

## Industrial Exoskeletons: Are We Ready for Prime Time Yet?

### Discussion Panel

Christopher R. Reid<sup>1</sup>, Maury A. Nussbaum<sup>2</sup>, Karen Gregorczyk<sup>3</sup>, Carisa Harris-Adamson<sup>4</sup>, Kadon Kyte<sup>1</sup>, Brian Lowe<sup>5</sup>, Marty Smets<sup>6</sup>, and Ron Zmijewski<sup>7</sup>

<sup>1</sup>The Boeing Company, <sup>2</sup>Virginia Tech, <sup>3</sup>Natick Soldier Research, Development, & Engineering Center, <sup>4</sup>University of California – Berkeley, <sup>5</sup>NIOSH, <sup>6</sup>Ford Motor Company, <sup>7</sup>Puget Sound Naval Shipyard

What is an exoskeleton? Exoskeletons are external devices that are worn for an intended purpose such as rehabilitation or replacement for lost physical functions like walking. Others have considered these systems from what earlier might have been a more science fiction perspective – such as increased mechanical leveraging, strength, and speed – though such applications are starting to become science fact. Examples of such emerging applications have, until now, been directed toward military applications, such as developing the “super soldier” concept. Exoskeleton technologies are also being increasingly applied in medical scenarios. However, industrial applications are still in their infancy despite a dramatic increase in commercial products being released to the market. With this infancy, designers of systems have focused on system function; but, what about user population safety, fit accommodation, and regulatory concerns? How should designers design for human user concerns while targeting system function? What considerations should customers and stakeholders contemplate before buying that next commercial off-the-shelf system? Ultimately, how do we use ergonomic approaches to better design, assess, and use exoskeletons to benefit labor-intensive occupational tasks, or most effectively adopt exoskeletons to enhance work that involves physical fatigue and risk of musculoskeletal injury? The session will start with initial lectures and introductions from the panel, followed by an encouraged panel discussion with the audience led by the moderators.

Moderators: Christopher R. Reid, chair & Maury A. Nussbaum, co-chair

### EXOSKELETONS FOR MILITARY USE: PERSPECTIVES & LESSONS LEARNED

Karen N. Gregorczyk, MS  
Natick Soldier Research, Development, & Engineering Center,  
Natick, MA

Over the last 10 to 20 years, a number of exoskeletons have been designed with the intent of easing the physical burden on dismounted warfighters and extending the duration of military field missions. These exoskeletons hold promise for improving warfighter endurance, reducing fatigue, and lowering the probability of musculoskeletal injuries. However, to ensure user safety and performance efficiency, the physical implications of using these types of devices have to be identified and understood before the devices are fielded.

The U.S. Army has considerable experience testing exoskeletons on soldiers. Three generations of an exoskeleton developed to carry backpacks, and two energy harvesting devices designed to power soldier equipment utilizing human movement, have been evaluated by our Biomechanics Team at the Army Natick Soldier Systems Center. Additionally, numerous wearable exoskeletons, funded under the Warrior Web program of DARPA, have been evaluated by the Army Research Lab’s Biomechanics Team. Over the course of these assessments, extensive empirical data have been obtained in the laboratory on the biomechanical, physiological, and human factors implications of wearing such devices.

Although these investigations have provided valuable insight into the effects of short-term wear of exoskeletons,

understanding the long-term implications of exoskeleton use is also critical. However, the exoskeleton technologies that have been assessed by the Army are not mature enough to be tested on soldiers in field trials. Therefore, the implications of long-term use are still unknown. It is likely that the long-term effects will be device dependent, but there is a dearth of information on the prescribed use of such technologies. Does using an exoskeleton reduce the fitness/strength of the individual wearing it because they do not need to work as hard? When the device fails, will users still have the physical capability to perform the task? What training will soldiers require to successfully incorporate wear and repair of exoskeletons into their field activities? How much augmentation is just enough to reduce the likelihood of injury and improve overall performance efficiency, yet not reduce the strength or the capabilities of the user? You may not want to use these devices all the time, but what is the optimal prescribed use? Additionally, if using the device changes your biomechanics in performing a task, will that result in injury over the long term even if pain or injury is not experienced in the short term? As part of this panel session, these issues, lessons learned from testing soldiers outfitted in exoskeletons, and recommendations for the successful development of future exoskeletons will be discussed from a military perspective.

## **ASSESSING INDUSTRIAL EXOSKELETON TECHNOLOGIES IN THE LAB**

Maury A. Nussbaum, PhD, CPE  
Industrial & Systems Engineering, Virginia Tech  
Blacksburg, VA

In recent projects, the Occupational Ergonomics and Biomechanics Lab at Virginia Tech has evaluated diverse technological approaches that have been employed to develop exoskeletons for occupational application. Our primary focus in this work has been on so-called passive technologies – those not requiring external or worn sources of power – as these are considered to be more market-ready at present (e.g., lighter, simpler, and potentially more cost-effective). Fundamental to our work is the assumption that future use of industrial exoskeletons has the potential to provide new solutions to help make work tasks more accessible, easier, and safer, but that more evidence is needed to determine which technological approaches are likely to be most effective in specific cases. More importantly, new evidence is also needed to ensure that unintended or preventable consequences are avoided to the extent possible.

Among existing passive technologies, we are examining three distinct current alternatives that are relevant for tasks that load the upper extremities. A diverse set of protocols have been developed, in part through collaborations with industry partners, to help in providing technology evaluations that are as broad as possible. These protocols have included, for example, basic efforts assessing range of motion, performing controlled sub-maximal efforts, and evaluating comfort, usability, and safety. Simulations of occupational tasks have also been used, particularly involving arm elevation, and have included light manual assembly and a mock repetitive drilling task.

Preliminary results indicate that available exoskeleton technologies can be effective at reducing shoulder loading for tasks involving arm elevation with or without tool use. Further, different technological approaches may be more effective in specific uses (or, for specific task demands). In some cases, there appears to be a potential for undesired outcomes, such as a reduction in the range of motion of motion of distal joints, discomfort due to localized contact pressure, or decrements in task performance. Such lab-based studies are considered useful for obtaining diverse outcome measures that may be impractical in the field.

## **THE EVALUATION AND APPLICATION OF PASSIVE EXOSKELETONS.**

Carisa Harris-Adamson, PhD  
Department of Medicine, UC-San Francisco  
Environmental Health Sciences, UC-Berkeley  
Berkeley, CA

Given the high incidence of work related back, knee and shoulder musculoskeletal disorders in the United States (BLS, 2015), and the potential for lost time associated with such injuries, the application of trunk, leg and upper limb exoskeletons to reducing the physical workload either for

individuals with high exposures, or for individuals needing assistance, is appealing. McGill (1997) postulated that injury occurs via one of three modalities: immediate force application due to shock or impact, repetitive cyclical loading and subsequent fatigue of the tissue strength, and sustained sub-failure load coupled with tissue fatigue. Passive exoskeletons reduce the biomechanical loads associated with lifting, kneeling or performing overhead work, but their impact on fatigue and usability is less well known. Further, the effect of wearing multiple devices together has not been studied. The UC Ergonomics Lab, is testing various devices created by students and faculty at the UC Berkeley Mechanical Engineering Department. Our laboratory based within subjects studies of crossover design include simulation of lifting, kneeling, and overhead tasks. Inertial motion capture is used to assess changes in kinematics and electromyography measures muscle activity and compares muscular fatigue when using the device to not using any device at all. Peak, average and % heart rate reserve is used to assess changes in whole body physiological workload and the Borg CR10 is used to assess workers rate of perceived exertion in both conditions. Body temperature and compression points while using exoskeletons are monitored. Surveys collect information on subjective comfort and usability while donning, doffing and wearing the exoskeletons.

One of our interests is whether the above outcome variables change with varying levels of work demands relative to worker capacity. It is possible that identifying the ideal use for exoskeletons incorporates purpose with task demand and worker capacity. For example, whether exoskeletons can be used to help individuals build their capacity when starting a new job or returning from an injury is as appealing as is their use during physically demanding tasks that increase risk of injury for most workers. Data from laboratory studies may help improve the prescription of exoskeletons in the workplace to those who may benefit the most.

## **THE POTENTIAL OF INDUSTRIAL EXOSKELETONS IN AEROSPACE MANUFACTURING**

Kadon Kyte, MS & Christopher R. Reid, PhD  
The Boeing Company, Charleston, SC

As customer demand on Boeing aerospace manufacturing products increases, solutions towards improving production efficiencies are being balanced with internal Lean efforts aimed at cutting costs. Automation is one viable method of meeting demand, yet is not currently mature and adaptable enough to handle all aspects of the build process. One intermediary step towards this future is to consider merging automation strengths with that of human strengths, a field known as wearable robotics (exoskeletons). Exoskeletons offer a potential ergonomic intervention of reducing risk of injury while improving worker efficiencies (e.g., quality or productivity); each a cost savings to Boeing.

Certain types of work, such as use of hand tools (e.g., drilling, riveting, torquing) or manual material handling (e.g., pushing/pulling, lifting/lowering, carrying), may require workers to perform repetitive and/or force-intensive tasks. This sometimes also means performing these tasks in

awkward and fatiguing postures, such as working overhead, below the waist, or below floor levels. Extended exposure to overhead work, in particular, may lead to muscular fatigue and a number of musculoskeletal disorders including tendonitis, rotator cuff tears, arthritis, sprains, and bursitis. According to a review of internal Environmental, Health, & Safety injury data (2009-2014), the back and shoulder are the two most injured body locations across the Enterprise. These locations also account for the two highest average yearly costs to the company, according to its Workers Compensation data (2011-2013).

Boeing Research & Technology (BR&T) is currently exploring Industrial Exoskeleton technology and its impact on reducing production- and service-related injuries in addition to that of human performance metrics. BR&T's effort was broken down into internal and external testing, with an overall aim of developing and establishing standards and methodologies to evaluate exoskeletons. The team's methodology was derived from validated NASA spacesuit studies that demonstrated the positive and negative ergonomic impacts of spacesuit design (Reid, et al., 2014). Internal evaluations focused on laboratory testing and shop trials of existing and prototype technologies. This testing gathered subjective survey and/or objective biomechanical assessment data to evaluate system effects on the human body. External testing involved both academic and corporate partners to complete a biomechanical assessment of a prototype upper-extremity device (Vest).

Results from external testing demonstrated a reduction in lower back risk, task completion time, and upper arm muscle demands. Subjective user feedback indicated that mechanics preferred using the Vest as oppose to not using it (i.e., ease of use; reduced strain and fatigue). Internal testing of a lower-body device with an attached articulated arm uncovered that anthropometric fit plays a major role in comfort and potentially effectiveness of an exoskeleton system. Outcomes of this research led to Conditional (experimental) Approval by Boeing Enterprise Medical for both systems within Boeing's production environment, for purposes of further evaluation of applicability and safety.

This presentation provides an overview of exoskeleton technology, presents key results and learnings from both internal and external objective testing, and offers next steps in its evaluation process. Exoskeleton systems are positioned as a next evolutionary step for advancing Boeing to the future of efficient manufacturing; especially for work that does not easily lend itself to risk mitigation through automation or engineering re-design.

**PERSPECTIVES FROM AUTOMOTIVE  
MANUFACTURING: EFFECTIVE  
IMPLEMENTATION IN A UNIONIZED WORK  
ENVIRONMENT**

Marty Smets, MSc  
Ford Motor Company,  
Dearborn, MI

One of the most challenging current aspects of proactive ergonomics is the ability to accurately estimate the risk

associated with composite work tasks. Ergonomists do very well at analyzing tasks in isolation, but lack sophistication in their tools to predict the cumulative effect of several work tasks, or to provide guidance on the most appropriate way to group a set of tasks to minimize risk. While we continue to improve in this area as a community, it is prudent to address the fatiguing nature of assembly work by developing methods to improve the capacity/demand ratio and minimize injury risk. Exoskeletons may offer a form of relief in this regard.

Despite their increasing presence in the media, in part driven by the sci-fi like nature of their potential, exoskeletons are only now starting to make their appearance in automotive manufacturing. Although the technology has become quite advanced in the health care field, there have been gaps in the availability of simple, useful exoskeletons with targeted industrial applications. To ensure success, we have found value in working hand-in-hand with our assembly operators and union counterparts to ensure all needs are met. In doing so, we can increase the likelihood that exoskeletons will add measurable benefit to the wellbeing of the assembly operator. Although it is of equal value, no amount of supportive empirical biomechanical data will help an implementation team if the operator declines to use an exoskeleton.

Since 2012, Ford Motor Co. has been investigating exoskeletons for the assembly line to reduce operator demands during challenging work tasks. Through these efforts, several useful points have been identified. As a member of this panel, I will be discussing some of these lessons learned including: (a) how to effectively trial and implement exoskeletons in a unionized work environment; (b) how to select an appropriate first use application and device; (c) how to track their long-term effectiveness; and (d) how to classify exoskeletons: Should they be used to increase capacity allowing for more demanding work? Or, should they be considered protective equipment that only increases the margin of safety?

**PERSPECTIVE FROM NAVAL SHIP MAINTENANCE**

Ron Zmijewski, MEng, MPA  
Puget Sound Naval Shipyard & Intermediate Maintenance  
Facility (PSNS&IMF),  
Bremerton, WA

The research, development, and testing and evaluation of any new products are always challenging propositions – from product inception, prototype design, lab and field testing, design for manufacturability, and ultimately to consumer adoption and product life cycle support. For product safety and reliability, most consumers are reliant on standards developing organizations (SDO) such as ANSI, ASTM, IEC, ISO, for test standards and independent testing performed by nationally-recognized test labs (NRTLs).

Human augmentation products such as exoskeletons and wearable robotics are newly emerging in the marketplace to augment and improve the performance of humans. Currently, it is estimated there are over 80 exoskeleton system manufactures with products targeted at the military, from where much early public sector funding came, and commercial applications for medical, industrial, and recreational products. In particular, Puget Sound Naval Shipyard & Intermediate

Maintenance Facility (PSNS&IMF) performs depot level naval ship maintenance and has a great need for industrial exoskeleton systems that can both augment and improve human performance – for industrial work applications such as powered tool holding and lift assist and loading processes – to minimize injury rates.

In late January of 2017, initial meetings were held at the National Institutes of Standards and Technology (NIST) to begin to form a team to define terminology and taxonomy as foundational steps toward the development of standards and test methods. To date, almost all test and evaluation efforts were performed somewhat in isolation by each exoskeleton system manufacturer to help support and validate their claimed benefits, and/or the private/public sector consumer to validate those claimed benefits. Some have been further evaluated in university labs capable of more in-depth testing and evaluation. In particular, the U.S. Navy Shipyards are capable of performing basic and fundamental testing, but do not have the resources to perform advanced testing needed to fully validate these systems.

As a consumer of the best industrial technologies in the world, PSNS&IMF seeks exoskeleton systems that are safe and reliable, that have been rigorously lab and field tested, and that have been certified by the appropriate governing agencies to meet recognized standards. Through these efforts, the consumer can be ensured that these technologies are safe and fit for consumption and conform to widely agreed to and adopted standards and test methods.

## EXOSKELETONS & MUSCULOSKELETAL HEALTH

Brian Lowe, PhD, CPE

National Institute for Occupational Safety and Health  
Cincinnati, OH

In 2016, several inquiries were received by NIOSH programs from industry stakeholders and technology developers requesting information about uses for, and perspectives on, exoskeletons and related devices. These inquiries were relayed to the NIOSH Musculoskeletal Health Program, because prevention of musculoskeletal disorders (MSDs) is one of the potential positive outcomes associated with these technologies. The recent flurry of interest in this topic conveyed to NIOSH parallels trends in the emergence of early development systems.

Wearable exoskeletons are intended to augment human physical capabilities to serve a number of purposes. Active robotic systems may assist the wearer as a force multiplier. Passive systems may provide a load transference to reduce localized muscular exertion about a specific joint(s). These devices may facilitate a longer working time under equivalent task loads relative to that of the un-augmented worker. Labor efficiency and productivity advantages in such situations may be perceived benefits, however the primary interest of the NIOSH Musculoskeletal Program is the long-term effects to musculoskeletal health. A key knowledge gap is in establishing that these technologies can be effective occupational safety and health (OSH) interventions and corresponding workplace practices that assure this effectiveness. This is currently a daunting task, given that

operating concepts and technologies are rapidly evolving and that a taxonomy and standardization of test methods are in their infancy.

NIOSH is one of several federal agencies in a workgroup that was formed to address issues of terminology and test method standardization within military, medical, and industrial use communities. Communicating the technical and performance capabilities of these devices among developers and users, and standardizing tests of these, ultimately informs the commercial marketplace and allows for better product comparisons and assessments.

OSH “best practices” will be needed to complement device testing and performance standards. Our Program has informally noted the use policies of a number of early adopter workplaces, which suggest that industry practices are evolving and that evidence-based practices need to be established. For example, some early adopters have suggested that high-risk operations should require mandatory use of wearable augmentation (similar to a PPE requirement). Others have indicated that use of the technologies is currently made optional to employees. Some early adopters require readiness-for-use screening (medical and fitness readiness) before an employee is authorized to use an exoskeleton device. Some are seeking approaches to predict users who will benefit most from the technology, or who will better tolerate potentially undesirable aspects of use. Other early adopters have suggested policies promoting only shorter-term use of the technologies.

The extent to which industrial use of exoskeletons and related technologies can prevent musculoskeletal disorders is not well established at present. OSH practices should ensure that enhanced productivity and labor efficiency do not sacrifice safety and long term musculoskeletal health of the user. There are a number of gaps in research and shared early adoption/use experiences that the OETG community can collectively address to establish that these technologies are beneficial to musculoskeletal health and prevention of workplace injury.

### Disclaimer

The findings and conclusions in this report are those of the author and do not necessarily represent the views of the National Institute for Occupational Safety and Health (NIOSH). Mention of any company name or product does not constitute endorsement by NIOSH.

## REFERENCES

- Bureau of Labor Statistics. Nonfatal Occupational Injuries and Illnesses Requiring Days Away From Work, 2015. Available at: <http://www.bls.gov/news.release/osh2.nr0.htm>. Accessed on February 20, 2017.
- McGill, S. The Biomechanics of Low Back Injury: Implications on Current Practice in Industry and the Clinic. *Biomechanics*. 1997; 30(5); 465-475.
- Reid, C., Harvill, L., Norcross, J., Benson, E., England, S., Young, K., Rajulu, S. (2014). *An Ergonomic Evaluation of the Extravehicular Mobility Unit (EMU)*

*Spacesuit Hard Upper Torso (HUT) Size Effect on Mobility, Strength, and Metabolic Performance.*  
Proceedings of the Human Factors & Ergonomics Society 58<sup>th</sup> Annual Meeting, Chicago, IL. pp. 1595-1599.