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Exoskeletons

White Paper

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Introduction

With the exoskeleton market expected to grow from USD $104.3 Million in 2016 to USD $2.8 Billion by 2023[1], many of us will be or have already been confronted with questions about this technology and its use in various industries. As an emerging technology, many questions and unknowns still exist regarding the ability of these devices to improve performance while maintaining or improving safety in the workplace. These questions often involve identifying and evaluating the characteristics unique to using an exoskeleton to further understand the technology's unintended consequences. Whether this is the case for an IH/safety professional or an organization, the goal of this paper is to help professionals understand conceptually what an exoskeleton is and how to effectively evaluate and determine if exoskeletons are a viable solution.

What is an Exoskeleton?

An exoskeleton is a wearable device or structure that "augments, enables, assists, and/or enhances physical activity through mechanical interaction with the body."[2] (Howard et al., 2019). The two major types of industrial exoskeletons are active and passive.

An **active exoskeleton** uses powered means to enhance the power of the worker. They are typically used for those who have permanent physical disabilities. They can allow paralyzed persons to walk and those with limited upper extremity function to once again use these limbs with dexterity. Since active exoskeletons are typically used by non-sedentary and those with permanent physical disabilities, they are not currently good candidates for workplace use. In the future, however, active exoskeletons may play a role in some return to work cases.

A **passive exoskeleton** uses springs and/or materials to store energy from human motion and uses that energy to support motion or a posture.[3] There are three common groups of passive exoskeletons currently used.

- Back assist exoskeletons can help support the lumbar spine while lifting or holding a load.
- Shoulder and arm assist exoskeletons are used to support the arms and shoulders during sustained overhead work. These can also provide an extra "arm" to hold a tool for a prolonged period.
- Leg assist exoskeletons can support the ankle, knee, or hip joints while carrying a load or be a chair alternative.[4]

For this paper, we will be focusing on passive exoskeletons as their use is primarily in the occupational setting.

Evaluating Exoskeletons for Occupational Use

Evaluating exoskeletons as an emerging technology can be difficult for industrial hygienists or organizations as the methods to measure performance can differ from manufacturer to manufacturer. Manufacturers' literature will often outline the benefits of using their exoskeletons, highlighting force reduction or elimination, but due to the various methods to validate these claims, it can be challenging for organizations to really understand the true benefit of using the devices. Failure to accurately evaluate perceived benefits correctly could lead to results underperforming desired expectations and may underestimate the transfer of force to unintended body parts, including the joints and spine.

In the next sections, we will provide the following information that may be helpful in evaluating whether exoskeletons would be helpful to improve performance and safety. These sections discuss the following:

- Hierarchy of Controls
- Interactions between the task, the worker, and the exoskeleton
- Interpreting manufacturer's data

Hierarchy of Controls

The first step in evaluating the need for an exoskeleton is to review the Hierarchy of Controls, which is a method to evaluate and assess how to implement feasible and effective control solutions. Controls are positioned on the hierarchy based upon their ability to reduce risk in a work task. Passive exoskeletons are often marketed as an engineering control. However, in evaluating the Hierarchy of Controls as pictured in Figure 1, use of an exoskeleton does not isolate workers from the hazard; in fact, the hazard still exists. An exoskeleton thus would be incorrectly categorized as an engineering control as the task is not altered; rather equipment is added to the individual. By definition, the exoskeleton may fall into the lower categories of Administrative Controls or Personal Protective Equipment (PPE) on the hierarchy pyramid. Thus, an exoskeleton is more accurately categorized as an administrative control or PPE.

Per ANSI's Risk Assessment Standard,[5] Administrative Controls are estimated to reduce hazard risk by 20% and PPE only by 5%. The priority should be on thoroughly assessing the task to determine whether the controls of elimination, substitution, or engineering are feasible. Exoskeletons should only be considered after the thorough assessments are completed and other controls are not available.

Understanding Exoskeleton Interactions in the Occupational Setting

The second step in evaluating the use of exoskeletons in your organization is to acknowledge the inter-relatedness of the task, the worker, and the exoskeleton. According to Dr. Maury Nussbaum of Virginia Tech, the decision to deploy exoskeletons in your organization involves the recognition of a complex interaction between the task, worker, and exoskeleton. Recognizing this interaction could reduce the worker physical demands, injury risk, and potentially enhance task performance.

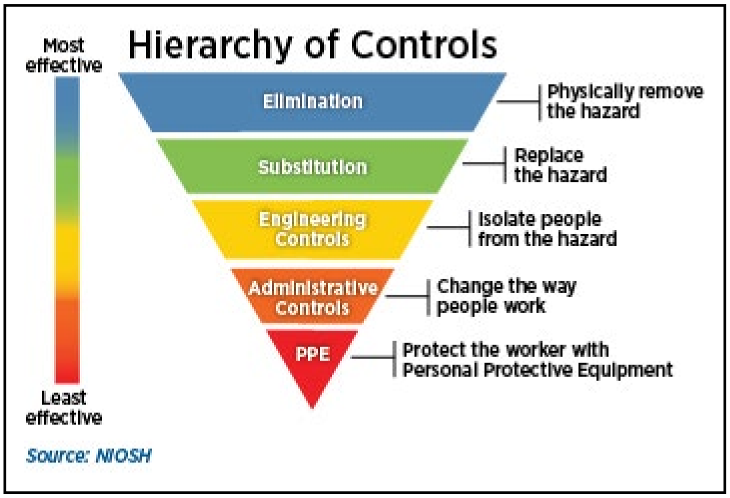

Figure 1. The Hierarchy of Controls.

However, Dr. Nussbaum cautions that very little is known about individual specific situations and the long-term interactions between an exoskeleton and an individual worker. Technology changes quickly and it is difficult for research to keep up with "new and improved" devices.[6]

Understanding the interaction between these three variables can help determine not only what will make the device effective, but also can help identify potential new hazards that may result with the introduction of an exoskeleton. The interactions consist of:

1. The Task – Defining the physical task requirements.

2. The Worker – Defining the worker's expectations and limitations to performing the task.

3. The Exoskeleton – Defining the objectives/capabilities of the exoskeleton.

Addressing the potential interactions and consequences is necessary to determine if the ideal solution is chosen or if it does not exist. It also provides a feedback loop for those considering the use of exoskeletons.[7]

Choosing an exoskeleton involves determining which exoskeleton is most suitable for the task and the degree of integrating it into the workplace. This raises questions and concerns especially for manual processes including:[8]

Task: Defining the task's physical requirements

- Is the task physically demanding and does the specific exoskeleton considered provide support to the back for lifting tasks or the shoulders for overhead or reaching tasks?
- If the task involves twisting (non-sagittal plane) and/or lifting, does the exoskeleton impact or create the potential for twisting? If so, this will likely increase the workload on the musculoskeletal system.
- Does the task require PPE or other items such tool belts? These may interfere with the exoskeleton fit and working postures.

Workers: Defining the worker's expectations to perform the task.

- Does the exoskeleton provide an appropriate level of fit for the worker demographics? Exoskeletons have limited adjustability and may not provide appropriate fit and comfort for all workers.
- Will workers share exoskeletons? If shared, then hygiene, including the presence of chemicals and cleanliness, is a concern.
- What supplies are required to sufficiently clean the exoskeleton and how long will this take?
- How will exoskeletons be securely and properly stored? This has implications for the time to readjust and fit the exoskeleton which can impact task efficiency. Some exoskeletons may require more time and effort to adjust straps or even require another worker to provide help with adjustments. Also, some units offer a variety of load springs that may need to be swapped out. This would require initial testing and training in setting up the exoskeleton for the workers and assure that the workers remember and use their individual support settings.

Exoskeleton: Defining the objectives/capabilities of the exoskeleton.

- What are the technical features of the exoskeleton such as its weight and its size?
- What are the storage requirements?
- Does the exoskeleton provide an expected ergonomic benefit?
- Once the exoskeleton is donned, does the exoskeleton change the time it takes to perform the task?

Understanding Exoskeleton Manufacturer Data

The next step after evaluating the interaction between the task, worker, and the exoskeleton is to review the manufacturer's information. This review assesses whether the device will provide the return on investment that is promised in the literature. Accurately understanding manufacture's performance claims and how they derived their findings is of utmost importance. When using an exoskeleton, the force does not suddenly disappear; rather, it is simply redirected to another area of the body. Therefore, as you interpret measured results of these devices, it is important to understand the tradeoffs.

Two commonly used measurement tools in exoskeleton product literature include employee perception and surface electromyography (EMG) studies.[9] Perception surveys are easy, cost effective tools to measure user comfort prior to and after the exoskeleton's implementation. While data is relatively instantaneous and easy to interpret, reliance solely on user's perception does not help measure where force may be transferred internally. Perception surveys may show positive impact on a short-term basis, before the user may experience cumulative musculoskeletal impacts.

The perception survey results may also be misleading since force transfers to other body parts, where localized nerve endings are not as prevalent to capture increased force levels or not measured in the study (e.g. discs). Further, an employee(s) who advocates for exoskeletons in the workplace will likely report positively, even if the unit does not respond or assist as expected. It makes sense to repeat perception surveys at both six months and one year after introducing exoskeletons as well as utilize other objective data to help quantify effectiveness (e.g. decrease in injuries, decrease in awkward postures, EMG readings).

Studies using EMGs may also be misleading if the data is not normalized or modulated for muscle length and velocity as these can influence the relationship between electrical and mechanical activity of a muscle. Surface EMG is a measurement technique where electrodes are placed onto (not into) the skin overlaying a muscle to detect the electrical activity of the muscles (muscle activation). One primary caution using this data is that even if the EMG produces a value relative to the volume of motor units active, the force generated strongly depends on other factors such as muscle fiber length, gain, and velocity. Each of these variables could affect the way the force results are interpreted, such as lower activation when muscles are stretched. For these reasons, EMG results must be used with caution when a broad range of activities is being performed.[10]

The evaluation of the exoskeleton manufacturer's results also depends on whether the location where the EMG is measured is enough. For example, measuring EMG in the shoulder region may show a reduction in stress, but the force will transfer to another part of the body, or, another part of the same muscle, that is unmeasured by the placement of the EMG electrode. Therefore, at first glance, the exoskeleton seems effective when looking at a local impact, but when looking at the connected structures of the musculoskeletal system, one finds negative impacts due to risk transfer. Measurement systems that use 3D muscle modeling (motion in space) are most accurate as they account for muscle volume when displaying muscle activation and effectively expanding the areas of observation. These measurement systems measure the forces imposed on the spine that could cause damage when the worker cannot perceive it since spinal force is cumulative and the effects will not necessarily be perceived or felt until after an injury occurs.[11]

Conclusion

Understanding how manufacturers communicate their device's benefits is important for industrial hygienists in determining whether to pursue a passive exoskeleton. How do you select the right device for a trial? In summary, considering the following concepts can allow better understanding of the limitations, when considering use of a passive exoskeleton.

- Most passive exoskeletons are designed to work within the sagittal plane; e.g., those tasks that do not require twisting. Work that is dynamic or that requires movements from the sagittal plane, will likely result in the user "fighting" the device, thereby transferring force to opposing joints when performing dynamic work. NIOSH's study warned that muscle strain could occur if a passive exoskeleton causes the user to move beyond the normal range of motion of a user's joint(s).[12]
- Assumptions made using static models may only capture muscle activation with the targeted one or two muscles engaged. As a result, displaying increased muscle activation in supporting or surrounding muscles during the work activity will be missed and will result in an underestimation of tissue load. Most research only examines biomechanical force reductions in the static position and not for dynamic postures.
- Finally, of the standards that currently exist, few exoskeletons in the market have been certified to comply with emerging international safety standards. This is mostly due to the infancy of exoskeleton standard development, and, since the volume of models on the market continues to outpace evaluation efforts.

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