EXOSKELETONS
Used as PPE for Injury Prevention

By Terry Butler and Jason C. Gillette

THIS ARTICLE FOCUSES ON THE PREVENTION of shoulder musculoskeletal disorders (MSDs) commonly associated with muscle fatigue and repetitive overuse in an occupational setting. The authors' purpose and motivation are the potential consideration of exoskeletons as PPE for shoulder injury prevention.

An upper body exoskeleton is a wearable technology engineered to improve upper extremity musculoskeletal health in professionals and skilled trade workers who engage in repetitive arm motion or static elevation of the arms. Some upper body exoskeletons (such as the one shown in the photos on pp. 32 and 34) are lightweight and transfer the weight of the arms from the shoulders, neck and upper back to the body's core, evenly distributing energy to reduce stress.

Injury Prevention & Ergonomic Assessment

OSHA offers advice for evaluating how to best protect a worker from injury. The first step is to try to eliminate the hazard. When elimination is not possible, it is best to identify a suitable engineering control. If that does not work, then the use of administrative controls should be considered. For example, a study found that welding tasks entail the risk of developing supraspinatus tendinitis and that shoulder pain decreased after relaxation and job modification (Herberts, Kadefors, Andersson, et al., 1981). Unfortunately, workers are sometimes expected to push through the pain associated with poorly designed jobs because an injury prevention solution is expensive to implement. Lastly, where the hazard cannot be eliminated or controlled, PPE must be used. PPE is any device or appliance designed to be worn by an individual when exposed to one or more safety and health hazards.

Previous research has established the association of shoulder muscle fatigue, discomfort and decreased performance as a function of arm position, particularly repetitive overhead motions (Chaffin, 1973). Through ongoing research, thresholds of exposure to risk factors (e.g., high force, long duration, high frequency, ergonomically unfavorable postures) have been proposed for different joints of the body (Rostykus & Mallon, 2017). One example is the rapid upper limb assessment tool, which is based on dose-response relationships for MSD injuries (Bernard, 1997; Marras, Allread, Burr, et al., 2000; Marras, Fine, Ferguson, et al., 1999; Törnström, Amprazis, Christmansson, et al., 2008). Another example is the Rodgers muscle fatigue analysis method, referenced in this article (Rodgers, 1992). Ergonomic assessments are a valuable tool for determining job tasks that involve risk factors where exoskeletons may be useful as PPE to potentially prevent MSDs.

Previous Studies on Muscle Fatigue & Exoskeletons

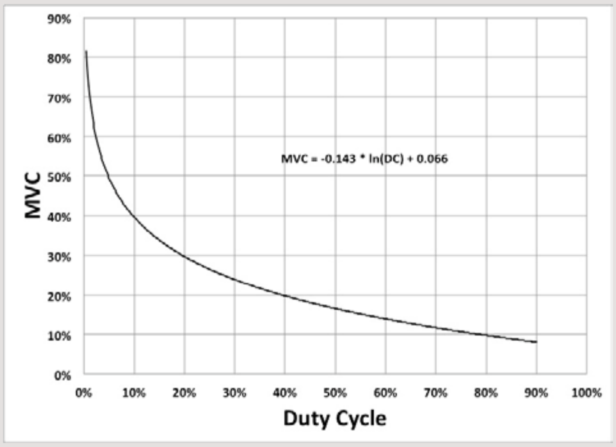
Fatigue is difficult to objectively assess, as it may involve both physical and mental components. An electromyography (EMG)-based study of repetitive hammering movements found that grip strength and elbow range of motion decreased with fatigue (Cote, Feldman, Mathieu, et al., 2008). Another study used near-infrared spectroscopy and found shoulder muscle fatigue was dependent upon shoulder angle, task frequency and force level (Ferguson, Allread, Le, et al., 2013). A 40% maximum voluntary contraction (MVC) guideline has been proposed as a threshold that should not be exceeded for more than 10% of the job cycle to avoid fatigue and potential injury to the shoulder (Chaffin, Andersson & Martin, 1999). American Conference of Governmental Industrial Hygienists (ACGIH, 2016) has further proposed threshold limit values (TLVs) that demonstrate the MVC level to produce upper limb localized fatigue decreases as the duty cycle increases (Figure 1).

KEY TAKEAWAYS

- **This article examines the potential consideration of exoskeletons as PPE for shoulder injury prevention.**
- **It provides a brief introduction to injury prevention and ergonomic assessment, and examines studies that have investigated shoulder muscle fatigue and ergonomic assessments of exoskeletons.**
- **The authors introduce a series of studies conducted to assess the potential use of exoskeletons as PPE.**
- **Test methods presented provide quantitative data to support decisions about whether exoskeletons should be classified as PPE.**

FIGURE 1

FATIGUE TLV FOR MVC (%) VS. DUTY CYCLE (%)

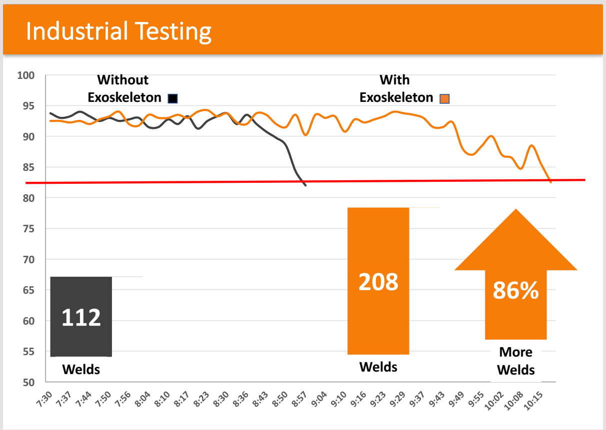


Note. From *Upper Limb Localized Fatigue: TLV Physical Agents 7th Edition Documentation*, by ACGIH, 2016, Cincinnati, OH: Author. Copyright 2016 by ACGIH. Reprinted with permission.

FIGURE 2

WELDING SIMULATION WITH & WITHOUT EXOSKELETON

The orange line indicates welding performance with the exoskeleton, and the black line indicates performance without the exoskeleton.



VMG CINEMATIC

Lab studies have utilized EMG sensors to measure shoulder muscle activity scaled to %MVC. It has been reported that endurance time significantly decreased when EMG amplitude increased from 20% to 40% MVC (Hagberg, 1981). EMG data have also indicated that the degree of upper arm elevation is the most important parameter influencing shoulder muscle load (Sigholm, Herberts, Almström, et al., 1984). Further studies have provided evidence that supporting the shoulder while working reduces muscle activity and potentially the risk of injury (Rempel, Janowitz, Alexandre, et al., 2011; Rashedi, Kim & Nussbaum, 2014). Recent studies have supported that upper body exoskeletons have the potential to be a useful, practical intervention for shoulder injury reduction without increasing low back loads, but suggest that further research is needed to test for any "unintended consequences" (Esfahani, Alemi, Kim, et al., 2017; Kim, Nussbaum, Esfahani, et al., 2018a; 2018b).

Authors' Studies to Assess Exoskeletons

This section describes a series of studies that the authors have undertaken to assess the potential use of exoskeletons as PPE. The exoskeleton assessed throughout these studies is the Levitate Airframe, a passive upper body exoskeleton designed to support the weight of the arms during overhead tasks. An initial assessment of the exoskeleton was performed by Bradley Chase, director of the ergonomics lab at University of San Diego, who collected EMG data while 15 participants completed tasks that capture multiple elements of industrial work with and without the exoskeleton. In Chase's study, he observed a statically significant 33% reduction in shoulder/neck muscle activity when wearing the exoskeleton during demanding work tasks in a lab environment. Chase stated that "the reduction in shoulder/neck muscle activity with the exoskeleton may lead to greater worker safety, comfort and productivity."

A second study assessing the exoskeleton was conducted at a Midwest manufacturing company and focused on taking four subjects to maximal fatigue. This study used welding and painting simulators to capture real-time performance and quality data (Butler, 2016). Maximal fatigue was delayed when using the exoskeleton by enabling the welder to maintain a quality weld for 73% longer, extending the endurance time by 71 minutes (Figure 2, p. 33). The weld quality scores plotted over time reinforce that fine motor control of muscles was maintained over the duration of the test. The results indicate that use of the exoskeleton postponed fatigue for welders involved in static work (stressful postures) and painters involved in dynamic work (long duration and high frequency). Participants who were experiencing shoulder pain prior to the start of the testing stated that while using the exoskeleton, their pain decreased or went away.

A third study at two John Deere manufacturing sites involved EMG data collection on the shop

LEVITATE TECHNOLOGIES

The exoskeleton assessed throughout these studies is the Levitate Airframe, a passive upper body exoskeleton designed to support the weight of the arms during overhead tasks.

floor with six workers from two different plants during their regular job shift while exposed to various kinds of physical and ergonomic stressors that are not easily simulated in a lab environment (Gillette & Stephenson, 2017). This innovative approach measured the physical benefits of wearing and not wearing the exoskeleton while performing job tasks that involve overhead postures. On-site data collections provided a real-world assessment of potential exoskeleton benefits as a form of PPE to reduce musculoskeletal disorder injuries of the shoulder. Data were collected on six experienced workers performing assembly, painting, parts hanging and welding tasks. This study utilized wireless EMG sensors to monitor the activity of eight muscles for 10-minute job cycles with and without the exoskeleton at the beginning and at the end of the work shift.

To emphasize the most strenuous aspects of a job task, one way to analyze results is to focus on the highest 10% of EMG amplitudes for the dominant arm (Figure 3). If we equate the highest 10% of EMG to a 10% duty cycle, then the ACGIH TLV for shoulder fatigue would be 40% MVC (Figure 1, p. 33). During the John Deere study, the exoskeleton resulted in a reduction of anterior deltoid (*p* = 0.08) and biceps brachii (*p* = 0.05) EMG with the exoskeleton. There were also modest reductions in upper trapezius and erector spinae EMG with the exoskeleton. A small portion of the anterior deltoid standard deviation range slightly exceeded the 40% MVC threshold with the exoskeleton. However, nearly all the standard deviation range exceeded the 40% MVC threshold without the exoskeleton. The erector spinae standard deviation range fell below the 40% MVC threshold with the exoskeleton but exceeded this threshold without the exoskeleton.

A fourth study was completed at Toyota Canada that assessed the exoskeleton during automotive undercarriage assembly (Gillette & Stephenson, 2018). Undercarriage assembly has fast cycle times and is typical of overhead work where there are two basic options for reducing ergonomic risk. One comes in the form of flipping the car on its side for assembly, which introduces ergonomic and financial challenges. The other is providing support for the arms while working to reduce muscle activation and fatigue. Eleven workers volunteered for this study, and data were collected for 10 overhead automotive assembly tasks. Approximately 12 minutes of data were collected on 11 employees performing 10 job tasks, with nine tasks having 10 repetitions, and one job task having three repetitions at multiple stations. Similar to the John Deere study, wireless EMG sensors were used to monitor the activity of eight muscles with and without use of the exoskeleton.

To place more emphasis on the repetitious nature of a job task, another way to analyze results is to focus on the highest 50% of EMG amplitudes for the dominant arm (Figure 4). If we equate the highest 50% of EMG to a 50% duty cycle, then the ACGIH TLV for shoulder fatigue would be 16.5% MVC (Figure 1, p. 33). During the Toyota Canada study, the exoskeleton resulted in a reduction of anterior deltoid (*p* = 0.001), biceps brachii (*p* = 0.001) and erector spinae (*p* = 0.03) EMG with the exoskeleton. There was a modest increase in upper trapezius EMG with the exoskeleton. The average anterior deltoid and erector spinae EMG fell below the 16.5% MVC threshold with the exoskeleton but exceeded this threshold without the exoskeleton. Average upper trapezius EMG exceeded the 16.5% MVC threshold both with and without the exoskeleton, so this is an area where additional intervention such as a neck support may be beneficial.

A Rodgers muscle fatigue analysis and a company-specific ergonomic risk analysis were completed on the 10 job tasks that were assessed with EMG at Toyota in Canada. In some cases, the risk to each body part matched in both analyses (Figure 5, p. 36); in others there was disagreement. When asked about the consistency of ergonomic risk assessment scores, a room full of automotive ergonomic professionals responded that some variability in scores is not unusual. If a job task is identified as having a high ergonomic risk score, then EMG can be used to determine whether there is a benefit to using an exoskeleton. For this job task, the ergonomic assessments indicated that the neck and right shoulder had high risk scores. EMG results demonstrate that anterior deltoid and upper trapezius muscle activity were reduced with the exoskeleton (although still slightly above the TLV for the upper trapezius), consistent with the body parts of concern (Figure 5, p. 36).

FIGURE 3

JOHN DEERE: MAXIMUM 10% EMG

John Deere EMG amplitude results. Average EMG amplitudes plus standard deviations are displayed. The blue line represents the 40% MVC ACGIH TLV for shoulder fatigue.

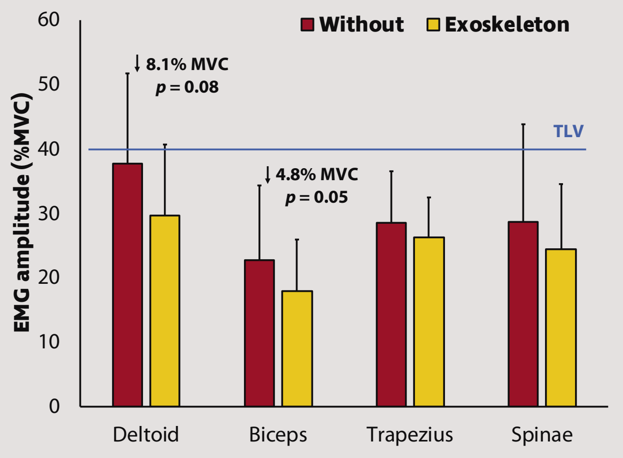


FIGURE 4

TOYOTA: MAXIMUM 50% EMG

Toyota EMG amplitude results. Average 10 employees' EMG amplitudes plus standard deviations are displayed. The blue line represents the 16.5% MVC ACGIH TLV for shoulder fatigue.

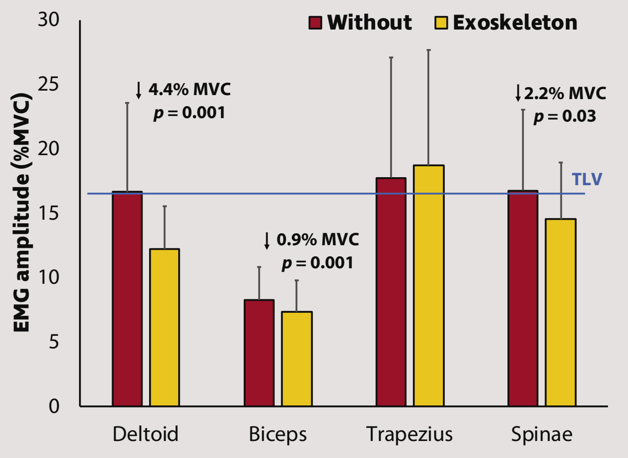


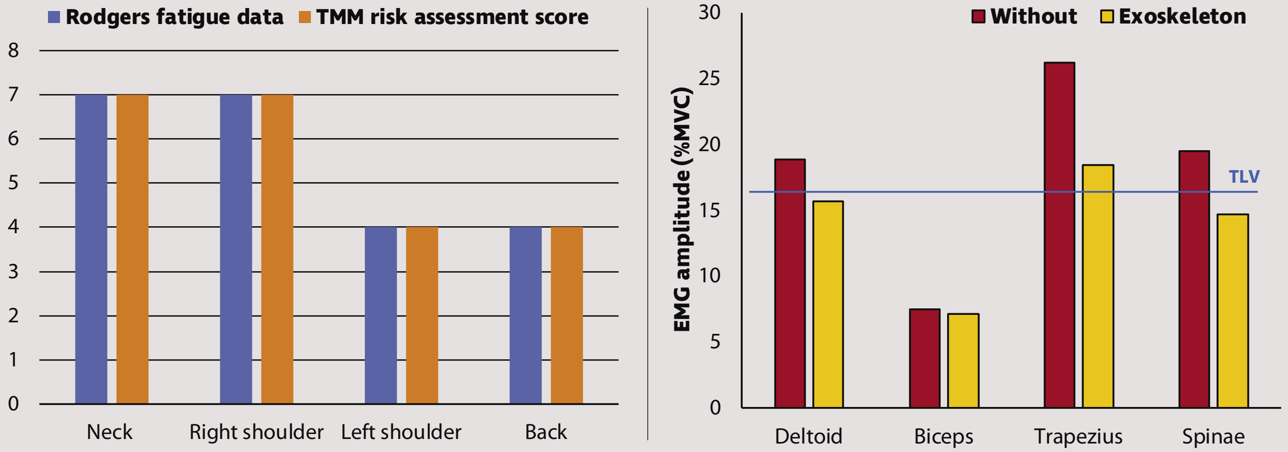
FIGURE 5

RODGERS MUSCLE FATIGUE ANALYSIS & COMPANY ERGONOMIC ANALYSIS

Figure 5a shows examples of Rodgers muscle fatigue analysis and company ergonomic analysis for job task #3. In Figure 5b, average EMG amplitudes for floor tubes are displayed to validate the risk analysis. The blue line represents the 16.5% MVC ACGIH TLV for shoulder fatigue.

FIGURE 5A

FIGURE 5B



Discussion

The focus of this article is on the potential use of PPE such as a passive activation upper body exoskeleton to help prevent MSD injuries to the shoulder. The authors have described lab-based, simulator and on-site data collections as possible methods to collect evidence about whether an exoskeleton serves as PPE. Lab-based studies benefit from being able to systematically manipulate posture conditions and additional measurement capabilities, but it is difficult to simulate industrial work conditions and participants may not be skilled at the tasks of interest. Simulators benefit from precise performance measurements but are limited to the specific application for which the simulator was developed. On-site studies benefit from real-world task conditions and experienced participants, but are potentially limited in measurement instrumentation and require coordination to minimize job disruption.

This series of studies indicate that workers with jobs that involve supporting or transferring loads above shoulder level (e.g., assembly, painting, welding, parts handling) may benefit from the use of the exoskeleton device assessed in the studies as PPE. Reduction in EMG with use of the exoskeleton would be expected to delay the onset of muscular fatigue and may reduce the risk of chronic shoulder injuries. From the jobs tested, the exoskeleton may be an ergonomic solution as PPE for tasks involving shoulder flexion of 30° to 170° that cannot be eliminated through work site modification. The EMG results show that the muscles are still working, but just not as hard, therefore lessening concerns for the development of muscle atrophy (Butler & Wisner, 2017). Analyzing maximum 10% EMG may be more appropriate for higher force/lower repetition jobs, while maximum 50% EMG may be more appropriate for lower force/higher repetition jobs.

The authors' studies assessed one design of passive upper body exoskeleton, but other exoskeletons may perform differently and, therefore, it is not known if they will meet the definition of PPE. PPE is personal. Respirators, gloves or safety glasses must be tested against different performance standards to demonstrate whether the level of protection meets the requirements to be called PPE. As demonstrated with the noted research findings, it can be argued that the same logic holds true for different manufacturers of exoskeletons. For example, doubling the weight of the exoskeleton will require the user to expend more energy just to carry the unit around and activate it to gain support when needed. The use of a passive exoskeleton must be balanced with the user's anthropometrics as well as job tasks, tools used and parts handled. This requires knowing the care, limitations and use of the technology so that employees can be properly trained.

As noted, PPE is personal and, as such, proper fit, like all other forms of PPE, is critical to its use. Like other forms of PPE, exoskeletons should have to pass performance standards to ensure that employees are adequately protected and not subject to unwanted risks. Unfortunately, no such standards exist. The basis of this research is to present test methods to obtain quantitative data to support decisions about whether exoskeletons should be classified as PPE.

When the care, limitations and use for PPE are clearly defined, proper training can be provided to the employee to prevent misuse or the introduction of unwanted risks into the work environment. To understand these risks, careful evaluation of the features and benefits of each exoskeleton must be considered. The exoskeleton design, weight and intended purpose must be applicable for the user and the work. Asking to see the data used to support marketing claims made by the manufacturer will help minimize misuse or potential negative effects on the user.

For example, it is important to consider how to extricate the user from the exoskeleton in case of an emergency. Having a single point of release or breakaway buckles in case the user gets caught on a moving line is a key consideration. The profile and how far away from the body the exoskeleton projects can also contribute to the risk of the device getting snagged by a part or moving line. Ensuring that the material and component parts of the exoskeleton that come in contact with the body are made of breathable and cool material is important to comfort and acceptance, like any PPE. Is the unit rated flame resistant in case of exposure to sparks or flame? Does the unit build up a static charge in highly atomized air as in an electrostatic spray booth? Is antimutilation (protective covers) available for use in high finish environments when working around painted parts to prevent scratches? How is the activation when raising the arms? Is it smooth or jerky? Smooth activation of the arm support is needed to control fine movements and prevent unwanted movements. What is the weight of the exoskeleton, and can it negatively impact the user by increasing the person's heart rate or increasing the forces on the joints, as can be found with some full-facepiece respirators or self-contained breathing apparatus?

These were all considerations when selecting the exoskeleton used in the studies at a Midwest manufacturing plant for John Deere and Toyota. The results from the research presented here are applicable to upper body passive activation exoskeletons with a weight less than 6.5 lb. Exoskeletons with a weight more than 6.5 pounds and design characteristics different from the unit tested may yield different performance results. They may have different limitations and, as such, their classification as a form of PPE may not be applicable.

The authors' studies provided quantitative evidence of the exoskeleton benefits in short-term, real-world working conditions, but longer-term studies are also needed. Exoskeletons should have to pass performance testing to ensure safety. The ASTM Committee F48 on Exoskeletons and Exosuits has begun developing such standards. **PSJ**

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For More Information

To learn more about the exoskeleton device tested in this article, contact Levitate's Joseph Zawaideh at josephz@levitatetech.com.