Abstract

Background: Exoskeleton (EXO) technologies are a promising ergonomic intervention to reduce the risk of work-related musculoskeletal disorders, with efficacy supported by laboratory- and field-based studies. However, there is lack of field-based evidence on long-term effects of EXO use on physical demands.

Methods: A longitudinal, controlled research design was used to examine the effects of arm-support exoskeleton (ASE) use on perceived physical demands during overhead work at nine automotive manufacturing facilities. Data were collected at five milestones (baseline and at 1, 6, 12, and 18 months) using questionnaires. Linear mixed models were used to understand the effects of ASE use on perceived work intensity and musculoskeletal discomfort (MSD). Analyses were based on a total of 41 participants in the EXO group and 83 in a control group.

Results: Across facilities, perceived work intensity and MSD scores did not differ significantly between the EXO and control groups. In some facilities, however, neck and shoulder MSD scores in the EXO group decreased over time. Wrist MSD scores in the EXO group in some facilities remained unchanged, while those scores increased in the control group over time. Upper arm and low back MSD scores were comparable between the experimental groups.

Conclusion: Longitudinal effects of ASE use on perceived physical demands were not found, though some suggestive results were evident. This lack of consistent findings is discussed, particularly supporting the need for systematic and evidence-based ASE implementation approaches in the field that can guide the optimal selection of a job for ASE use.

Keywords: Prospective study; ergonomic intervention; manufacturing; perceived physical demand; musculoskeletal discomfort

1. INTRODUCTION

Exoskeleton (EXO) technologies have gained increasing attention for occupational application as a way to increase the ability of a user to complete manual tasks in diverse work settings. By increasing physical capacity, using an EXO may reduce the physical requirements of a task so that the user experiences a lower risk of injury and achieves enhanced performance. A number of controlled laboratory studies have provided consistent evidence that using an EXO can reduce muscle activity levels, perceived exertion, and metabolic costs [1–8]. In some cases, EXO use can improve task performance, likely due to a reduction in muscle fatigue or enhanced steadiness of body movement [9,10]. The magnitude of such beneficial effects, however, clearly depend on the specific task conditions (e.g., symmetric *vs*. asymmetric trunk bending, lifting *vs*. carrying) and individual differences such as gender [4,11,12]. Existing work also points to potentially undesirable effects of using an EXO, including elevated contact pressure [e.g., 13–15], limited range of joint motions [e.g., 16–18], and altered working postures such as knee extension [15]. Overall, accumulating laboratory-based evidence supports EXO use as having clear efficacy as an intervention to control the risks of work-related musculoskeletal disorders, but also highlights the need to optimize the match among an exoskeleton, a task, and a user to maximize beneficial effects and minimize undesirable outcomes.

To support the safe adoption and use of EXOs in practice, however, field-based evidence is critical to an understanding of actual effectiveness, practicality, safety, and user acceptance [19,20]. Some work has been reported from field testing of EXOs, ranging from less than an hour to up to a 3-month period, in automotive assembly [9,21–24], manufacturing [25], warehousing [26,27], and agriculture settings [28,29]. Arm-support exoskeletons (ASEs) were typically field-tested for jobs that involve overhead assembly and overhead lifting, while back-support exoskeletons (BSEs) were tested for jobs that involve manual material lifting, shoveling, or require prolonged trunk bending. Findings from these studies have generally agreed with laboratory-based evidence, in that using an EXO can reduce physical demands.

Subjective measures were typically the primary outcomes in the noted field studies, though some have assessed muscle activity in two to four muscle groups and/or heart rate while workers used an EXO [23,25–27,29]. Specific to ASEs, their use has led to ~10-26% reductions in the shoulder (anterior deltoid, biceps brachii, trapezius) and low back muscle groups (lumbar erector spinae) during overhead automotive assembly and overhead lifting tasks. ASE use also reduced mean heart rate, with De Bock et al. [27] reporting up to a 19% reduction during overhead work in a distribution facility, and Marino [30] finding a 3.4% decrease during stocking tasks in a retail store. The prior study, however, demonstrated that the magnitude of beneficial effects of an ASE can be substantially less in the field (picking orders from a high rack), compared to a controlled laboratory setting. Overall, this field-based evidence related to ASEs suggests that the results obtained from laboratory task simulations may be generalizable to the field, though the magnitude of beneficial effects can be smaller.

Field studies of EXO use also provide richer information in important aspects of EXO use, including practicality, safety, and user acceptance. For example, laboratory-based studies have highlighted concerns about the fit, comfort, and usability of an EXO, and later field studies showed that such aspects are in fact key drivers of user acceptance. The latter is analogous to the adoption of wearable sensor technologies, in acceptance appears to be strongly affected by factors including comfort and usability [31,32]. Users also may need sufficient time to establish their perceptions about *true* usability. For example, Hensel [22] reported a substantial decrease in the perceived usability of a BSE between the beginning and end of a 4-week evaluation among auto-assembly workers. Field work has also highlighted that EXO benefits may be task specific. BSEs, in particular, may be less effective for tasks that are dynamic and/or involve diverse working postures, given that relatively smaller reductions in physical demands and higher discomfort were found compared to more static tasks or those with limited variability [22,25]. Safety concerns have also been identified in field studies, including getting on and off a pallet jack [26]; using an EXO in confined spaces [23]; difficulty in perceiving loads immediately after doffing the EXO [23]; and getting caught by sharp edges, and working near or with electrical sources [28].

Investigating the longer-term effects of EXO use is still essential, however, since there may be a long latency period for the effects of EXO use to be evident on worker health (e.g., development or change in severity of a work-related musculoskeletal disorder). In the current work, we aimed to address this need using a prospective, controlled field study of the effects of using an ASE among workers in several automotive assembly facilities over a period of 18 months. Effects of ASE use were determined based on subjective responses regarding musculoskeletal discomfort and work intensity. Given the dearth of long-term field studies on EXOs, we also sought to share lessons learned throughout the course of the study, to support future study designs and field implementations of EXO technologies.

2. METHODS

2.1 Experimental design

This study was a partnership between academic researchers and Engineering and Ergonomics Specialists at Ford Motor Company. We used a longitudinal, controlled research design. Workers were recruited from final assembly processes at nine automotive manufacturing facilities in Northern America, and they participated voluntarily between April 2018 and December 2019. Data were collected via questionnaires, described below, over the course of 18 months: the day when participation began and without EXO use (Baseline), and again at 1, 6, 12, and 18 months after the baseline (i.e., M1, M6, M12, and M18).

2.2 Arm-Support Exoskeleton (ASE)

The ASE used was the EksoVest™ (Ekso Bionics, Inc., Richmond, CA; unit mass = 4.3 kg). This ASE (Figure 1) included a U-shape neck pillow and back pads, along with adjustability in trunk length, waist belt length, and arm cuff size. Smets [24] completed an initial multi-phase evaluation of earlier versions of this ASE in an automotive manufacturing facility. Positive feedback from the users supported the current larger-scale and longer-term investigation.

INSERT Figure 1 Here

2.3 Participants

All participants were final assembly operators who worked daily on an overhead line at which the vehicle passed above the operators while they performed assembly work from below; less than 8% of workstations typically require overhead work at a facility. Jobs were reviewed initially for inclusion in the study by a governance team consisting of Engineering and Ergonomics Specialists, to ensure that there were no other additional risks introduced with EXO use (e.g., potential for snags on equipment, tight space). Participants were then recruited on a voluntary basis after being contacted by their Ergonomics Specialist. Participants were recruited in a 1:2 ratio into an EXO group (*n* = 65) and a control group (*n* = 133). To the extent possible, efforts were made to ensure that both groups had comparable overhead work or were positioned at the same workstations. We provided participants in both EXO and control groups with a Bluetooth speaker (approximate value = $15) as a gift for their voluntary participation. Participants in the EXO group were also allowed to keep the ASE, if desired, after the end of the study period.

Twenty-four participants (36.9%) in the EXO group and 50 (37.6%) in the control group withdrew from the study, mainly due to a job transfer to non-overhead work or because of loss of interest. In addition, two manufacturing facilities underwent major facility changes, during which vehicle production temporarily stopped and no data were obtained after the first few milestones. Data from these facilities were excluded from further analysis. Hence, analyses were based on a total of 41 participants in the EXO group (30 males, 3 females, 8 not reported) and 83 in the control group (47 males, 14 females, and 22 not reported). Demographic information and job demand are summarized in Table 1 for each facility. Note that video recordings were not obtained for 40 participants (16 in EXO group and 24 in control group); participants either declined to be recorded or were not present when recordings were being made. As such, physical demand scores were not available for these participants.

This study was reviewed and approved by the National Joint Committee on Health and Safety at Ford Motor Company and by the Institutional Review Board at Virginia Tech. Participants were informed that participating in the study was voluntary and that they could withdraw from the study at any point with no negative consequences. All collected data were anonymous and confidential and were used only for academic research.

INSERT Table 1 Here

2.4 Procedures

Engineering and Ergonomics Specialists were trained on sizing and fitting the EXO by the EXO manufacturer. An engineer at Ford and a representative from Ekso Bionics Inc. travelled to each participating facility to ensure a customized fit and to train each participant in EXO donning, doffing, and use, as well as to train the local Ergonomics Specialists. Local Ergonomics Specialists ensured a proper fit of the EXO throughout the study, by replacing damaged parts (e.g., straps) and refitting the EXO as needed.

Data were collected via questionnaires, by local Ergonomics Specialists at the five milestones (i.e., Baseline, M1, M6, M12, and M18). If participants were not available on the day of data collection, follow-up data collection was attempted. Collected data included self-reported demographic and anthropometric information (gender, age, body mass, and stature), responses regarding musculoskeletal discomfort, and responses regarding perceived work intensity. Work intensity is a construct that has been considered to affect the risk of developing a work-related musculoskeletal disorder (WMSD) [34,35]. Work intensity was measured here using two statements adopted from the cross-validated psychological climate and effort measures questionnaire [36]: Q1. “When I work, I really exert myself to the fullest” and Q2. “I feel exhausted at the end of a shift”. Respondents were asked to respond to each statement on a scale of 0 (strongly disagree) to 10 (strongly agree).

The Cornell Musculoskeletal Discomfort Questionnaire (CMDQ) was used to capture self-reported discomfort [37], since responses to symptom questionnaires can be a leading indicator of WMSD development [38]. Earlier work reported that the CMDQ has good test-retest reliability and validity, albeit examined in non-English versions [39,40]. The CMDQ is a 54-item questionnaire containing a body map diagram and questions about musculoskeletal aches, pain, or discomfort in 20 body regions during the previous week. Respondents are asked to indicate the frequency and severity of discomfort, and the extent to which discomfort interferes with their work. Subsequently, responses are assigned numerical scores and the product of these scores yields a single musculoskeletal discomfort (MSD) score for each body region [41]. Our analyses focused on the neck, upper extremity, and the low back, based on existing work regarding the effects of ASE use.

We estimated physical demands on the upper limbs for each of the participants. Upon participant consent, Ergonomics Specialists made video recordings of several job cycles, and these videos were used as the basis for estimating physical demands using the occupational repetitive action (OCRA) method [42]. Scores for two OCRA factors (the posture factor based on the percentage of time exposed, and the force factor) were obtained, based on the video recordings and information on tool and part masses. A single physical demand score was produced by summing these two scores. Note that since only a subset of the OCRA factors were used here, scores reported below should not be considered as representing actual magnitudes of physical demands, but rather only for relative comparisons.

2.5 Statistical analysis

All statistical analyses were conducted in R software [43]. Descriptive statistics (means and standard deviations) for all measures were computed at each of the five data collection milestones with respect to the experimental groups and manufacturing facilities. Outcome measures of interest were MSD scores (neck, shoulder, upper arm, forearm, wrist, and low back) and responses to the two work intensity questions. For bilateral body parts, the side that had the higher MSD score was included in analysis.

To assess whether there were differences across facilities and between the experimental groups at the study initiation, linear models were first fit for each of the outcome measures at Baseline, using the *lm* function [43]. Specifically, we examined the effects of *Facility* as a fixed effect for a given experimental group, and the effects of *EXO use* as a fixed effect for a given facility, while adjusting for age (years), body mass (kg), stature (m), and estimated physical demands. Prior to analyses here and below, MSD scores were log-transformed to satisfy parametric model assumptions, and the S1 facility was selected arbitrarily as the reference level for the models. For clarity, summary results are reported in the original units after back transformation.

To assess changes in outcome measures over time, linear mixed models were then fit, using the *lmer* function [44], while adjusting for baseline values, age, body mass, stature, and estimated physical demand. Initial exploratory analysis indicated no clear linear relationships between outcome measures and milestones (i.e., *Time*), nor any clear temporal correlations across milestones. An examination of mixed-effects model fits also did not lead to statistically significant results when *Time* was set as a continuous variable. While it is clear that temporal effects may need to be modeled with more complex models in future work, in this exploratory study, we considered *Time* as a categorical variable with five levels to avoid assuming linear temporal changes. We included 1st- and 2nd-order interaction terms of *EXO use*, with *Facility* and *Time* as fixed effects, to examine if the effects of EXO use were facility- and time-dependent. Participants in the same manufacturing facility could have exhibited non-independence in the outcome measures. To evaluate this, a random intercept term for *Facility* was examined in addition to a random intercept term for *Participant*. Including the former did not improve model fits, and thus was not included in the final models. In the following results, baseline values are presented to help in visualizing the outcomes over time; these values were extracted from a model that did not include baseline values as a covariate. Statistical significance was determined at $p<0.1$ given the exploratory nature of the study.

2.3.1 Missing data

Due to withdrawal and participant unavailability, there was a total of roughly 40% missing data. Figure 2 shows the number of missing data points over time in each of the manufacturing facilities. To address this high prevalence of missing data, we used multivariate imputation using chained equations (MICE). MICE produces asymptotically unbiased estimates when data are missing at random or missing completely at random [45] though estimates can be biased when data are missing not at random [46]. Multiple imputation involves, at each imputation, replacing missing values with imputed values drawn from their predicted distribution in non-missing data. We performed multiple imputations to impute missing values (MSD scores and responses to the work intensity questions) using the *mice* package [47], while including all variables in the mixed models (i.e., *Facility*, *Time*, *EXO use*, age, body mass, stature, and physical demands). We generated 200 completed datasets, given that the statistical power and precision of estimates can be improved with a larger number of imputations (m). Note that Graham et al. [48] suggested m = 40 for 50% missing data and Twisk et al. [49] noted that mixed model results can be unstable even with 100 imputations. We then fit separate linear and mixed models on each imputed dataset and combined the estimated coefficients and standard errors using the rules from Rubin [47].

INSERT Figure 2 Here

3. RESULTS

3.1 Baseline characteristics

Baseline MSD scores and responses to work intensity (WI) questions, both raw and imputed, are summarized in Table S1 in the Appendix. For a given experimental group, coefficients from the linear models indicate that these scores and responses were generally comparable to the reference (S1 facility), though there were several exceptions. Among the control group, the S3 facility had significantly higher neck, upper arm, forearm, and low back MSD scores; and the L3 facility had higher responses to the first WI question. Among the EXO group, the S3 facility had significantly higher forearm MSD scores and the S2, L1, and L2 facilities had significantly higher responses to either or both of the WI questions. For a given facility, however, there was no significant difference between the control and EXO groups, except that the EXO group in the L1 facility had relatively lower responses to the first WI question.

3.2 Effects of EXO use on perceived work intensity over time

A summary of mixed model results is presented in Table S2 in the Appendix, and longitudinal responses to the questions are shown in Figure 3. Across facilities, responses to both work intensity questions did not differ significantly between the EXO and the control groups. Responses to question Q1 were significantly affected only by the respective baseline value (β = 0.47, S.E. = 0.07, $p < 0.0001$). Responses to question Q2 were significantly affected by the respective baseline value (β = 0.65, SE = 0.07, $p < 0.0001$) and stature (β = -3.58, S.E. = 2.01, p = 0.076).

INSERT Figure 3 Here

3.3 Effects of EXO use on musculoskeletal discomfort (MSD) scores over time

Longitudinal MSD scores for the neck, shoulder, wrist, and low back are shown in Figure 4, and in Figures S1-S3 in the Appendix for the upper arm, forearm and the lower extremity. Across body regions and facilities, MSD scores were not significantly different between the EXO and the control group. MSD scores for each of the body regions considered (except the upper arm) were affected mainly by the respective baseline value (p = <0.0001–0.026). Shoulder MSD scores were also positively associated with body mass (β = 0.008, S.E. = 0.004, p = 0.075). Though not statistically significant, shoulder MSD scores in the EXO group decreased in a later phase of the study, compared to the control group. Upper arm, forearm and low back MSD scores were quite similar between the experimental groups, and upper arm and forearm MSD scores were generally low (median scores < 5), regardless of experimental groups. A summary of mixed model results is presented in Table S3 in the Appendix.

INSERT Figure 4 Here

4. Discussion

This study was the first, to our knowledge, to investigate the longitudinal effects of using an ASE in the field over a period of 18 months. Contrary to some existing evidence, our results suggest no clear effects of ASE use on work intensity or MSD scores. Rather, such effects varied substantially across participants, and depended on facilities and time (i.e., the duration of use). These results, in fact, suggest a need for further investigation on implementation strategies of exoskeletons in the field.

Arm-support exoskeleton (ASE) as a moderator to reduce physical demands

Earlier field studies have indicated that ASEs can reduce physical demands in an actual work environment, as evidenced by reductions in shoulder muscle activity [23,27] and in perceived strain in the neck and shoulders or MSD scores [21,24]. Our results, however, indicate that after accounting for age, body mass, stature, and job demand, using an ASE had little impact on perceived work intensity or MSD scores (Figure 3). Though there was no significant *EXO use* × *Facility* × *Time* interactions, some facilities exhibited exceptional patterns that are notable (see Figures S4-S7 in the Appendix). Examples of such exceptions are the S2 and L1 facilities, wherein neck MSD scores decreased in the EXO group over time, after the 6-month milestone (Figure S4). Also in the L1 facility, the EXO group showed a reduction in shoulder MSD scores at the 18-month milestone (Figure S4). These outcomes, with exceptions, agree with existing studies, though beneficial effects (i.e., reductions in MSD scores) were not immediate and were only observed after an extended period of ASE use (≥6 months). These current results – specifically the presence of only facility-specific beneficial effects of ASE use – may be unexpected, but should be considered in the context of several potentially influential aspects.

First, existing evidence indicates that the effects of ASE use are task specific [13,23,27]. Even for a job involving elevated arm postures, using an ASE can have a minimal or negative impact on physical demands at the shoulder. Gillette and Stephenson [23] examined ASE use for six different assembly jobs that involved prolonged elevated arm postures in two heavy equipment vehicle manufacturing facilities. They found that the beneficial effects of ASE use varied among these jobs, and that use at one job actually led to an increase in shoulder muscle activities. Similarly, De Bock et al. [27] reported no beneficial effects of ASE use during a warehouse job – placing windshields to a shoulder-level storage rack. In the current study, Ergonomics Specialists identified candidate overhead jobs (i.e., on an overhead line where the vehicle passed above the operators) that might have benefit from ASE use. It is possible that this identification process, based on the simple overhead job definition, was insufficient to identify beneficial use cases for the ASE; in practice, though specific selection criteria were developed, it would still be a challenge to select specific jobs following the criteria since participation was voluntary.

Second, the effects of ASE use on muscle activity levels varies substantially across users [e.g., 25,27]. Large confidence intervals were generally observed here for the MSD scores of each body region, and which may have been due to differences in anthropometry (e.g., body shapes) and the physical workplace across facilities. For example, even for comparable overhead jobs, participants may have adopted different body postures depending on aspects of the work environment (e.g., location of parts and physical space).

Third, the pattern of ASE usage was not controlled in the current study; as noted earlier, this was a result of the fact that participation was voluntary. Participants in the EXO group could use the ASE each shift for the duration they preferred. In other studies [12,23,27], an ASE was used for a prescribed duration. Smets [24] reported a mean estimated daily ASE usage of 7.6 h, though the usage duration was not prescribed. However, users in that study had a small team to support them, who could react quickly to issues of fit or comfort. In the current study, we initially implemented a mechanical counter to each ASE to monitor individual usage patterns, yet data from this were found to be unreliable. Participants were asked to self-report their daily usage pattern using a paper form, though the vast majority of participants failed to do so. Although systematic data collection efforts were not successful, it was clear that usage patterns were quite variable both within and between participants, such as using the ASE at a particular time during a shift (e.g., nearing the end of a shift), throughout a shift, or and/or a particular day (e.g., when feeling tired).

Fourth, and perhaps most important, Ford has a rigorous virtual ergonomics process that, by design, designed workstations to minimize the associated physical demands. According to the company’s ergonomic standards, operators performing overhead work are limited in the amount of time they can work overhead each cycle. As a result, the jobs examined here were deemed to have low-moderate risks, even though all involved overhead work and participants indicated that the intensity of their job is rather high (Figure 3). In such workspaces, it may be reasonable to expect that introducing an ergonomic intervention could lead to only slight improvements in perceived musculoskeletal discomfort. However, the fact that some benefits may have occurred (albeit small) supports the potential benefits of an ASE for overhead work tasks. To guide the adoption of ASEs, further investigation will be required to determine if such small reductions in perceived musculoskeletal discomfort leads to positive health outcomes. Our results also imply that ASEs might be more effective for work settings in which engineering controls cannot be easily modified/designed to reduce physical demands (e.g., construction, mining, building maintenance). Further investigation is clearly needed to better identify specific work environments that can maximize EXO benefits.

Unexpected effects of using an ASE on physical demands

ASE use had little impact on forearm, upper arm and low back MSD scores (Figure 4). When wearing an ASE, its structural components can cause high contact pressure when interfacing with the body parts of a wearer [27,50] and increase loads on a different body region such as the low back [16,50]. Such unwanted effects were not found here in terms of musculoskeletal discomfort (i.e., MSD scores), suggesting they may not be barriers to long-term ASE use as a workplace intervention. Interestingly, though limited to the S3 and M1 facilities (Figure E.1), wrist MSD scores for the EXO group remained consistent over time, whereas those for the control group increased over time. This divergence in scores may indicate that ASE use has a positive mediating influence, in that participants might have worked differently when using an ASE and thereby reduced cumulative wrist discomfort. Informally, participants noted an initial adjustment period in their movement patterns to adapt to ASE assistance. However, though specific to the

L3 facility (Figure E.4), such a change in work strategies/movement patterns may also have contributed to an increase in perceived work intensity, and which might be related to cognitive (e.g., ease of use) and utility aspects (e.g., disturbance to work processes), which are important components of exoskeleton acceptance [49].

Limitations

Though considerable efforts were made to coordinate and manage this large scale, long-term field study, data were missing to an increasing degree at the study milestones. 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). Caution should thus be exercised when generalizing the current results. As discussed above, usage patterns were not successfully obtained, it is unclear regarding the extent to which variability in outcome variables was caused by differences in usage patterns. When analyzing longitudinal effects, especially in the context of data whose missingness characteristics are probably related to dropout over time, it would be useful to consider alternative imputation strategies such as a conditional imputation where missingness itself is a function of group membership (EXO use or control), facility, or MSD levels. A more sophisticated timeseries model that accounts for current MSD levels as a function of prior MSD levels would also be interesting to study in a larger trial. Due to the limited data available, such approaches were not further explored in this study.

Furthermore, physical demands on the upper limbs were estimated only at the beginning of the study, and this estimation was rather simplistic (reflecting overall loading on the shoulder complex during a job). More detailed monitoring of physical demands throughout the study may have helped to delineate longitudinal effects of ASE use, and would have retrospectively contributed to enhanced job selection for ASE use. Future work should thus consider incorporating a method to log or monitor physical demands in the shoulder complex intermittently or continuously over an entire study period.

Conclusions

Longitudinal effects of ASE use on perceived physical demands were not found, though some suggestive results were evidence. This lack of a consistent finding may be due to the fact that the current workstations were already ergonomically optimized, but it also emphasizes important aspects of ASE implementation in the field. The current results could have arisen from a lack of systematic EXO implementation approaches for effectively selecting a job for ASE use while accounting for job characteristics, and individual and workspace differences. Some changes in perceived work intensity and wrist MSD scores were found with ASE use, which may indicate that using an ASE has an influence on how a worker performs their job. Future EXO implementation approaches should account for such influences and, ideally, quantify any changes in working methods as a moderating and/or medicating effect. Future studies will need to focus on systematic, evidence-based EXO implementations to bridge the gap between laboratory and field study findings, and we recommend that such studies include a broader range of tasks and reliable measures of exoskeleton usage. Such efforts will enhance the design of future exoskeleton devices that perform effectively across a broad range of individual characteristics, jobs, and workspace settings.

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Figure 1. Example of an assembly operator performing a task while using the EksoVest™ [33]

Figure 2. Illustration of missing data in each of the manufacturing facilities for the control group (Left) and the EXO group (Right), at each of the data collection milestones. Rectangles display the proportions of missing (dark grey) and non-missing (white) data, and the numbers in shaded boxes are the number of missing values.

Figure 3. Longitudinal responses to work intensity question **Q1** ("When I work, I really exert myself to the fullest") and **Q2** ("I feel exhausted at the end of shift") in each experimental group. Points in the graphs are median values estimated from mixed using the imputed dataset, and error bars are 95% confidence intervals. Note that responses were obtained on a scale of 0 (strongly disagree) to 10 (strongly agree).

Figure 4. Longitudinal **neck**, **shoulder**, **wrist**, and **low back** MSD scores in each experimental group. Points in the figure are median values estimated from mixed models using the imputed dataset, and error bars are 95% confidence intervals.