Applied Ergonomics 122 (2025) 104400

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

# Active back exosuits demonstrate positive usability perceptions that drive intention-to-use in the field among logistic warehouse workers

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ARTICLE INFO

*Keywords:*
Occupational exoskeletons
Back exoskeletons
Active exoskeletons
Human factors
Human-machine-interactions
Acceptance
Work-related musculoskeletal disorders

ABSTRACT

Back exosuits offer the potential to reduce occupational back injuries but require in-field acceptance and use to realize this potential. For this study, 146 employees trialed an active back exosuit in the field for 4 h, completing an acceptance usability survey. Comparing the 80% of employees willing to continue wearing this device (N = 117) to those who were not (N = 29) revealed that employees willing to wear this device for a longer-term study generally were more likely to perceive this back exosuit to be effective (helpful) and compatible (minimally disruptive) to their everyday work. Using an optimal tree approach, we demonstrate that intent-to-use could be predicted with 78% accuracy by interacting features of perceived exosuit effectiveness and work compatibility. This study reinforces the importance of task matching, noticeable relief, and unobtrusive design to facilitate short-term employee acceptance of industrial wearable robotic technology.

## 1. Introduction

Low back pain (LBP) is a global burden (Chen et al., 2022; Hoy et al., 2014). It is considered the most expensive health condition in the United States due to its high prevalence and associated disability linked to decreased productivity and costly treatments (Dieleman et al., 2020; Hartvigsen et al., 2018; Hoy et al., 2014). The causes of LBP often have no single origin (Marras, 2012; Marras et al., 2016). However, biomechanical risk factors, such as peak and cumulative backloads during work-related manual material handling, are determinants of LBP (Coenen et al., 2013; Marras et al., 2000; Norman et al., 1998). Ergonomic interventions, education, and exercise are methods that have been implemented to reduce the risk of developing LBP (Sowah et al., 2018; Wurzelbacher et al., 2020).

Engineering controls, such as installing lift tables, rollers, or workplace redesign, can effectively mitigate LBP in the workplace (Marras et al., 2000; Wurzelbacher et al., 2020). In situations where engineering controls are not possible, exosuits and exoskeletons (herein referred to as exos) can be introduced with the goal of reducing LBP (Baldassarre et al., 2022). Exos are wearable devices that can assist their human operator (Toxiri et al., 2019). Collectively, exos can noticeably and successfully offload joints (Bär et al., 2021; Kermavnar et al., 2021; De Looze et al., 2016), enhancing the maximum acceptable load people would be willing to lift (Raghuraman et al., 2023) and potentially mitigating the risk of lifting-related low back injury (Zelik et al., 2022). However, the relative benefit versus interference provided by industrial exos is a task-dependent construct (Baltrusch et al., 2020; Kim et al., 2021; Luger et al., 2021; Quirk et al., 2023a), creating the need for research to move out of laboratories and into the field to understand how these devices perform for workers who are exposed to a diverse array of tasks (Baldassarre et al., 2022; Bär et al., 2021; Crea et al., 2021; Kermavnar et al., 2021).

Like other technological innovations, gaining workers' acceptance can be complex, dependent on usability, perceived usefulness, and perceived compatibility (Davis, 1989; Jacobs et al., 2019; Venkatesh and Davis, 2003). However, the relative importance of these factors can change over time. For computer software usage, ease of use can overcome initial barriers, but overall usefulness is more influential towards

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https://doi.org/10.1016/j.apergo.2024.104400
Received 20 January 2024; Received in revised form 12 September 2024; Accepted 30 September 2024

gaining acceptance (Davis, 1989). Emerging literature suggests that premises of technology acceptance apply to exos (Baldassarre et al., 2022; Crea et al., 2021; Elprama et al., 2022). Multiple studies have revealed that device intent-to-use is a balance between perceiving a device as effective, capable of being helpful for work tasks while also being compatible with an operator and having minimal negative costs such as discomfort, restriction, or impeding productivity (Gonsalves et al., 2023; Hensel and Keil, 2019; Kim et al., 2022; Schwerha et al., 2022). Understanding factors contributing to exo acceptance is important because acceptance will increase adherence and the potential of exos to achieve injury risk mitigation via cumulative usage (Kim et al., 2022; Wurzelbacher et al., 2020; Zelik et al., 2022).

Although the literature is beginning to reveal what features promote the acceptance of exos, most of this work has been conducted with passive exos that assist a user via the deformation of springs or elastic bands. For passive exos, device intent-to-use is related to device-specific factors, such as device weight, comfort, and assistance level (Bethel et al., 2021; Schwartz et al., 2021; Schwerha et al., 2022). Active exos are considered more complicated than their passive counterparts, using device-specific sensor-informed controllers to dictate when and how much assistance an actuator should provide to a user (Babič et al., 2021; Toxiri et al., 2019). However, this complexity might improve device-task matching (Babič et al., 2021; Poliero et al., 2021; Quirk et al., 2023a). To date, there are mixed results on whether active exos can improve (Poliero et al., 2021, 2022; Quirk et al., 2023a; Schwartz et al., 2022) or decrease (Govaerts et al., 2024) device usability and utility (effects) in laboratory settings. These differential results are likely explained by differences in the device-task combinations in which they are observed. Because of the extra cost, weight (Govaerts et al., 2024), complexity (Ralfs et al., 2023), and the fact there are fewer commercially available active back exos, it remains unknown whether active back exos can be accepted and achieve high intent-to-use in a real-world industrial workplace (Baldassarre et al., 2022).

To understand the impact of an active exo outside of a laboratory environment, we initiated a randomized control trial (RCT) in an industrial setting. As part of recruitment, we asked warehouse workers to trial an active back exosuit in the field for up to 4 h before determining whether they would like to participate in the RCT. The objectives of this 4-h field trial were to facilitate recruitment into the subsequent RCT and to determine device factors influencing a worker's intent-to-use an active back exosuit in an industrial setting. We hypothesized workers who sought to continue using this device in the RCT would perceive it to have higher usability and usefulness than those who did not. Our secondary objective was to understand user perception of an active back exosuit by describing reasons for dissent via post-use anonymous surveys.

## 2. Methods

### 2.1. Participants and recruitment

Recruitment occurred at six logistics warehouses, operated by the same company in the southeastern United States, between late January and early May 2023. Between- and within-building variability were high when considering the goods being manually lifted by employees, ranging from apparel, medical devices, and industrial parts. These buildings were not climate-controlled, and monthly regional temperatures ranged from approximately 6–30.5 °C (43–87 °F) and 53–100% humidity. Utilizing regularly scheduled employee meetings, the research team introduced the exosuit and its intended purpose while being sensitive not to make injury reduction/prevention or productivity claims. In these meetings, workers were told the study was recruiting "full-time employees who bend and lift regularly (>50% of their day)" to evaluate the exosuit during a 4-h trial on a regular working day. Workers were told the 4-h field trial intended to determine their interest in participating in a 4-month RCT, in which they would be randomized to wear this exosuit during work or to a control group that would not wear the exosuit. To promote voluntary participation, workers were told that their employer did not expect them to participate; however, they were informed they would be compensated with branded study gifts (i.e., water bottles, badge lanyards, and pens). Employees who expressed interest were scheduled for a 4-h trial during their work shift. Device demonstrations were conducted by the research team at least three times in each warehouse to ensure employee awareness and to facilitate the inclusion of interested employees.

### 2.2. Exosuit specification

The device used for this study was the SafeLIFT from Verve Motion based on a prototype described in laboratory studies (Chung et al., 2024; Quirk et al., 2023a, 2023b). The SafeLIFT is a soft, active back exosuit fitted to a participant by a backpack element and two thigh wraps spanned by an actively actuated nylon ribbon cable (Fig. 1). Actuation was controlled by an adaptive sine impedance controller informed by three inertial measurement units (IMU) integrated into the exosuits' back panel and thigh wraps. For this study, participants had access to 3 generic controller strategies that a shoulder-mounted remote could control. The top button placed the exosuit in a neutral mode where the device delivered a negligible 10N pretension. The middle button activated a medium (80%) assistance mode, such that the device applied assistance using an asymmetric sinusoidal impedance profile (Chung et al., 2024) with a maximum lifting force of 200N and a maximum lowering force of 25N. Finally, the bottom button activated maximum (100%) assistance mode, delivering 250N when lifting and 40N when lowering. In both medium and maximum assistance modes, the exosuit delivered assistance to a user when the trunk engaged in greater than 15° trunk flexion (i.e., bending, lifting, or sitting), ensuring the device was neutral when participants were standing or walking without manual controller changes (Chung et al., 2024).

### 2.3. 4-Hour field trial details

The 4-h device trial was included as part of the screening process for our larger clinical trial and thus followed a standard protocol. Participants were assigned a specific time for a device fit and training session. Upon arrival, participants were informed of the potential risk of wearing the back exosuit and signed a Risk and Release Form. The Risk and Release Form outlined risks, not benefits, and absolved Harvard of any fault due to injury. The industrial partner would still treat any injury from device usage as a workplace injury and compensate accordingly through their normal process. Employees were simply unable to seek legal recourse against Harvard due to their participation in the trial. Participants unwilling to sign this form were not eligible to complete the trial. Participants were provided with a sanitized exosuit. Study team members and a Verve Motion representative conducted a brief fitting process that took approximately 5 min. Device fit ensured the participants' shoulder strap length and thigh wrap circumference were comfortable. Participants were then guided on how to don, doff, and adjust the device, including how to tighten the thigh wraps, sternum, and shoulder straps (Fig. 1) so participants could don and doff the exosuit between breaks. Following fitting, participants performed dynamic movements, refitting when necessary for device discomfort or restriction.

Following device fitting, participants were trained on the active components of the exosuit in a 3-min educational session. Participants were instructed to stand straight as they powered on the device, allowing it to calibrate to their normal standing posture (Chung et al., 2024). Participants were informed of the three assistance levels controlled by the shoulder-mounted remote (described above in *Exosuit specification)*. Although participants could try maximal assistance during training, they were discouraged from using this setting during their 4-h field trial, consistent with the suit acclimation strategies deployed by the


**Fig. 1.** Verve SafeLIFT exosuit, which includes the actuated ribbon (Y-Strap), adjustable components, remote to control actuation strategies, and depiction of the chest/sternum straps.

manufacturer. In this training, the study team explained that participants should consider the mass of an object prior to selecting the assistance level. This would allow them to select maximum, medium, or neutral at their own discretion depending on the anticipated load and how they found the device interacted with the task, for example, placing the device in neutral when sitting. Furthermore, participants were shown how to troubleshoot (power cycle) the device if it began to apply too little assistance.

After device training, participants returned to their regular workstations to use the device for up to 4 h. Specific and average time of use could not be determined for participants due to the anonymous nature of the survey. Furthermore, summaries of usage time for a single exosuit could have included multiple participants, training time, and demonstrations by the study team. Participant duties varied, including lifting and lowering items from trucks, pallets, rollers, and racking, including lifting from standing order pickers (with a fall harness worn beneath the back exosuit). Some of these employees also conducted logistical and finishing work such as computing, pallet wrapping, and equipment-aided stationary tasks, including forklift and standing-lift operations. These job duties were listed by the industrial partner and observed by the research team. Participants could return to the study team for assistance. At the end of the field trial, participants returned the device. Participants interested in joining the RCT provided their contact information to the research team. Regardless of interest, participants were compensated with branded study gifts.

### 2.4. Anonymous survey data collection

Participants were asked if they would complete an anonymous survey to provide feedback on their back exosuit experience. These participants were provided a tablet, linking them to an online REDCap (Research Electronic Data Capture) survey licensed by Harvard's School of Public Health. REDCap is a secure, web-based software platform designed to support data capture for research studies, providing an intuitive interface for validated data capture (Harris et al., 2018). Participants electronically consented (agree or disagree) to provide anonymous data. This consent form was consistent with Helsinki's guidelines and approved by Harvard Medical School's Internal Review Board (IRB22-0308). A research team member explained consent language to the participants, and participants were encouraged to ask questions. If participants consented, the survey began. Otherwise, the survey would close, and the participant was thanked for their time.

The survey collected no personal identifiers; however, it collected demographic categories (age, weight, height, sex, length of employment, activity level outside of work, history of LBP longer than three days) (Table 1). We collected a single binary yes/no question if participants would be interested in participating in an RCT that could involve using this back exosuit. Those that responded 'No' were then given multiple-choice selections for possible reasons they declined as well as a box to type non-provided rationale. For example, 'Returning to School' was specifically provided by one employee indicating they would be leaving their job prior to the start of the study. The survey then asked ten exosuit experience questions with 5-point Likert Scale response options that range from strongly agree to disagree (Table A1). Sensitive to workflow, this survey was designed to ask questions from three a-priori selected categories (usability, effectiveness, and compatibility), with a singular question on device usability. To keep the survey under 5 min, for some survey questions, dissenting opinions rendered clarifiers where participants could select from multiple reasons for dissent (Table 2). Employees could select the "other" option to annotate a specific reason (Table 2).

### 2.5. Data and statistical analysis

Data were automatically exported from REDCap and then organized and visualized using custom MATLAB code (The MathWorks, Natick, MA, United States). In some cases, questions (Q7-9 in Table A1) were transformed so that agreement reflected a positive perception of the device for ease of interpretation. Participants were put into two groups, Interested and Not Interested, based on their answers about their intention to continue using the back exosuit as part of an RCT.

All statistical analyses were performed in Minitab 21(Minitab LLC, State College, PA, United States). Data were compared between Interested and Uninterested participants to measure intent-to-use. Statistical approaches varied by data type. Ten Likert-Scale questions about device usability and utility were compared using a Mann-Witney test. Seven nominal data and demographics features were compared with a chi-square test for likelihood ratios. To correct type-1 error, tests were Bonferroni adjusted for the 17 comparisons with an alpha $<0.003$ considered significant. Upon checking variable correlation using

Spearman's ρ, a predictive analytic optimal classification decision tree approach was taken to determine the strongest predictor(s) of intent to join the RCT. Using the automated machine learning feature in Minitab, a classification and regression tree model was trained upon significant Likert-Scale data split by participant interest to join the study. Nodes were split using a Gini method, and an optimal tree was defined within one standard deviation of the minimum misclassification cost. A 10-fold cross-validation was used to assess the stability of model accuracy.

## 3. Results

### 3.1. Survey completion and description of study population

In total, 148 surveys were completed. However, two participants did not consent, rendering data from 146 anonymous surveys. Most (117 or 80%) participants were interested in using the device as part of an RCT. Twenty-nine participants were uninterested, as outlined in Fig. 2.

### 3.2. Group differences in demographics

Participants in the interested and uninterested groups were compared for demographic, medical, workplace, and physical activity differences. Groups were similar for many factors (Table 1). However, individuals without a history of LBP lasting longer than three days in their lifetime and those of short stature (<5′3″) were less likely to join the RCT.

### 3.3. Group differences in exosuit survey responses

Questions about participant experience represented usability, perceived effectiveness, and compatibility. For all but one of these exosuit questions, significant differences showed the interested group being more likely to have favorable opinions of the exosuit (higher scores) than the uninterested group (Table A1). Although not the focus of this study, a supplemental analysis demonstrated similar results when comparing those who agreed to want to use the device frequently to those with a neutral or lower opinion. (Table S1).

Breaking down results by category, the exosuit was found to be easy to use and adjust by the majority of participants (91.8%), to the extent that the perception of device usability between the interested group and uninterested group was not statistically significant (W = 1689.0, p = 0.030, Table A1 Q1).

Overall, the exosuit was perceived as beneficial in the workplace (71–78% agreement Table A1 Q2-5). There was a significant group difference showing the interested group was more likely to feel they would lift safer (W = 1413.0, $p < 0.001$, Table A1 Q5) and would be less likely to experience an injury at work with a back exosuit (*W=1509.1,* p = 0.002, Table A1 Q3) than the uninterested group. Larger disparities between the groups were identified in their perception that the exosuit

**Table 1**
Proportion and Chi-Square Test results for participant demographics, LBP history, work history, and activity levels. Significant differences are demonstrated with an *.

| Feature | Interested | Uninterested | Statistics (χ2 & p) |
|---|---|---|---|
| Sex at Birth | | | |
| Men | 72 (62%) | 16 (55%) | χ2 = 0.39 |
| Women | 45 (38%) | 13 (45%) | p = 0.531 |
| Age Range | | | |
| 18–25 | 26 (22%) | 11 (38%) | |
| 26–35 | 37 (32%) | 6 (21%) | |
| 36–45 | 22 (19%) | 4 (14%) | χ2 = 6.01 |
| 46–55 | 18 (15%) | 2 (6%) | p = 0.198 |
| 56+ | 14 (12%) | 6 (21%) | |
| Mass Range | | | |
| <120 Lbs | 4 (3%) | 3 (10%) | |
| 120-150 Lbs | 25 (21%) | 6 (21%) | |
| 150-180 Lbs | 36 (31%) | 5 (17%) | χ2 = 4.26 |
| 180-210 Lbs | 23 (20%) | 8 (28%) | p = 0.372 |
| >210 Lbs | 29 (25%) | 7 (24%) | |
| Height Range* | | | |
| <5′3″ | 10 (8%) | 8 (27%) | |
| 5′3″-5′6″ | 24 (21%) | 0 (0%) | |
| 5′6″-5′9″ | 33 (28%) | 7 (24%) | χ2 = 17.17 |
| 5′9″-6′0″ | 26 (22%) | 9 (31%) | p = 0.002* |
| >6′0″ | 24 (21%) | 5 (18%) | |
| History of Activity Limiting Back Pain* | | | |
| No | 46 (39%) | 21 (72%) | χ2 = 10.44 |
| Yes | 71 (61%) | 8 (28%) | p = 0.001* |
| Job Tenure | | | |
| <6 Months | 24 (15%) | 10 (34%) | χ2 = 4.73 |
| 6–24 Months | 57 (55%) | 8 (28%) | p = 0.094 |
| >24 Months | 36 (30%) | 11 (38%) | |
| Activity level outside of work | | | |
| Very Active | 18 (20%) | 8 (28%) | χ2 = 2.20 |
| Sometimes Active | 64 (49%) | 14 (48%) | p = 0.333 |
| Inactive | 35 (31%) | 7 (24%) | |

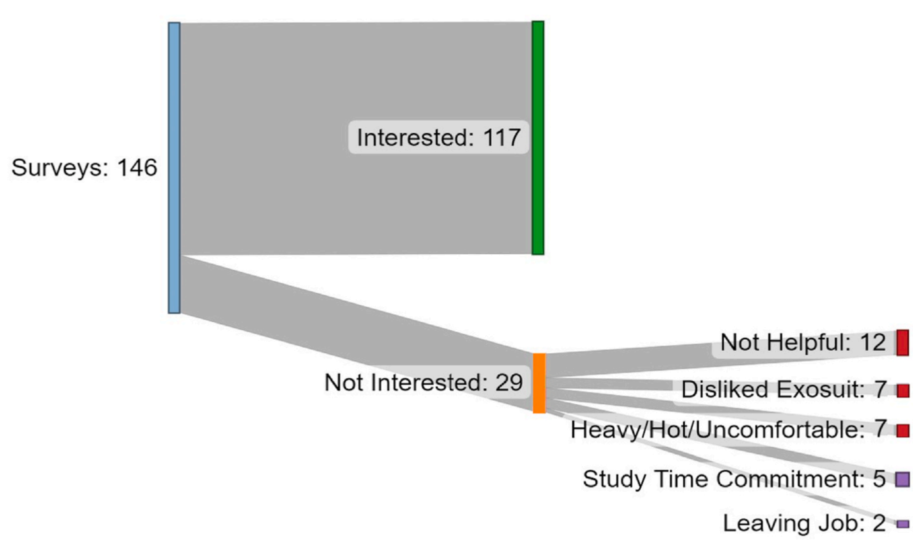


**Fig. 2.** Group breakdown for those interested or uninterested in continuing to use the exosuit in the RCT. The rationale for why participants did not wish to continue is branched. Red responses correspond to exosuit burdens, whereas purple responses correspond to study burdens. Participants could provide more than one answer, which explains why more reasons were provided than people in the uninterested group. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

would reduce their level of physical fatigue (W = 1345.5 p < 0.001, Table A1 Q4) and the global impression that the exosuit was helpful for their job (W = 1221.0, p < 0.001, Table A1 Q2 & Fig. 3).

For the majority of employees, the exosuit was perceived to be compatible with their work (69–75% agreement; Table A1 Q6-8). There were significant disparities between the interested and uninterested groups when considering exosuit comfort (W = 1419.0, p < 0.001, Table A1 Q6), restriction (W = 1383.0 p < 0.001, Table A1 Q7), and disruption (W = 1227.0 p < 0.001, Table A1 Q8) to the user's natural movement and balance. Lower levels of agreement and smaller group disparities were captured in the perception that the device had to be removed too often (W = 1645.5 p = 0.017, Table A1 Q9 & Fig. 4); however, participants did not always understand this question well (see discussion).

### 3.4. Key features that determine intent-to-use

To identify the strongest predictors for intent-to-use, an optimal decision tree was developed using survey questions to predict participant groups (Interested or Uninterested). Given the strong overlap between the desire to join the RCT and the answer to "wanting to use the device frequently as part of my job," this factor was removed from the model and is presented in our supplement. Perceived exosuit effectiveness – queried as "I found the exosuit helpful for my job," was the strongest predictor for intent-to-use. In those who found the device helpful, predictions were further improved by considering device compatibility, queried as "finding the exosuit did not disrupt the user's motion" (Fig. 5). Hence, those willing to join the RCT agreed with the device's effectiveness without perceived incompatibility. This optimal model achieved 78% accuracy (76% sensitivity, 86% specificity, and precision 85%), with 76% accuracy upon cross-validation. Given all Likert scale questions varied between groups and were not perfectly correlated (Table A2), each feature could modify prediction accuracy with varying strength (Figure A1). However, these models were often less stable upon cross-validation.

### 3.5. Overall exosuit usability and assessment of dissenting answers

Differences between participants who did and did not want to join the RCT were most often explained by their answers about exosuit effectiveness and compatibility with their work. Despite low overall levels of disagreement (4–13%), our survey captures categories for dissent, which were normally logically opposite to the question (Table 2). However, upon reviewing these categories, a theme emerged that some disagreement could be explained by a lack of job suitability (see discussion). In addition, anecdotally, we identified difficulties with participants' interpretation of the need to remove the device too often (Q9, Table 2), evidenced by employees citing removal for regular breaks or restroom use (Q9, Table 2). This question was included to capture instances of job incompatibility requiring the removal of the device for differences in work tasks or the use of equipment. It was not intended to capture the removal of the device for regularly scheduled breaks. Nevertheless, five of the study participants indicated a desire for a suit that did not have to be removed for breaks.

## 4. Discussion

In this study, we quantified 146 survey responses from participants who evaluated an active back exosuit for 4 h during their logistic warehouse jobs. Participants answered questions about their experience with the exosuit regarding usability, effectiveness, and compatibility. As a proxy for intent-to-use, after participants completed the 4-h field trial, participants indicated whether they were 'interested' or 'uninterested' in joining a 4-month RCT. From survey responses, we identified individuals with intent-to-use were more likely to have a history of LBP and be greater than 5′3″ in height. Using an optimal tree approach, we demonstrate that intent-to-use depends on an interaction between perceived exosuit effectiveness (helpfulness) and work compatibility (disruption to natural movements).

### 4.1. Influence of device usability on intent-to-use

The majority (91%) of participants who trialed the back exosuit agreed or strongly agreed that it was easy to use and adjust, with no significant differences between groups (Table A1). Usability, the perception a device requires little or no effort to use, is a good starting point in the design and evaluation of a device (Brooke, 2013). However, training and education can improve poor device usability (Venkatesh and Davis, 2003). This study found that the Verve SafeLIFT achieved high usability following a brief 5-min fit and training session. This

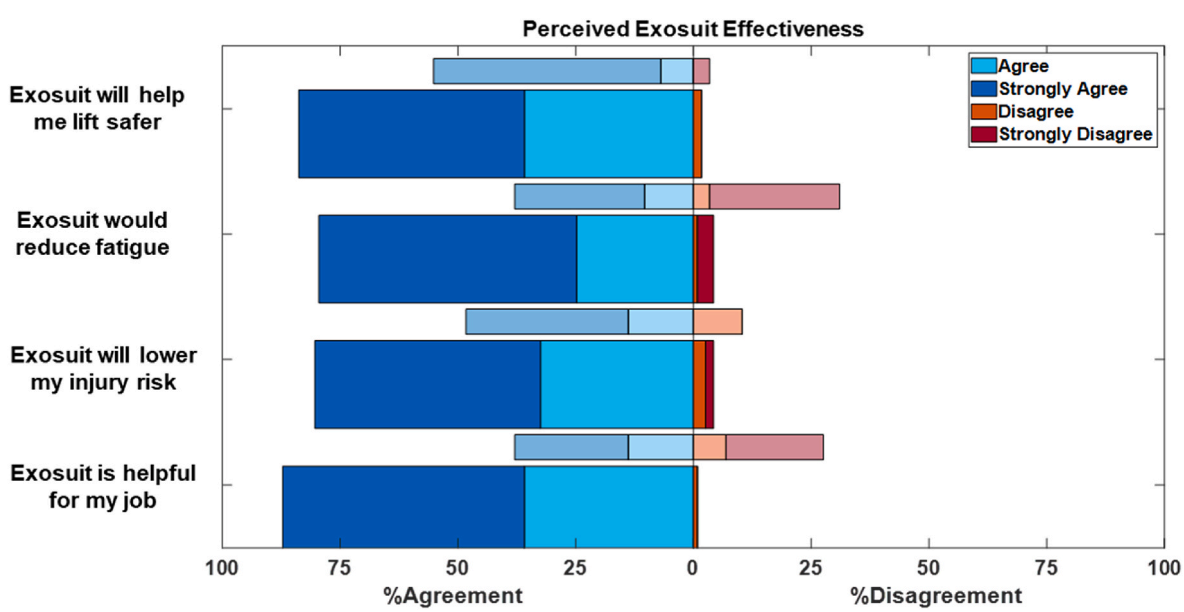


**Fig. 3.** Difference in proportion of agreement and disagreement between interested (N = 117, wide bars) vs uninterested participants (N = 29, narrow transparent [lighter colored] bars) for questions focused on exosuit effectiveness.

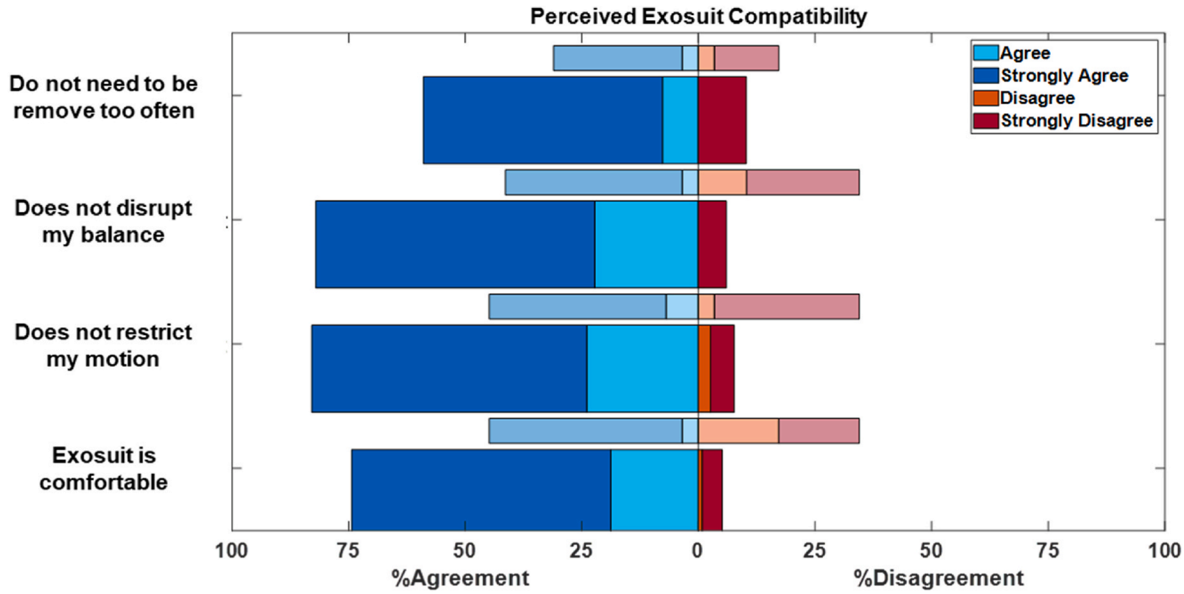


**Fig. 4.** Difference in proportion of agreement and disagreement between interested (N = 117, wide bars) versus uninterested participants (N = 29, narrow transparent [lighter colored] bars) for questions focused on exosuit compatibility.

finding improves the generalizability of previous work that demonstrated a similar prototype device achieved excellent System Usability Score values in a laboratory setting (Chung et al., 2024). Given that device usability only trended towards being different between groups (Table A1), it was the weakest predictor in the decision tree model (Fig. A1) for classifying interested versus uninterested groups. This finding suggests, consistent with other technology, that device usability does not equate to high intent-to-use once exceeding a minimum proficiency threshold (Davis, 1989; Venkatesh and Davis, 2003).

### 4.2. Influence of device effectiveness on intent-to-use

Unlike usability, device effectiveness highly depends on job suitability factors (Baltrusch et al., 2020; Govaerts et al., 2024; Kermavnar et al., 2021; Lewis et al., 2015). In this study, we found that participants who intended to use this device for a 4-month RCT had a higher level of agreement regarding device effectiveness (Table A1 Q2-5 & Fig. 3). The largest differences between groups were found in the questions probing whether the exosuit was perceived as "helpful for the participant's job." For this reason, and consistent with others, a metric of device effectiveness was necessary to determine device intent-to-use (Baldassarre et al., 2022; Bethel et al., 2021; Elprama et al., 2022; Kim et al., 2022; Schwerha et al., 2022). For example, the perception that a device reduces the physical requirements of a task is correlated with reported intent-to-use (Hensel and Keil, 2019). Of interest, our study asked a similar question, showing that while there was a noticeable disparity between group perceptions of whether the exosuit made users less physically tired at work (Fig. 3), it was only ranked as the 4th highest predictor for a participant to join the RCT (Fig. A1). The difference between these studies might be explained by question wording, such that the question "helpful for my job" could be interpreted as an individual finding the device both effective and compatible with their job. This potential for question wording to reflect both constructs of effectiveness and compatibility allows for the possibility that study participants could differentially prioritize either construct in their response.

### 4.3. Perceived work compatibility on intent-to-use and interaction with benefit

Despite a history of developing increasingly effective devices, device compatibility has gained more recent attention in the literature as an essential factor related to exo intent-to-use (Babič et al., 2021; Baldassarre et al., 2022; Bethel et al., 2021; Elprama et al., 2022; Kermavnar et al., 2021; Kim et al., 2022; Schwerha et al., 2022). In this study, users who intended to join the RCT had a higher level of perceived device compatibility than those who were uninterested (Table A1 Q6-8). Generally, group differences for compatibility were greater than group differences for effectiveness. Hence, the second and third strongest predictors for intent-to-use were whether participants found the exosuit to be restrictive or disruptive to their work (Figure A1). This finding is consistent with the literature showing user acceptance reflects the perception that the benefits of the exosuit will outweigh the residually summing negative qualities (Baldassarre et al., 2022).

Unlike other studies, our study did not identify device compatibility as a strong predictor of intent-to-use (Kim et al., 2022; Schwerha et al., 2022). An explanation for this discrepancy could arise because perceived device effectiveness and compatibility are dependent upon the device used, individual characteristics, and the tasks an individual is exposed to in the workplace (Baldassarre et al., 2022; Bethel et al., 2021; Elprama et al., 2022). The exosuit used for this study had a design aimed at improving compatibility (Babič et al., 2021; Kermavnar et al., 2021; Schwartz et al., 2021; Schwerha et al., 2022). Soft, lightweight interfaces improve device comfort and compatibility (Bethel et al., 2021; Riemer and Wischniewski, 2023), which may explain why compatibility factors like device comfort were not the most important factor determining intent-to-use, as found in other studies (Kim et al., 2022; Schwerha et al., 2022). Beyond the contribution of device architecture to comfort, kinematic compatibility can also be conflated with discomfort (Babič et al., 2021). Laboratory work has validated that the control strategy used by SafeLIFT can minimize movement restriction (Quirk et al., 2023a) and the potential balance disruption from mistriggers during complex lifting tasks (Chung et al., 2024). For these reasons, device compatibility could have been improved to the extent that fewer users experienced these issues, thereby making device effectiveness a more important predictor of intent-to-use. However, the relative importance of device incompatibility becomes more pronounced over time as perceptions of device comfort often decrease with continued use (Hensel and Keil, 2019).

### 4.4. LBP history and participant size on intent-to-use

Two features related to demographics and anthropometrics

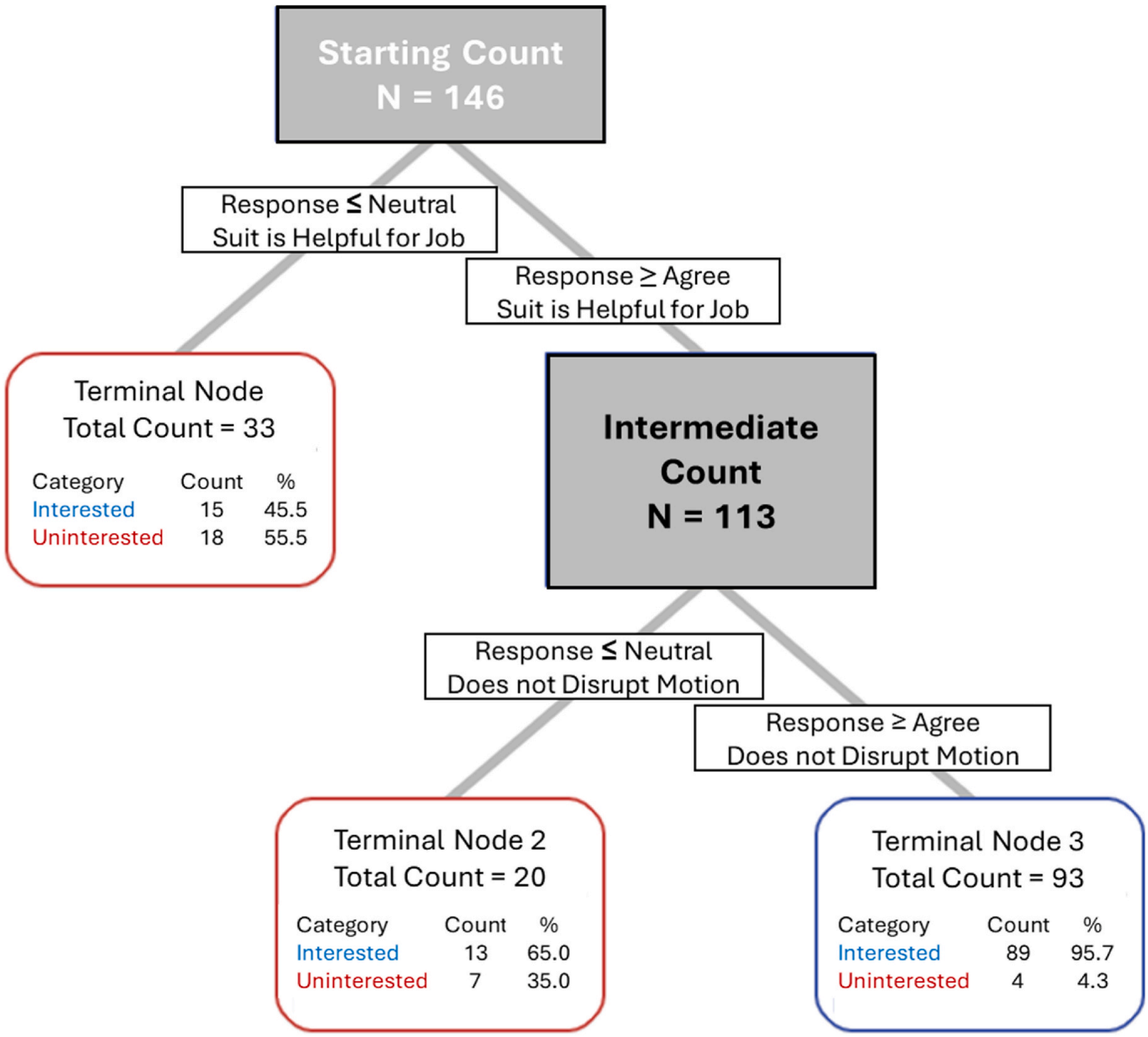


**Fig. 5.** Optimal decision tree model designed to predict participants willing to join (interested) the study versus those who disagreed (uninterested). Counts in each terminal node display participants' proportion (count and %) within the two classification categories.

explained device intent-to-use. First, we found participants with a history of activity-limiting LBP, which lasted longer than three days, were more likely to seek to use the back exosuit (Table 1). These data suggest injury history can sculpt intent-to-use. This finding is not particularly surprising. A recent study of experts observing exo users in the workplace identified older adults and those with more medical conditions were likely to use back exos regularly (Riemer and Wischniewski, 2023). Individuals with LBP are believed to be more willing to accept a back exo if there is potential to mitigate the recurrence of previous injuries, even when faced with device incompatibility (Kozinc et al., 2021). This higher tolerance for device incompatibility might stem from studies showing back exosuits can increase perceived self-efficacy for individuals with LBP (Baltrusch et al., 2021) and reduce their fear of performing activities of daily living (Quirk et al., 2023b). Although it is unknown if the psychological benefits gained by individuals with chronic LBP apply to those with a history of LBP, a history of LBP might have an immediate impact on the perception of device effectiveness. For example, some participants disagreed that the exosuit could prevent injuries because they had never previously experienced a workplace injury and were not concerned about injuring their backs at work (Table 2 Q3).

In addition to back pain history, a user's height represented a second demographic factor related to their intent-to-use. Shorter individuals were less likely to want to advance with the study. It has been demonstrated that soft exos can be more uncomfortable for petite individuals, as structures can feel too large on the back and hips (Riemer and Wischniewski, 2023). While only partially related to height, these findings coincide with the vendor's recommendation that users of the SafeLIFT should have a torso length (seventh cervical to fifth lumbar vertebra) longer than 17".

### 4.5. *General exosuit perception and job suitability*

In this study, we obtained a field-based understanding of reasons for dissent, providing a unique opportunity to offer a qualitative foundation for reduced intent-to-use. Although overall levels of disagreement were low regarding device efficacy and compatibility (Table 2), a theme that emerged from dissenting opinions was that some employees who participated in the field trial might not have had a suitable job. As demonstrated in Fig. 2, twelve participants did not join the RCT because the back exosuit "would not help their job." Finding the suit was not helpful could be partially related to a lack of job suitability (Riemer and Wischniewski, 2023). Recruiting from a logistics warehouse, it was known employees performed a variety of job functions, which could include a combination of trailer loading/unloading; roller line loading/unloading; inducting; walking (while pushing or pulling); order picking on the floor, under racking, or on raised platforms; using equipment such as stand-up forklifts; and sitting computer work.

**Table 2**
Study questions, number of participants who disagreed, and reasons for dissent.

| Question (N/N total [%] of disagreeing participants) | The rationale for dissent (# of respondents) |
|---|---|
| ***Q1:*** *I think the exosuit is easy to use and adjust (4/146 [4%])* | • Suit requires too much to remember (2)<br>• Exosuit must be adjusted too frequently (3) |
| ***Q2:*** *I think the exosuit is helpful for my job (9/146 [6%])* | • Exosuit applied too little assistance (7)<br>• Too little exposure to the device (1)<br>• Job had too little bending (1) or too much diversity (1) for the suit to be helpful. |
| ***Q3:*** *I think using an exosuit in the workplace would lower my injury risk at work (9/146 [6%])* | • Had no injury in the past (8)<br>• Not concerned with developing back injuries (5) |
| ***Q4:*** *I think using an exosuit in the workplace would lower how physically tired I feel at work (14/146 [10%])* | • Job not tiring (10)<br>• Not enough exposure to the exosuit to form an opinion (4) |
| ***Q5:*** *I felt I lifted safer with the exosuit (3/146 [3%]).* | • N/A |
| ***Q6:*** *I think the exosuit is comfortable (16/146 [11%])* | • Uncomfortable on their shoulders (10), lower back (6), neck (5), and thigh (3).<br>• Additional discomfort included heat discomfort (6), and overall device weight (6). |
| ***Q7:*** *I do not think the exosuit restricts my motion at work (19/146 [13%])* | • Exosuit restricted reaching forwards (9), leaning forwards (8), and overhead reaching (8) |
| ***Q8:*** *I do not think the exosuit disrupted my motion (17/146 [12%])* | • Bumping into objects (6)<br>• Applying too much force (6) or applying assistance at the wrong time (5) |
| ***Q9:*** *I do not think the exosuit needs to be removed too often (17/146 [12%])* | • Removal for jobs involving sitting (9), work/restroom breaks (5), suit discomfort (4), and equipment use (3) |
| ***Q10*** *I would like to use the exosuit frequently as part of my job (15/146 [10%])* | • N/A |

Note participants had the option to select more than one reason if they disagreed with a statement.

Working with warehouse management, we attempted to provide exosuits to employees who met specific job requirements. Although participants were screened for self-reported bending more than 50% of their day and having sustained periods without sitting (>1.5 h), we did not measure for how long they engaged in consecutive dynamic bending, which may explain why some participants identified disagreement due to "too little bending" (Table 2, Q2). Furthermore, some participants found the device needed to be removed too often for sitting or equipment use (Table 2, Q9), further supporting the theme of job incompatibility. Owing to logistic limitations and the anonymous design of this study, workload qualities were not measured, including average load lifted and a participant's perceived fatigue or body discomfort at the end of a shift. For some employees, workplace demands could have been too low, which may explain why some reasons for dissent included not finding their job tiring (Table 2, Q4) and not finding their job likely to induce back injuries (Table 2, Q3).

Given that the relative assistance and hindrance provided by specific back exosuits are task-dependent (Baltrusch et al., 2020; Govaerts et al., 2024; Kermavnar et al., 2021; Poliero et al., 2021, 2022), periods spent with limited lifting from below waist height would result in a task-exosuit mismatch. Logistic work simulation studies findthe biomechanical and perceived effectiveness of a passive back exosuit is diminished with the inclusion of lifting and lowering objects from waist-height locations (Iranzo et al., 2022; Mitterlehner et al., 2023). Although it has been demonstrated this active back exosuit can predictably apply over 80% of its peak assistance over an extensive range of trunk extensions (53–127°), the suit applies negligible forces if the trunk is in flexion between 0 and 20° (Chung et al., 2024; Quirk et al., 2023a). Thus, limited lifting from below waist height can explain why some respondents expressed that the exosuit was not "helpful for their job" and felt that the device provided "too little assistance" (Table 2). Our result that job suitability impacts the intent-to-use back exosuits is consistent with another study finding participants were more likely to use an exosuit if the object being lifted was 20.4 kg or greater (Schwerha et al., 2022). These findings highlight the importance of identifying proper use cases when evaluating exos over long-term use.

### 4.6. Limitations

In this study, intent-to-use was interpreted from participants' answers to the question, "I think I would like to participate in a research study using the exosuit" after they had worn the suit for 4 h. Although there is some uncertainty about whether groups should be split to include those with a neutral opinion, considering 19/33 participants with a neutral opinion on this question would consider joining the study (Table A1), supplementary analysis suggests splitting participants expressing they would agree or strongly agree to "use the device frequently as part of their job" and had little impact on study results and interpretation (Table A1&S1-2). The primary difference was that the overall accuracy of our prediction model was stronger on cross-validation (81.5%) than "I would like to join a study" (76%), and that device comfort became the second most important predictor rather than movement disruption (Fig. S1). Although these results were similar, subtle differences could be attributed to question constructs. For example, a participant's intent to join the study may have been outweighed by their concern about how the device could disrupt their workflow, as noted in other studies (Kim et al., 2022). A desire to use the device frequently could be related to how the device feels on the user's body or the projected aid it provides. Further discrepancies between these models can be attributed to the fact that some participants did not join the study for reasons unrelated to the exosuit (Fig. 2). Accounting for multiple responses, 4 participants dissented, citing the research study would take up too much time (N = 3), it would be too difficult to remember study activities (N = 1), or because of returning to school mid-study (N = 1). Additional ambiguity arises with individuals with an intent-to-join the study even if they had unfavorable opinions (i.e., N = 3 disagreed with using the device frequently and still wanted to join Table A1). This disconnect could explain the low correlation between using the device frequently and willingness to join the RCT. However, lower correlation coefficients can also be explained by the use of binary categorization. Thus, correlations between five-point scales were more likely to be strong than their binary counterparts (Table A2 and S2).

Survey questions were developed to cover three anticipated themes identified in the literature. However, more constructs define human robotic interactions (Elprama et al., 2022), and the specific questions we selected were not previously validated for evaluating these constructs. We identify that questions could be interpreted differently amongst participants due to semantics and construct verbiage. It is often cited that despite use of validated psychophysical scales, other perceptual constructs can influence study specific survey questions (Bock et al., 2022; Crea et al., 2021). To improve interpretation across the literature, there would be a benefit to leverage an existing minimum set of valid human robotic questions to refine question language. Due to the anonymity of the survey, we cannot determine if those who indicated interest to participate also joined the 4-month RCT. Another limitation of this study is that the 146 participants who completed this survey had a baseline level of technology acceptance in their willingness to join our 4-h field trial. In contrast, we did not collect surveys from employees who were uninterested in trying the device. However, although not quantified, the study team noted some participants would only join the 4-h field trial after a peer completed it. This study is also limited by generalizability. Although exosuits have commonalities, perceptions likely depend on interactions among characteristics related to the device, task, user, and environment, and only one type of exosuit was used in this study. Lastly, we were unable to quantify the job demands, as they were highly variable among participants and across days. Future studies should investigate specific job demands and their influence on device intent-to-use. Despite these limitations, a strength of this study was that it followed a relatively large number of participants when compared to other field studies implemented to date, which range from 10 to 60 participants (Bethel et al., 2021; Hensel and Keil, 2019; Kim et al., 2022; Smets, 2019).

## 5. Conclusion

This study demonstrated a soft, active, back exosuit can achieve high usability (91% agreement) and is perceived as effective and compatible (69–78% agreement) when rated by 146 participants during logistics warehouse work, including those who were uninterested in continuing use after an initial 4-h field trial. In this study of logistics warehouse workers, using an optimal tree model to classify the 117 participants (80%) willing to continue onto a 4-month study, we revealed the intent-to-use an active back exosuit was primarily driven by perceived effectiveness (i.e., people perceived the device would reduce the physical burden of their job), once refined by perceived compatibility (i.e., general comfort, with minimal movement disruption and restriction). Poor job suitability due to a lack of lifting/lowering below waist height, sitting, and equipment use was identified as an underlying reason not to continue, which likely explains the reduced perception of device helpfulness in the uninterested group. Future analysis of the data from the 4-month RCT will help to understand whether the intent-to-use the device is sustainable over time and if active back exosuits can reduce LBP in industrial working populations.

## Data, code, and materials availability

All data needed to support the conclusions of this manuscript are included in the main text or Supplementary Materials. Derived data supporting the findings of this study are available from the corresponding author C.J.W on request.

## CRediT authorship contribution statement

**Adam Hess:** Conceptualization, Data curation, Methodology, Project administration, Writing – original draft, Writing – review & editing, Formal analysis, Investigation, Visualization. **Jesse V. Jacobs:** Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Sarah Sullivan:** Conceptualization, Methodology, Project administration, Writing – original draft. **Dionna O. Roberts Williams:** Conceptualization, Data curation, Methodology, Project administration, Writing – original draft. **Lou N. Awad:** Conceptualization, Funding acquisition, Writing – review & editing. **Diane Dalton:** Conceptualization, Funding acquisition, Writing – review & editing. **Conor J. Walsh:** Conceptualization, Methodology, Project administration, Resources, Supervision, Writing – review & editing. **D. Adam Quirk:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Professor, Conor J Walsh is an inventor of at least one patent application describing the exosuit components described in the paper that have been filed with the U.S. Patent Office by Harvard University. Harvard University has entered into a licensing agreement with Verve Inc., in which Dr. Walsh., has equity interest and a board position. The other authors declare they have no competing interests.


## Acknowledgment

We want to thank our funders, the National Institute of Arthritis and Musculoskeletal and Skin Diseases, for funding this project as part of the Helping to End Addiction Long-Term (HEAL) initiative (4UH3AR076731-02) and Liberty Mutual Insurance. We thank Liberty Mutual Insurance for recruitment support. We also thank Verve Motion for equipment setup and device training. Importantly, we thank the logistics workers willing to trial the back exosuit for this study.

J.V.J. is an employee of Liberty Mutual Insurance, a co-sponsor of the research. Any opinions, findings, conclusions, or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of Liberty Mutual Insurance.


## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apergo.2024.104400.

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