ASSESSMENT AND BEST PRACTICES FOR UPPER BODY EXOSKELETONS

With upper body exoskeletons, as with any PPE, it is critical to understand the capabilities, the care, and the proper use to ensure adequate protection from the hazards for which the exoskeleton is being deployed. Below are some guidelines to achieve this.

Best Practices For Assessments:

Credible 3rd party performance testing that:

- Tests exoskeleton for range of postures and task durations expected in target environment
- Compares muscle activity with and without the exoskeleton
- Performs tests under real world conditions on the job or realistic lab-based simulations
- Normalizes collected muscle data (e.g., percent maximum voluntary contraction or %MVC)
- Evaluates the results using an established standard (e.g., ACGIH Threshold Limit Value)

Best Practices for Deployment:

- Selecting target job tasks with postures and movements that match the exoskeleton design
- Individualized exoskeleton fitting to ensure maximum comfort and full range of motion
- Adequate arm support level for the weights handled while in different postures
- Ensure that arm support level is consistent with studies used to validate the exoskeleton
- Training of employees on the capabilities, limitations, use, donning & doffing, storage, care, and maintenance of the exoskeleton

Best Practices for Periodic & Ongoing Monitoring:

- Confirm exoskeleton support settings are matched to job task and weights handled
- Make any needed exoskeleton adjustments to improve fit and/or support settings
- Verification of user comfort and acceptance of exoskeleton
- Check that user is not using awkward postures and exoskeleton has clearance from surroundings
- Replacement of broken, worn, or contaminated components

Background Information for Assessments:

For practical assessment, exoskeletons need to be tested under realistic working conditions, either on-site or in a lab-based setting. Testing both on-site and in a lab-based setting may be useful for confirmation of results. Testing should include dynamic motions while handling different weights, when performing different types of jobs, and when working in different postures that mimic the intended use of the exoskeleton. Monitoring motion, and activation of the muscles that the exoskeleton is designed to support and the muscles of surrounding joints is encouraged. Testing a variety of muscles can document benefits of primary exoskeleton support and potential drawbacks of offloading to other muscles. For example, measuring the anterior deltoid (shoulder), upper trapezius (shoulder/neck), erector spinae (lower back) and biceps brachii (elbow/shoulder) muscles with and without a shoulder support exoskeleton is recommended. Measuring a single job, single muscle, or single posture may overestimate or underestimate the benefits and risks of exoskeleton usage. If a normalized EMG baseline (such as %MVC) is not used, then it will be difficult or impossible to compare the testing results with other studies.

Comparing Exoskeleton EMG Data against an Established Standard:

EMG data should be compared to an established standard to assess the risk of a job task resulting in muscle fatigue and whether or not that risk is reduced by exoskeleton usage. The ACGIH Threshold Limit Value (TLV) for upper limb localized fatigue is an example of a standard that is recommended for comparisons with and without an exoskeleton (ACGIH, 2016). Figure 1 shows the TLV graph in percent maximum voluntary contraction as a function of percent duty cycle. Activity at or above the line (TLV) represents an increased risk for localized muscle fatigue and potential development of musculoskeletal disorders due to repetitive overuse. The harder the muscle works (%MVC), the less amount of time (% duty cycle) permitted before exceeding the TLV. Appendix 1 lists detailed steps how to calculate fatigue risk by comparing EMG data to the ACGIH fatigue TLV curve. Figure 2 shows an example of fatigue risk values for different job tasks with and without an exoskeleton.

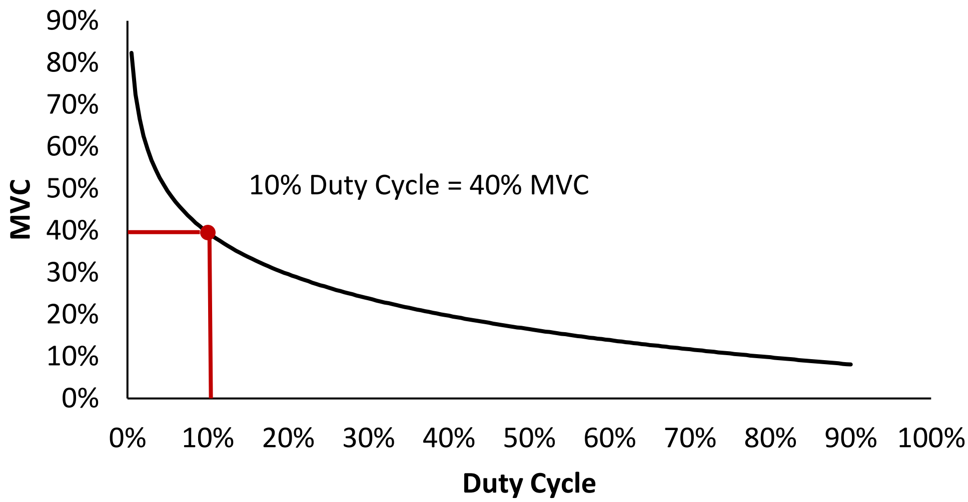

Figure 1: ACGIH TLV for upper limb localized fatigue (ACGIH, 2016). Highlighted point demonstrates that if the duty cycle is 10%, then the muscle activity must be below 40% MVC to avoid fatigue.

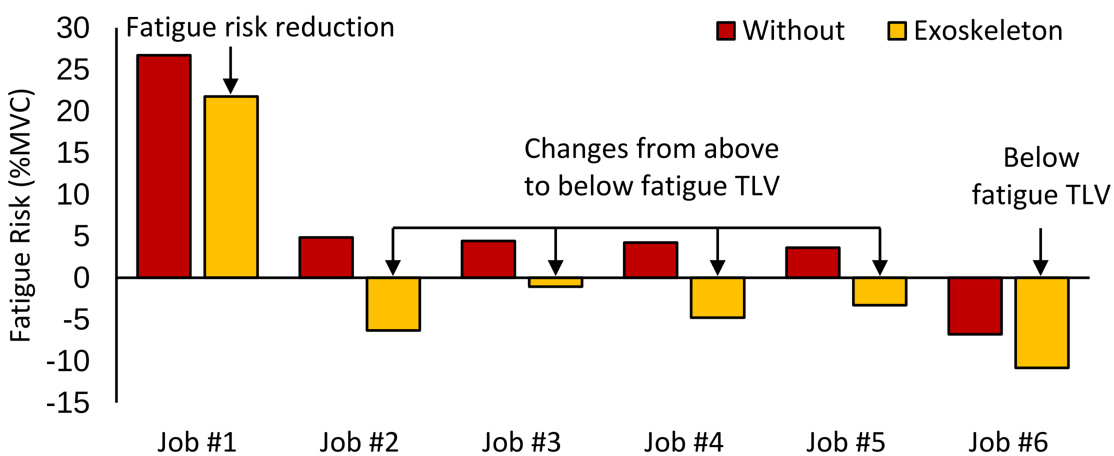

Figure 2: Job #1: reduces fatigue risk, but above TLV (exoskeleton recommended plus controls). Jobs #2-#5: reduces fatigue risk from above to below TLV (exoskeleton recommended). Job #6: reduces fatigue risk, but job below TLV (exoskeleton lower priority).

Concluding Thoughts:

Once an exoskeleton is in use, it is important to monitor that the level of support is consistent with the studies that were used for assessment in order to maximize the fatigue reduction benefits and to help ensure the greatest potential for injury reduction. Exoskeleton support levels that are too low may increase the risk of fatigue because the muscle activity benefits reported in the assessment may not be provided in the workplace. In contrast, exoskeleton support levels that are too high may also increase the risk of fatigue as the user has to exert excessive force to return to a neutral posture. In conclusion, read the fine print to know if the exoskeleton you are deploying has been tested under similar conditions to your target job tasks and has been assessed using established methods.

Assessing the benefits of an exoskeleton through EMG analysis or motion capture that can be tied back to EMG results by way of the method noted in Appendix 1, is a best practice. This best practice permits the evaluation of results using an established standard (e.g., ACGIH Threshold Limit Value).

Takeaways:

- Measuring the anterior deltoid (shoulder), upper trapezius (shoulder/neck), erector spinae (lower back) and bicep brachii (elbow/shoulder) muscles with and without a shoulder support exoskeleton is recommended
- Need to normalize EMG against a baseline such as %MVC, percent Maximum Voluntary Contraction
- When using EMG, the data should be compared to an established standard to assess the risk of a job task

Reference: American Conference of Governmental Industrial Hygienists (ACGIH), 2016. Upper limb localized fatigue. Threshold Limit values (TLVs). https://www.acgih.org

Appendix 1: Steps to compare EMG data with the ACGIH fatigue TLV curve

Experimental Protocol Step: We recommend that participants perform maximum isometric contractions (MVICs) as a way to normalize the EMG data to strength capacity. For example, we have participants perform 5 second (2 seconds ramp up, 3 seconds at maximum) MVICs in 90° shoulder flexion, 90° shoulder abduction, seated elbow flexion, and prone spinal extension.

Pre-Analysis Step: During and after data collection, EMG data should be inspected for non-physiological signal patterns due to the sensor losing contact or the sensor being bumped by the surroundings. Depending on the situation, the EMG sensor may need to be reattached or repositioned with data collection restarted or the data may just need to be cropped.

Step 1: Filter the EMG data to reduce noise. We recommend using 4^{th}-order, zero-lag Butterworth filter with a bandpass frequency of 20 to 450 Hz to reduce skin movement artifacts and high frequency noise. A frequency analysis can indicate if the surrounding environment is creating signal interference, as we have detected welding equipment at 200 Hz and 400 Hz.

Step 2: Smooth and collapse the EMG data. After rectification, we recommend using a 10 Hz low pass Butterworth filter to create a linear envelope and then collapsing the data into non-overlapping one second windows. Another common option is to smooth and collapse the data using a root mean squared (RMS) technique.

Step 3: Normalize the EMG data. We recommend normalizing the EMG data by MVICs, which will allow comparison the ACGIH fatigue TLV in the steps that follow. In addition, we recommend processing the MVIC data using Steps 1 and 2, with the exception of using an overlapping window to find a one second maximum amplitude.

Step 4: Determine when a muscle is active. We recommend defining a muscle being active when it is above 5% MVC during the one second intervals, then determining the mean active EMG amplitude when the muscle is active. The percent duty cycle is determined by dividing the number of seconds the muscle is active by the total duration of the job task.

Step 5: Determine the fatigue risk value. The TLV can be determined by entering the percent duty cycle into the ACGIH equation for upper limb localized fatigue (ACGIH, 2016):
$TLV = 100 (-0.143 \ln (\text{duty cycle}/100) + 0.066)$
The fatigue risk value is then calculated as the mean active EMG amplitude minus the TLV.

Interpretation: 1) exoskeleton reduces fatigue risk, but above TLV (exoskeleton recommended plus controls); 2) exoskeleton reduces fatigue risk from above to below TLV (exoskeleton recommended); 3) exoskeleton reduces fatigue risk, but task below TLV (exoskeleton lower priority); and 4) exoskeleton increases fatigue risk (exoskeleton not recommended).

Reference: American Conference of Governmental Industrial Hygienists (ACGIH), 2016. Upper limb localized fatigue. Threshold Limit values (TLVs). https://www.acgih.org