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Usability, user acceptance, and health outcomes of arm-support exoskeleton use in automotive assembly: an 18-month field study

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Running Head Title:
Long-term exoskeleton usability and health outcome

Usability, user acceptance, and health outcomes of arm-support exoskeleton use in automotive assembly: an 18-month exploratory field study

Abstract

Objective: Examine arm-support exoskeleton (ASE) user experience over time, identify factors contributing to ASE intention-to-use, and explore whether ASE use may influence the number of medical visits.

Methods: An 18-month, longitudinal study with ASE (n=65) and control groups (n=133) completed at nine automotive manufacturing facilities.

Results: Responses to six usability questions were rather consistent over time. ASE use perceived effective in reducing physical demands on the shoulders, neck, and back. Perceived job performance, and overall fit and comfort, appeared to be key determinants for ASE intention-to-use. Based on medical visits among both groups, ASE use may decrease the likelihood of such visits.

Conclusions: These field results support the potential of ASEs as a beneficial ergonomic intervention, but also highlight needs for further research on ASE designs, factors driving intention-to-use, and health outcomes.

Keywords: Ergonomic intervention, wearable robot, prospective study, overhead work

1. Introduction

Upper extremity, work-related musculoskeletal disorders (UE-WMSDs) remain an important occupational health problem. In the United States, ~7.6% of lost workday cases were due to work-related shoulder problems in 2019, leading to a median of 22 lost workdays (*cf.* a median of 7 lost workdays for back problems[1]. The shoulder is among the body regions involving the highest cost per U.S. worker's compensation claims across industries [2] and in automotive manufacturing in particular [3]. Epidemiological literature indicates that the development of UE-WMSDs is associated positively with occupational physical exposures such as repetitive tasks, non-neutral postures, forceful exertions, and overhead work [e.g., 4–6]. While diverse interventions have been used to control such exposures, it can be a major challenge to reduce or prevent UE-WMSDs for some work tasks, such as assembly or maintenance tasks requiring prolonged/repetitive arm elevation. The recent emergence of exoskeleton (EXO) technologies offers a new intervention approach.

EXOs are defined as "a wearable device that augments, enables, assists, or enhances motion, posture, or physical activity" by the ASTM International Technical Committee on Exoskeletons and Exosuits (ASTM F48; [7]. One common occupational application is arm-support exoskeletons (ASEs), designed to reduce physical demands on the shoulder. Recent reviews emphasize that the efficacy of ASEs is well supported by several cross-sectional, lab-based studies [8,9]. In fact, many studies have demonstrated that using an ASE can reduce shoulder muscle activity (e.g., deltoid and trapezius muscle groups), perceived exertion, and localized muscle fatigue [e.g., 10–14]. Both noted reviews, though, also highlighted a lack of strong evidence for the effectiveness and suitability of ASEs based on long-term, field-based studies.

Though still much scarcer that lab-based studies, an increasing number of studies have reported outcomes from using ASEs in field settings [15–21]. These studies generally have supported findings from lab-based studies, showing that using an ASE can reduce physical demands on the shoulder (e.g., reduced muscle activity in the shoulder region, perceived discomfort/exertion). Interestingly, though, De Bock et al. [19] compared the impacts of using an ASE between laboratory and actual work environments, finding that the magnitude of beneficial effects of ASE use was smaller in the latter. We also observed relatively small, positive impacts of using an ASE on neck and shoulder discomfort during an 18-month field test in an automotive assembly environment [21], which contrasts with more substantial benefits obtained in earlier lab studies that examined the same or other ASEs [10,22].

Earlier field studies also revealed usability and safety concerns that were often not fully identified or understood from lab-based studies. Such concerns include difficulty in perceiving loads immediately after doffing the EXO [16] and the importance of thermal comfort [15]. Further, Amandels et al. [23] examined a back-support exoskeleton (BSE) in a manufacturing shop floor, and suggested that discomfort from wearing the BSE outweighs beneficial effects. They attributed this to the fact that workers perform diverse tasks (i.e., not just lifting), and that an actual work environment can be more challenging than a typical laboratory (e.g., heat, noise, work pressure). Hensel & Keil [24] noted that using a BSE can be a distraction during auxiliary tasks, negatively influencing perceived usability and user acceptance (i.e., intention to use). These studies suggest a challenge exists in gaining user acceptance with a BSE in the field.

Whether workers will accept an ASE, though, is a critical question in promoting use in the field, independent of how effective an ASE may be in reducing physical demands. A few field studies have indicated that the perceived usefulness and comfort of an EXO are key determinants [24–26]. However, outcomes in these studies were based on user experiences with an EXO ranging from <1 hour to a 4-week period. Importantly, none of these or related studies has yet reported whether ASE use can lead to injury reduction. Therefore, longer-term evaluations are needed to understand whether perceived usability and opinions regarding ASE use are stable over time, and to explore health outcomes with ASE use. To address these needs, we conducted a prospective, controlled field study using an ASE among workers in several automotive assembly facilities, over a period of 18 months. This prospective design allowed us to examine ASE user experience over time, identify factors contributing to ASE intention-to-use, and explore whether ASE use can contribute to positive health outcomes.

2. Methods

Data collection occurred over a course of 18 months as part of a larger study that was a partnership between academic researchers and Engineering and Ergonomics Specialists at a large North American automotive manufacturer. This study was reviewed and approved by the UAW/Ford National Joint Committee on Health and Safety and by the Institutional Review Board at Virginia Tech. A detailed description of the participants, experimental design, and procedures can be found in a companion paper [21]; thus, only an overview is provided below.

2.1. Participants

All participants were final assembly operators who worked daily on an overhead line, and who performed assembly work from below on the underbody of a vehicle. Participants were recruited from nine automotive manufacturing facilities in Northern America and participated between April 2018 and December 2019. A total of 65 and 133 participants were recruited on a voluntary basis into an ASE and a control group, respectively. Withdrawals from the study occurred, mainly from job transfers to non-overhead work or loss of interest, and involved 24 participants (36.9%) in the ASE group and 50 (37.6%). Further, two manufacturing facilities underwent major facility changes shortly after the start of the study, and data from these facilities were excluded from further analysis. Thus, in final analyses, we included a total of 41 participants in the ASE group (30 males, 3 females, and 8 not reported) and 83 in the control group (47 males, 14 females, and 22 not reported). Respective means (interquartile range: Q3-Q1) of age, body mass, and stature were 38.0 (15.0) years, 83.9 (21.5) kg, and 1.79 (0.1) m for the ASE group; and 38 (15) years, 86.2 (23.5) kg, and 1.75 (0.10) m for the control group.

2.2. Experimental design and procedures

A longitudinal, controlled research design was used to obtain *in situ* data regarding ASE use. Perceptual responses were collected via questionnaires, described below, at baseline (i.e., the day when participation began, without ASE use), and again at four milestones after baseline, specifically after 1, 6, 12, and 18 months (i.e., M1, M6, M12, and M18). Questionnaire data were obtained by local Ergonomics Specialists at the four milestones. If participants were not available on the day of data collection, follow-up collection was attempted. The ASE used by each participant was the EksoVest™ (Ekso Bionics, Inc., Richmond, CA; unit mass = 4.3 kg;

Figure 1). This ASE included a U-shape neck pillow and back pads, and it could be adjusted in terms of trunk length, waist belt length, and arm cuff size.

(Figure 1 about here)

2.3. Data Collection

At each milestone, participants were asked to respond to the questions listed below related to usability, using a 0–10 scales; the questions were modified from earlier studies [27,28]. They were also asked to provide open-ended feedback to each question except the one regarding thermal comfort:

- Overall fit and comfort – "*What is your perception of the overall fit and comfort of the exoskeleton when performing your job*": 0 = no discomfort and 10 = most discomfort
- Thermal comfort – "*What is your perception of the thermal comfort typically (and/or feelings of sweatiness)?"*: 0 = no discomfort and 10 = most discomfort
- Perceived balance – "*What is your perception of balance (or any sense of imbalance) while using the exoskeleton*": 0 = perfectly balanced and 10 = off balanced
- Perceived range-of-motion (ROM) – "*Do you feel that your range of motion was at all limited while using the exoskeleton*": 0 = no limitation and 10 = extremely limiting
- Overall perceived job safety – "*When using the exoskeleton to perform your job, how do you think this affected your overall safety*": 0 = substantially less safe, 5 = no difference, and 10 = substantially safer

- Perceived job performance – "*Overall, does using exoskeleton positively or negatively affect your performance?*": 0 = substantially worse, 5 = no difference, and 10 = substantially better.

Participants were also asked to respond to three open-ended questions: "*What do you most like about the exoskeleton?*" (Like); "*What do you least like about the exoskeleton?*" (Dislike); and "*If you could change anything about the exoskeleton, what would you change?*" (Change). At M12 and M18, participants were asked to share their overall feeling about the exoskeleton (positive, neutral, or negative) and to indicate their intention to use it in the future ("yes" or "no", though some reported "maybe"). Among the respondents to this intention question, three participants gave responses at both milestones, and their responses were consistent. Thus, we only included their first responses in analysis. The questionnaire used is presented in Appendix A.

Throughout the study period, facility occupational health personnel recorded all medical visits made to the onsite plant nurse, following their standard occupational health and safety & injury management process. First time occupational visits (FTOVs) were included for further analysis only if the reported concern was categorized as being 'ergonomics' related (i.e., ones associated with sprains/strains) in the upper extremity or the back. We excluded any incidents involving the fingers. Across the seven facility sites and 18-month period, there were a total of 41 and six medical visits recorded in the control and ASE groups, respectively. The most common body parts reported in these visits were the shoulder and wrist (see Appendix B for details). None of the included visits resulted in any lost workdays. Note that the wider industry rate of lost workday cases due to overexertion and bodily reaction was 105 per 10,000 full-time employees in automotive manufacturing [29].

2.4. Statistical analysis

All statistical analyses were conducted on data from the ASE group unless stated otherwise, using R software [30]. Given the exploratory nature of the work, statistical significance was determined at $p<0.1$. To assess temporal changes in responses to each of the usability-related questions, separate generalized estimating equations (GEEs) were fit. These models included *Time*, *Facility*, and their interaction as predictor variables, along with age, body mass, stature, and hot/cold season as covariates. We performed GEEs using imputed data using the *geeglm* function [31]. Roughly 40% of usability question responses were missing due to withdrawal and participant unavailability. To address this, we used multivariate, multiple imputation with bootstrapping. We imputed responses to the usability-related questions by generating 2000 completed datasets using the *bootMice* function in the *bootImpute* package [32]. Subsequently, we fit separate GEEs on each imputed dataset, and combined the estimated coefficients and standard errors using the *bootImputeAnalyse* function in the package. Note that we considered responses to the usability-related questions (i.e., 0–10 scales) as interval scale [33]. Open-ended feedback was explored initially using the *tidytext* package [34] to identify high-frequency words. Then, verbatim feedback along with the high-frequency words were reviewed and categorized by the lead author. Identified categories were summarized for each question.

To examine the extent to which responses to the usability-related question was associated with reported intention-to-use the ASE (Yes/No), a multiple logistic regression analysis was performed on the original (i.e., non-imputed) data. We used median values of responses to each usability-related question across the milestones as inputs (due to missing data). Responses to the question about balance were generally close to zero, so a logistic regression model was fit, including all usability-related questions (except the balance) as explanatory variables. Note that three participants reported "maybe", and their responses were excluded. To complement the multiple logistic regression results, a decision tree analysis was performed to identify potential decision pathways contributing to an intention to use the ASE, using the conditional interference tree (*ctree*) function of the *party* package [35]. Given the explanatory nature of this latter analysis, *ctree* was employed since it uses statistical inference procedures when splitting to: 1) avoid selecting a predictor that maximizes separation (i.e., source of potential selection bias); 2) accommodate all types of responses and explanatory variables; and 3) correct for multiple testing across several predictors.

We also explored whether using the ASE affected the occurrence of medical visits over the study period. As noted above, included in this analysis were only incidents associated with sprains/strains. A multiple Cox proportional hazards regression analysis was performed to estimate hazard ratios for medical visits between the ASE and control groups, using the *coxph* function [36], while including age, body mass, and stature as covariates. In cases of multiple medical visits, the gap time formulation was used; gap time is the time since the previous event, and the time index is reset to zero after the event [37]. The assumption of a proportional hazard was examined using scaled Schoenfeld residuals [38], and this assumption was satisfied.

3. Results

3.1. Responses to questions related to usability

A summary of GEE results is presented in Appendix C, and longitudinal responses to the questions are shown in Figure 2. In general, responses to all questions remained statistically consistent over time and across the facilities, with one exception. Regarding the latter, responses to the question about perceived ROM had a significant higher intercept for the S2 facility, compared to the reference (i.e., S1 facility; Appendix C). On average, participants indicated minor concerns about overall fit and discomfort, moderate-to-high concerns with thermal discomfort, minimal concerns with balance, minor concerns with perceived ROM, equivalent or slightly better perceived safety, and slightly better perceived job performance.

(Figure 2 about here)

The five most frequent categories of comments obtained for each of the usability-related questions are presented in Table 1, along with respective examples. Categories with the same frequency were counted once, and no comments were made for the question about thermal comfort.

(Table 1 about here)

3.2. Open-ended feedback

Figure 3 shows the five most frequent categories of comments obtained from each of the open-ended questions (Like, Dislike, and Change). Most comments (64.1%) from the Like question indicated participants liked the arm support from the exoskeleton and related reduction in shoulder strain/discomfort and other body parts (e.g., arm, back, and neck). Categories of comments obtained from the Dislike and the Change questions were rather similar, and it appeared that participants prioritized improving aspects related to ASE fit and comfort. The five most frequent categories regarding Change were to improve thermal discomfort, the arm cuff, bulkiness, the ASE weight, and the rigid trunk structure. These categories were followed by improving the time to don and doff the ASE (5.5%), ROM (5.5%), and waistbelt comfort (4.3%).

(Figure 2 about here)

3.3. ASE intention-to-use

Sixteen participants responded "yes" regarding their future intention-to-use the ASE, and 11 responded "no". Table 2 provides results of the logistic regression analysis that examined the contributions of the usability-related question responses (except the balance question) to intention-to-use. Perceived job performance was the only statistically significant predictor. The model coefficient indicated that the odds to use the ASE increase 179% for a unit increase in perceived job performance.

(Table 2 about here)

Figure 4 shows the decision tree that was generated to identify factors contributing to intention-to-use the ASE. This tree consists of five nodes, with the root node being "Perceived job performance". When perceived job performance was ≤6.5, ~70% of respondents reported having no intention to use the ASE. When perceived job performance was >6.5, all respondents who had a response regarding overall fit and comfort of ≤4.7 reported "Yes" regarding intention-to-use.

When overall fit and comfort was >4.7, only 60% of respondents reported "Yes" about intention-to-use.

(Figure 4 about here)

3.4. Medical visits

Results of Cox proportional hazards regression analysis are shown in Figure 5. The probability of a medical visit was affected significantly by age (p = 0.03, hazard ratio = 0.95) and by EXO use (p = 0.09, hazard ratio = 0.48). The probability of making a medical visit decreased by 5% with a unit-increase in age, and by 52% when the ASE was used. Survival curves are shown in Figure 5; the median survival was ~580 days for the control group and this level was not reached for the ASE group.

(Figure 5 about here)

4. Discussion

We investigated diverse responses regarding using an ASE in an automotive manufacturing environment over a period of 18 months. Responses from ASE users to the six usability-related questions remained rather consistent over time (Figure 2). Participant feedback indicated that using an ASE was perceived effective in reducing physical demands on the shoulders (and possibly the neck and/or back) during actual automotive assembly. Participant feedback, though, highlighted concerns related to the design of the ASE used in the study (e.g., profile, weight) and its physical interface with the user's body segments (e.g., arm cuff, waist belt). Key determinants of exoskeleton intention-to-use appeared to involve perceived performance as well as overall fit and comfort. Information was also obtained to suggest the potential for ASE use to decrease the likelihood of a work-related medical incident. Each of these major outcomes is discussed subsequently in more detail.

Effectiveness of an ASE in reducing physical demands on the shoulder and other body regions

Existing lab- and field-based studies have demonstrated that using an ASE can reduce muscle activity in the shoulder region, metabolic costs, and/or fatigue during overhead work [e.g., 10,14,39], though the magnitude of such benefits appear to be relatively smaller in field vs. lab studies [16,19]. We also reported earlier that there were only slightly lower musculoskeletal discomfort scores reported for the neck and shoulder in a group that used an ASE (*vs.* no ASE) during automotive assembly work [21]. The current results agree with those earlier reports, in that the current participants reported the same or slight better perceived safety and job performance using an ASE (Figure 2). Participant comments indicated that, with assistance from the ASE, they felt less likely to have an injury, had less strain and/or pain on the shoulder, and could work longer with less effort. In fact, assistance from the ASE and related benefits were the aspects of the ASE that were most liked (Figure 3), supporting that the users (i.e., actual assembly workers) perceived benefits in terms of reduced strain and fatigue in the shoulder during their daily work.

Furthermore, current results support that ASE use may have beneficial effects on other body regions, such as the neck and the back. Less strain/pain on the arm, back, and/or neck was one aspect that participants liked about using the ASE (Figure 3). Smets [15] reported a similar finding, that there was less work-related discomfort on the shoulders, arms, neck, and back after a regular use of the same ASE examined here. While a reduction in perceived strain/pain on the neck may be attributed to the neck pillow included with the ASE, Hefferle et al. [18] examined two ASEs without a neck pillow and found a significant reduction in perceived strain on the neck during automotive work. A meta-analysis study by Bär et al. [9] showed that using an ASE significantly reduces physical demands (e.g., perceived strain) in the musculature surrounding and/or crossing the shoulder joint (i.e., neck, upper arms, shoulder). Their meta-analysis did not find a significant reduction on perceived strain on the back, yet several studies have reported reductions in back extensor activity and/or perceived strain with ASE use [e.g., 15,16,18,40]. Kim et al. [41] discussed potential postural support provided by the rigid structure of an ASE, which could assist in maintaining more neutral trunk postures during work. Indeed, the current participants commented that the ASE helped with their postures, though one common change participants wanted was being more flexible on the back.

Concerns about ASE design and physical interface

Results from several earlier studies indicate that physical comfort when wearing an exoskeleton is a key factor influencing user acceptance and intention-to-use [e.g., 24,26,42]. Fit and comfort are important for the exoskeleton to function properly and for the user to use it comfortably for a long duration. In the current study, participant comments about overall fit and comfort highlighted specific concerns involving the arm cuff, waist belt, and back mesh panel/plate (Table 1; Figure 1). The former two are physical interfaces that transmit/distribute external forces from the ASE to the corresponding body part. Fit concerns seemed to have caused discomfort *hotspots* due to chafing, rubbing, and high localized pressure. The back structure of the ASE was rigidly connected to the waist belt, so the back mesh panel did not follow the user's trunk motion closely. This limitation appeared to have caused some rubbing on/digging into the user's back due to relative motions between the user's trunk and the back mesh panel. The rigid back structure was a major reason that participants felt rigid/stiff when moving, though participants also favorably commented about postural correction/support provided by this structure. Participants also expressed concerns about the added bulkiness by the ASE components (e.g., protruding ASE shoulder joints) and the device weight (note: the unit mass of the ASE tested = 4.3 kg). The bulkiness, especially, seemed a major source of safety concerns such as snag hazards. It should be noted that different ASEs use different design approaches, involving relatively larger or small "footprints", and that the EksoVest™ tested here was since discontinued and replaced with a new version that has a more minimal design (e.g., the shoulder joint mechanism was re-designed to have a smaller physical footprint).

To understand comfort, several studies have quantified interaction forces/pressures at the user-exoskeleton interface, or assessed contact pressures with different physical interface designs or materials [e.g., 43–47]. Levesque et al. [43], in particular, offered several interface design recommendations, including a cuff that can accommodate large inter- and intra-subject variability in limb shape and dimensions, as well as changes due to muscle contraction, and that can tilt to maintain broad contact regardless of body segment movements. Kozinc et al. [45] reported that pressure tolerance is highly variable between individuals, and lower for females. Further, to the authors' knowledge, there limited understanding of relationship between comfort and pressure relationships when using exoskeleton technologies over relative long periods. Large inter-individual variability in limb shapes/dimensions and pressure thresholds, and a lack of comfort-pressure relationships, suggest that it is challenging to design comfortable physical interfaces for an exoskeleton, and further research is thus recommended.

ASE intention-to-use

Perceived job performance appeared to be a key determinant of ASE intention-to-use (Table 2); as noted earlier, a unit-increase in perceived job performance (higher is better) significantly increases the odds to use the ASE by 179%. Overall fit and comfort was another important determinant of intention-to-use, based on the decision tree (Figure 4). Perceived job performance can be considered as an indicator of perceived usefulness in the Technology Acceptance Model (TAM) [48] or performance expectation in the Unified Theory of Acceptance and Use of Technology (UTAUT) [49]. Our results are consistent with earlier work that showed perceived usefulness and/or comfort are key determinants of exoskeleton intention-to-use [24–26,50].

Interestingly, though, the most common answer to "*If you could change anything about the exoskeleton, what would you change?*" was related to thermal discomfort (Figure 3). In a similar automotive assembly setting, Smets [15] noted that thermal comfort was a major reason for not wearing an ASE. Yet, thermal comfort was not selected here as an important determinant by either a logistic regression or a decision-tree analysis. This outcome may have occurred because participants considered thermal comfort as part of overall fit and comfort, such that the second most common comment was "Hot" (Table 1). Given that participants generally experienced moderate to high levels of thermal discomfort (Figure 2), responses to the thermal comfort question may not have had sufficient statistical discriminative power to predict intention-to-use. Our results suggest that overall fit and comfort should not be limited to just physical interfaces and exoskeleton designs but should instead also include thermal comfort.

Thus, to facilitate ASE adoption and use in occupational settings, the effects of ASE use on perceived performance, usefulness, and comfort are likely critical aspects to be considered. These aspects can be viewed as being associated with perceptive factors (perceived ease of use, and perceived usefulness) in the endogenous domain within the Exosystem Use Intent Model (EUI) proposed recently by Purcell [51]. The EUI has two broad domains – *exogenous* (originating outside from the user) and *endogenous* (internal to the user) – and is a modification of the Theoretical Interesting Model (TIM) [52] that was developed based on TAM and UTAUT. In the EUI, exogenous factors of the TIM were modified to reflect only the physical and environmental aspects of a human-machine system in the workplace, and the factors include individual (i.e., self-efficacy), social (i.e., psychosocial), and task contexts (i.e., compatibility with task). The EUI assumes that exogenous factors can moderate any of the behavioral, perceptive, affective factors. This assumption suggests that the perceived performance, usefulness, and comfort of an ASE should be examined while also considering exogenous factors. In the current study, some participants mentioned a social concern, such as wanted or unwanted attention form coworkers. Safety concerns such as snag hazards suggest that despite rigorous safety analysis prior to deploying to candidate workstations, the bulkiness of the ASE remained a concern for some users, which implies that the ASE examined was not sufficiently compatible with the workspace. Further research is needed to understand better how and to what extent exogenous factors affect intention-to-use for a given ASE and a specific job.

Can using an ASE reduce the risk of musculoskeletal problems?

In the current literature, using an ASE is often considered a promising intervention to reduce work- related shoulder injuries, given that ASE use can lower physical strain and fatigue in the shoulder musculature. However, it is still an open question if using an ASE (or any exoskeleton) can or will lead to a reduction in injury risk, and to our knowledge no formal study has reported on injury reduction with exoskeleton use [53,54]. We found that those who used the ASE were roughly half as likely to make a medical visit (Figure 5) that involved an injury to or pain in the upper extremity (excluding fingers) or back. We consider this a promising and suggestive outcome, though we also suggest caution in interpreting it given the large number of dropouts and moderate sample size. We emphasize, though, that this promising outcome may be attributed partially a higher safety locus of control with ASE use, given that such control can be a predictor of industrial accidents and injuries [55,56]. A subset of workers used the ASE in each facility, which might have influenced their behaviors. For example, increased attention from coworkers and supervisors may have made some participants less willing to make a medical visit. More generally, a Hawthorne effect may have been present [57]. Therefore, future work will be required to provide evidence, with a larger sample size, longer use duration, and tracking of exoskeleton use. Also recommended is the inclusion of additional predictors (e.g., reductions in muscle activity or metabolic costs, changes in postures or movements).

Limitations

The current study had several strengths, given the use of a longitudinal design and *in-situ* data collection from actual assembly workers. However, some important limitations should be acknowledged. First, there were missing data. Multiple imputation was used to address missing responses, which assumes no systematic pattern in missingness. We considered this assumption reasonable, in that missing responses likely depended on the circumstances of individual participants (e.g., changes in work shift, vacation). Second, psychosocial factors were not formally considered. A few participants noted, though, that they liked or disliked the attention that they received from colleagues when using the ASE. Including psychosocial aspects is recommended in future efforts, since high psychosocial demands are a risk factor for work-related musculoskeletal disorders and injuries [58,59]. Third, data were not obtained prior to the Month 1 milestone. While responses regarding usability were stable over a period of 18 months, it is unclear how quickly participants established such perceptions. Fourth, the questionnaire questions were not exhaustedly validated, so care should be taken in interpreting the results. Fifth, we did not have sufficient data regarding actual ASE use during the study period. Though obtaining such data was attempted, the results were too sparse to be of use, and ASE use patterns seemed to substantially vary across the participants. Some participants used the ASE infrequently (e.g., 1-2 hours/day for 1-2 days per week, during cool days), while some used it as much as 4-10 hours/day for 4-5 days per week. Future field studies would clearly benefit from including periods of use to better quantify both the benefits and limitations of exoskeletons. Sixth, randomization was not used when selecting either participants or participating facilities, nor were participant randomized to the ASE vs. control groups. Both design limitations resulted from unavoidable practical limitations. Of note, though, demographic characteristics and task demands were generally comparable between the two groups [21] and Facility was included in statistical analyses. Despite the lack of randomization, we believe the current results still allow for assessing confounding, heterogeneous groups, and selection bias to some extent.

Conclusions

Results from an 18-month field trial of an ASE in automotive assembly showed that, as intended by exoskeleton design, users perceived less strain and fatigue in the shoulders, and experienced positive effects on job performance, without major safety concerns. However, there were more considerable concerns about ASE fit and comfort related to the exoskeleton design and physical interface. Thermal comfort appeared to be an important perceptual aspect. Furthermore, our results corroborated that perceived job performance (i.e., perceived usefulness) and overall fit and comfort are key factors in determining one's intention to use an ASE, and we obtained a preliminary indication that ASE use could reduce the risk of UE-MSDs. To support the safe and effective adoption and use of ASEs in the field, future work should investigate approaches to: 1) enable the design of more comfortable physical interfaces, 2) improve our understanding of exoskeleton intention-to-use by including additional factors (e.g., physical demands, behavioral and psychosocial aspects, and workspace constraints), 3) investigate temporal changes in exoskeleton usability perceptions and use opinions over a 1-month period to assess how quickly users establish steady-state perceptions and opinions, and 4) perform a more rigorous investigation on health outcomes from long-term exoskeleton use.

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Tables and Figures

Table 1. Five most frequent categories of the comments obtained from each question related to usability. In the table, *n* is the number of total comments, percentages are the relative frequency of comments in each category, and percentage accounted for is the total percentage accounted for by the five most frequent categories.

Table 2. Results of logistic regression on intention-to-use the ASE.

Figure 1. Example of an assembly operator performing a task while using the EksoVest™ [60]

Figure 2. Longitudinal responses to usability-related questions regarding ASE use. For questions about overall comfort & fit, thermal comfort, perceived balance, and perceived range of motion (ROM), responses ranged from 0 to 10, and a higher value is worse. For questions about overall perceived safety and perceived job performance, responses ranged from 0 to 10, with 0 = substantially less safe (or worse), 5 = no difference, and 10 = substantially safer (or better). Error bars indicate 95% confidence intervals.

Figure 3. Five most frequent categories of comments obtained in response to the following questions: "*What do you most like about the exoskeleton?*" (Like); "*What do you least like about the exoskeleton?*" (Dislike); and "*If you could change anything about the exoskeleton, what would you change?*" (Change). Percentage values are the relative frequencies of comments for each category.

Figure 4. Decision tree to identify factors influencing intention-to-use the ASE (Yes vs. No). The root node of Perceived job performance traverses down to the leaf (terminating) nodes. Leaf nodes show the proportion of Yes (Y) and No (N) responses.

Figure 5. Left: Hazard ratios associated with each coefficient in the Cox proportional hazards regression model (Left); error bars indicate 95% confidence intervals. Right: Survival curves showing the difference in probability of a medical visit due to an injury and/or pain in the upper extremity (excluding fingers) or the back.

Figure 1

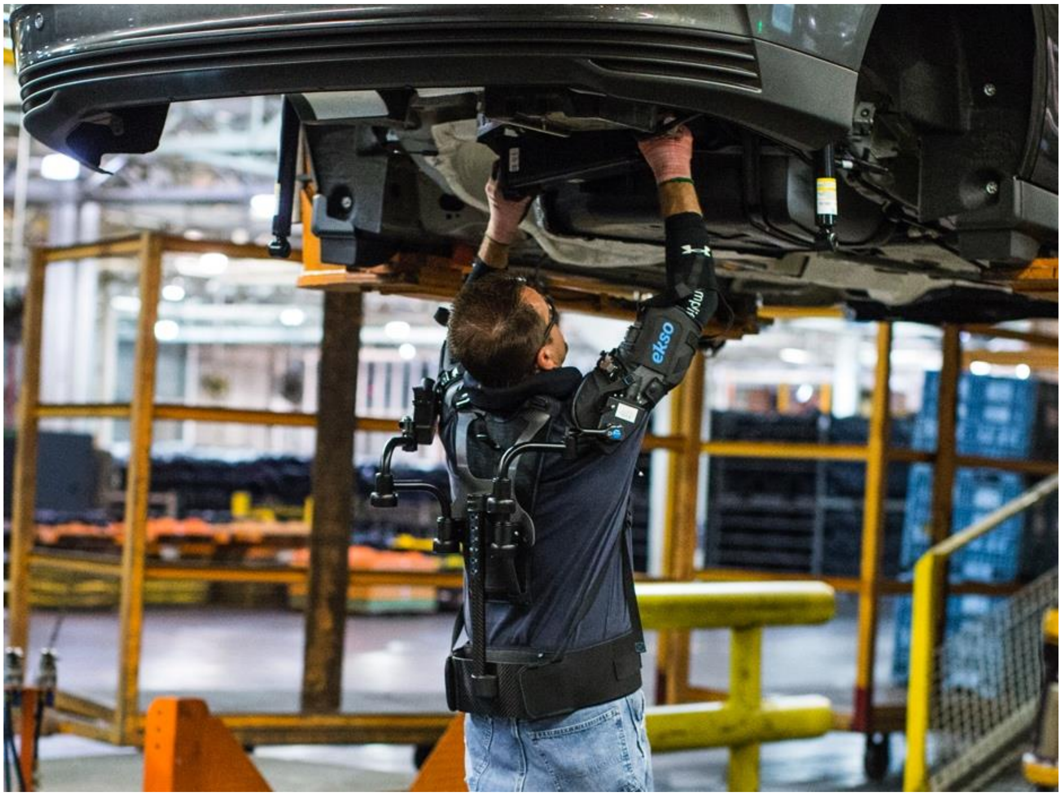

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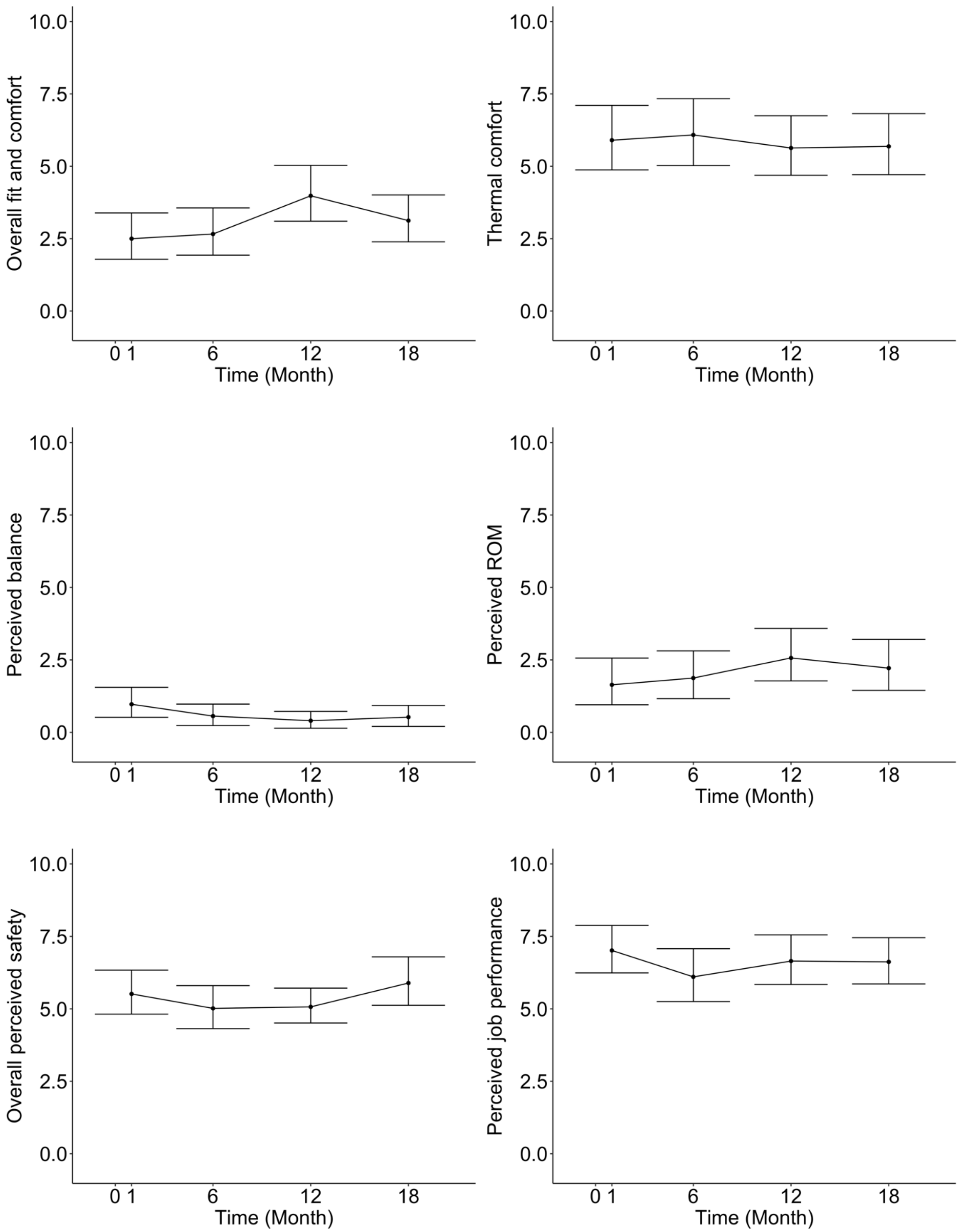
Figure 2



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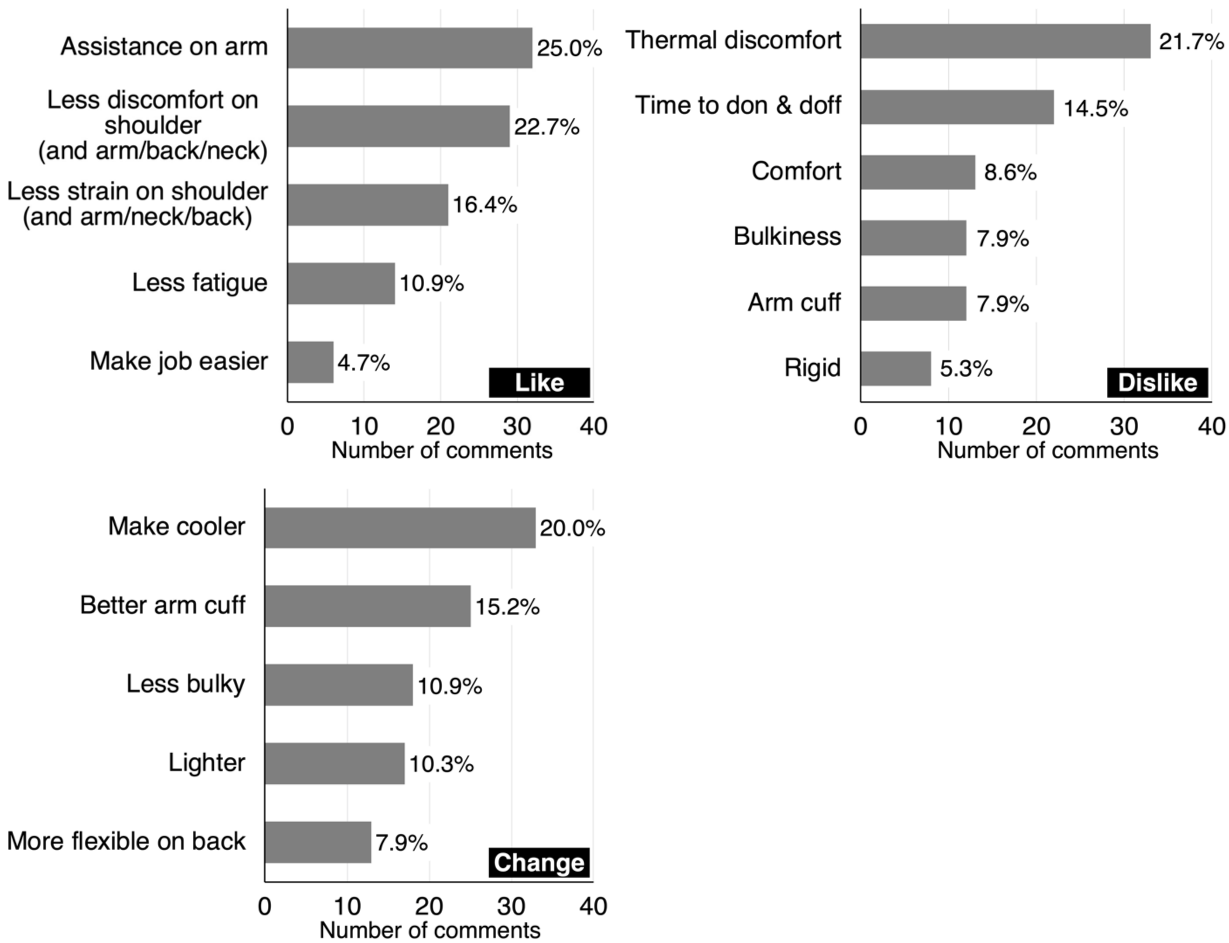

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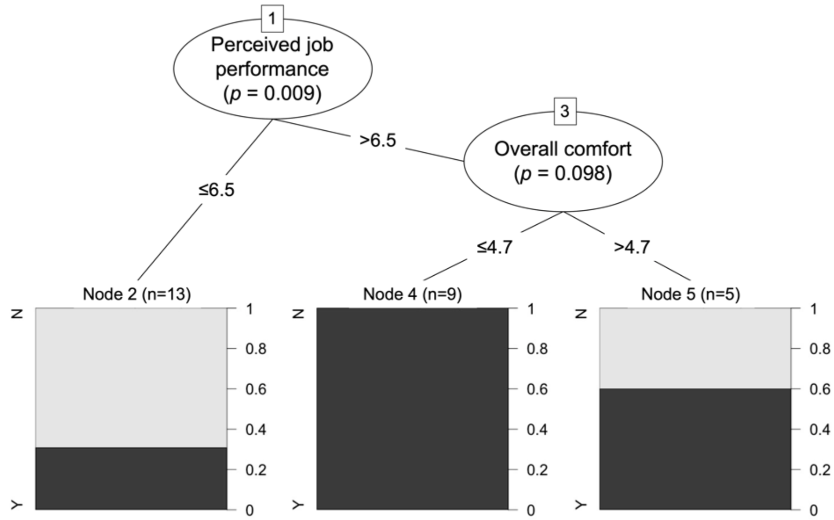

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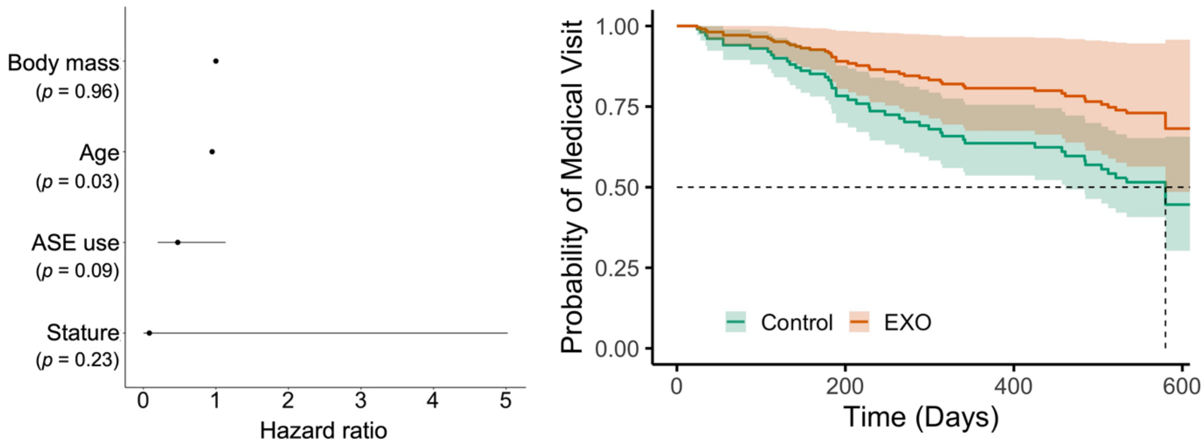

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	5 most frequent categories	**Example comments**
Overall fit and comfort (*n*=109)	• Arm cuff (25.7%) • Hot (18.3%) • Rubbing on/digging in the body (11.9%) • Waist belt (11.9%) • Feel rigid/stiff (8.3%) • Bulkiness (7.3%) Percentage accounted for = 83.5%	• Upper arm chaffing in/from the arm cuff • Very hot during summer months • The ASE rubs the back and/or shoulders • Need more padding in the waist belt • Feels rigid/stiff – can't rotate the trunk or fully extend the back • Need to be more aware of surroundings
Perceived balance (*n*=14)	• Bending forward (71.5%) • Trunk twisting (14.3%) • Mediolateral balance (7.1%) • Squatting (7.1%) Percentage accounted for = 100%	• Bending forward or getting back up • Twisting quickly, or twisting to grab a part • Feeling laterally unbalanced • Squatting on an inclined surface
Perceived ROM (*n*=83)	• Reaching (38.5%) • Trunk bending (37.4%) • Trunk twisting (14.5%) • Sitting/squatting (4.8%) • Arm motion (2.4%) • Stretching (2.4%) Percentage accounted for = 100%	• Reach forward, backward, or across the body • Bend forward to get parts near/on the ground • Rotate the trunk (feels rigid) • Slight need to adjust arm motions while performing the job
Overall perceived Safety (*n*=46)	• Snag hazards (34.8%) • Feel less likely to have a shoulder injury (15.2%) • Less strain on shoulders (and back) (13.1%) • Bulkiness (11.0%) • Helps with posture (11.0%) • Less likely to drop materials due to shoulder assistance (6.5%) Percentage accounted for = 91.6%	• Worry that the ASE can snag on vehicles or a gun hook • Feel less likely to have shoulder injuries • Less fatigue, aches, or pain on the shoulders and/or back • Feels tight in the working area • Improve/correct postures
Perceived job performance (*n*=87)	• Less pain on shoulder (and arm/neck) (21.8%) • Less fatigue (20.7%) • Assistance on arm (19.5%) • Less strain on shoulder (and neck) (12.6%) • Unable to move quickly (5.8%) Percentage accounted for = 80.4%	• Can go longer, and use less effort to do the same amount of work • Extra assistance on arm eliminates aches and pain • Easier to punch shields into place • Less shoulder and neck pain, and not as tired • Feel that it takes longer to complete a cycle, and movements are slowed down

Table 2

Table 2. Results of logistic regression on intention-to-use the ASE.

	β	**Odds Ratio**	**95% CI**	***p***
Intercept	-0.93	0.39	-7.78, 5.98	0.78
Overall fit and comfort	-0.19	0.83	-1.09, 0.66	0.65
Thermal comfort	-0.08	0.92	-0.73, 0.52	0.79
Perceived ROM	-0.16	0.85	-0.88, 0.46	0.61
Overall perceived safety	-0.62	0.54	-1.92, 0.26	0.24
Perceived job performance	1.02	2.79	0.32, 2.16	**0.02**