Effects of an arm-support exoskeleton on perceived work intensity, discomfort, usability, acceptance, and health outcomes: Results from an 18-month field study in automotive assembly

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A Team Effort

Ford EXO Governance Team

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Patty Racco | TS
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Carlo Bishop | NJCHS
Robb Miller | NJCHS
Sean Coughlin | NJCHS

Virginia Tech Research Team

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A Quick Overview

- **What**: Field trial to assess the protective benefits of a wearable arm-support exoskeleton (ASE)
- **Context**: Ford Assembly plants in the US, work requiring prolonged/repetitive arm elevation (“overhead” work)
- **Study Design**: 18-month prospective trial
- **Sample**: workers given ASEs + others as a control group
- **Diverse Outcome Measures**: subjective responses, medical visits

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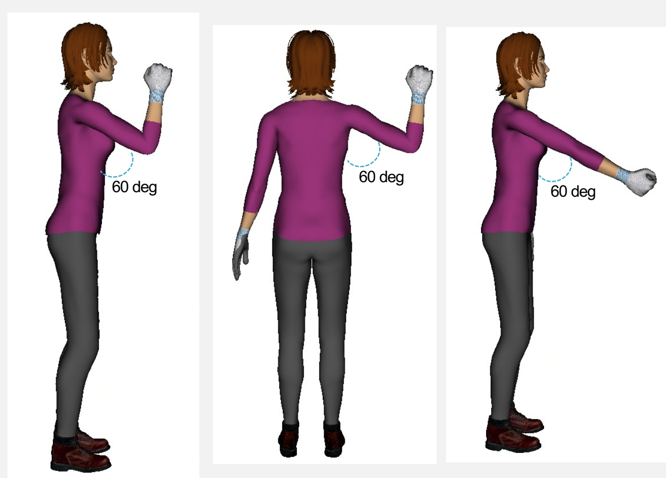
Overhead work is a major risk factor for shoulder MSDs[1,2]

Overhead work **defined as** any work performed with the hands above the acromion or >60° shoulder flexion or abduction[3]

Overhead work is often an unavoidable part of job tasks

- e.g., for electricians, automotive assembly workers, carpenters



[1] Buckle & Devereux (2002) [2] Nordander et al. (2016)
[3] Grieve & Dickerson (2008)

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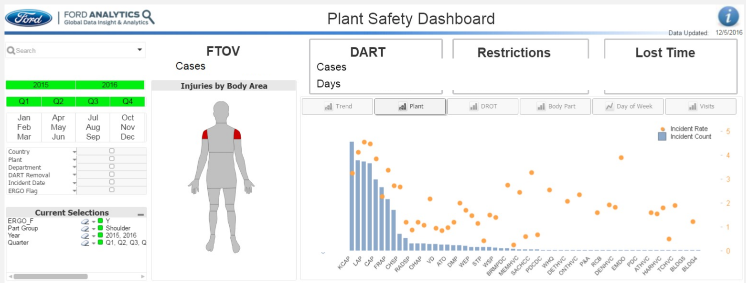
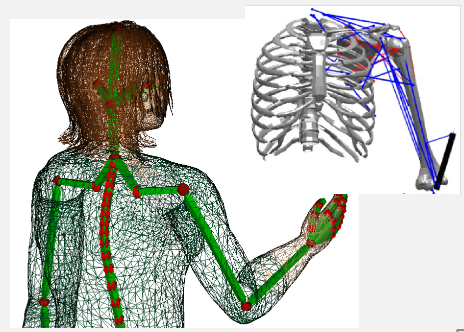
Shoulders continue to be one of the most injured body regions, and one of the costliest to return to full functionality



Current shoulder biomechanical models lack important anatomical detail



Shoulder Injury Costs and Projected ROI

- Across lost time categories, shoulders are one of the most commonly-injured joints and are very costly to return to full functionality
- A single shoulder injury is >10x the cost of 1 arm-support EXO

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Lab- and field-based evidence of effects of arm-support exoskeleton (ASE) use

- **Beneficial** effects[1,2,3,4]
  - Decreased activity in shoulder and neck muscle groups
  - Decreased discomfort and perceived exertion
  - Improved arm steadiness
- **Concerns**[5,6,7]
  - Thermal discomfort
  - Movement restrictions
  - Discomfort at pressure points
  - User acceptance and use-intention

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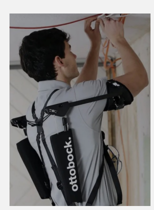
eksobionics.com



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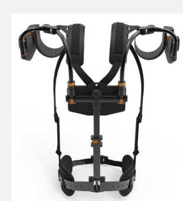

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[1] Gillette & Stepheson (2019) [2] Motmans et al. (2019)
[3] Smets (2019) [4] Spada et al. (2017)
[5] Marino at al. (2019) [6] Amandels et al. (2019)
[7] Ferreira et al. (2020)

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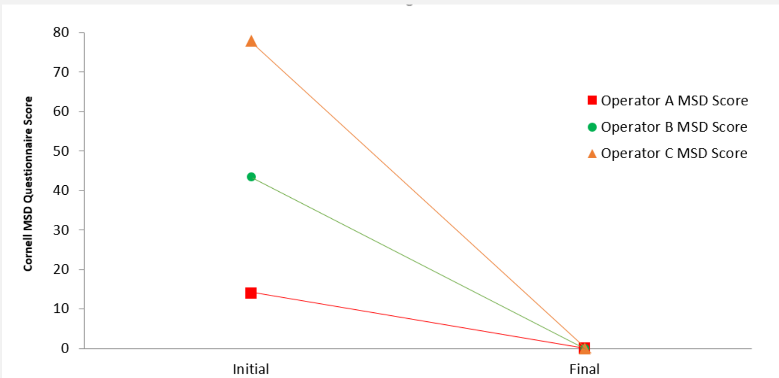
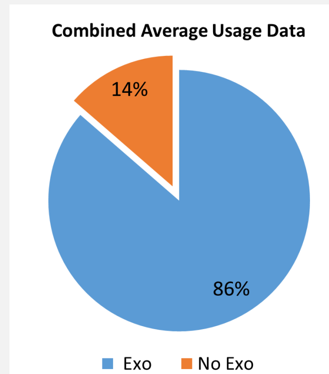
Three-month pilot study at two plants (2018) suggested reduced MSD symptoms and strong self-regulated ASE use[1]





MSD symptom changes across 90 days of daily EXO use during overhead work

Average use: 7.7 hours/day or 86% of a shift

[1] Smets, 2019

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DOI: 10.1080/24725838.2018.1563010

APPLICATION

Check for updates

A Field Evaluation of Arm-Support Exoskeletons for Overhead Work Applications in Automotive Assembly

Marty Smets
Technical Expert - Human Systems and MFG Virtualization Advanced Digital Engineering | FORD Motor Company, Glendale, MI, USA

OCCUPATIONAL APPLICATIONS The results of this field trial suggest that when made available for optional usage during overhead automotive assembly, arm-support exoskeletons can lead to a substantial decrease in self-reported musculoskeletal discomfort in the neck and shoulders. Participants (assembly operators) chose to use the device for 86% of their shift and indicated they would continue to use it daily if provided the opportunity. The results of this investigation suggest that when used alongside a traditional proactive ergonomics program, arm-support exoskeletons may reduce some risk factors associated with the development of shoulder injuries. The approach presented may be useful for practitioners that are starting to explore arm-support exoskeletons in their workplace. Several areas of improvement were highlighted for future design consideration, including further reducing weight and improving thermal comfort.

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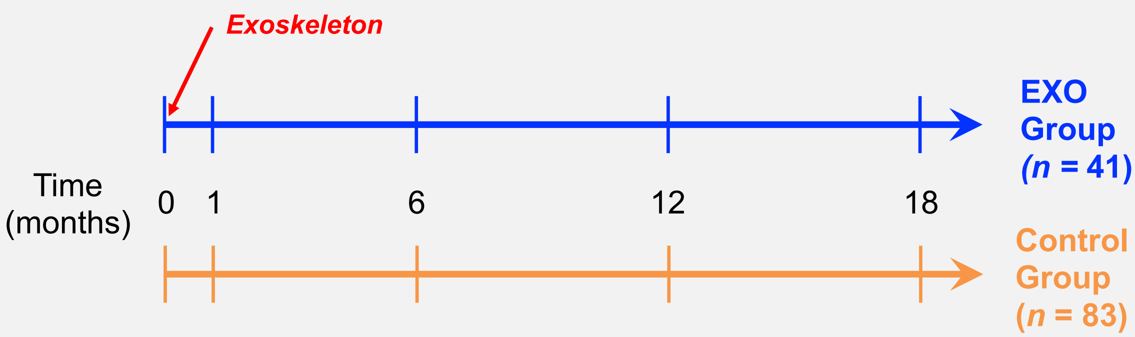
Study Design: Prospective & Controlled

1. Follow a group of workers forward in time
2. Two groups: provided an EXO or not (control)
3. Establish a “baseline” and track up to 18 months
4. Data collection milestones: Baseline (0), 1, 6, 12, and 18 months



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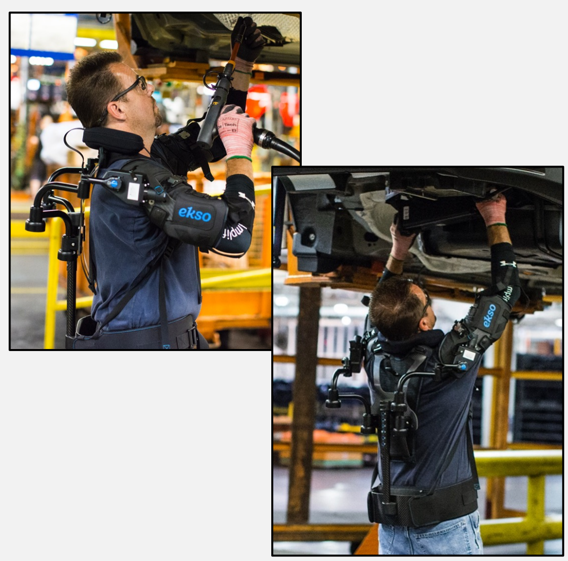
ASE Used: EksoVest (Ekso Bionics, Inc.)

- **Mass**
  - 4.3 kg
- **Assistance**
  - Four support levels
- **Adjustable**
  - Trunk length, waist belt length, & arm cuff
- **Training**
  - Baseline: Ekso Bionics rep. – for customized fit and EXO donning, doffing, & use
  - During the study: Local Ergo Specialists



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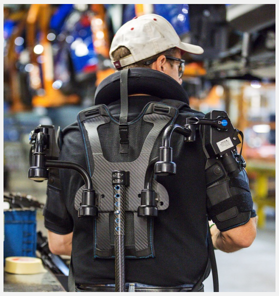
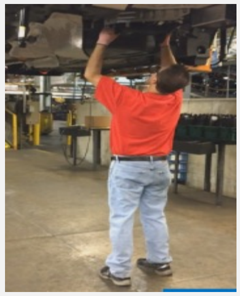
EXO vs. Control Groups



Subjects:
Operators using EXOs



Controls:
Operators performing daily overhead work but NOT using EXOs

Design Aspects

- Recruitment from 7 facilities
- Candidate tasks selected based on likely ASE effectiveness
- Participation was voluntary
- Screened for prior shoulder MSDs
- EXO use was voluntary
- No random assignment

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Diverse Outcome Measures Obtained

- **Worker level**
  - Age, gender, stature, body mass
- **Task level**
  - Physical demands (tools, duty cycle, …); quantified using revised OCRA[1]
- **Subjective responses**
  - Work intensity (10-point scales); Musculoskeletal symptoms (Cornell MS Discomfort Questionnaire[2])
- **Usability Reponses**
  - Comfort, ROM, Safety, Performance (10-point scales)
  - Open-ended responses
  - Usage rates
- **Health-related data**
  - Medical visits

EXO Group only

[1] Colombini et al. (2013)
[2] ergo.human.cornell.edu

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Groups were initially similar in several dimensions

	EXO Group					Control Group				
Facility	***n***	**Age (years)**	**Body mass (kg)**	**Stature (m)**	**Job demand**	***n***	**Age (years)**	**Body mass (kg)**	**Stature (m)**	**Job demand**
S1	10	40 (9)	93.0 (14.1)	1.76 (0.03)	22.8 (0.2; 5)	14	39 (10)	97.5 (27.9)	**1.80 (0.10)**	**16.4 (11.0; 8)**
S2	5	38 (13)	83.9 (10.0)	1.78 (0.07)	20.7 (7.0; 5)	12	45.5 (17.2)	89.6 (6.0)	1.76 (0.12)	17.6 (2.7; 4)
S3	5	25 (5)	74.4 (25.4)	1.78 (0.08)	23.8 (6.2; 3)	8	27 (6)	78.2 (9.7)	1.79 (0.09)	29.2 (2.0; 5)
M1	5	43 (6)	83.0 (22.6)	1.78 (0.10)	23.7 (3.4; 4)	10	44 (6.5)	89.6 (26.5)	1.72 (0.11)	23.1 (1.8; 8)
L1	5	31 (3)	77.1 (18.6)	1.78 (0.05)	20.8 (9.0; 5)	12	37 (6.3)	82.8 (13.3)	1.75 (0.08)	20.9 (10.3; 12)
L2	7	30 (16.5)	80.6 (19.3)	1.70 (0.14)	21.4 (9.5; 3)	12	31 (7.5)	88.5 (22.7)	1.78 (0.09)	24.7 (11.7; 8)
L3	4	46.5 (0.5)	84.0 (14.1)	1.74 (0.05)	–	15	44 (11.5)	71.4 (22.8)	1.70 (0.12)	22.8 (5.4; 9)
Overall	41	38 (15)	83.9 (21.6)	1.78 (0.1)	22.8 (7.0)	83	38 (15)	86.2 (23.5)	1.75 (0.10)	17 (8.6)

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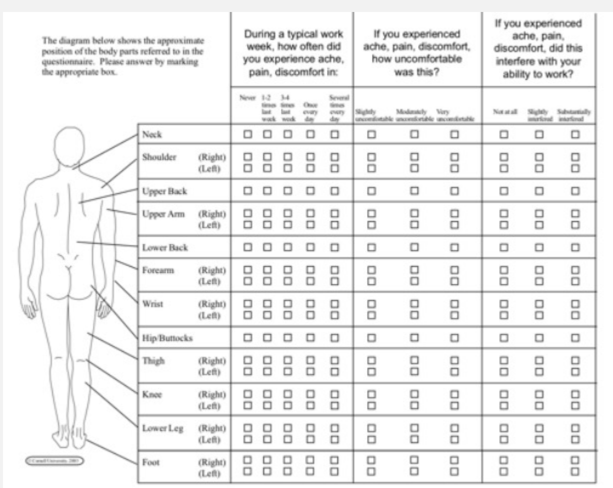
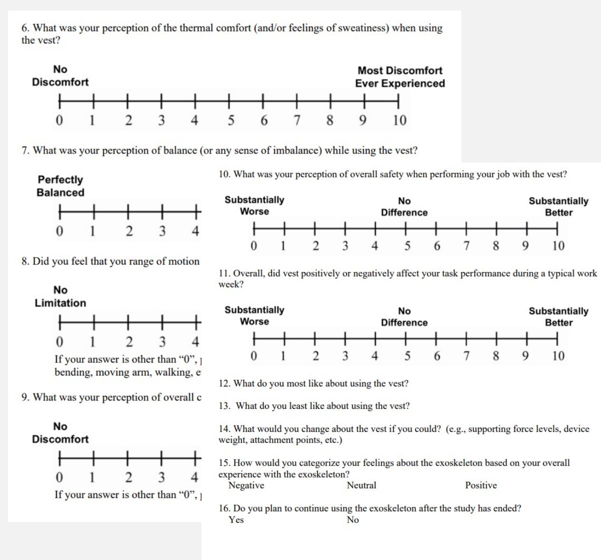
Questionnaires


The diagram below shows the approximate position of the body parts referred to in the questionnaire. Please answer by marking the appropriate box.

	During a typical work week, how often did you experience ache, pain, discomfort in:	If you experienced ache, pain, discomfort, how uncomfortable was this?	If you experienced ache, pain, discomfort, did this interfere with your ability to work?
	Never / 1-2 times last week / 3-4 times last week / Once every day / Several times every day	Slightly uncomfortable / Moderately uncomfortable / Very uncomfortable	Not at all / Slightly interfered / Substantially interfered
Neck			
Shoulder (Right) (Left)			
Upper Back			
Upper Arm (Right) (Left)			
Lower Back			
Forearm (Right) (Left)			
Wrist (Right) (Left)			
Hip/Buttocks			
Thigh (Right) (Left)			
Knee (Right) (Left)			
Lower Leg (Right) (Left)			
Foot (Right) (Left)			

Cornell MSD Questionnaire to measure MS symptoms


6. What was your perception of the thermal comfort (and/or feelings of sweatiness) when using the vest?
No Discomfort — Most Discomfort Ever Experienced: 0 1 2 3 4 5 6 7 8 9 10

7. What was your perception of balance (or any sense of imbalance) while using the vest?
Perfectly Balanced: 0 1 2 3 4

8. Did you feel that you range of motion
No Limitation: 0 1 2 3 4
If your answer is other than "0",
bending, moving arm, walking, e

9. What was your perception of overall c
No Discomfort: 0 1 2 3 4
If your answer is other than "0",

10. What was your perception of overall safety when performing your job with the vest?
Substantially Worse — No Difference — Substantially Better: 0 1 2 3 4 5 6 7 8 9 10

11. Overall, did vest positively or negatively affect your task performance during a typical work week?
Substantially Worse — No Difference — Substantially Better: 0 1 2 3 4 5 6 7 8 9 10

12. What do you most like about using the vest?

13. What do you least like about using the vest?

14. What would you change about the vest if you could? (e.g., supporting force levels, device weight, attachment points, etc.)

15. How would you categorize your feelings about the exoskeleton based on your overall experience with the exoskeleton?
Negative Neutral Positive

16. Do you plan to continue using the exoskeleton after the study has ended?
Yes No

Questions adopted from earlier work to assess work intensity and aspects of usability

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RESEARCH ARTICLE

AMERICAN JOURNAL OF INDUSTRIAL MEDICINE WILEY

Effects of an arm-support exoskeleton on perceived work intensity and musculoskeletal discomfort: An 18-month field study in automotive assembly

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Funding information

Ford Motor Company

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 a 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

ergonomic intervention, manufacturing, musculoskeletal discomfort, perceived physical demand, prospective study

Institution at which the work was performed: Ford Motor Company and Virginia Tech.

Am J Ind Med. 2021;64:905–914. wileyonlinelibrary.com/journal/ajim 905

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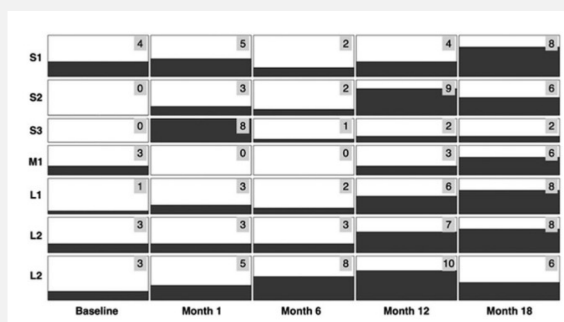
Analysis approach

- **Statistical models**
  - Linear mixed models
  - Adjusted for baseline, age, body mass, stature, and estimated physical demand
- **Imputation used to address missing data**
  - Roughly 40% missing overall
  - Imputation x200, using Multivariate Imputation by Chained Equation (MICE) in R software
  - Unbiased when data missing at random



Missing data (black) at each milestone and in each facility (control group)

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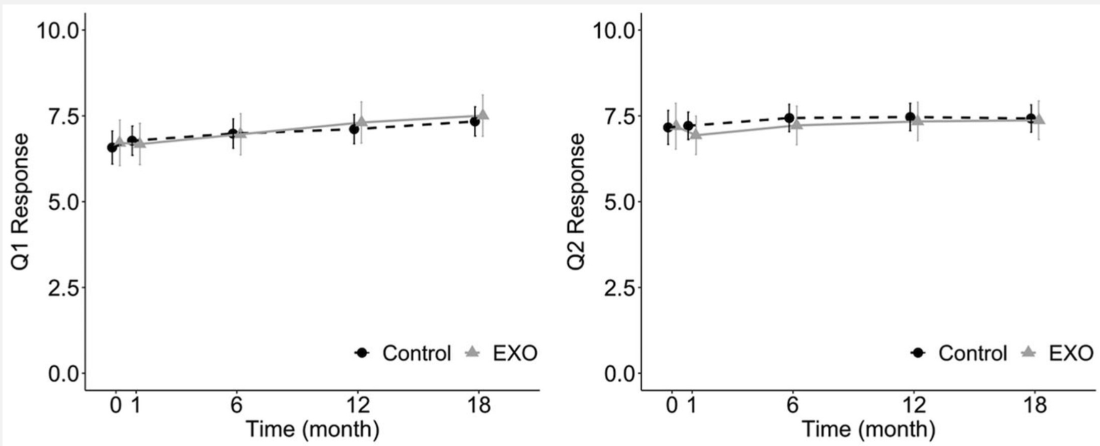
Perceived work intensity was unaffected by EXO use

"When I work, I really exert myself to the fullest" (10 = agree)

"I feel exhausted at the end of a shift" (10 = agree)



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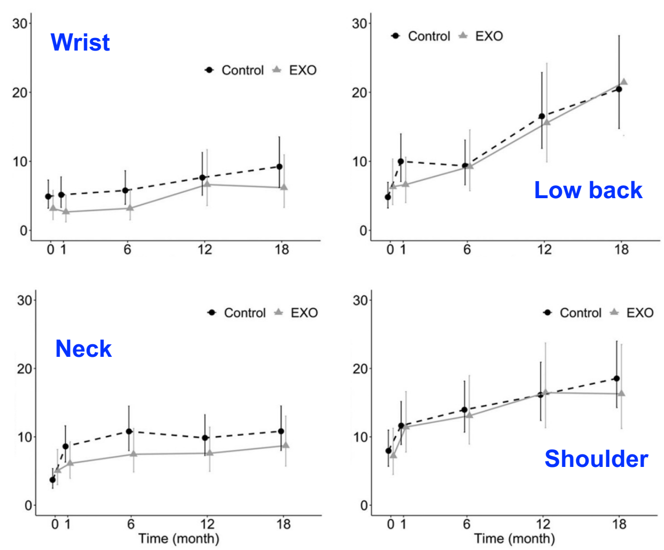
MSD scores overall did not differ significantly between groups



- Results are suggestive for neck and shoulder
- No evidence for adverse effects overall
- Some distinct effects in specific facilities

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Discussion

- **No clear effects of ASE use on perceived work intensity or MSD scores**
  - These effects varied across participants and between facilities, and over time
- **Some facilities had exceptional patterns**
  - Some evidence for beneficial effects (↓ MSD scores)
  - Typically, after extended use (≥6 months)
- **Caution needed in interpreting results**
  - Imputation approach assumed no systematic pattern in “missingness”
  - Somewhat simplistic approach to estimating physical demands
  - ASE use may have affected job demands (changing work methods)

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FAST TRACK ARTICLE

Usability, User Acceptance, and Health Outcomes of Arm-Support Exoskeleton Use in Automotive Assembly

An 18-month Field Study

Sunwook Kim, PhD, Maury A. Nussbaum, PhD, and Marty Smets, MS

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, overhead work, prospective study, wearable robot

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 seven lost workdays for back problems).[1] The shoulder is among the body regions involving the highest cost per US 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.[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 (eg, deltoid and trapezius muscle groups), perceived exertion, and localized muscle fatigue.[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 (eg, 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 (ie, not just lifting), and that an actual work environment can be more challenging than a typical laboratory (eg, heat, noise, work pressure). Hensel and Keil[24] noted that using a BSE can be a distraction during auxiliary tasks, negatively influencing perceived usability and user acceptance (ie, 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 less than 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

From the Department of Industrial & Systems Engineering, Virginia Tech, Blacksburg, Virginia (Dr Kim, Dr Nussbaum); Manufacturing Technology Development, Ford Motor Company, Glendale, Michigan (Mr Smets).

Funding Sources: Support for this work was provided by an “Alliance” grant from Ford Motor Company to Virginia Tech.

Conflicts of interest: None declared.

Ethical Consideration & Disclosure(s): This study was reviewed and approved by the National Joint Committee for Health and Safety at Ford Motor Company and by the Institutional Review Board at Virginia Tech (VT IRB#: 18–353). All participants were recruited voluntarily and gave verbal consent for study participation.

Clinical significance: In an 18-month study of arm-support exoskeleton (ASE) use in automotive manufacturing, usability responses were consistent over time and ASEs appeared effective in reducing physical demands. Perceived performance, and fit and comfort, were key determinants for ASE intention-to-use. ASE use also may decrease the likelihood of a work-related medical visit.

Supplemental digital contents are available for this article. Direct URL citation appears in the printed text and is provided in the HTML and PDF versions of this article on the journal’s Web site (www.joem.org).

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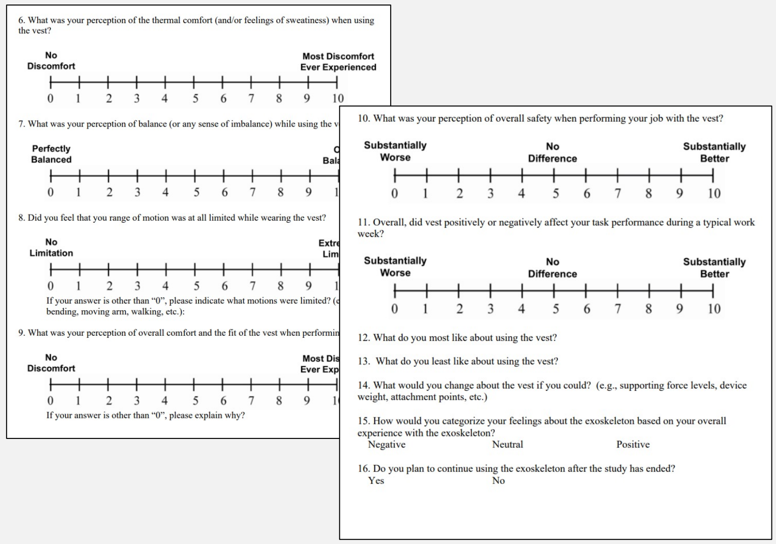
Usability themes assessed at all milestones

- Overall fit and comfort
- Thermal comfort
- Balance
- Range of motion
- Job safety
- Job performance
- Likes/dislikes/changes
- Open-ended questions



6. What was your perception of the thermal comfort (and/or feelings of sweatiness) when using the vest?

No Discomfort — Most Discomfort Ever Experienced

0 1 2 3 4 5 6 7 8 9 10

7. What was your perception of balance (or any sense of imbalance) while using the v

Perfectly Balanced — C Bala

0 1 2 3 4 5 6 7 8 9 1

8. Did you feel that you range of motion was at all limited while wearing the vest?

No Limitation — Extre Lim

0 1 2 3 4 5 6 7 8 9 1

If your answer is other than "0", please indicate what motions were limited? (e bending, moving arm, walking, etc.):

9. What was your perception of overall comfort and the fit of the vest when performin

No Discomfort — Most Dis Ever Exp

0 1 2 3 4 5 6 7 8 9 1

If your answer is other than "0", please explain why?

10. What was your perception of overall safety when performing your job with the vest?

Substantially Worse — No Difference — Substantially Better

0 1 2 3 4 5 6 7 8 9 10

11. Overall, did vest positively or negatively affect your task performance during a typical work week?

Substantially Worse — No Difference — Substantially Better

0 1 2 3 4 5 6 7 8 9 10

12. What do you most like about using the vest?

13. What do you least like about using the vest?

14. What would you change about the vest if you could? (e.g., supporting force levels, device weight, attachment points, etc.)

15. How would you categorize your feelings about the exoskeleton based on your overall experience with the exoskeleton?
Negative Neutral Positive

16. Do you plan to continue using the exoskeleton after the study has ended?
Yes No

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Additional questions @12 and 18 months

- **Feelings about the ASE (positive / neutral / negative)**

  "How would you categorize your feelings about the exoskeleton based on your overall experience with it?"

- **Intention to use the ASE (yes / maybe / no)**

  "Do you plan to continue using the exoskeleton after the study has ended"

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Medical visits

- **All medical visits to onsite plant nurse**
  - Recorded by facility occupational health personnel
  - Followed standard health and safety & injury management process
- **Analysis based on:**
  - First time occupational visits (FTOVs)
  - Only if reported concern categorized as “ergonomics” related, and:
    - associated with sprains/strains
    - occurred in upper extremity or back
    - excluded incidents involving the fingers

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Analysis approaches

- **Usability question responses**
  - Generalized estimating equations (GEEs)
  - Independent variables: *Facility* and *Time*
  - Responses assumed to be on an interval scale[1]
- **Open-ended responses**
  - Word frequency analysis
- **Use intention**
  - Decision tree to identify predictors
- **Medical visits**
  - Cox proportional hazards regression analysis
  - Age, body mass, stature included as covariates

[1] Wu & Leung (2017)

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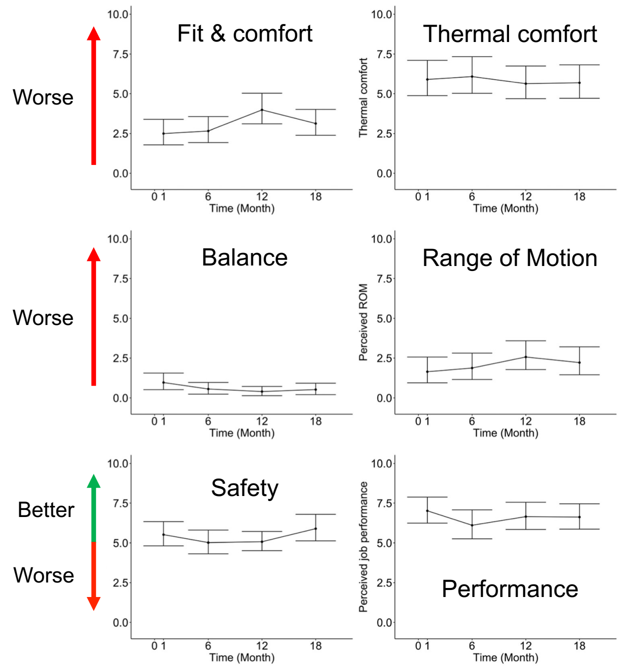
Usability responses typically consistent over time and across facilities

- Minor concerns about overall fit and discomfort
- Moderate-high concerns with thermal discomfort
- Minimal concerns with balance
- Minor concerns with range of motion
- Same or slightly better perceived job safety
- Slightly better job perceived job performance



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Most frequent words in open-ended responses

Overall fit & comfort (*n*=109)	cuff, hot, rubbing, waist belt, rigid/stiff, bulky
Balance (*n*=14)	bend forward, trunk twist, ML balance, squat
ROM (n=83)	Reach, trunk bending/twisting, sitting/squatting, arm motion, stretching
Job safety (*n*=46)	Snag hazard, less strain, bulky, posture, drop material
Job performance (*n*=87)	Less pain (shoulder/arm/neck), less fatigue, arm assistance

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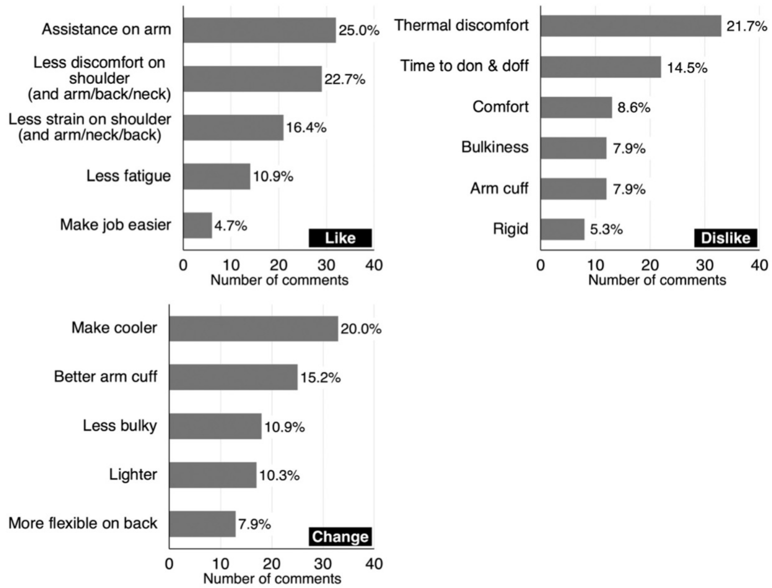
ASE: Likes, dislikes, and suggested changes



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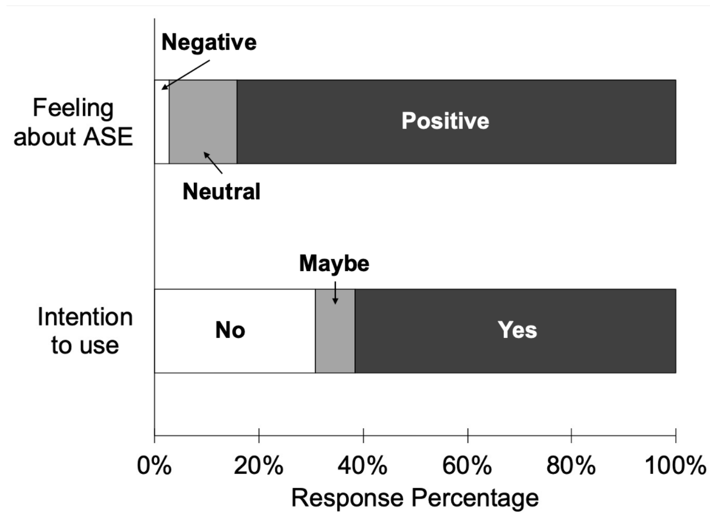
ASE: Feelings about and use-intention



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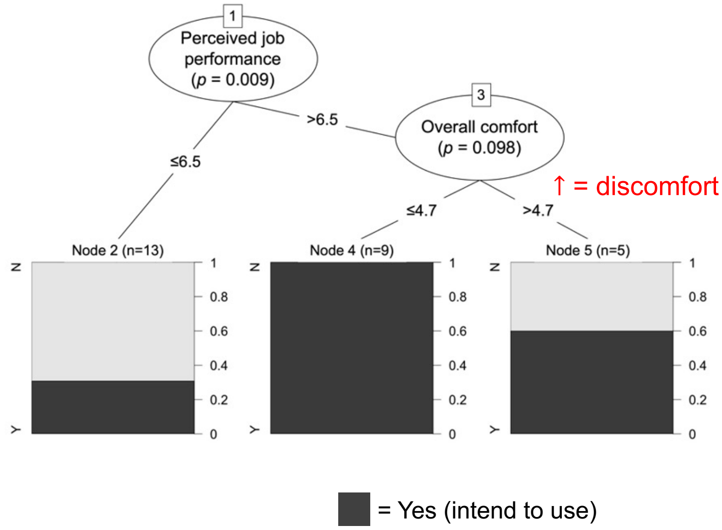
Use-intention best predicted by improved job performance and high overall comfort



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Medical Visits

- Across 7 facilities and 18 months
  - 41 visits in the control group
  - 6 in the EXO group
- Most common body parts reported:
  - Shoulder and wrist
- None of the included visits → DAFW

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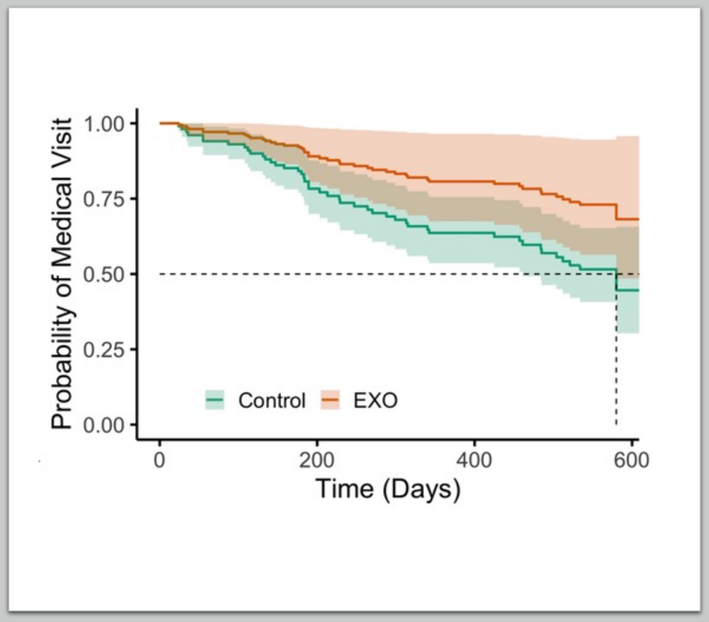
Probability of a medical visit affected by age & EXO use

- *P* (medical visit)
  - ↓ 5% with unit-increase in age
  - ↓ 52% using the ASE
- **Median survival duration**
  - Control: ~580 days
  - EXO: not reached



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Discussion

- Responses to **thermal comfort, perceived balance,** and **perceived ROM** consistent over time
- Responses to **overall fit and discomfort** and **overall job safety** statistically changed at Month 12
- Responses to **job performance** were somewhat better at Month 1 (potential novelty effect)
- Only 62% of participants indicated an ASE use-intention, though a majority (~84%) expressed positive feelings about it
- Intention-to-use was positively associated with perceived usability, comfort, and perceived benefit (performance)[1,2,3]

[1] Hensel & Keil (2019)
[2] Moyon et al. (2019)
[3] de Looze et al. (2016)

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Challenges Experienced

- Missing data (e.g., turnover)
- Data collection
- Characterizing job demands
- Tracking EXO usage

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Considerations for future work

1. Study design did not include **randomization**
2. Why were **exceptional results** obtained in some facilities?
3. Quantifying **changes in work methods** with ASE use
4. Jobs examined likely had only low-moderate risks (i.e., was there **limited room for improvements**?)
5. Are even **longer-term studies** needed (i.e., WMSDs vs. visits)?
6. How to **identify relevant use-cases** (and use-intention)?
7. Did not consider **psychosocial aspects** (e.g., liked/disliked attention)
8. ASE **technologies are evolving**

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Acknowledgements

- This work was supported though the Ford-VT Alliance Program
- Any opinions expressed here do not necessarily represent those of Ford Motor Company

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