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Understanding contributing factors to exoskeleton use-intention in construction: a decision tree approach using results from an online survey

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ABSTRACT
Work-related musculoskeletal disorders (WMSDs) are a major health concern in the construction industry. Occupational exoskeletons (EXOs) are a promising ergonomic intervention to help reduce WMSD risk. Their adoption, however, has been low in construction. To understand the contributing factors to EXO use-intention and assist in future decision-making, we built decision trees to predict responses to each of three EXO use-intention questions (Try, Voluntary Use, and Behavioural Intention), using online survey responses. Variable selection and hyperparameter tuning were used respectively to reduce the number of potential predictors and improve prediction performance. The importance of variables in each final tree was calculated to understand which variables had a greater influence. The final trees had moderate prediction performance. The root node of each tree included EXOs becoming standard equipment, fatigue reduction, or performance increase. Important variables were found to be quite specific to different decision trees. Practical implications of the findings are discussed.
Practitioner summary: This study used decision trees to identify key factors influencing the use-intention of occupational exoskeletons (EXOs) in construction, using online survey data. Key factors identified included EXOs becoming standard equipment, fatigue reduction, and performance improvement. Final trees provide intuitive visual representations of the decision-making process for workers to use EXOs.

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Exoskeleton acceptance; implementation; decision making; ergonomic intervention; workplace injuries

1. Introduction

Construction workers perform manual tasks that are often physically demanding and continue to experience high rates of work-related musculoskeletal disorders (WMSDs; CPWR 2018; Schneider 2001; Wang et al. 2017). While there has been a decline in WMSD rates in the US construction industry over the past decade, the rate in 2020 remained ∼6% higher than the mean of 25.4 per 10,000 full-time workers for all private industries combined (BLS 2022a). With approximately 7.5 million construction workers in the U.S. (BLS 2022b), the number of workers affected by WMSDs is substantial, and these disorders impose a significant economic, personal, and social burden. For example, associated financial losses to construction workers were estimated to be $46 million in 2014 (Wang et al. 2017), and the total medical costs per WMSD claim were estimated to be $10,961, based on workers' compensation claims in Washington State from 1999 to 2013 (Marcum and Adams 2017). Therefore, controlling WMSDs continues to be an important need in the construction industry.

Occupational exoskeleton (EXO) technologies have emerged as a promising intervention in recent years (de Looze et al. 2016; Howard et al. 2020; Nussbaum et al. 2019). EXOs are quite promising, given that an EXO can assist the wearer during various physical activities by providing on-body support (e.g., external joint torques) and can reduce exposure to high physical demands. Recent systematic reviews have reported both beneficial and some potentially adverse effects of using an EXO during various job tasks, including those relevant to construction, while highlighting that these effects depend on the specific EXO

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designs used and task conditions (Bär et al. 2021; Kermavnar et al. 2021; Theurel and Desbrosses 2019). Despite the promise of EXO technologies as an intervention in construction, actual adoption of EXOs in the workplace has been limited (Crea et al. 2021). In particular, there is little evidence of widespread acceptance or use of this technology at construction sites beyond initial pilot testing (Davila Delgado et al. 2019).

To accelerate the adoption of EXOs in the workplace, there is value in understanding the factors that promote or impair user acceptance of this technology (or, EXO use-intention). Recently, Elprama, Vanderborght, and Jacobs (2022) proposed a theoretical framework for user acceptance based on results from previous empirical studies (e.g., Elprama et al. 2020; Fox et al. 2019; Moyon, Poirson, and Petiot 2019) and existing technology acceptance models such as the Technology Acceptance Model (TAM; Davis 1985) and the Unified Theory of Acceptance and Use of Technology (UTAUT; Venkatesh et al. 2003). Their framework includes five broad themes that contribute to EXO use-intention – physiological, psychosocial, policy, work, and implementation factors - and that support a comprehensive understanding of an individual's EXO use-intention. Several studies have examined EXO use-intention in manufacturing or retail store environments, either without or with hands-on experience of an EXO during actual or simulated job tasks (e.g., Hensel and Keil 2019; Kim, Nussbaum, and Smets 2022; Schwerha et al. 2022; Siedl and Mara 2021). In these studies, the major determinants of EXO use-intention included comfort, perceived job performance, and/or task-technology fit.

Construction workers, however, perform their tasks at a fast pace, often in a constantly changing and/or complex work environment (Forde and Buchholz 2004; Kramer et al. 2009; van der Molen et al. 2005), with task variability that differs from the typical repetitive tasks in manufacturing and retail environments. A recent review by Antwi-Afari et al. (2023) identified a lack of knowledge regarding the acceptance of EXOs by construction workers as a current research gap in facilitating their use of EXOs. Earlier work has discussed the application potential of EXOs in construction as an alternative ergonomic intervention (Kim et al. 2019; Okpala et al. 2022; Zhu, Dutta, and Dai 2021), yet there is a lack of studies that have examined user acceptance aspects of EXO technologies in this sector. Andrade and Nathan-Roberts (2022) suggested, in their scoping review, that discomfort is a key barrier to EXO acceptance in construction and other industrial sectors. Kim et al. (2019) and Okpala et al. (2022) engaged manager or higher-level construction stakeholders in their respective interview ($n = 26$) and survey ($n = 51$) studies, and these individuals reported both positive attitudes and concerns related to potential EXO use in construction (e.g., usability and safety). To gain an understanding of EXO use in the construction industry, Mahmud et al. (2022) obtained opinions from 18 experts in academia, industry, and government regarding the facilitators of and barriers to EXO adoption in construction. They offered potential solutions (e.g., education, establish best practices) to mitigate the barriers perceived by the experts. Building on these findings, though, further effort is needed to refine our understanding of what contributes to EXO use-intention in construction. Such an understanding may help to facilitate decision-making to improve EXO implementation in the construction (or other) workplace.

We sought to identify factors that contribute to EXO use-intention in construction using a data-driven approach; we did so by developing predictive models from the results of an earlier online survey. These predictive models were used to provide insights that could be generalised to a broader population, beyond the specific survey respondents. That survey was completed to understand potential benefits, barriers, and facilitators to the adoption of exoskeleton technologies in construction (Gutierrez et al. 2024), and it included three questions linked to EXO use-intention, each of which was of interest here. Our approach was based on decision trees. A decision tree is a statistical data mining technique, offering an intuitive, easily explainable outcome (i.e., a visual representation of classification paths or a tree) to the user (Apté and Weiss 1997). Recently, two studies used decision trees to identify key determinants of EXO use-intention in manufacturing environments, based on task characteristics and usability responses (Kim, Nussbaum, and Smets 2022; Schwerha et al. 2022). Previously we completed an initial exploratory decision tree analysis on a subset of the noted survey data (Moore et al. 2021), which suggested that perceived productivity and fatigue reduction were related to reported willingness to try an EXO. Hence, we adopted this technique here with a focus on predicting EXO use-intention, with the expectation that the final decision trees would enable a detailed understanding of the factors that positively (or negatively) influence a construction worker's EXO use-intention, and could serve as a tool for informed decision-making for future EXO implementation.

2. Methods

2.1. Overview of online survey

We used data from a self-administered online survey to assess EXO use-intention. Survey responses ($n = 361$) were obtained between July 31, 2020, and January 9, 2021. The study protocol was approved by the Institutional Review Boards of Virginia Tech and the University of California, San Francisco. A detailed description of the survey, including questions, procedures, and descriptive findings, can be found elsewhere (Gutierrez et al. 2024). In brief, the survey included 65 open- and closed-end questions regarding EXO knowledge; work history; demographic information; job task characteristics; and perceived benefits, health and safety concerns, and facilitators for adoption and use of EXOs in construction. Individuals were eligible to participate if they had current or prior experience working in construction, supervising construction workers, or managing a construction company. The survey was delivered using an online survey platform (Qualtrics, http://berkeley.qualtrics.com). Prior to answering any survey questions, participants gave informed consent and were made aware that they could withdraw their consent and/or participation at any time; if they consent, they then needed to watch a 3-min. EXO introductory video.

2.2. Potential predictors of EXO use-intention

Among the survey questions, we selected 47 questions as a broad set of potential predictors of EXO-use-intention (see Appendix A), by excluding questions that were open-ended or specific to individual trades (e.g., perceived risks related to roofing). The selected questions were then categorised into seven groups: 1) demographics; 2) job demands; 3) musculoskeletal pain; 4) EXO knowledge/experience; 5) perceived social implications of EXO use; 6) opinions about EXO use; and 7) perceived potential risks.

2.3. EXO use-intention questions

We considered responses to the following three questions as indicative of self-reflected use intention: *If given the option, would you want to try an exoskeleton?* (Try); *If my employer provided an exoskeleton, I would use it voluntarily* (Voluntary Use); and *I would wear an exoskeleton for an entire workday* (Behavioural Intention). The first question had response options of *yes, maybe,* or *no*; as such, this question may reflect a more exploratory intention to use the EXO technology than the latter two questions. The latter two questions were responded to using a 5-point scale (1 = *strongly agree*, 2 = *agree*, 3 = *neither agree nor disagree*, 4 = *disagree*, 5 = *strongly disagree*). Only ~2% and ~4% of responses (excluding missing responses) were *strongly disagree* for the 'Voluntary Use' and 'Behavioral Intention' questions, respectively. Thus, we re-coded this response as *disagree*.

The 'Try', 'Voluntary Use', and 'Behavioral Intention' questions were answered respectively by 227, 226, and 224 respondents. Respondents who completed <70% of the 47 predictor questions tended to not answer most questions. Therefore, we excluded their data from subsequent analyses, resulting in 160 data points for the 'Try' question, and 159 each for the 'Voluntary Use' and 'Behavioral Intention' questions.

2.4. Missing data imputation and variable selection

'Try', 'Voluntary Use', and 'Behavioral Intention' datasets each had about 5.3% missing data. To address these, we used multivariate imputation using chained equations (MICE) – a widely used technique that generates multiple imputations and pools them into one imputed dataset. This approach can produce unbiased estimates when data are missing at random or missing completely at random (White, Royston, and Wood 2011); given lack of evidence otherwise, we assumed one of these situations applied. We used the *mice* package (van Buuren and Groothuis-Oudshoorn 2011) in R statistical software (R Core Team 2022) to generate separate complete datasets for the 'Try', 'Voluntary Use', and 'Behavioral Intention' questions.

Given the relatively large number of predictors ($n = 47$), a variable selection technique was used to identify a subset of predictors to increase efficiency in obtaining EXO use-intention prediction models. Specifically, we used the *Boruta* algorithm (Kursa and Rudnicki 2010), which is a feature selection method built on the random forest classification algorithm and is designed to iteratively remove features that are less important than random probes. We used the *Boruta* package in R (Kursa and Rudnicki 2010) to identify important variables related to the target variable for each dataset (i.e., responses to 'Try', 'Voluntary Use', or 'Behavioral Intention' questions). The variables identified are listed in Table 1.

2.5. Decision trees

Separate decision tree models were developed to predict a response to each of the three EXO use-intention questions, using recursive partitioning and regression trees

Table 1. Summary of potential predictors for EXO use-intention.

Category	Try	Voluntary Use	Behavioural Intention
Demographics	Age Company size	Age Years of experience	Age Gender
Job demands	How tired for a typical week How tired for a typical day		How tired for a typical day How many workdays per week
Musculoskeletal pain	How much shoulder pain for a typical month How much back pain for a typical month	How much shoulder pain for a typical month How much back pain for a typical month	How much shoulder pain for a typical month How much back pain for a typical month
EXO knowledge / experience	Aware of EXO in construction		
Perceived social implication of EXO use	See: Envious See: Cool	See: Envious See: Cool See: Curious	See: Envious See: Cool
Opinions about EXO use	Agree: Reduce fatigue Agree: Make work easier Agree: Increase productivity Agree: Share with co-workers Standard equipment Useful	Agree: Reduce fatigue Agree: Make work easier Agree: Increase productivity Agree: Share with co-workers Agree: Concern about cleaning Standard equipment Useful	Agree: Reduce fatigue Agree: Make work easier Agree: Share with co-workers Agree: Increase productivity Standard equipment Useful
Perceived potential risks	Concern: Ladder Concern: Noise Concern: Struck	Concern: Ladder Concern: Machine (in and out of it) Concern: Slip Concern: Scaffold Tipping	Concern: Ladder Concern: Confined space

(RPART). Specifically, we used the *rpart* package in R (Therneau, Atkinson, and Ripley 2015), which supports changing several model hyperparameters. These included: 1) the maximum depth of any node of the final tree (*max_depth*), which is the maximum number of levels or nodes in the tree from the root node to the leaf node; 2) the minimum number of data in a node (*min_n*), which is the minimum number of data points in a node to further split the node into child nodes; and 3) the minimum improvement of the tree required when splitting/branching a node (i.e., complexity parameter or *cp*), which is used in a pruning process to simplify the tree by removing nodes that do not contribute significantly to the accuracy of the tree. To optimally select/tune these three hyperparameters, and to estimate the final tree performance, we used 10 replications of a 5-fold cross validation (CV) with an independent test set, following the procedure described by Raschka (2018):

- split dataset randomly into training and validation sets, using a 5-fold CV with an 80:20 ratio
- for each hyperparameter set, apply the 5-fold CV on the training set
- fit the decision tree on the complete training set using the hyperparameters that produce the best results in the 5-fold CV procedure
- evaluate the tree model using the validation set
- repeat the steps above nine more times
- fit the final decision tree on the complete data set with the best hyperparameters

The replication of a 5-fold CV was implemented with each of the three datasets ('Try', 'Voluntary Use', and 'Behavioral Intention') using the *tidymodels* package in R (Kuhn and Wickham 2020). Combinations of hyperparameters were generated using the space-filling parameters grid function in this package (*grid_max_entropy*), with *max_depth*, *min_n*, and *cp* set to respective ranges of 2 - 10, 5 - 25, and 0.0001 – 0.9. For model evaluation, we generated four common performance metrics (Alaa 2020; Grandini, Bagli, and Visani 2020):

- Balanced accuracy (range = 0 – 1): the arithmetic mean of sensitivity (i.e., true positive rate) and specificity (i.e., true negative rate)
- Cohen's Kappa (range = -1 – 1: a statistical measure of inter-rater agreement for categorical items
- F1-score (range = 0 – 1): the arithmetic mean of recall and precision
- Area under the receiver operator curve (AUC-ROC; range = 0 – 1): the area under the ROC curve that is a plot of sensitivity against specificity for all threshold values that are used to distinguish positive from negative classification results

To interpret balanced accuracy, F1-score, and AUC-ROC, we concluded that decision tree prediction performance was high when a value was >0.9, moderate when a value was 0.7–0.9, low when a value was 0.5–0.69, based on the arbitrary interpretation used by Swets (1988). For Cohen's Kappa, we considered that performance was high when a value was >0.8, moderate when a value was 0.61–0.8, and fair when a value was 0.41–0.6 (Grandini, Bagli, and Visani 2020).

Finally, the importance of a variable in the final decision trees was computed using the *vip* package in

R (Greenwell and Boehmke 2020). This approach is used to quantify which variables had large influences on the predicted outcome, by assessing the direction and magnitude of changes in the predicted outcome with respect to changes in the values of a variable. Such results can help understand which variables are more important in a given decision tree.

3. Results

3.1. Prediction performance of decision trees

Table 2 summarises the prediction performance of the decision tree for each EXO use-intention question, as estimated using the repeated 5-fold CV. Performance was rather comparable across the three use-intention questions, and the results for each question are presented in more detail subsequently.

3.2. Try—'if given the option, would you want to try an exoskeleton?'

A tree was generated from the complete Try dataset, with $max\_depth = 5$, $min\_n = 7$, and $cp = 0.00289$. The final tree had 'Standard equipment' as the root node, along with 12 leaf or terminal nodes (Figure 1). Five leaf nodes were associated mainly with a 'Yes' response (i.e., *Yes* leaf nodes), two were *No* leaf nodes, and four were *Maybe* leaf nodes. One leaf node had mixed responses of 'Yes' and 'Maybe'. The nine most important variables are shown in Figure 2; these variables were in the categories of opinions on EXO use, demographics, job demands, and perceived potential risks.

A large portion (75%) of the respondents fell into the *Maybe* leaf nodes that were associated mainly with a *Maybe* response. In particular, one *Maybe* leaf node accounted for ∼53% of respondents, and those individuals responded that EXOs will become standard equipment over time. Four *Yes* leaf nodes showed that respondents indicated being likely to try an EXO if they thought that EXOs could reduce fatigue, or if they experienced a less than moderate level (4 – 4.5)

Table 2. Summary [mean (SD)] of decision tree performance metrics for three EXO use-intention questions.

Question	Balanced Accuracy	Kappa	F-1	AUC ROC
Try	0.73 (0.03)	0.48 (0.08)	0.63 (0.06)	0.75 (0.10)
Voluntary Use	0.71 (0.05)	0.48 (0.07)	0.59 (0.08)	0.74 (0.06)
Behavioural Intention	0.73 (0.03)	0.44 (0.04)	0.59 (0.04)	0.78 (0.03)

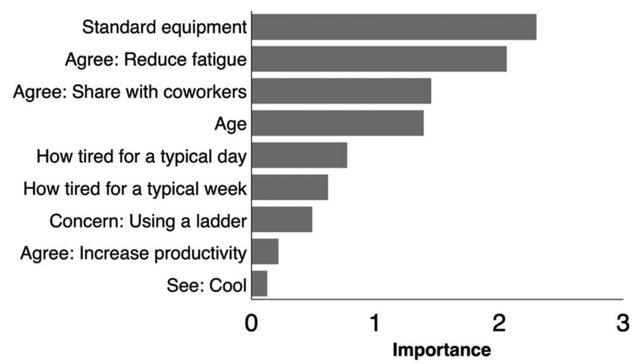

Figure 2. Nine important variables in the *Try* decision tree. Note that importance values were zero beyond the ninth variable.

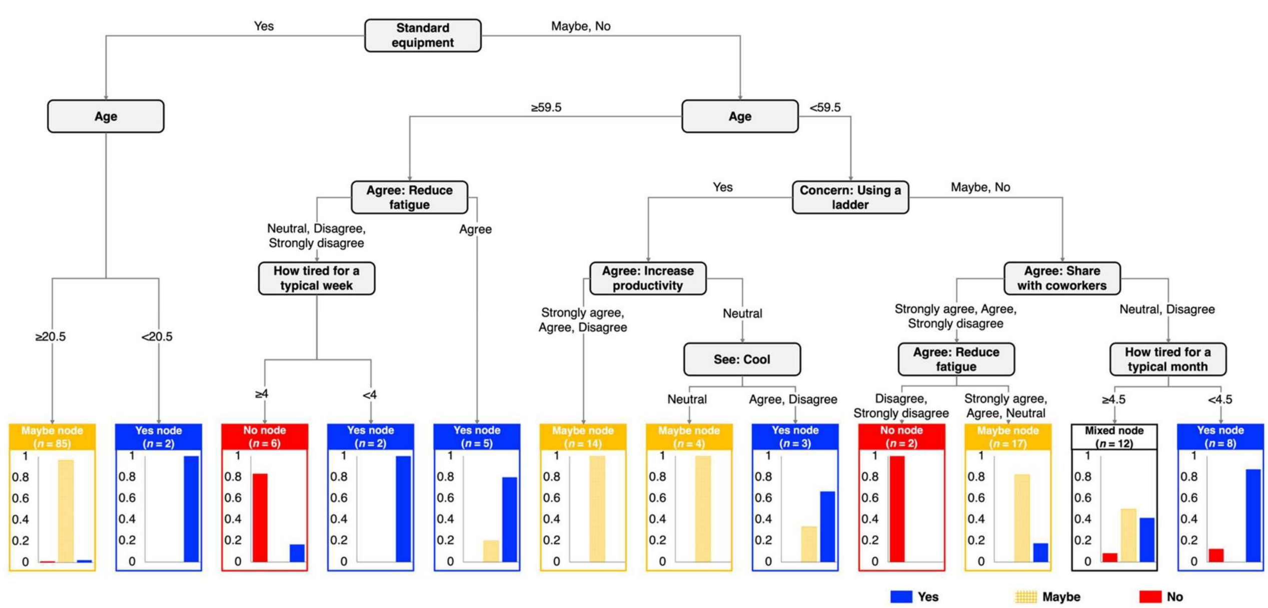

Figure 1. Decision tree to identify responses to the Try question *If given the option, would you want to try an exoskeleton?* with three response options (No, Maybe, or Yes).

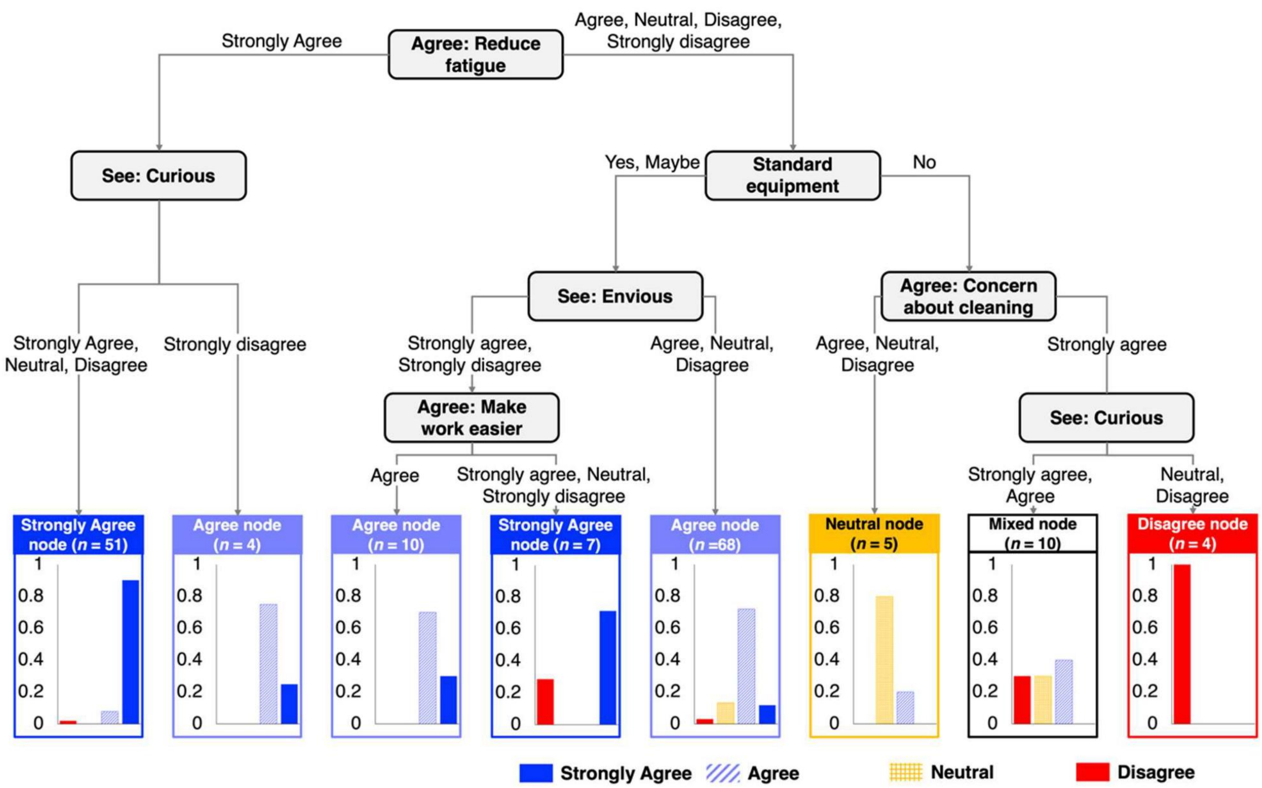

Figure 3. Decision tree to identify a response to the Voluntary Use question *If my employer provided an exoskeleton, I would use it voluntarily?* with four response options (Strongly Agree, Agree, Neutral, Disagree).

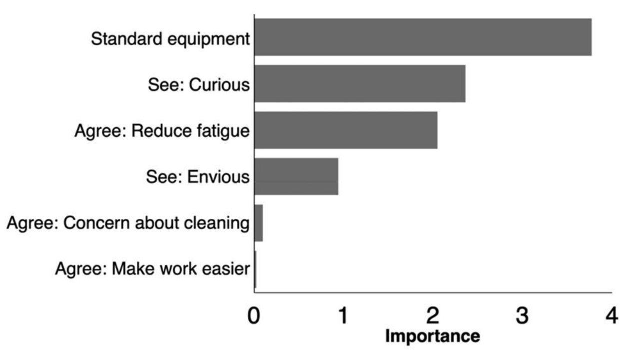

Figure 4. Six important variables in the *Voluntary Use* decision tree. Note that importance values were zero beyond the sixth variable.

of physical tiredness (see 'How tired for a typical week' and 'How tired for a typical day' nodes). The 'How tired for a typical week' node shows that the respondents who were older than 59.5 years still indicated a desire to try an EXO when their tiredness level for a week was <4, even when they did not agree about the effectiveness of EXOs.

3.3. Voluntary Use—'if my employer provided an exoskeleton, I would use it voluntarily'

A tree was generated from the complete 'Voluntary Use' dataset, with $max\_depth = 5$, $min\_n = 11$, and $cp = 0.00758$. The final tree had 'Agree: Reduce fatigue' as the root node and eight leaf nodes (Figure 3). There were two *Strongly agree* and three *Agree* leaf nodes. The remaining three leaf nodes were associated with a mixed response (i.e., 'Agree', 'Neutral', or 'Disagree') or a 'neutral' response. The six most important variables are shown in Figure 4, which reflected opinions on EXO use and social implications.

Most (~88%) of the respondents fell into either the *Strongly Agree* or *Agree* leaf nodes. Specifically, those who indicated they strongly agreed that EXO use reduces fatigue, or that EXOs will become a standard equipment, were in the *Strongly Agree* or *Agree* leaf nodes, as shown in Figure 3. Even when respondents did not indicate strongly agreeing with the potential for fatigue reduction with EXO use, they were still associated with *Strongly Agree* or *Agree* leaf nodes, as long as they responded that EXOs were likely to become standard equipment. Otherwise, the respondents belonged to either mixed, *Maybe*, or *No* leaf nodes.

3.4. Behavioural Intention—'I would wear an exoskeleton for an entire workday'

A tree was generated from the complete 'Behavior Intention' dataset, with $max\_depth = 9$, $min\_n = 17$,

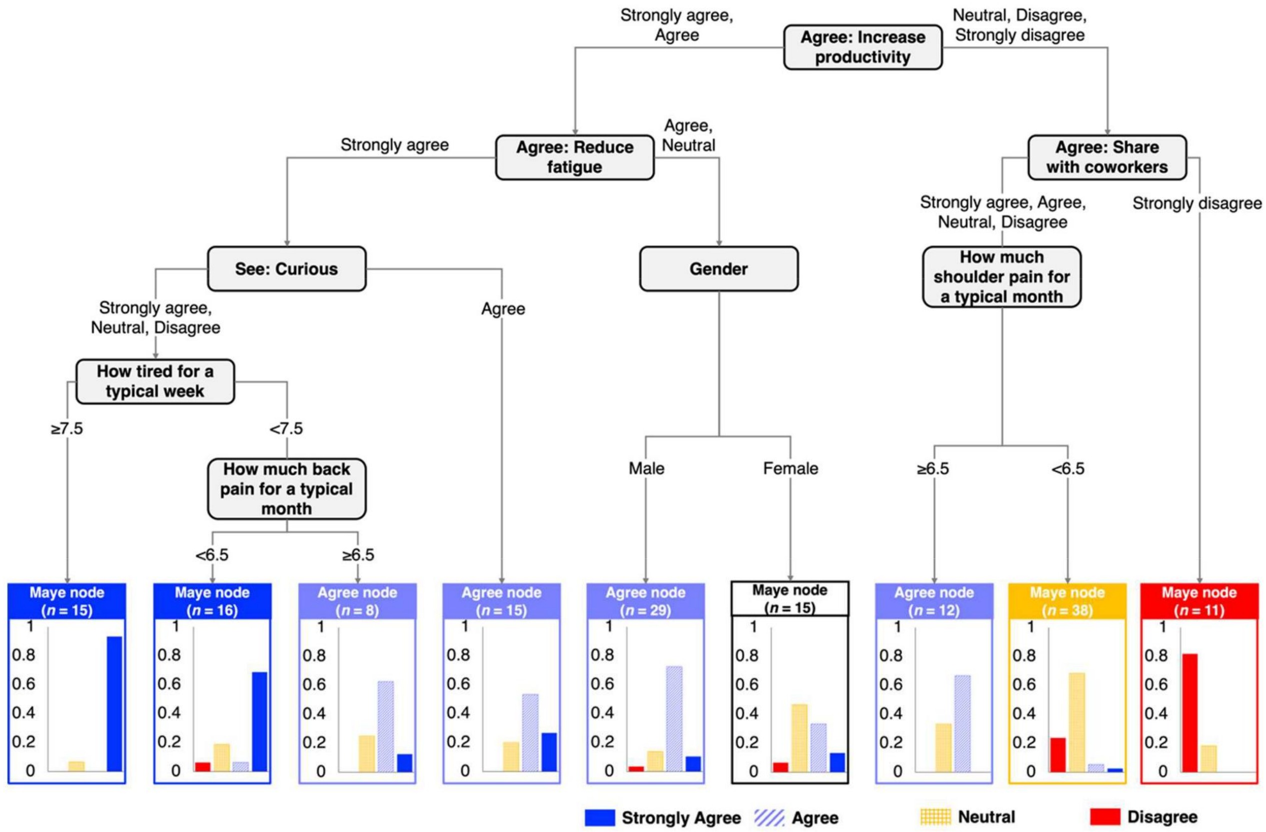

Figure 5. Decision tree to identify a response to the Behavioral Intention question *I would wear an exoskeleton for an entire workday* with four response options (Strongly Agree, Agree, Neutral).

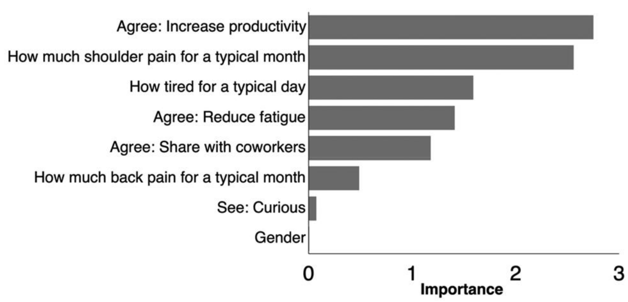

Figure 6. Eight important variables in the *Behavioral* Intention decision tree. Note that importance values were zero after the seventh variable.

and $cp = 0.0154$. The final tree had 'Agree: Increase productivity' as the root node and had nine leaf nodes (Figure 5). Two leaf nodes were associated with a 'Strongly Agree' response and four with an 'Agree' response. The remaining three leaf nodes can be considered as mixed responses of 'Neutral' or 'Disagree'. The eight most important variables are shown in Figure 6, and these variables were generally related to opinions on EXO use, demographics, social implications, musculoskeletal pain, and job demands.

Strongly Agree and *Agree* leaf nodes accounted for about 60% of the respondents. When respondents reported that EXO use could increase their productivity, they were likely to fall to *Strongly Agree* or *Agree* leaf nodes, with one exception. This exception was that female respondents were associated with a *Neutral* leaf node if they provided agree or neutral responses regarding expected fatigue reduction with EXO use. About 38% of respondents did not agree that EXO use could increase productivity, resulting in either *Neutral* or *Disagree* leaf nodes. However, respondents belonged to an *Agree* leaf node if they reported more than a moderately-strong level (≥ 6.5) of shoulder pain for a typical month ('Shoulder pain for a month' node). The 'How much back pain for a typical month' node shows that respondents reporting a < 6.5 level of back pain tended to indicate a more 'Agree' response (vs. 'Strongly Agree') than those reporting a level ≥ 6.5.

4. Discussion

To help identify the primary drivers of EXO use-intention in construction, we used separate decision trees to predict responses to three questions indicative of self-reflected EXO-intention to use (namely, the 'Try', 'Voluntary Use', and 'Behavioral Intention' questions). These decision trees yielded moderate prediction performance overall (Table 2). Our major finding was that EXO use-intention appears to be most influenced by opinions on EXO use or the perceived social implications of EXO use (see Figures 2, 4, and 6) – specifically, respective responses to *Do you think an exoskeleton could become standard equipment over time?* or *I think wearing an exoskeleton could make me more productive*. Furthermore, important (or influential) variables were found to be quite distinct between the different decision trees for EXO use-intention. We discuss these findings in more detail below.

4.1. Key influential variables in EXO-intention to use decision trees

Opinions about trying or voluntarily using an EXO were influenced substantially by two common variables – the degree of agreement that EXOs will become standard equipment over time ('Standard equipment') and that EXO use can reduce fatigue ('Agree: Reduce fatigue') (see Figures 2 and 4). We may interpret standard equipment as being readily available and widely used at a construction site. Given this interpretation, it is perhaps not surprising that respondents were more likely to indicate that they would try/use an EXO when agreeing with the potential for it becoming standard equipment. It is unclear, though, whether respondents perceived EXOs as becoming part of their standard *work tools* or as *personal protective equipment* to reduce adverse effects. The latter perspective may have been the case, given that the 'Agree: Reduce fatigue' variable was identified as among the important variables. Additionally, earlier authors defined EXOs as an ergonomic intervention in their studies, and found that perceived effectiveness of EXO use (e.g., a reduction in effort and/or fatigue) is an important variable for EXO-use intention (Crea et al. 2021; Ferreira et al. 2020; Hensel and Keil 2019). In retrospect, we should have clarified the meaning of 'standard equipment' to construction workers, and doing so is recommended for future efforts.

When EXOs were not expected to be standard equipment, the opinion about EXO sharing ('Agree: Share with coworkers') was found to be important in the Try decision tree (Figures 1 and 2). Responding 'Neutral' or 'Disagree' to this variable led respondents to be in either mixed or *Yes* leaf nodes. Otherwise, the respondents were led to be in *Maybe* or *No* leaf nodes. However, it is not clear to us how the level of agreement regarding EXO sharing affected a decision to voluntarily use an EXO. Respondents may have had diverging ideas about whether an EXO should be sharable, yet still converged to the same decision about voluntary use. Interestingly, both 'Strongly Agree' and 'Strongly Disagree' responses were associated with *Maybe* or *No* leaf nodes. Those with the former response may have had other concerns (e.g., hygiene), but were still comfortable with the idea of sharing an EXO. Schwerha et al. (2021) noted that hygiene concerns were raised in nearly every manufacturing company in their field testing, especially when EXOs were expected to be shared among workers. On the other hand, those with the latter response here likely viewed EXOs as a personal device and may have had concerns about wearing an additional personal device (that they did consider as standard equipment).

The Voluntary Use decision tree revealed that a potential social implication ('See: Envious') was an important factor influencing a decision to voluntarily use an EXO. Yet, regardless of how strongly respondents agreed (or disagreed) with the statement *Why don't I have one?*, they had expressed agreement with EXO voluntary use (i.e., *Strongly Agree* or *Agree* leaf nodes). When respondents provided extreme responses (i.e., 'Strongly Agree' or 'Strongly Disagree'), perceptions about seeing co-workers use an EXO appeared to contribute to a stronger positive agreement, depending on their response to the 'Agree: Make work easier' node (Figure 3). Earlier studies have suggested that peer perception or pressure can affect the decision to use an EXO (e.g., Baltrusch et al. 2020; Cha et al. 2019; Elprama et al. 2020; Kim et al. 2019). Overall, we suggest that social influences on EXO-intention to use is bidirectional between the wearer/user and their co-workers.

In the Behavioural Intention decision tree, a response to the statement *I would wear an exoskeleton for an entire workday* was influenced strongly by two variables: 'Agree: Increase productivity' and 'How much shoulder pain for a typical month' (Figure 6). That productivity plays an important role in EXO-intention to use is consistent with earlier studies. For example, a long-term field study on the use of an arm-support EXO in automotive assembly found that self-perceived job performance and comfort were key contributors to EXO use-intention (Kim, Nussbaum, and Smets 2022). The importance of these two contributors was also supported in the study of Schwerha et al. (2022); they examined the use of different EXOs in various manufacturing environments by providing participants with hands-on EXO experience for a short duration. Furthermore, Elprama et al. (2020) showed that performance expectancy (i.e., how useful exoskeletons seem to be for work) is a predictor of EXO use-intention, using the UTAUT framework. Interestingly, respondents in the current study provided more 'Agree' than 'Neutral' responses when they also reported having moderate or higher levels of shoulder pain (Figure 5), despite not agreeing that EXO use can increase their productivity. A contrast can be observed in the 'Back pain for a month' node, where, depending on their response at this node, respondents led to be in either a *Strongly agree* or an *Agree* leaf node. When respondents reported having moderate or higher levels of back pain, their responses became less positive, albeit still at the level of 'Agree'. In general, these results on back and shoulder pain parallel the finding of Baltrusch et al. (2020), who found that workers with back pain were open to the use of a back-support EXO.

4.2. Practical implications

Our results may help guide future EXO introduction and implementation strategies to improve worker buy-in for and engagement with EXO use. For example, when EXOs are first introduced to workers, information could be provided about continuing efforts to actively advance safety, EXO design and evaluation, and usability standards for occupational EXOs via standards developing organisations such as the International Organisation for Standardisation (ISO) and ASTM International (Bostelman and Hong 2018; Lowe et al. 2019). Worker opinions on expected benefits, specifically fatigue reduction and work performance gains, were key influential variables in all the decision trees developed here. This finding emphasises the need for effective and efficient selection of EXOs that best suit individual construction workers and work tasks, especially given that the effectiveness and subjective experiences of using an EXO are specific to EXO designs and task characteristics (e.g., Kermavnar et al. 2021; Ojelade et al. 2023; Theurel and Desbrosses 2019), as well as individual characteristics such as gender (Madinei et al. 2020). Improved EXO selection could ensure that construction workers (as EXO users) experience the benefits of EXOs while minimising potential adverse effects (resulting from poor EXO selection or task/EXO mismatch). However, there is as yet no simple method to select an 'optimal' EXO, so involving workers with comprehensive knowledge of their needs and workplaces should be considered prior to EXO introduction (Siedl and Mara 2022). Additionally, as suggested by Elprama et al. (2020), EXO training or demonstration may be valuable to help users improve their understanding of EXO functionality and application and, perhaps, to maximise EXO benefits.

Some consideration should be given as well to the management of potential social influences from EXO implementation, since both seeing a co-worker wearing an EXO or being seen wearing an EXO may affect EXO-intention to use. Siedl and Mara (2022) also noted a need for sufficient measures to manage negative group dynamics with EXO implementation in food retail and corporate logistics organisations. One such measure could be selecting an EXO design that will be socially accepted at work (Baltrusch et al. 2020) and accepted by workers, since they can perceive the same device as being 'cool' or 'funny' (Cha et al. 2019). In addition to social influences, caution should be used when involving workers who suffer from existing musculoskeletal pain, since they may be more inclined to use an EXO for an entire workday. There are some reports that using a back-support EXO can have positive short-term effects on task performance and low-back discomfort for those who had low to moderate levels of self-reported back pain (Baltrusch et al. 2020; Kozinc et al. 2021). However, there is a lack of evidence on the long-term effects of EXO use on individuals with musculoskeletal pain. When implementing EXOs, safety and medical personnel in an organisation may thus need to clearly communicate with potential EXO users about the scope and limitations of the current evidence of EXO use, and to adopt a conservative decision-making approach especially for those with existing or previous musculoskeletal pain/injury.

5. Study limitations

Several limitations in this work should be acknowledged. First, the study sample was limited to those who were fluent in English (since the online survey was provided in English only), and a majority of survey respondents were male. Caution is thus required in generalising the current results to construction workers who are racial minorities or do not speak English, or to females. Second, the survey did not include specific questions regarding opinions or thoughts that can be formed only by or after using an EXO in practice. Specifically, several variables that might contribute to EXO use-intention were not considered in the decision trees, including EXO fit and comfort, and potential issues related to maintenance, repair, and logistics (e.g., storage and cleaning). Notably, fit and comfort have been considered key variables in field-based studies of EXO use (e.g., Hensel and Keil

2019; Kim, Nussbaum, and Smets 2022; Schwerha et al. 2022). A recent study suggested that hands-on EXO experience can lessen perceived concerns about safety and negative effects of EXO use (Narasimhan Raghuraman et al. 2022). If so, our survey respondents may have been more critical of EXO use than if they had had such experience. In addition, questions about resistance to innovation (e.g., change in work routines and culture with EXO use) could have been incorporated to supplement the questions associated with the technology acceptance framework (Nnaji et al. 2023). Third, responding to our online survey was voluntary, leading to possible sampling bias. Those who volunteered may have already had some interest in EXO technologies and, if so, might have responded somewhat more positively than a random sample. Fourth, the prediction performance of the decision trees was moderate. Given this, and that the key variables identified in the decision trees were consistent with extent literature, it might be more advisable to use the decision trees to guide EXO introduction and implementation strategies, rather than to predict specific responses of a potential user. Fifth, continued use of an EXO was not examined, although successful technology implementation depends on continued use (i.e., post adoption). As suggested by Nnaji et al. (2023), future efforts are needed to assess the post-adoption behaviour of workers during EXO use, to better facilitate effective implementation of this technology in the construction industry. Such efforts, and inclusion of the potentially important variables noted above, will likely help develop decision trees with enhanced prediction performance.

6. Conclusions

We developed decision trees to predict responses to three EXO-intention to use questions (i.e., 'Try', 'Voluntary Use', and 'Behavioral Intention' questions). Important (influential) variables were identified as associated with these responses. These variables were related to perceptions regarding: (1) EXOs becoming standard equipment over time; (2) anticipated fatigue reduction with EXO use; (3) social reactions to seeing co-workers wearing an EXO; (4) performance increases with EXO use; and (5) level of musculoskeletal pain experienced in a typical month. Fatigue reduction with EXO use was the only variable common across all three decision trees, while other influential variables were often specific to different decision trees (i.e., specific question about EXO use-intention). Findings from this study provide a basis for future research to help guide the effective introduction and implementation of EXOs in construction worksites, and subsequently to improve the decision trees (e.g., for better prediction performance and to predict long-term use intention).

Disclosure statement

No potential conflict of interest was reported by the authors.

Ethics statement

The study procedures were approved by the Institutional Review Boards (IRBs) of Virginia Tech (IRB #20-075) and the University of California, San Francisco (IRB #18-25003), and conducted in compliance with the ethical principles for research involving human subjects expressed in the Declaration of Helsinki.

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Appendix A

Table A.1. Summary of potential predictors of EXO-use-intention.

Category	Variable
Demographics	Age
	Gender
	Job experience
	Years of experience
	Company size
Job demands	How physically challenging
	How tired for a typical week
	How tired for a typical day
	Work Hours (day)
	Work days (per week)
Musculoskeletal pain	How much shoulder pain for a typical week
	How much shoulder pain for a typical month
	How much back pain for a typical week
	How much back pain for a typical month
EXO knowledge/experience	EXO knowledge
	Aware of EXO in construction
	Tried EXOs previously
Perceived social implication of EXO use	See: What is that? (Curious)
	See: They are injured (Injured)
	See: How cool! (Cool)
	See: they're old (Old)
	See: They are physically weak (Weak)
	See: Why don't I have one? (Envious)
Opinions about EXO use	Agree: Reduce fatigue
	Agree: Increase productivity
	Agree: Share with co-workers
	Agree: Make work easier
	Agree: Concern about adjusting
	Agree: Concern about cleaning
	Agree: Concern about storing
	(EXO being) Standard equipment
	Useful
Perceived potential risks	Concern: Fall
	Concern: Slip
	Concern: Trench
	Concern: Scaffold tipping
	Concern: Scaffold collapse
	Concern: (electric) Shock
	Concern: Noise
	Concern: Dust
	Concern: Vibration
	Concern: Temperature
	Concern: Muscle fatigue
	Concern: Struck by or caught in
	Concern: Ladder
	Concern: Confined
	Concern: Machine (in and out of it)