Proceedings of the
2018 Ergo-X Symposium

Exoskeletons in the Workplace — Assessing Safety, Usability, and Productivity

October 1, 2018 — Philadelphia, Pennsylvania

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NIOSH [2019] Proceedings of the 2018 Ergo-X Symposium: Exoskeletons in the Workplace — Assessing Safety, Usability, and Productivity. By Lowe B, Billotte W, Brogmus G, McDowell T, Reid C, Rempel D, Srinivasan D (Editors). Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2020-102, https://doi.org/10.26616/NIOSHPUB2020102.

DHHS (NIOSH) Publication No. 2020-102

DOI: https://doi.org/10.26616/NIOSHPUB2019102

October 2019

Preface

Exoskeletons and Exosuits are wearable technologies designed to augment the human musculoskeletal system to improve physical performance. Their potential value extends across disciplines, and includes improving industrial worker capabilities and enhancing medical rehabilitation. The concept is not new; patent designs are traceable to the 1800s. but they moved from science fiction to reality in the 1970s with research and development by the military to enhance warfighter capabilities and have taken off in the past decade in the industrial sector with improved designs and materials. Now many manufacturers are investing heavily in the evaluation of exoskeletons for assembly and warehouse jobs to reduce fatigue and injury and improve productivity. In response to the rapid market growth, industrial users and researchers unified in late 2017 to form the ASTM **F48 Exoskeletons and Exosuits** Standards Committee to create guidelines on the safe design and adoption of this wearable technology.

For the past 3 years, Boeing, Ford, Toyota, and BMW on the private industry side, Navy and Army on the military side, and a number of medical institutions, have been conducting research on exoskeleton and exosuit technology. This work, including user assessment and implementation findings has been primarily internalized to each institution, though some of their broader findings have been shared publicly. During discussions in early 2018 with ASTM F48 and the Human Factors & Ergonomics Society (HFES) executive leaderships, it became apparent that there was an opportunity for both organizations and their members to leverage each other's expertise to help accelerate exoskeleton and exosuit design and standards using human factors and ergonomics principles in user-centered design. These principles were already being actively explored in the ASTM F48.02 subcommittee task groups on exoskeleton and exosuit anthropometric size and shape, usability, ergonomics, safety, and training.

This joint coordination and planning led to the first national symposium, titled "ErgoX Symposium: Exoskeletons in the Workplace – Assessing Safety, Usability, & Productivity," which was held on October 1, 2018 prior to the Human Factors & Ergonomics Annual Meeting in Philadelphia, PA. The ErgoX symposium provided a forum for designers, users and researchers to share insights and findings in a public setting on human factors issues related to exoskeleton and exosuit technology. The format included TEDx style presentations with discussion panels and product interaction with developers and vendors in the same floor space. Experts from the military, medical, and industrial domains participated as users, developers, regulatory, or university sector speakers and attendees.

The content of the symposium attracted support and participation from many companies (e.g. Liberty Mutual, Boeing, Mawashi, Levitate), U.S. Federal agencies, (e.g. NIST, FDA, NIOSH, VA, etc.), universities, international Federal agencies, and scientific bodies (National Academy of Sciences). With a little over 130 attendees, this initial symposium included both US (84%) and non-US (16%) attendees, with from the latter comprising eight countries in Europe, Asia, and the Caribbean. The majority of attendees were from private industry (34%), followed by academia (29%), government (27%), and then exoskeleton developers (8%). Based on exoskeleton domain of interest, attendees and their organizations were grouped into the industrial (61%), military (27%), and medical (10%) representations.

This report summarizes important points made by presenters and panelists. the success of the exoskeleton and exosuit symposium and the rapid rate of development of this technology and research has led the organizers to plan another Symposium prior to the next HFES meeting in Seattle, Washington on October 28, 2019, continuing in subsequent years. Lessons learned from this year will carry forward into the program for 2019, with the intention to continue to demonstrate iterative progress for user-centered design and industry standards.

Christopher R. Reid, PhD
Secretary-Treasurer, Human Factors and Ergonomics Society, Symposium Chair

David Rempel, MD
Symposium Co-Chair

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President, Human Factors and Ergonomics Society, Symposium Co-Chair

Executive Summary

The *Proceedings of the 2018 Ergo-X Symposium: Exoskeletons in the Workplace* have been assembled to disseminate the speakers' presentations and to summarize the question and answer/discussion periods that followed the presentations within each session. The proceedings appear by session and include summary points with links to presentation slides from speakers who agreed to provide them. The Ergo-X Proceedings Editors identified and documented the summary points and gave presenters of specific content (such as keynote presentations) an opportunity to review, edit, and approve the content.

Here are some of the key summary points from the 2018 Ergo-X Symposium:

- Metabolic demand may be a predictor of fatigue onset; however, we need a better understanding of how the positive or negative effect of an exoskeleton on metabolic demand affects injury prevention/risk.
- The fit of the exoskeleton system is complex. Static assessments of fit that do not consider task dynamics are insufficient; multivariate anthropometric data are critical to fit.
- Simulation and digital human modeling technologies have potential use in (1) assessing the interface between the user and exoskeleton and (2) reducing the test and evaluation burden of using human subjects.
- Existing exoskeleton systems require a period of adaptation by the end user. For a new user, task performance is not likely to reach a steady state immediately. We need to establish acceptable test durations for exoskeleton trials.
- Cognitive and psychomotor effects of exoskeleton use have been observed and are likely task dependent.
- Industrial exoskeleton designs should be compatible with off-the-shelf tools, equipment, and personal protective equipment, rather than relying on specialty tools and custom interfaces.
- Although industry speakers presented examples of wider-scale deployment of overhead support exoskeletons, overhead work with tool support appears to be the most mature industrial-use case at present.
- The FDA oversees devices marketed/prescribed for medical use. Early adoption of medical exoskeletons may be more promising among individuals who are less adapted to other mobility-assistive technologies for their disabilities.
- In the rehabilitation domain, clinics can utilize exoskeletons to assist therapists in delivering appropriate therapeutic doses.
- ASTM Committee **F48 on Exoskeletons and Exosuits** and other standards organizations offer a forum for sharing exoskeleton knowledge.

Feedback gathered from attendees and participants revealed 19 different topics (see the word cloud) that were issues or concerns for exoskeleton developers, researchers, and end users in 2018 and moving forward. The top four topics were (1) return on investment (ROI) considerations; (2) size, shape, and fit of exoskeletons on users; (3) longitudinal effects of exoskeleton usage; and (4) "What metrics are right?" for measuring safe, effective, or reliable system design and integration for users or patients.

Technology needs, gaps, and concerns of the 2018 Ergo-X Symposium participants.

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Acknowledgments

Important contributors to the development of this document were Lois Smith and Julie Freeman (former HFES administration); Steve Kemp, HFES; and Dawn Castillo, Hongwei Hsiao, Kathleen Goedel, Seleen Collins, Elizabeth Clements, and Vanessa Williams, NIOSH.

Ergo-X Symposium sponsorship was provided by the following:

Liberty Mutual Insurance

The Boeing Company

Mawashi Science & Technology

Levitate Technologies, Inc.

ASTM International

Northern Illinois University

National Academy of Sciences, Board on Human Systems Integration

List of Speakers by Session

Session	Speakers
Keynote 1 (morning)	Bruce Floersheim, GoXStudio
Opening Session	William Billotte, NIST
Keynote 2 (afternoon)	Sudhakar Rajulu, NASA Johnson Space Center
Exoskeleton User Discussion Panel	Kendra Betz, U.S. Veterans Affairs Robert Schram, Toyota Ron Zmijewski, U.S. Navy Human Assistive Technology Moderator: Robert Fox, General Motors
Research Methods 1—Design for Population Accommodation & Performance	Monica Jones, University of Michigan Joseph Parham, U.S. Army Natick Soldier Research Development & Engineering Center (NSRDEC) Lei Stirling, Massachusetts Institute of Technology Moderator: Krystyna Gielo-Perczak, University of Connecticut
Exoskeleton Developer Discussion Panel	Brandon Frees, Ekso Bionics Chris Beaufait, Sarcos Robotics Marty Linn, General Motors Ignacio Galiana, Harvard Wyss Institute Moderator: Christopher Reid, The Boeing Company
Research Methods 2—Assessing System Usability	Alix Dorfman, Underwriters Lab (UL), Wiklund Kadon Kyte, The Boeing Company Kevin Purcell, U.S. Army Public Health Center Moderator: Carisa Harris-Adamson, University of California, San Francisco/University of California, Berkeley

Session	Speakers
Research Methods 3—Assessing Safety	Ian Marcus, U.S. Food & Drug Administration Roger Bostelman, NIST Angela Boynton, U.S. Army Research Laboratory Moderator: Brian Lowe, NIOSH
Research Methods 4—Assessing Ergonomics	Marty Smets, Ford Motor Company Maury Nussbaum, Virginia Tech Karen Nolan, Kessler Foundation Moderator: Cathy White, Dow Chemical Company
Closing Discussion Panel	Delia Treaster, Ohio Bureau of Workers Compensation Gerard Francisco, TIRR Memorial Hermann Hospital Donald Peterson, Northern Illinois University/ASTM Committee F48 on Exoskeletons and Exosuits Moderator: Cindy Whitehead, U.S. Navy–Naval Sea System Command

Editors' Note: The symposium organizers invited all speakers to submit their presentation content and to include this content in session summaries. The presentation slides and summaries included here are for speakers who gave permission to include their content.

Conference Sessions

Session Title

Keynote 1, *Wearable Robotic Systems: Global Landscape and Opportunities*

View the slides: https://higherlogicdownload.s3.amazonaws.com/HFES/42fffbb4-31e1-4e52-bda6-1393762cbfcd/UploadedImages/Keynote_Bruce_Floersheim.pdf

Speaker

Bruce Floersheim, WearRAcon/GoXStudiom

Summary Points

- A show of hands indicated the audience was a relatively equal mix of government, industry, and academia.
- The "wow factor" of exoskeleton technology helps from a marketing standpoint. In addition, the movie industry has increased the technology's visibility.
- Drivers of the industry include public curiosity and the fact that people are living longer. As their bodies break down, they still want to be able to do the same activities, and therefore the technology has advanced.
- North America is playing a bit of a catch-up game in comparison with the rest of the world in this arena. Europeans and Asians have been doing this work on a scale that is more organized and integrated.
- Insurance costs are increasing across the board. Insurance companies are showing more interest in these technologies.
- Many labs are focusing on "return function," that is, trying to return some function to users such as stroke survivors and patients with paraplegia.
- This goal is common for lower-body systems.
- An "enhance function" focus puts emphasis on fully functioning users and taking them to increased capability.
- The desire for enhanced quality of life is slowly trickling into this technology.
- Getting access to the technology will be a factor in consumer adoption; industrial users will be the first and main adopters.
- Large companies are procuring systems and testing them in warehousing and manufacturing facilities.

- Computing feedback and controlling the feedback loop are important factors for fully optimizing and individualizing the technology for particular wearers.
- At present, the power source is probably the Achilles heel (weak point).
- We need to figure out better ways to provide power in order to shrink the size and cost of systems.
- Industry is leading the drive to promote development and adoption of these systems.
- One goal is to allow an aging workforce to continue to do physically demanding jobs, as long as they desire to continue such work.
- Exo-assist technologies are of interest to labor organizations as a means of improving worker capability and quality of life, without fully replacing the worker.
- Question: Can these technologies broaden the demographics for persons who are capable of performing highly demanding jobs?
- Stakeholders should seek involvement with standards development (ISO, ASTM).
- Traditional industrial robotics manufacturers may start making their presence known in this technology area.
- There are many start-ups in the commercial market in the United States and Europe, where there is more access to capital investment. In Asia, technologies are primarily coming out of "old line" industrial companies.
- The companies are developing the technologies for their own workforce but are also starting to look for external sales opportunities.
- Exo-system technologies are out there. Question: What can be done to make them "seamless"?

Q&A/Discussion

- Question: Does a decreased metabolic rate correlate with or confirm a reduction in injury? We are still at the early end of understanding this relationship, and a number of pilot programs are looking at this. Fatigue is an indicator of an increased risk of injury. We are operating on the assumption that reducing metabolic cost increases the time to get to the fatigued state and therefore reduces injury. We need more data to assess rates of injury.

Session Title

Opening, *Update on ASTM Committee F48 on Exoskeletons and Exosuits and other Standards Efforts*

View the slides: https://higherlogicdownload.s3.amazonaws.com/HFES/42fffbb4-31e1-4e52-bda6-1393762cbfcd/UploadedImages/Keynote_Bill_Billotte.pdf

Speaker

William Billotte, NIST/ASTM Committee F48 on Exoskeletons and Exosuits

Summary Points

- "We are the future" platform.
- Exoskeletons will use quantum computing, artificial intelligence, and high-performance computing.
- We need standards to ensure exoskeletons are safe, are reliable, and perform as intended.
- The ASTM Committee F48 on Exoskeletons and Exosuits was established in September 2017.
- F48 subcommittees were formed around a life-cycle approach. The speaker gave an overview of each subcommittee.

Q&A/Discussion

- Terminology work is ongoing, such as defining an exoskeleton and determining whether an exosuit is a type of exoskeleton.
- Participants discussed the scope of ASTM F48. It likely excludes traditional prosthetics, but new prosthetics that are more akin to wearable robotics would fall under its scope.
- Standards are meant to facilitate innovation. We need to investigate what metrics are going to work best for the exoskeleton community.
- Standards are living documents to revise and improve over time.

Session Title

Keynote 2, *Ergonomic Assessment of a Space Suit: From the Perspective of Population Analysis, Fit, Accommodation, Comfort, and Performance*

View the slides: https://higherlogicdownload.s3.amazonaws.com/HFES/42fffbb4-31e1-4e52-bda6-1393762cbfcd/UploadedImages/Keynote_Sudhakar_Rajulu.pdf

Speaker

Sudhakar Rajulu, NASA Johnson Space Center

Summary Points

- A spacesuit is a type of exosuit. NASA has been dealing with an ensemble system in the spacesuit for many years.
- The fit of the suit in a static situation may not be the same as in a dynamic situation.
- We need to make donning and doffing simpler.
- In microgravity, the legs need little mobility. The arms—shoulders, elbows, and wrists—need the most mobility. Joint bearings will be necessary for lower-limb mobility for the Mars expedition.
- The Russian Space Agency selects cosmonauts who have very similar, restrictive anthropometric profiles.
- The Apollo program used a similar restrictive sizing approach, combined with minor adjustments/alterations. Since the Shuttle program, NASA has fit a wider range (5th percentile female vs. 95th percentile male). NASA made its equipment sizing inclusive of a wider anthropometric variation.
- Each spacesuit costs several million dollars.
- The Shuttle suit incorporated a Hard Upper Torso (HUT) instead of a soft suit upper component.
- For the Mars mission, the suits need to be modularized and highly adjustable so that individual suit components can be interchanged and exchanged. It is difficult to carry spare parts for individual crewmembers because of payload considerations.
- The current approach to studying and improving suit fit issues is merging full body scans with CAD models of the hard suit components.
- Shoulder topography changes with movement from static to dynamic poses.
- Models under development will simulate what happens to the shoulder as the user goes through a dynamic motion. We will be able to apply this to the entire population.

- Monte Carlo simulations represent variation across the entire body size and shape range for a particular suit type, to determine who will fit into it.
- When designing a suit or exoskeleton, we need to understand how it restricts or limits natural movement.
- The goal is for an exoskeleton to fit everyone, not a specific subpopulation.
- Because testing everyone is too time consuming, we need to improve methods of virtual simulation with the entire population.

Q&A/Discussion

- Use of the hands is important in suited operations. Augmenting hand function is a priority. Upper arm (shoulder) excursions and mobility are also under study. The NASA exercise countermeasures group has considered looking at exoskeletons for rehabilitation purposes to counteract the muscle atrophy and bone loss expected in a journey to Mars.
- What should the next steps be for exoskeletons? We need to enable users to don and doff systems without assistance, and we need to make sure the active modes don't cause problems.

Session Title

Exoskeleton User Discussion Panel

Moderator

Robert R. (Bob) Fox, General Motors

Speakers

Robbie Schram, Toyota

Introducing Exoskeletons into the Toyota Manufacturing Environment

View the slides: https://higherlogicdownload.s3.amazonaws.com/HFES/42fffbb4-31e1-4e52-bda6-1393762cbfcd/UploadedImages/User_Discussion_Robert_Schram.pdf

Kendra Betz, U.S. Veterans Affairs

Exoskeletons as Assistive Technology for Rehabilitation: Clinical Perspectives

View the slides: https://higherlogicdownload.s3.amazonaws.com/HFES/42fffbb4-31e1-4e52-bda6-1393762cbfcd/UploadedImages/User_Discussion_Kendra_Betz.pdf

Summary Points

- In 2016, Toyota built 2 million vehicles and sold 2.5 million, involving 40,000 workers across 13 manufacturing locations.
- The focus of Toyota exoskeletons has been on the shoulder, upper back, and arm.
- Toyota has used passive upper-body exoskeletons for overhead work and for under-chassis work.
- The company conducted trials of exoskeletons in seven plants, with the most deployment in Canada, Indiana, Kentucky, and Texas.
- It has deployed 239 exoskeletons in the United States and Canada, which are in use now in Paint and Assembly; it will deploy up to 440 in 2019.
- Nearly all deployed exoskeletons are the Levitate device; an additional 15 Eksobionics Eksovests have also been deployed.
- The Levitate AirFrame trial
    - — Toyota has tested the Levitate AirFrame in 10 processes, of which more than half involved “no good” shoulder postures.
    - — The company used subjective team member feedback (rating perceived exertion, discomfort, and equipment usefulness) at three of its motor manufacturing plants (in Kentucky, Indiana, and Canada).

  - — Results showed that 70% to 80% of team members preferred using the device. They also showed a 73% average reduction in perceived exertion and 44% reduction in discomfort ratings.
  - — Iowa State also collected %MVC (maximum voluntary contraction) measurements via electromyography (EMG) with use of the AirFrame at the plant in Canada.
  - — EMG results showed that with the AirFrame an overall reduction in %MVC (that is, decreased fatigue) occurred for the shoulder (5.8%) and the back (4.1%) but not for the biceps (for which %MVC increased for certain tasks).
  - — Strength tests showed no reductions and some increases over the course of the study.
- Toyota and Levitate co-developed "mutilation covers" to reduce damage (from contact between the exoskeleton and the product—cars) and to increase user confidence.
- A second EMG trial used %MVC, Toyota's internal ergo assessment tool (TEBA), and ACGIH's Upper Limb Localized Fatigue equation.
  - — Researchers mapped TEBA to ACGIH's Upper Limb Localized Fatigue TLV (Threshold Limit Value) in order to use TEBA to screen jobs that may benefit from exoskeleton use.
- The plan for moving forward involves these actions:
  - — Inventory all jobs using TEBA criteria or injury data and calculate TLV.
  - — Use the Hierarchy of Controls before using an exoskeleton (which Toyota considers a form of PPE); perform a risk assessment to ensure no new hazards emerge with the exoskeleton.
  - — Finalize standards (mandatory or voluntary); monitor long-term outcomes; put different types/models to trial.
- Exoskeletons are a form of assistive technology for use by individuals with disabilities.
- For these applications we use the HAAT model: a Human performing an Activity with an Assistive Technology within a context.
- Candidates for exoskeletons are often full-time wheelchair users, with little or no ability to walk, or those who are regaining the ability to walk through rehabilitation.
- The FDA has cleared four exoskeleton devices: ReWalk, Indego, Ekso, and Hybrid Assistive Limb (HAL) by Cyberdyne. HAL, the device most recently cleared, requires an overhead harness support system and therefore is for indoor use.
- Clinical decisions incorporate research, professional experience, and especially the client experience and perspective.

- A video showed the process for putting the exoskeleton on and the necessity of assistance for the user to go from sitting to standing and walking.
- Exoskeletons are useful for a subset of individuals with disabilities; they must meet certain criteria. Individuals who have had more time to adapt to their disability are more likely to be okay with use of a wheelchair but are interested in advances in exoskeleton technology.
- In some cases, there is a steep learning curve for clinicians and clients because of the devices' complexity.
- It is critical for all device options to be available for trial, to match the candidate to the optimal exoskeleton technology.
- Current exoskeletons do not yet support the client to move at normal walking speeds, but this feature will improve as the technology advances.
- Exoskeleton users need a trained companion, a limitation for deployment to certain environments and circumstances.
- Skin injury and protection are significant concerns for clients with neurologic injuries.
- The VA has developed the VA National Clinical Protocol, with resources to help clinicians with evaluation, training, and inclusion/exclusion criteria.
- Being able to lease the exoskeleton for an extended trial before purchasing it has been extremely helpful for successful implementation.
- Many exoskeleton research projects continue, including a randomized control trial (RCT) at 10 VA sites led by Drs. Spungen and Asselin.
- Here are a few other points about exoskeletons and ethics:
    - Better technology is always on the horizon; limited competition = high costs (in addition to care, repair, and maintenance costs).
    - Consider the "research while implementing" ethics of developing standards while implementation is taking place; we need responsible, experienced participants in the standards-making process.
    - CLOUT (Clinical Limits of Use Tools) provides a matrix of application functions/limitations for each device.

Q&A/Discussion

- Here are some common threads among exoskeleton users:
    - Users must like the device to use it and benefit from it.
    - End users and vendor/manufacturers must share feedback with each other.
    - The complexity of the workplace affects user adoption.
    - Embrace the technology and work to advance its adoption to increase its effectiveness.

- Advice to vendors/manufacturers included the following:
  - Listen to users about features, fit, and design details: keep your ear to the ground.
  - Interact with users in the worksite.
  - Tailor devices to applications.
  - Intuitive usability is currently a complexity and challenge to overcome.
- Question: What is the minimum exposure the user will need to have with the device to provide useful feedback?
  - Toyota uses a slow ramp-up, from 30 minutes to a full 2 hours and up to a month for industrial use, and from a few days to a week for military.
  - In the medical domain, a functional minimum for "lease-to-own" users is that they must be able to get in the device with minimal assistance, achieve a sit-to-stand, and walk 10 meters with minimal supervision.
- Question: How do you manage the program you have? And do you expect that ramping up the same program will support it?
  - Internal standards provide guidelines on the lifecycle of the program.
  - A selection process helps identify potential users.
  - On the production floor, we have point people at the main plants, along with medical, safety, and shop reps.
  - We are already out of the testing phase and are in the implementation phase, so we are expecting this model to fit.
- Question: In terms of outcomes, how do exoskeletons compare to traditional physical therapy?
  - Outcomes are different from those with traditional therapy and vary more. Users have increased capabilities but not at a functional norm, so some prefer the mobility they have achieved in their wheelchair.
- Question: How are you selling these devices to leadership? In the medical domain, how can you make the economics more feasible?
  - Toyota has added a digital transformation and human mobility "pillar" to the company; it is not just a car company but also a mobility provider. This is a cultural priority, so it is now easier to get a "foot in the door." The exoskeletons continue to provide ROI and are getting better. There is a bit of competition; when leadership sees a competitor's video on their exoskeleton deployment, it is more likely to support adoption.
  - In the medical domain, we need more competition to drive innovation. We have too few models to choose from, and this is driving up costs.

- Question: Do you think you affect the lower extremities and change posture with an exoskeleton?
    - We did not do any lower-extremity evaluation. We are looking at strength testing and injuries. Short-term, we have not seen any strength decrements, but long-term evaluation will be necessary.
- Question: Do you actually see user dropout? If so, why?
    - Toyota: Yes, some don't want to use devices, but others use them full-time. Fit and comfort are the usual reasons for rejection, and we wonder about whether we should make device use mandatory.

Session Title

Research Methods 1—Design for Population Accommodation & Performance

Moderator

Krystyna Gielo-Perczak, University of Connecticut

Speakers

Monica Jones, University of Michigan

Three-Dimensional Anthropometric Data for Exoskeleton and Exosuit Design

View the slides: https://higherlogicdownload.s3.amazonaws.com/HFES/42fffbb4-31e1-4e52-bda6-1393762cbfcd/UploadedImages/Population_Accommodation_Monica_Jones.pdf

Joseph Parham, U.S. Army Natick Soldier Research Development & Engineering Center (NSRDEC)

Anthropometric Considerations in Exoskeleton Development

View the slides: https://higherlogicdownload.s3.amazonaws.com/HFES/42fffbb4-31e1-4e52-bda6-1393762cbfcd/UploadedImages/Population_Accommodation_Joe_Parham.pdf

Leia Stirling, MIT

Quantifying Physical and Cognitive Fit for Assessing Exoskeletons

View the slides: https://higherlogicdownload.s3.amazonaws.com/HFES/42fffbb4-31e1-4e52-bda6-1393762cbfcd/UploadedImages/Population_Accommodation_Leia_Stirling.pdf

Summary Points

- Human measurement and modeling methods are an opportunity to inform the design and evaluation of exoskeletons.
- No two people are the same size and shape.
- The Anthropometric Survey of U.S. Army Personnel (ANSUR) and other data sets are typically one-dimensional.
- Three-dimensional (3D) scans give richness of size and shape.
- Models and data are publicly available at www.humanshape.org. These data can be exported for 3D shape in computer-aided design (CAD) systems.
- Range-of-motion scans (dynamic) show what happens to the shape when the joint moves through the range of motion.

- No actual person looks like a 5-percentile or 95-percentile body model. There are approaches for morphing body shape models from GHBMC (Global Human Body Models Consortium) and Total Human Model for Safety (THUMS) onto finite element models so they are more representative of a broader population.
- We need dynamic, rapid-loading models for crash tests. We can use quasi-static loading models for exoskeletons at a mechanical interface to quantify shape deformation, flesh deformation, and pressure points through finite element (FE) modeling.
- A skeletal geometry model with CT and MRI produces a parametric representation of the skeletal system as a function of age, gender, and other variables.
- These models and data provide opportunities to develop quantitative measures of fit, to customize fit, and, at a population level, to inform sizing requirements.
- ANSUR is one of the largest anthropometric survey databases in the world. The survey was conducted in 2011–2012 and collected data on 12,000 soldiers, including 93 anthropometric measurements and 3D scans.
- Typical exoskeleton testing involves small samples. We can reference anthropometric databases to see where those subjects fall within a population.
- Users of equivalent height and weight can vary substantially across other anthropometric variables.
- Common measurements obtained in a semi-nude condition are not reflective of the full gear and equipment required of a soldier. What is the delta between the two conditions? We refer to this as "encumbered anthropometry."
- Dynamic fit and static fit are different in terms of joint alignment with the system. Statically determined alignment may not predict alignment in dynamic tasks.
- Cognitive fit is a consideration: Does use of the system affect ability to perform other psychomotor tasks?
- Users vary in the time they require to learn how to use systems. The design of active controllers can be based on the individual user's style of adaptation.
- Spacesuit fit is based on observations of the suit technician and subjective feedback from the suit wearer. Methods have been developed to provide the suit technician with quantitative information about what is not visible from outside the suit. Technicians are interested in relative motion between the human and the encasing suit.
- Relative coordination measurements involve collecting inertial measurement unit (IMU) data on the human and IMU data on the suit to evaluate relative motion between the two.
- An example from the gait cycle is at the point of heel off—hypothesized to be the foot lifting out of the boot as the suited subject is walking. These measurements align with subjective response of the suit user.

- An open question: How does fit affect performance?
- Exoskeletons may affect visual attention and reaction time performance of some users, with wide variability. Some tests of exoskeleton use have shown an impact on inherent cognitive capabilities.
- Perceived increase in overall workload has been assessed with the NASA TLX scale.

Q&A/Discussion

- There are a number of population-level descriptions for anthropometry, but we also need population-level descriptions of biomechanics.
- In a short-term (3-day) study, users may not achieve adaptation or steady-state performance with the system, but the study may indicate immediate "intuitiveness" of use. The underlying fit to the person affects the rate of adaptation, or of achieving steady-state performance.
- Customers ask vendors about the impact of exoskeleton use on quality of work. This is likely task-specific. Ideal fit may depend on the task. Different operational performances may require different adjustments or alignments.
- Question: What are specific variables to measure for addressing adaptation to exoskeleton systems? Individuals have different responses to perturbations, and this variability may be important to the design of control systems. There are examples of humans responding as both overdamped or underdamped systems when subjected to perturbation.

Session Title

Exoskeleton Developer Discussion Panel

Moderator

Christopher R. Reid, The Boeing Company

Speakers

Chris Beaufait, Sarcos Robotics

Achieving Technical and Manufacturing Readiness for the Commercialization of Powered Exoskeletons

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Marty Linn, General Motors

Roboglove—A Human Grasp-Assist Device

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Brandon Frees, Ekso Bionics

Exoskeletons—Ideas for Implementation and Change Management

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Summary Points

- Developers of powered exoskeletons aim to combine human strong points such as instinct, intelligence, and judgment with robotic attributes such as strength, endurance, and precision.
- Developers want to augment worker performance while keeping workers out of harm's way.
- A major goal is to reduce occupational injuries and musculoskeletal disorders. One way to achieve this is to reduce worker fatigue and fatigue-related injuries.
- Developers also want to develop exoskeletons that can decrease times for users to recover from injuries and musculoskeletal disorders.

- One of the challenges of powered exoskeleton development is to increase efficiency in order to reduce power consumption. This will allow the use of completely untethered units and the use of smaller, lighter battery packs.
- Powered exoskeleton designs should ensure that the exoskeleton follows the movements of the worker and not vice-versa.
- Exoskeletons need to be adaptable to diverse environments.
- Designs should be compatible with off-the-shelf tools and equipment; avoid specialty tools and custom interfaces when practical.
- Another goal is to increase worker productivity.
- Designs should allow the worker to operate at a normal pace and within the existing work environment.
- Designs should limit modifications to normal work operations; exoskeleton use should be integrated with existing work processes instead of forcing employers to alter work operations to accommodate exoskeleton use.
- One of the major challenges for developers is to create worker buy-in.

Q&A/Discussion

- Efforts are underway to integrate wearable sensors into exoskeletons. Developers and researchers are collecting data on muscle activity, motion, force, metabolic metrics, and so on. New, flexible electronics will facilitate such exoskeleton designs. The use of instrumented under-suits is also being explored.
- Exoskeleton designs and applications must evolve to ensure user buy-in.
- Exoskeleton developers hope that exoskeletons will eventually become mandatory PPE in certain work processes and environments.
- Exoskeleton developers must create pathways to move designs from the research and development realm into the user space. There must be "pay points" that demonstrate worker benefits. Developers must identify and define problems, and exoskeleton use must yield solutions to those problems. At the same time, exoskeletons must have realistic price points.
- Developers must address psychosocial aspects of exoskeleton use. Interactions among exoskeleton users and the social environment are important and should be evaluated.
- Exoskeleton aesthetics are important to some users. Sleek designs are typically favored, but opinions are mixed.

Session Title

Research Methods 2—Assessing System Usability

Moderator

Carisa Harris-Adamson, University of California

Speakers

Kevin Purcell, U.S. Army Public Health Center

Exoskeleton Usability: Task Differences and Anthropomorphism

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Kadon Kyte, The Boeing Company

Perspectives on Exoskeleton Usability: Insight from Boeing Factory Introduction

View the slides: https://higherlogicdownload.s3.amazonaws.com/HFES/42fffbb4-31e1-4e52-bda6-1393762cbfcd/UploadedImages/Usability_Kadon_Kyte.pdf

Alix Dorfman, Underwriters Lab (UL), Wiklund

Assessing System Usability: Research Methods and Special Considerations for Rehabilitative Exoskeleton Evaluation

View the slides: https://higherlogicdownload.s3.amazonaws.com/HFES/42fffbb4-31e1-4e52-bda6-1393762cbfcd/UploadedImages/Usability_Alix_Dorfman.pdf

Summary Points

- The ISO 9241-11 definition of usability emphasizes achieving "…specified goals with effectiveness, efficiency and satisfaction in a specified context."
- Exoskeletons have been scoring at a 4 or 5 on a 7-point Likert scale for usability. Higher usability is critical to exoskeleton success.
- If usability is poor, the exoskeleton will not be adopted.
- There is a strong connection between reduced metabolic cost and a higher usability rating.
- Methods to assess metabolic cost/energy expenditure include these:
    - — VO2
    - — Core temperature

  - — Augmentation factor—developed by Dr. Mooney and colleagues; predictive measure of power transfer to the user from the exoskeleton.
  - — PoLoTAE—Position and Load Test Apparatus for Exoskeletons (developed by NIST)
- For medical and therapeutic devices, usability should also consider the individual assisting with the therapy.
- In military applications, there is not much literature on usability yet.
- Marketing classifications adopted from usability practitioners include Features vs. Benefits:
  - — Feature—a previously specified task that an exoskeleton can help the user perform, which tends to be related to a fixed task. This contrasts with Benefit—what the user wants in the first place (solution to a user's problem), which tends to involve a dynamic task with unspecified subtasks.
- An application example is the original Lockheed HULC, which was designed to increase a warfighter's ability to carry a large load while minimizing fatigue. The HULC accomplished that specific goal. However, the soldier/warfighter has other tasks beyond going from point A to point B, such as accomplishing many sub-goals.
- One company's approach is to identify where the issues are in terms of geographical location and with respect to the individual.
  - — First, identify high-risk tasks by using safety data. Look at all safety incidents and pinpoint by body part, various risk factors, and geographic location to define issues to address.
  - — Second, strategically align with different programs.
  - — Third, apply the best technology for the right application.
- Industrial work types include these examples.
  - — Postural assist activities: maintaining a static posture for extended periods, such as when working with overhead wire bundles, using fine motor skills, and working near the ground.
  - — Hand tool usage: riveting/bucking, drilling, torqueing
  - — Equipment relocation/moving: workstands, tool/equipment carts
  - — Manual material handling: Lifting/lowering, pushing/pulling, carrying
- Industrial use cases include these examples.
  - — Systems installations: doors, seats, lavatories
  - — Structures work: drilling, installing fasteners
  - — Paint work: sanding, masking, painting
  - — Move teams (hoping to get more into this application area): work stands, carts, large-part moving and assembly

- User-centered design goal: We need to embed the end user into the entire product development process, to reduce injuries, maximize human performance and product quality, and improve ease in implementation into production systems.
- User-centered design approach: Start from the initial meeting with the supplier, before the system is brought into the lab for testing. Have the perspectives of the end user in mind through all aspects of the exoskeleton evaluation. When a company comes on site to demonstrate an exoskeleton system, two or three mechanics will participate to give candid feedback, enabling initial down selection.
    - Specification of requirements
    - Design
    - Simulation
    - Prototype building
    - Human testing
- Usability testing approach: Involve end-users throughout.
    - Site visit: supplier and end-user feedback; quick assessment
    - Lab assessment: simulated environments; end-user test pool
    - Field assessment: production shop trial
    - Testing over time, to address problems
    - Targeting workers who have a negative experience, to make them champions
- One speaker described results of a 6-month trial of a shoulder vest system.
- Usability metrics: primarily subjective (Likert Scale: 1–7)
    - Usefulness, adjustability, restriction, fit, thermal, balance, comfort, overall rating
    - Metrics also included open-ended responses
- Metrics vary over time in a consistent way. All items rated highest in the first month, with good initial feedback; then ratings all dipped in the second month. As issues were identified and addressed, ratings increased again in the third month.
- Other considerations impacting usability
    - Interaction of the exoskeleton with PPE: coveralls, fall harnesses, tool belts, hard hats
    - Extent of integration: single vs. multi-user (shared)
    - Maintenance needs: end-user, tool cribs, exoskeleton vendors

    - One speaker highlighted the importance of social factors. The unwanted attention of using systems affected usability most. Even if objective metrics (time to task completion) improve, employees will not wear the systems if they receive unwanted attention or comments.
    - Quality of life, employee engagement
- Application of human factors engineering (HFE) of medical devices is helping medical device manufacturers address the regulatory imperative (that devices are safe and effective) and the commercial imperative (that devices are efficient and satisfying).
- HFE is important because people make mistakes. FDA wants manufacturers to figure out the ways in which people can make mistakes with a device. This is known as risk or hazard analysis.
- Manufacturers should mitigate risks. This should be design-based mitigation or instruction/information based (such as labeling). Residual risk should be brought to a minimum, through testing; no product can be completely risk free.
- Formative testing: identify all potential use-related hazards (risk analysis).
    - Identify all critical/high-risk tasks performed by users.
    - Identify the interface's strengths and weaknesses.
    - Identify potential use errors that could result in serious harm.
- Summative testing: perform a human factors validation study to demonstrate that the device design supports safe, effective use.
    - To be representative of the intended users, include in the sample at least 15 users per distinct use group (that is, people who will use the device in different ways, such as patients, caregivers, and therapists).
- The FDA expects testing with a representative group of users (per age, gender, occupation, and experience using the device). The user group may be distinct if they use the device in a different way (for example, the physical therapist will use the device differently than a patient).
- Validation testing should contain at least 15 participants per distinct user group.
- User-group characteristics to consider include these:
    - Patient—level of paralysis, enrollment in a rehabilitation clinic, level of independence/role of caregiver in their life, anthropometric profile
    - Caregiver—roles/responsibilities in patient's life; recruit actual caregiver or representative substitute
    - Physical therapist—methods and any other assistive equipment they use with their patients
- Representative use scenarios: The FDA expects that the tasks participants perform are representative critical, high-risk, difficult, frequent tasks. Tasks should follow natural workflow.

- Consider the percentage of patients who can complete tasks on their own, their reliance on caregiver, and other physical limitations and safety concerns preventing them from completing the task.
- Representative environment: The FDA expects consideration of elements that might affect use of the system, such as facility layout, accessories, furniture, lighting level, sounds or distractions, who is present, and access to help. For instance, is the system typically donned/doffed in the home environment or physical therapy clinic? Who is typically there to assist the user? The researcher must include realistic performance-shaping factors.
- Representative device—The FDA expects researchers to ensure that testing is comprehensive and includes pre-use and post-use (product maintenance). Validation testing requires that the device is comprehensive relative to the final product; all parts are product equivalent; and the effects of using prototypes in early stage research are minimal. Usability testing is not efficacy testing.
- In formative evaluation, aesthetic and comfort preferences are commercial imperatives.
- Outcome: No errors or problems with use should occur that could cause serious harm.

Q&A/Discussion

- Some users initially gravitate to exoskeletons because of a "coolness" or "newness" factor. This initial enthusiasm can drop off in early use before increasing again. In the military, the culture is different. When it defines a system as "mission critical," personnel tend to adopt the technology even if they dislike it.
- Effects on balance were difficult to assess in laboratory representations of tasks, particularly those representative of ascending/descending work platforms.
- A conference participant asked about perspectives on making devices mandatory for certain jobs, on the basis of determined criteria. One opinion was that the systems have not matured enough nor existed long enough to be treated similarly to PPE.
- Subjective approaches are prevalent in usability testing. A participant asked about objective measures for assessing usability. The speaker mentioned that metabolic cost has a direct relationship with usability and that a human factors evaluation includes assessing risk and identifying high-severity risks with potential for harm. Evaluations should establish tasks in which risks can be confronted for the purpose of identifying user mistakes. Error rates are a measurable way to determine residual risk.
- A participant asked about assessment of fall risks. Focus groups with physical therapists have raised this issue. For industrial use, laboratory tests of fall risks are challenging because of the need for overhead harness systems.

Session Title

Research Methods 3—Assessing Safety Panel

Moderator

Brian Lowe, National Institute for Occupational Safety and Health

Speakers

Ian Marcus, U.S. Food and Drug Administration (FDA)

Assuring the Safety of Medical Exoskeletons: An FDA Reviewer Perspective

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Roger Bostelman, National Institute of Standards and Technology (NIST)

Toward Standard Test Methods for Exoskeletons

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Angela Boynton, U.S. Army Research Laboratory

Assessing Safety of Physical Augmentation Technologies for the Dismounted Soldier

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Summary Points

- The FDA discussed how the U.S. medical exoskeleton regulatory framework is focused on patient access to high-quality, safe, effective medical devices of public health importance.
- The FDA reviewed what the Agency considers a medical device and when FDA requirements may apply. A medical device is defined by technology and intended use. The current federal regulation for powered lower-extremity exoskeletons is 21 CFR 890.3480.
- The FDA discussed the wide range of potential risks that affect the overall safety of medical exoskeletons.
- The FDA advocated that medical exoskeleton developers should feel free to contact them with questions and/or concerns and to submit a pre-submission for feedback prior to initiating timely and costly testing.

- NIST discussed the development of the Position and Load Test Apparatus for Exoskeletons (PoLoTAE). Others can easily duplicate this wall-based set of tests to do their own testing.
- NIST discussed the development of artifacts for use in measuring the movement of an exoskeleton with an optical tracking system.
- NIST is developing six task-based tests and one knee test. Testing with volunteers (5th to 95th percentile) from NIST is ongoing.
- The U.S. Army Research Laboratory (ARL) has been working in the exoskeleton space as an organization for over 20 years.
- ARL was very involved in the DARPA Warrior Web program and evaluated all the exoskeleton prototypes.
- ARL is looking at dismounted-soldier applications for exoskeletons and is using a safety-assessment approach in its testing methodology.
- Soldier applications differ from industrial or medical applications of exoskeletons. The safety assessment must take into account dynamic environments, different ranges of motion, high-paced activities, and challenging temperatures and terrains.
- Stability is a key measure for exoskeleton testing.

Q&A/Discussion

- Panelists discussed stability as a measure and combining different metrics to address specific stabilities, such as medio-lateral stability.
- Panelists discussed future test methods for hip, shoulder, and elbow. Making the data public could enable others to try different analytical techniques.
- Panelists discussed the goal of taking the mentioned test methods and introducing them into the standards development process through the ASTM Committee F48 on Exoskeletons and Exosuits.
- Panelists discussed data sharing across the military, industrial, and medical exoskeleton application areas. Data sharing would be facilitated by developing generic test method standards that cover common tasks and requirements.

Session Title

Research Methods 4—Assessing Ergonomics

Moderator

Cathy White, Dow Chemical Company

Speakers

Marty Smets, Ford Motor Company

Perspectives on Implementing an Exoskeleton Program in Automotive Manufacturing

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Maury Nussbaum, Virginia Tech

Lab-Based Assessments of Occupational Exoskeletons: Overview of Methods and Results

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Summary Points

- Assessing an exoskeleton's effectiveness, in terms of reducing physical demands in a laboratory setting, involves challenges:
  - — Task context (simulated industrial work vs. basic motor tasks)
  - — Relevant independent variables that can interfere with or influence user-exoskeleton interaction
  - — Relevant and feasible dependent measures to monitor
- Certain task-related factors can be manipulated in laboratory simulations: external loads, tools, postures, workstation configurations, precision demands, and work patterns (for example, pacing or duty cycles).
- How do we account for familiarization and learning effects, and hence, what are acceptable test durations? How do we account for adjustability in some exoskeletons?
- Does every device and every new iteration of a device need to be empirically tested? Are there better approaches?

- Dependent variables currently under study are muscle activations, subjective perceptions (such as discomfort), joint kinematics, kinetics, task performance, usability, joint range of motion, metabolic demands, postural control and slip-trip-fall risks, interface pressures, coordination, dynamic stability, endurance time, fatigue, and model-derived estimates of strength and spine forces.
- Which of these measures are most useful (and feasible) for guiding decision making? How do we resolve inconsistencies between measures and/or studies?
- Fatigue and performance may be the most important to consider, as we move forward.
- We need to understand both anticipated and unanticipated outcomes of exoskeleton use.
- What is the role of lab-based evaluations in this field, given that industries have embarked on their own field trials based on their specific use cases?
- An approach for field implementation of exoskeletons is to treat use of passive exoskeletons as solely for increasing endurance rather than augmenting strength and not to use them for speeding up the return to work or assisting a restricted worker.
- Fit and functionality testing by actual industrial operators at Ford helped in redesigning early arm-support exoskeleton prototypes, in terms of increasing ROM and device adjustability, regulating thermal comfort, etc.
- A follow-up phase of exoskeleton field-testing among workers performing overhead assembly work showed high acceptance by operators and lower discomfort.
- Ongoing work will assess effects of long-term exoskeleton use on reduction in operator discomfort and shoulder injury risk.

Q&A/Discussion

- Fatigue and performance were highlighted as important measures (for industry decision makers), but metabolic cost was not highlighted. It was suggested that metabolic demand may be an indirect indicator of fatigue but may not be related to injury risk or performance.
- Ergonomic assessment is difficult in the workplace. We need to perform predictive analysis. A participant asked whether exoskeleton technology should be treated as PPE and rolled out as such, and when to go from voluntary use to mandatory use. We need more research on these topics, not just to mitigate risk factors but also to understand long-term and cumulative effects. We need better data and standardization. We also must navigate the political landscape in unionized workplaces with a focus on lowering injury claims and on lost-time compensation.
- Because of complications with hygiene (due to sharing) and time spent in fitting, Ford's approach is to use exoskeletons individually in the current trial.

- When asked about psychological implications, the speaker responded that the study data are too preliminary to determine whether users become emotionally attached to exoskeletons and to comment on implications.
- The Ford-VT study involves only North America and uses standardized questionnaires. Some things are managed globally and others by the local plant. A trained team instructs every site coming into the trial now. The focus is on establishing and raising level of awareness of these tools and paving the way for large-scale implementations as sensors and devices get better.
- Many exoskeleton prototypes are being researched, but only shoulder exoskeletons are currently under study for production implementation.

Session Title

Closing Discussion Panel

Moderator

Cindy Whitehead, U.S. Navy—Naval Sea System Command

Speakers

Ben Petro, U.S. Office of the Secretary of Defense (Presented by Cindy Whitehead)

DoD Views on Exoskeleton Development and Use

Delia Treaster, Ohio Bureau of Workers Compensation

Some Thoughts on Industrial Exoskeletons from a Worker Compensation Perspective

Gerard Francisco, TIRR Memorial Hermann Hospital

Rehabilitation Application of Wearable Exoskeletons

View slides for B. Petro, D. Treaster, G. Francisco: https://higherlogicdownload.s3.amazonaws.com/HFES/42fffbb4-31e1-4e52-bda6-1393762cbfcd/UploadedImages/Closing_Whitehead_Treaster_Fancisco_closing.pdf

Donald Peterson, Northern Illinois University/ASTM Committee F48 on Exoskeletons and Exosuits

Exosystems Testing, Validation, and Standardization

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Summary Points

- Cindy Whitehead presented prepared comments from Dr. Petro, U.S. Office of the Secretary of Defense.
- The insurance industry is numbers driven. The number and the cost of claims are important.
- The State of Ohio is monopolistic for workers' compensation. This means that employers are insured by the state or are self-insured; there are no private insurers for Ohio workers' compensation.
- The manufacturing environment and work tend to be more predictable than other industries such as public employment and construction employment.

- Postural demands are prevalent in construction work. Posture can be constrained by the finished environment and restrictions in how materials can be carried/handled in finished environments. Technology assistance is necessary in these applications.
- The back and shoulder represent the #1 and #2 body part injuries in terms of costs to workers' compensation systems.
- Manual patient handling in the health care industry is a problematic task and significant source of injuries. Handling of nursing home residents is a special OSHA emphasis area because of high injury rates. Current patient lifting/handling aids have shortcomings. There is a need for exoskeletons designed specifically to assist in patient handling/transfer.
- Wearable robots improve the services that rehabilitation professionals provide to patients and assist in delivering the appropriate therapeutic dose. These professionals' perspective on exoskeletons is that they provide assistance to therapists but are not a substitute for them.
- More frequent and longer therapy sessions may be more feasible and cost effective to deliver with augmentation from wearable robots.
- One hundred thirty-five countries are represented on ASTM standards committees. Some countries put consensus standards, such as those developed by ASTM, into law.
- Companies are looking at automation of people and their interactions with machines.
- Strength-augmentation exoskeletons have been constructed from off-the-shelf parts for just a few hundred dollars. The low cost is advantageous for disposability.
- Performance thresholds for these low-cost devices are still unknown. This suggests the need for standards.
- Modular systems may have various configurations, depending on anthropometries and accessories. We need to know how to match the standard(s) with modular systems.
- ASTM membership has benefits to both faculty and students.

Q&A/Discussion

- Panelists described the benefits of participation in relevant organizations bringing together end users, developers, and academics, such as the ASTM Committee F48 on Exoskeletons and Exosuits and the WeaRAcon association.
- A less expensively produced exoskeleton is in development for use in pediatric and adult populations.

- The Ohio Bureau of Workers' Compensation is sponsoring basic exoskeleton research in industry environments, by universities in Ohio.
- The Department of Defense will focus on close-combat military applications with significant ballistic protection.
- WearRAcon, Wearable Robotics Association (Europe), and ASTM F48 committees are fertile grounds for collaboration on this topic.

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Promoting productive workplaces through safety and health research

DHHS (NIOSH) Publication No. 2020-102
DOI: https://doi.org/10.26616/NIOSHPUB2020102