party* package (Hothorn, Hornik, & Zeileis, 2006) in R software (R Core Team, 2021). The *ctree* function uses statistical inference procedures when splitting to avoid selecting a predictor that maximizes separation (i.e., source of potential selection bias), accommodates all types of responses and explanatory variables, and corrects multiple testing across several predictors. Thus, we considered the *ctree* method as more effective than other Classification and Regression Tree (CART) methods, given that our study was exploratory. We set the following options for the *ctree* function: ‘logmincriterion’ (i.e., the split criterion for splitting) = 0.1; ‘minsplit’ (i.e., the minimum sum of weights in a node in order to be considered for splitting) = 10; ‘minbucket’ (i.e., the minimum sum of weights in a terminal node) = 3; ‘teststat’ and ‘splitstat’ (i.e., test statistics for variable selection and splitpoint, respectively) = ‘quadratic’; and ‘testtype’ (i.e., method to compute the distribution of test statistics) = MonteCarlo.

### **3. Results**

#### **3.1. Questionnaire Responses**

Table 3 provides a summary of the responses to all but the open-ended responses to the questionnaire used in Sessions 1 and 2. Significant differences were found for three questions, which related to perceived balance, comfort, and range-of-motion. For each of these questions, “better” responses were provided after the second session, with all three being close to 0 values (i.e., perfectly balanced, no discomfort, or no limitation to range-of-motion).

1 Table 3 Summary [mean (SD) and range] of questionnaire responses from Sessions 1 and 2 (see Appendix A for complete questions and  
2 associated scales). N/A: not applicable, as this question was not asked in a given Session. Wilcoxon signed-rank tests were used to compare results  
3 obtained from the two sessions (bold *p* values highlight significant differences between sessions; and *N<sub>r</sub>* is the reduced sample size after excluding  
4 pairs with the same values).

Question	Session 1		Session 2		Sessions 1 v. 2		
	<i>N</i>	Mean (SD) Range	<i>N</i>	Mean (SD) Range	<i>N</i>	Wilcoxon <i>W</i>	<i>p</i> value
How long to feel comfortable using EXO (min.)	33	7.85 (7.46) 0 – 30	N/A	N/A			
Perception of balance (0 = perfectly balanced, 10 = off balanced)	33	1.52 (2.56) 0 – 9	28	0.61 (1.62) 0 – 7	14	89.0	<b>0.02</b>
Perception of overall comfort and fit (of EXO when performing your job) (0 = no discomfort, 10 = most discomfort ever experienced)	33	3.24 (3.11) 0 – 9	28	1.64 (2.02) 0 – 7	21	181.5	<b>0.02</b>
Limits to range-of-motion (0 = no limitation, 10 = extremely limiting)	33	2.27 (2.81) 0 – 9	27	1.41 (2.10) 0 – 9	15	95.0	<b>0.05</b>
Perception of thermal discomfort (0 = no discomfort, 10 = extreme discomfort)	33	1.52 (2.28) 0 – 7	28	1.21 (1.62) 0 – 7	16	83.0	0.45
Chest discomfort (0 = no discomfort, 10 = extreme discomfort)	33	0.85 (1.84) 0 – 7	28	0.50 (1.48) 0 – 6	6	18.5	0.12
Waist discomfort (0 = no discomfort, 10 = extreme discomfort)	33	0.42 (1.20) 0 – 4	28	0.54 (1.67) 0 – 7	5	7.0	1.00
Thigh discomfort (0 = no discomfort, 10 = extreme discomfort)	12	1.67 (2.35) 0 – 6	9	1.89 (2.42) 0 – 6	3	4.0	0.79
Worked differently when using the EXO (0 = not differently, ad 10 = extremely differently)	33	4.03 (2.40) 0 – 8	28	4.75 (2.81) 0 – 10	20	65.5	0.15
Effects of EXO on overall safety (0 = substantially less safe, 10 = substantially more safe)	33	5.45 (1.33) 0 – 9	28	5.36 (1.97) 0 – 10	11	28.5	0.72
Effect of EXO on ability to perform job (job performance) (0 = substantially worse, 10 = substantially better)	33	5.91 (1.84) 0 – 9	28	5.93 (1.84) 0 – 10	18	103.5	0.45
Perception about EXO weight (0 = not at all heavy, 10 = extremely heavy)	31	0.84 (1.21) 0 – 4	28	1.14 (1.80) 0 – 6	12	28.5	0.43
Ability to perform job smoothly? (0 = not disruptive, 10 = extremely disruptive)	N/A	N/A	28	1.86 (2.27) 0 – 8			
Would use EXO if available? (hrs/shift)	31	4.58 (3.46) 0 – 8	28	4.61 (3.49) 0 – 8	14	48.0	0.80

Responses to all questions were generally positive. For example, results for perceptions of wearing discomfort (either thermal or on specific body parts) had mean responses closer to the “no discomfort” anchor than the “extreme discomfort” anchor, ranging from 0.42 to 1.67. Scores for the effects of the EXO on work safety and job performance were slightly higher than the mid-range, indicating that the EXOs were perceived somewhat helpful. Participants reported little concern about perceived EXO weight and indicated on average that they would wear the EXO approximately 4.5 hours during their shift. While some participants indicating being comfortable almost immediately after donning an EXO, others required additional time (note that the trials were not continued past 30 minutes).

### **3.2. Qualitative Responses**

A total of 262 comments were collected from the 61 surveys completed across both sessions, and the comments were then coded into four themes and 11 categories (Figure 1). A summary of the 11 categories along with counts is given in Table 4. Within each category, data were coded as either a positive or negative comment; sample quotes are provided in Appendix B. Positive comments were related to better perceptions of usability, while negative comments generally related to a lower level of usability. Categories with related quotations are summarized below (quotes are provided verbatim, except to enhance clarity).

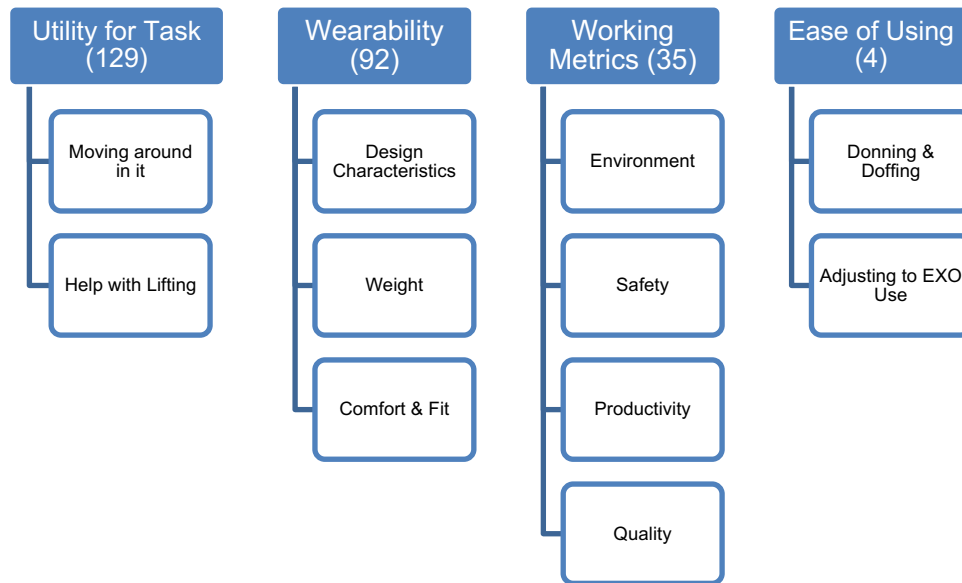


Figure 1. Four themes related to EXO use determined from qualitative responses. Numbers indicate the total number of related responses.

Table 4 Emergent categories for EXO use obtained from qualitative responses

Theme	Category	# of Comments	Positive	Negative
Utility for Task	Moving around in it	67	felt that it gave them better posture (not just a BSE but an ASE enabled using better back posture); allowed natural movement	off balance; harder to move arms and elbows; had to push down on (back) exo; reduced range of motion; difficulty twisting; difficulty walking; had to take extra steps or move back differently; metal (on side) sometimes bumped into things
	Help with Lifting	62	helped with lifting arms and back	none noted
Wearability	Design Characteristics	55	liked cuffs; liked straps because they felt more secure	didn't like cuffs; didn't like straps; too bulky; needed low clearance; belt prevented them from bending down; thighs slid; needed protective cover
	Weight	7	liked the light weight; not a hindrance	felt one was too heavy
	Comfort & Fit	30	comfortable because the EXO was not too tight	some cuffs slid; metal on top of shoulders caused discomfort; waist was sometimes uncomfortable; chest and back piece were sometime uncomfortable; straps rub; some didn't quite fit certain individuals
Working Metrics	Environment	10	none noted	some designs too hot; hot under chest; couldn't move in tight spaces
	Safety	5	none noted	felt that they could get snagged on something; clearance issues
	Productivity	7	none noted	slowed them down
	Quality	13	none noted	stopped over quality concerns; worried about bumping into object or damaging it
Ease of Using	Donning & Doffing	3	easy to don/doff	Donning and/or doffing took too long
	Adjusting to EXO Use	3	easy to get used to; comfortable from the start	would take time to get used to

#### Moving around in it

This category was about body movement when using an EXO, suggesting that EXOs may affect the way in which a person moves. The comments were split between being positive and being negative. Positive comments were associated with how well the EXO could help maintain a particular (or better) posture and provided back support. Negative comments reflected a participant's inability to move freely, how the EXOs could make the person feel off-balance, the need to push down in order to get support back up, and how different components of the EXOs rubbed or affected movement.

## Help with Lifting

One of the most frequent comments was that the EXO did help with lifting. Interestingly, participants noted this about both the ASEs and BSEs. Such comments were provided even when the participant had concerns about other aspects of the EXO (e.g., comfort). All the comments regarding this theme were positive.

## Design Characteristics

A range of designs existed within the four EXOs that were tested. For example, some were looser fitting and others were more tightly secured to the body. Interestingly, participant comments were split regarding EXO design differences (e.g., cuffs and straps), with some designs receiving both positive and negative comments from different participants.

## Comfort and Fit

Elements related to comfort were design characteristics (e.g., looser, or more secure) and aspects of issues (whether or not the EXO could be adjusted to fit not only the body size but shape). While we used developer guidelines to ensure a good fit, some of the EXOs seemed to fit different body types better than others.

## Quality

Participants who worked in dynamic areas and interacted with many parts, concerned that the EXO might damage the product. None of the comments was positive. Instead, participants expressed concerns that they could bump into something with front, side, or back pieces of an EXO, and break something. Such concern was provided for both ASEs and BSEs.



## Environment

Participants wore the exoskeletons on their regular jobs in a variety of manufacturing environments. These working conditions differed according with respect to the temperature/humidity/dust as well as spatial constraints. The comments within this category were related to how the work environment could affect one's experience when wearing an EXO.

## Weight

Participants noted positive and negative comments about the weight of the EXOs. Some liked the lighter weight EXOs, and others indicated some of the EXOs were too heavy.

## Productivity

There were no positive comments, perhaps because many of the current participants worked on assembly lines that had established assembly times. Some participants expressed that wearing an EXO slowed them down considerably, so they would not meet their productivity goals.

## Safety

Only negative comments were provided related to safety. Participants expressed concerns that the EXO could get stuck on something and that could lead to an adverse event.

## Adjusting to EXO Use

Participants had comments regarding how EXOs or an EXO program would be implemented at their worksite. They questioned whether users would need time to adapt to an EXO, or whether some EXOs are so intuitive and easy to use that they could be utilized without much training. The comments provided were diverse, with some participants stating that they could use them right away and others believing that it would take some time to get used to.

## Donning and Doffing

Donning & Doffing was the category with few comments. As mentioned in the previous section, some EXOs tended to fit different body types better than others. Donning & Doffing was an aspect that had both positive and negative comments. Some participants noted that they were easy to don/doff, while others thought that donning/doffing took too long.

### **3.3. Decision Tree for EXO-Use-Intention**

Figure 2 shows the resulting decision tree that explains EXO-use-intention in terms of task characteristics and usability responses. The tree has a total of nine nodes, among which five are leaf nodes. The root node is “Perception of Discomfort”, which is divided into two nodes (“Object Weight” and “Ability to Perform Job”). For the branch in which the comfort response was  $\leq 5.5$  (i.e., moderate or lower levels of discomfort), participants reported being likely to use an EXO regardless of object weight. However, when participants perceived no difference in safety or less safe, and when the object weight was  $\leq 20.4$  kg, participants reported being less likely to use an EXO. For the branch in which the comfort response was  $> 5.5$  (moderate or higher levels of discomfort), participants reported being unlikely to use an EXO, especially when they perceived no difference or worse job performance. If participants perceived better job performance with EXO use, more than 60% of participants indicated an intent to use an EXO.

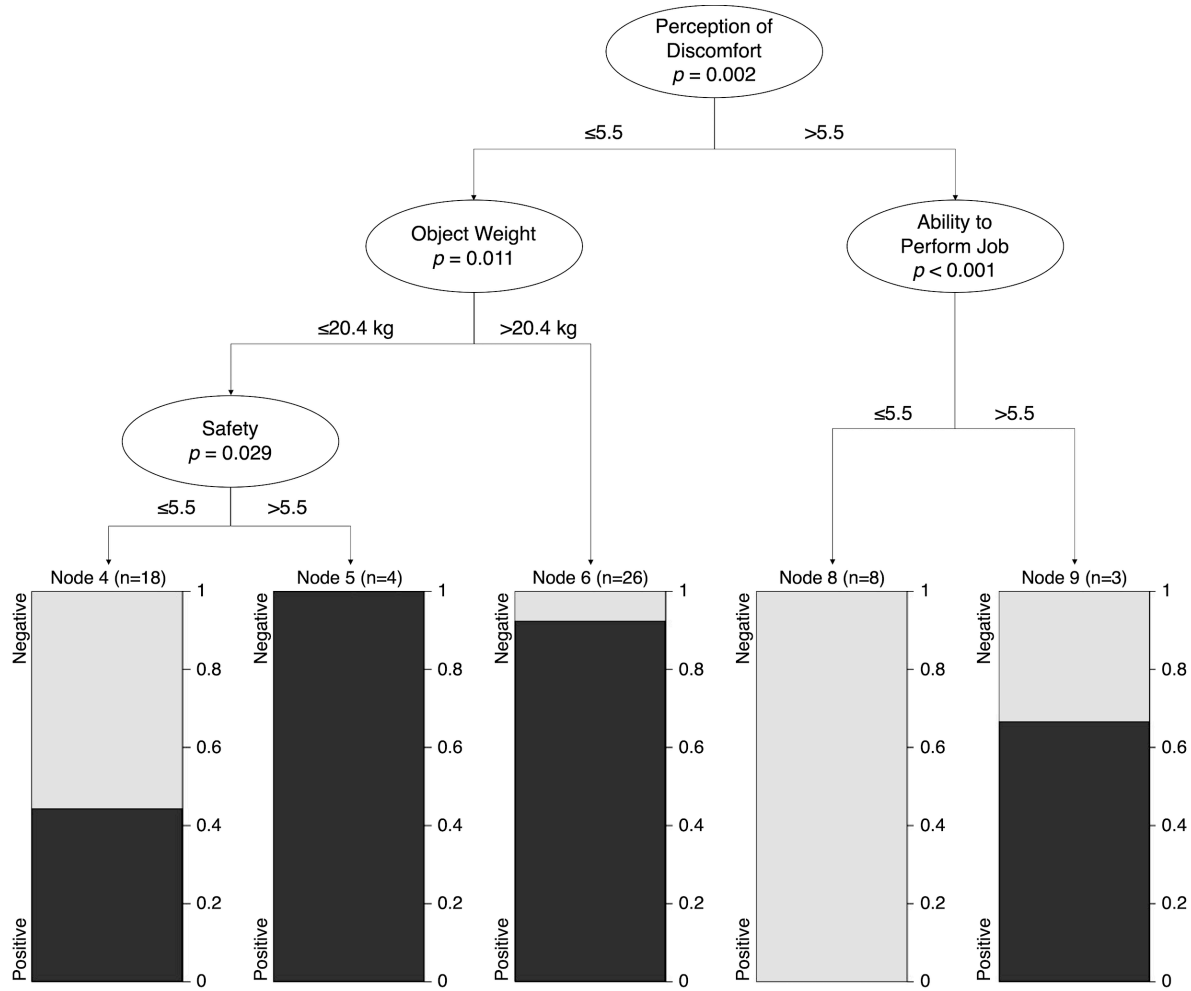


Figure 2. Decision tree developed to identify task characteristics and usability responses as predictors for the EXO-use-intention. The tree starts from the root node of Perception of Discomfort, then travels downward to the leaf (terminating) nodes. Leaf nodes are presented as bar graphs that show the distributions of Positive and Negative responses to the EXO-use-intention question; a participant's response to the question was coded as Negative or Positive, based on reported hours of likely EXO use (see text). Note that  $n$  values are the total number of responses in that node, and that in each node the  $p$  value indicates the strength of the association between the variable and EXO-use-intention.

#### 4. Discussion

In the current study we examined the use of different EXOs during a variety of static and dynamic tasks in actual manufacturing environments. The tasks involved diverse physical demands at the arms,

1 shoulders, and/or back. Responses to perceived usability questions appeared to be stable between two  
2 sessions, except those regarding perceived balance, overall comfort and fit, and range-of-motion (Table  
3 3). For these questions, participants reported significantly lower values in the 2<sup>nd</sup> session, meaning that  
4 they felt more comfortable, less restricted, and more stable than in the 1<sup>st</sup> session. This contrasts with the  
5 finding from a field study by Hensel & Keil (2019), in which participants gave initially high ratings for  
6 usability and these ratings significantly decreased during a period of BSE use (3 weeks). It is unclear if  
7 this contrast is because participants were exposed to an EXO for a relatively short duration in the current  
8 study, or because the task requirements were different (more variable). Regardless, that participant  
9 perceptions about EXO use changed over time here and in the noted study suggests that there may be  
10 some level of novelty effects when using an EXO – “first responses to a technology, not the pattern of  
11 usage that will persist over time as the product ceases to be new.” (Sung, Christensen, & Grinter, 2009, p.  
12 45). Thus, when implementing EXOs in practice, it may be important to provide workers with multiple  
13 and/or prolonged exposures to an EXO, so that potential novelty effects can wear off and workers can  
14 have a more accurate assessment of EXO use.

15  
16 Comparison of participant comments from the current field study to those from our prior focus group  
17 study (Schwerha et al., 2021) offers further information on EXO implementation. The prior study  
18 involved 10 focus groups with industry personnel who experienced EXOs only for a brief period ( $\leq 10$   
19 min) and were then asked to perform several tasks (e.g., walking around, mimicking their job tasks) in a  
20 conference or a training room onsite. Interestingly, many of the comments were similar between the  
21 studies, but a few were divergent. In the former, participants expressed concerns about work quality,  
22 noting that the bulkiness of an EXO may increase the change of damaging/scratching products. Concerns  
23 were also expressed about “fit” of an EXO. Though all EXOs were adjustable to fit different body sizes,  
24 some EXOs still did not appear to fit some body types/shapes well, which may have discouraged  
25 participants from using them. Participants in both studies indicated that EXO use could reduce fatigue, by

1 reducing musculoskeletal loads, and that wearing an EXO could have adverse safety implications (e.g.,  
2 getting caught on something in the environment or impairing integration with PPE).

3  
4 There were also diverging comments between the focus group and field studies, which were related more  
5 to task utility and productivity. For example, participants in the current field study noted that wearing an  
6 EXO may slow them down, though participants in the focus group study considered that wearing an EXO  
7 would likely provide a benefit to productivity. This divergence suggests that workers may better perceive  
8 the potential impacts of EXO use when using an EXO during their actual job tasks. We thus recommend  
9 that EXOs be tested by workers in the field, performing their normal work tasks, before determining  
10 whether an EXO is appropriate for a given worker and task, and what specific EXO might be most  
11 effective. Furthermore, given that small- and medium-sized enterprises (SMEs) can have higher risks of  
12 work-related injuries than larger one (Champoux & Brun, 2003; Hasle & Limborg, 2006; Legg, Olsen,  
13 Laird, & Hasle, 2015), and that strong interest in EXO use was shown among SMEs (Schwerha et al.,  
14 2021), to promote EXOs in SMEs future work may need to develop a rapid tool or approach that can help  
15 practitioners and/or workers to effectively assess an EXO for a given job.

16  
17 Four themes regarding EXO use were synthesized based on participant comments (Figure 1): utility for  
18 work, wearability, working metrics, and ease of using. These themes correspond to several key aspects of  
19 EXO user acceptance proposed by Moyon et al. (2019). The key aspects are physical, occupational,  
20 cognitive, and affective. Physical aspects include body pain/strain, comfort, and morphological  
21 adaptation. Occupational aspects include disturbance to work processes, being flexible with other tasks,  
22 task assistance, and task errors. Cognitive aspects include ease of learning/use, and perception of  
23 workload. Affective aspects include satisfaction and positive connotation. Thus, it appears that utility for  
24 work and working metrics are compatible with occupational aspects, wearability is among the physical  
25 aspects, and ease of using is among the cognitive aspects. Interestingly, a theme related to affective  
26 aspects did not emerge in the current study, perhaps because our questionnaire did not effectively capture

1 this aspect or due to the short duration of EXO use. Note that participants here used a given EXO  
2 typically for no more than 30 minutes in each session. It should also be noted that many of the negative  
3 comments in each of the four themes (Table 4) are associated with physical constraints from wearing an  
4 EXO (e.g., restricted movements, bulkiness) and with the EXO interfaces (e.g., straps, cuff designs),  
5 suggesting the importance of EXO design to minimize discomfort.

6  
7 Results from earlier studies indicate that a key factor contributing to EXO-use-intention is the wearing  
8 comfort of an EXO (e.g., de Looze et al., 2016; Moyon et al., 2019; Siedl et al., 2021). Similarly, the  
9 perception of discomfort was one of the determinants of EXO-use-intention in the current decision tree  
10 (Figure 2). The perception of discomfort was the root node that parts into two immediate nodes, “Object  
11 Weight” and “Ability to Perform Job”. When participants experienced a level of discomfort that was less  
12 than moderate ( $\leq 5.5$ ), they were also likely to be positive about EXO use. This positive intention was the  
13 case especially when an object handled was heavy ( $> 20.4$  kg), unless using an EXO was perceived to  
14 negatively affect safety. The “Object Weight” node thus can be considered to be related to the fit between  
15 task requirements and a given EXO, specifically the task-technology fit (Goodhue & Thompson, 1995;  
16 Siedl et al., 2021). When participants experienced higher than moderate discomfort, they were less likely  
17 to accept an EXO. Yet, interestingly, participants still may accept an EXO if they perceive that using an  
18 EXO is useful (i.e., improving job performance). It is unclear if this willingness to tolerate a certain level  
19 of discomfort for job performance is due to production pressures in SMEs (Bonafede et al., 2016; Masi &  
20 Cagno, 2015). Overall, the current decision tree indicates that perceived comfort, task-technology fit,  
21 perceived safety, and perceived usefulness are each associated with EXO-use-intention.

22  
23 As a field study, the current work had several advantages, including the use of a range of actual tasks and  
24 working environments, and multiple EXO designs. Several constraints and limitations were also present,  
25 though, that should be recognized. One important limitation was the duration of EXO use, and time of  
26 day for data collection. Each session was relatively short (i.e.,  $\leq 30$  min. for a given EXO), and as noted

1 above was completed between late morning and midafternoon. Though coordination efforts were made  
2 prior to each data collection, time constraints were unavoidable since data were collected during actual  
3 production and managers usually had to assign an additional worker to perform the work (one participated  
4 in the study, and another filled in when the worker was fitted to an EXO or when completing the  
5 questionnaire). Our sample was also somewhat limited, though comparable to other field studies with  
6 EXOs. Users' acceptance of technology has been investigated using theoretical frameworks such as the  
7 extended technology acceptance model (ETAM; Wang & Sun, 2016), the senior technology acceptance  
8 model (STAM; Chen & Chan, 2014), and the unified theory of acceptance and use of technology  
9 (UTAUT; Venkatesh et al., 2003). These models show that individual characteristics such as age and  
10 gender have moderating effects on intention to use a technology. Given the small sample size and that we  
11 were only able to recruit one female participant, age and gender specific differences were not explored.  
12 Due to the limited sample size, the decision tree was not cross validated, so caution should be taken when  
13 applying the decision tree directly to implement EXO technologies in a workplace.

14  
15 In summary, our results indicate that responses to usability-related questions were rather consistent  
16 between the two sessions, but with some exceptions (perceived balance, overall comfort and fit, and  
17 range-of-motion). Participant responses were more positive for these questions in the 2<sup>nd</sup> session,  
18 suggesting a need for multiple and/or prolonged exposure to an EXO to allow users to have an accurate  
19 assessment. We identified four themes regarding EXO use – utility for work, wearability, working  
20 metrics, and ease of using, and many negative comments on these themes were related to physical  
21 constraints from wearing an EXO, and to the EXO interfaces. The decision tree developed shows that  
22 perceived comfort, task-technology fit, perceived safety, and perceived usefulness are each associated  
23 with EXO-use-intention; it further suggests that participants may accept an EXO for better job  
24 performance even if it causes some level of discomfort. Given these results, to promote EXO use in  
25 practice, future work is needed to inform EXO designs that better accommodate a variety of body shapes  
26 and minimize discomfort, and to further develop a decision tree while considering how production or

other psychosocial and organizational factors influence EXO-use-intention. In addition, future efforts should address practical challenges associated with EXO implementation, such as how to introduce EXOs for successful adoption and to determine an effective EXO for a given task and user. For the EXO introduction, participants in the current study initially became comfortable with wearing an EXO during their work on average after ~8 min. of use. Yet, with only brief exposures to EXO use, is it unclear if they developed effective work strategies and motor skills to fully benefit from EXO use, and they further provided several negative comments related to the EXO physical interfaces. These comments may suggest usability and discomfort problems with longer-term use. Thus, an understanding of systematic approaches to enable an effective introduction of EXOs in the field will help in creating best practices for effective implementation and sustainable use of EXOs in manufacturing and other industry sectors.

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