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# Industrial exoskeletons: Need for intervention effectiveness research

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## Abstract

Exoskeleton devices are being introduced across several industry sectors to augment, amplify, or reinforce the performance of a worker's existing body components—primarily the lower back and the upper extremity. Industrial exoskeletons may play a role in reducing work-related musculoskeletal disorders arising from lifting and handling heavy materials or from supporting heavy tools in overhead work. However, wearing an exoskeleton may pose a number of risks that are currently not well-studied. There are only a few studies about the safety and health implications of wearable exoskeletons and most of those studies involve only a small number of participants. Before the widespread implementation of industrial exoskeletons occurs, there is need for prospective interventional studies to evaluate the safety and health effectiveness of exoskeletons across various industry sectors. Developing a research strategy to fill current safety and health knowledge gaps, understanding the benefits, risks, and barriers to adoption of industrial exoskeletons, determining whether exoskeleton can be considered a type of personal protective equipment, and advancing consensus standards that address exoskeleton safety, should be major interests of both the occupational safety and health research and practice communities.

## KEYWORDS

exoskeleton, human augmentation, intervention effectiveness, PPE

## 1 | INTRODUCTION

The origins of wearable technology can be traced back to the 16th century when the first pocket watch was introduced.<sup>1</sup> Until the 19th century wearable technology was limited to keeping track of time. In 1890, a Russian inventor, Nicholas Yagn, was granted a patent for an external “apparatus for facilitating walking, running, and jumping.”<sup>2</sup> Yagn's device involved long springs attached to each leg and compressed gas bags to store the energy for the spring action. The device was intended to augment Russian soldiers' ability to run. An external wearable framework that augments a human's natural physical ability in walking, bending, lifting, and running is now commonly referred to as an “exoskeleton.” ASTM International defines the term exoskeleton as a “wearable device that augments,

enables, assists, and/or enhances physical activity through mechanical interaction with the body.”<sup>3</sup>

Exoskeleton is a term that is often used to refer to different applications with different purposes. In rehabilitation medicine, exoskeletons are used to restore function.<sup>4</sup> For example, these devices enable assistive ambulation for spinal cord injury<sup>5,6</sup> or multiple sclerosis patients.<sup>7</sup> These devices can also be used as assistive appliances to restore function to an arm or leg, or as a therapeutic device to train an individual's muscles or nervous system to help overcome a disability.<sup>8</sup> These types of rehabilitative devices should be contrasted with *industrial* exoskeletons. The purpose of an industrial exoskeleton is to augment, amplify, or reinforce the performance of a worker's existing body components—primarily the lower back and the upper extremity.

Wearable exoskeletons are also an emerging technology for the military. Beginning with interest and funding by the Defense Advanced Research Projects Agency in the U.S. Department of Defense in the early 2000s,<sup>9</sup> exoskeleton technology has been a focus of the United States and other nations.<sup>10</sup> Military exoskeletons are intended to enhance the physical capabilities for dismounted combatants.<sup>11</sup> Warfighter performance exoskeletons are evaluated on their ability to augment mobility during load carriage with loads up to 68 kg and speeds up to 13.2 km/h.<sup>12</sup>

Two major types of industrial exoskeletons can be distinguished.<sup>13</sup> An “active” exoskeleton can be powered through actuators such as electric motors, pneumatics, hydraulics, or a combination of these technologies, and is often referred to as a “robotic exoskeleton.” Natural human movement powers a “passive” exoskeleton through springs and counterbalance forces. Most commercially available industrial exoskeletons can be grouped into the following categories: (a) back assist, (b) shoulder and arm assist, (c) tool holding/support, and (d) leg assist.<sup>14</sup> Back assist exoskeletons are used primarily to provide general support for the lumbar spine, to maintain a correct posture, and to assist during lifting or static holding tasks.<sup>15</sup> Shoulder assist and supernumerary (nonanthropomorphic) arm tool holding support exoskeletons are used to support the upper extremities during sustained overhead work or to assist in holding heavy tools.<sup>16</sup> Leg assist devices provide augmentation to the hip, knee, or ankle joint in simple locomotion or while carrying a load,<sup>17,18</sup> or serve as an alternative to a chair for relief of prolonged standing.<sup>19</sup>

Industrial exoskeletons are touted as having multiple benefits. Among these are productivity gains, work quality improvements, and a reduction the risk of work-related musculoskeletal disorders (WMSDs). Despite a paucity of prospective intervention effectiveness studies that clearly demonstrate net benefits from industrial exoskeleton use, industrial exoskeletons are already being introduced in a wide range of industries such as construction, mining, manufacturing, warehousing, and in other industries involving workers performing manual material handling (MMH) tasks.

This commentary highlights some of the potential benefits and risks of industrial exoskeletons and cautions that before widespread implementation of industrial exoskeletons occurs prospective interventional studies<sup>20</sup> be conducted to evaluate the effectiveness of exoskeletons across various industry sectors. Maximizing the benefits and reducing the risks of industrial exoskeletons requires a comprehensive research strategy to fill the gaps in knowledge about the role of exoskeletons in the workplace. Developing a research strategy to fill current knowledge gaps, understanding the benefits, risks, and barriers to adoption of industrial exoskeletons, and advancing consensus standards that address industrial exoskeleton safety should be major interests of both the occupational safety and health research and practice communities.

## 2 | POTENTIAL BENEFITS

The rise of a commercial market has raised expectations about the benefits of industrial exoskeletons. Productivity gains from

elimination of physical fatigue, reduction of time-to-completion measures, and faster product flow rates and quality enhancements from improved first-time quality checks, are among the expectations about industrial exoskeletons, but such expectations may be inflated.<sup>21</sup> From an occupational health and safety perspective, the promise that industrial exoskeletons could potentially result in reductions in risk factors associated with WMSDs, reduce medical costs for WMSDs, and reduce lost work days is the expectations that has garnered the most attention.<sup>22</sup>

Reduction in the occurrence of WMSDs from heavy physical work has been a goal of occupational safety and health research and practice for decades.<sup>23</sup> Wearable exoskeleton devices may be beneficial in reducing musculoskeletal loads that are not otherwise abated by engineering process changes.<sup>24,25</sup> They may then lead to the reduction of the WMSD symptoms and, possibly, WMSD incidence rates. However, intervention studies to date have involved only small numbers of participants (many studies with <15 participants) which makes it more difficult to draw firm conclusions about the benefits of industrial exoskeletons despite the expectations about their role in injury prevention.<sup>16,26-33</sup>

Lifting and handling of heavy materials and supporting heavy tools (overexertion injuries) are contributors to the development of all WMSDs.<sup>34</sup> Such injuries account for approximately 30% of all lost time workplace injuries and illnesses in 2016.<sup>35</sup> The direct costs of injuries in the United States due to overexertion—lifting, pushing, pulling, turning, throwing, or catching—bodily reactions, and repetitive motions to be \$18.39 billion, or 33.17% of the total workplace injury direct costs based on 2016 data from Liberty Mutual, the U.S. Bureau of Labor Statistics, and the National Academy of Social Insurance.<sup>35</sup> Worldwide, WMSDs rank number three out of the top 25 diseases by global burden, and their burden of disability is increasing over time.<sup>36,37</sup> In the United States, the economic impact of WMSDs is increasing rapidly. WMSDs accounted for an aggregate economic impact of \$367.1 billion in 1996, and \$796.3 billion in 2009-2011, an increase of 117%.<sup>38,39</sup>

If exoskeletons achieved reductions in the mechanical stressors associated with MMH tasks, they would have the potential to reduce high rates of WMSDs seen in many industries. A number of studies have been published about the use of exoskeletons in reducing MSDs in steel manufacturing,<sup>40</sup> construction,<sup>41-43</sup> and automobile manufacturing<sup>44</sup> and healthcare.<sup>45</sup>

### 2.1 | Low-Back exoskeletons

Studies of low-back industrial exoskeletons for dynamic lifting, static holding of a load, stooped or bent postures, use assessment of muscle activity, muscle fatigue, and spinal loading to determine the effectiveness of the device. For example, dynamic lifting using a passive exoskeleton designed to decrease the load to the spine and improve posture found that exoskeletons decreased muscle activity and reduced spinal muscle loading, resulting in a decrease in overall spinal muscle fatigue.<sup>15,26</sup> Static trunk bending reduced muscle

activity and spinal loading.<sup>15</sup> A wearable exoskeleton has been designed to habituate construction workers to work in more neutral postures to reduce low-back strain.<sup>42</sup>

## 2.2 | Upper extremity exoskeletons

One type of shoulder assist exoskeleton is generally a light-weight device (some <2 kg) that provides passive augmentation to support the arms in an elevated posture. A second design for upper extremity assistance is a nonanthropomorphic, vest-mounted mechanical stabilizing arm.<sup>16,32</sup> This design supports greater tool weights (payload) and essentially bypass the upper limb in transferring the payload directly from the mechanical arm to the vest and torso of the worker. They can be expanded in structure with links spanning the lower torso to the ground to further unload the torso from the mass of the system. Heavier tools may be supported because the tool is mounted through a gimbal directly to the mechanical arm. These systems are heavier than the combined mass of the mechanical stabilizing arm and vest, often weighing over 5 kg.

Studies have shown that upper extremity exoskeletons may have a role in reducing shoulder WMSDs. Shoulder assist exoskeletons have been shown to decrease shoulder discomfort while increasing productivity and work quality among painters and welders.<sup>46</sup> Decreased deltoid muscle electromyographic findings have been shown for various types of overhead tasks while using a shoulder-assist exoskeleton.<sup>16,28,47</sup> Spinal compressive forces decreased by nearly 20% and shear forces decreased by 30%.<sup>29</sup>

When upper extremity exoskeletons are used along with a proactive ergonomics program, such devices may reduce risk factors associated with work-related shoulder injuries.<sup>48</sup> Newer research avenues involving combining collaborative robotics and exoskeleton mechanics to develop a hand exoskeleton for use with a robotic manipulator arm are also being pursued.<sup>49</sup>

## 3 | POTENTIAL RISKS

With benefit also comes risk. The U.S. Consumer Product Safety Commission (CPSC) highlighted several potential hazards of powered exoskeletons to consumers.<sup>50</sup> The CPSC warned that muscle strain could occur if a powered exoskeleton moves beyond the normal range of motion of a user's joint(s). Wearable devices could cause skin irritation or chemical burns if an exoskeleton battery leaks corrosive materials. If an exoskeleton battery suddenly discharges its stored energy thermal burns would occur. Workers can experience these and other risks.

Wearing some types of exoskeletons can result in increased chest pressure, and possible decreases in chest excursions.<sup>15</sup> In one study, a heavy tool (13.6 kg) with a nonanthropometric stabilizing arm resulted in increased load to the spine.<sup>32</sup> This illustrates the importance of matching an exoskeleton system appropriately to the task characteristics. While upper extremity exoskeleton devices have

been shown to decrease muscle loading on the shoulder, there may be broader physiological consequences on the body such as increased antagonist muscle activity, postural strains, cardiovascular demand, and modified kinematics.<sup>27</sup> For instance, in a study involving eight subjects, upper-extremity exoskeleton devices did not reduce the total load on the worker, but rather shifted the load from the shoulders to the lower back and legs.<sup>16</sup> Other risks include pressure wounds or compressed nerves from prolonged use.

Concerns about hygiene have emerged in worker interviews and among early adopters in construction industry trials.<sup>51</sup> Lack of hygienic practices for devices used by multiple users could spread infectious diseases particularly in warmer climates.<sup>52</sup> Cleaning of an exoskeleton or individualizing as an item of personal protective equipment (PPE) clothing may alleviate these concerns.

Some exoskeletons are unwieldy or cumbersome and may limit the user's overall mobility, including the ability to move out of the way of a falling object. Research in user feedback suggests that postural balance while wearing a full-body, nonanthropomorphic exoskeleton with articulating support arm, is a concern.<sup>33</sup> Some exoskeletons can significantly shift the user's center of gravity causing balance problems and diminished recovery strategy—the human body's response to a loss of balance.<sup>52</sup> Data shows that human recovery strategy following a collision was negatively impacted by the use of an exoskeleton.<sup>53</sup> In addition, human factors related to the introduction of a wearable device, such as decreased vigilance or distraction from other safety measures, could also impact safety.<sup>18</sup> There is emerging work addressing how exoskeleton physical augmentation affects cognitive demands in tasks.<sup>54</sup>

Related to the use of exoskeletons as a control technology for mitigating workplace risk is the potential for over-reliance on exoskeleton technology. For example, a production engineer may remove an overhead MMH hoist and use an exoskeleton instead. This reconfiguration of an MMH task is often considered an improvement in safety. However, the use of an exoskeleton in place of a more effective engineering control represents a type of over-reliance on exoskeleton technology. The overhead hoist eliminates the biomechanical stress associated with the MMH task on the shoulders, but task redesign to use lighter weight tools, require less handling and holding time and more ergonomically appropriate postures, is the more preferred mitigation strategy. Residual risks—risks that cannot be feasibly eliminated through engineering controls—would be suitable for exoskeleton use.

Transference of risk is an additional consideration when thinking about using industrial exoskeletons. Increasing acceptable tool-holding duration by means of exoskeleton augmentation could increase other concurrent exposure durations such as hand-transmitted vibration,<sup>55</sup> noise, and exposure to respirable toxins. Field exposure studies are needed in this new area of risk transference exposures. Furthermore, accumulating studies about the risks associated with the use of industrial exoskeletons require interventional effectiveness research to characterize hazards, provide risk reduction strategies, develop best practices and safety standards.

## 4 | EXOSKELETONS AS PPE

The potential role of industrial exoskeletons in reducing the risk of WMSDs is consistent with the idea that industrial exoskeletons may be a new type of PPE that can be used along with other elements of the hierarchy of controls to prevent work-related injury.<sup>56</sup> The National Robotics Initiative 2.0 has characterized an emerging class of workplace technologies as “Smart PPE” and as “performance and amplification devices” (PAADs).<sup>57</sup> PAADs can amplify a person’s physical capabilities to more easily enable worker to perform tasks that are physically demanding and mentally challenging, thereby improving worker well-being. Even though some organizations have mandated use of upper limb exoskeletons for processes identified with overhead postural exposure, there is no current consensus in the occupational safety and health community on whether it is appropriate to classify exoskeletons as a type of PPE. Furthermore, there is an empirical question as to whether current exoskeleton configurations can meet “protection” criteria for PPE.

For example, the traditional function of PPE is that of a mechanical barrier. The effectiveness of any type of PPE is characterized by the impenetrability of the barrier to biologic, chemical, or physical agents or its resistance to contact trauma for the user. For example, some PPE such as antivibration gloves serve as incomplete barriers to hazardous energy. Research on antivibration gloves cautions against reliance on them to prevent hand-arm vibration risks and emphasizes that all other aspects of the hierarchy of controls should be prioritized before use of antivibration gloves.<sup>58</sup>

## 5 | ADOPTION BARRIERS

If the effectiveness of exoskeletons in reducing WMSDs can be established through intervention effectiveness studies, there may still be a number of barriers to adoption. Commercialization of exoskeletons may be impeded by technical challenges. First, there is a need for lighter, more compact, and more affordable actuators to power exoskeletons. A survey of user-centered design requirements for a wearable robotic supernumerary arm for use in construction found that workers prioritize lowered weight and enhanced dexterity, seek adjustable autonomy and transparency of the robot’s intent, and prefer a device that looks distinct from a human arm.<sup>59</sup> Second, more efficient and robust control strategies are needed to promote dexterous mobility functionalities. Third, lighter, denser, and longer-lasting batteries are needed for active or “robotic” exoskeletons. Fourth, few exoskeletons in the market have been certified to comply with emerging international safety standards.<sup>60</sup>

In addition, other barriers to acceptance include general discomfort, for example, a chest pad of a back assist exoskeleton making uncomfortable contact with the thoracic region.<sup>61</sup> Thermal discomfort has been described and can be exacerbated in the summer months in warmer environments.<sup>48,62</sup> A detailed model of factors supporting positive acceptance of exoskeletons can aid in overcoming barriers to

adoption.<sup>63</sup> In sum, methods to assess an exoskeleton’s readiness for implementation in specific work settings are needed.

In 2019, an assessment process was developed for evaluating the impact of the use of active and passive exoskeletons by workers.<sup>64</sup> The assessment process involves solution identification, laboratory validation, pilot testing, and in-line testing. In-line testing requires phases of planning, preparation, data collection, and data analysis.<sup>64</sup> This assessment was applied to seven commercially available passive and active exoskeletons for the back, shoulder, and hand support. The study revealed a number of obstacles in testing exoskeletons. There was a lack of tangible testing objectives, too few subjects, a lack of portable evaluation methods, and the absence of acceptance criteria to switch from one phase in the testing process to another. Presently, ASTM Committee F48 is standardizing usability assessment instruments specifically for the purpose of identifying and developing methods for assessing the usefulness and usability of exoskeletons and exosuits.

To facilitate the successful assessment adoption of exoskeletons, a virtual reality-based tool for the exoskeleton integration in industrial lines has been proposed that would aid in the identification of the optimal areas and tasks for application, the fine tuning of the active elements of the exoskeleton based on simulation results and the effective and safe training of workers into the correct use of different exoskeletons.<sup>65</sup> Another proposal involves the use of digital human modeling to validate the benefits of exoskeleton for manual handling work and tested this approach in two industry sectors: car disassembly and automotive suppliers.<sup>66</sup>

Since the current development of industrial exoskeletons focuses on technical details without considering organizational factors or production requirements unrelated to muscular loads, the current commercially available industrial exoskeletons are not at an advanced enough level of readiness for most workplaces.<sup>67</sup> For examples, concerns may arise about the application of exoskeletons in surgical operating rooms by medical personnel. In the operating room, personnel is not allowed to wear anything below the elbow joint. This organizational job requirement may pose a challenge in designing exoskeletons for operating room personnel.

Finally, an important barrier to adoption of exoskeletons in the workplace involves the level of trust between workers and employers when a new technology is introduced, especially a wearable technology. Use of any new technology requires that a number of conditions be satisfied including beliefs about performance expectancy.<sup>68</sup> If workers believe that a wearable technology like a “fitness” wrist band will improve their fitness, workers are more likely to wear it.<sup>69</sup> Similarly, if workers are shown that the use of exoskeletons can reduce the risk of WMSDs, they are more likely to adopt the new technology. Despite efforts to develop assessment tools to show the readiness of exoskeletons for widespread implementation in the workplace, insufficient information on the effectiveness of industrial exoskeletons in reducing injury outcomes, and increasing productivity may contribute to the slow adoption of exoskeletons in the workplace.<sup>70</sup>

## 6 | STANDARDS

Safe adoption of an emerging technology is aided by robust international consensus standards.<sup>71</sup> A number of studies have promoted the development of standards that specifically target the industrial exoskeleton. One example is the *Robo-Mate* industrial exoskeleton project aimed sponsored by the European Commission which was aimed at development of an industrial robot that can reduce WMSDs from MMH tasks.<sup>72,73</sup> These types of studies have helped the standards developing organizations like the International Organization for Standardization (ISO) and ASTM International actively advance safety standards for exoskeletons.<sup>13</sup>

An applicable standard for exoskeletons is ISO 13482.<sup>74</sup> ISO 13482 specifies requirements and guidelines for the inherently safe design, protective measures, and information for use of personal care robots. ISO 13482 focuses on three types of personal care robots: (a) mobile servant robots, (b) personal carrier robots, and (c) physical assistant robots. Physical assistant robots include “wearable robots (e.g. exoskeletons) that are fastened to the body of the user as well as mobility aids (e.g. robotic walking frames, support devices for standing up) extending the physical abilities of the user in a supplementary or augmentary manner.”<sup>69</sup>

ISO 13482 describes nine possible hazards of exoskeletons: (a) uncontrolled release of stored energy; (b) power failure or shutdown; (c) hazards due to shape of exoskeleton; (d) hazardous vibrations; (e) hazards due to stress, posture, and usage; (f) hazards due to exoskeleton motion; (g) mechanical instability generally and while carrying loads; (h) instability in case of collision; (i) instability while donning/doffing exoskeleton; and (j) hazardous physical contacts with exoskeleton and moving parts.<sup>74</sup> For each hazard, the ISO 13482 standard describes risk reduction steps following the hierarchy of controls: (a) inherently safe design; (b) safeguards and complementary protective measures; and (c) providing information to the operator to assist in achieving an acceptable level of safety. ISO 13482 further defines a low-risk type exoskeleton which provides low-powered, physical assistance and which can be overpowered by the user if needed in a single fault condition.<sup>74</sup>

To verify compliance with the safety criteria of personal care robots per ISO 13482, ISO is developing a technical report, ISO/DTR 23482-1, which describes recommended safety-related test methods.<sup>75</sup> A companion technical report, ISO/TR 23482-2, aims to assist robot manufacturers to design and assess for safety compliance with ISO 13482 requirements.<sup>76</sup>

In May 2019, ASTM International published two standards for exoskeletons: F3323 on terminology; and F3358 on labeling and other informational requirements.<sup>3</sup> These standards were developed by the ASTM International's Committee on Exoskeletons and Exosuits (F48).<sup>25</sup> In addition to terminology, the ASTM F48 Committee is also developing standards on wearing, care, and maintenance of exoskeletons; load handling when using exoskeletons; recording environmental conditions for utilization with exoskeleton test methods; safety considerations in designing and selecting exoskeletons; assessing system training for exoskeletons;

recommendations on usability testing metrics for exoskeletons; utilization of digital human modeling for exoskeleton evaluation; designing for population accommodation; and ergonomics of the exoskeleton/exosuit system.<sup>25</sup>

## 7 | CONCLUSION

Published studies to date support in part expectations that exoskeletons can improve workplace safety and aid employers in taking proactive measures to prevent WMSDs,<sup>77</sup> but the evidence base, especially with regard to the potential of unintended consequences of long-term exoskeleton use is still in development. More research is needed to ensure safe introduction and use of exoskeletons in the workplace. Importantly, conducting interventional effectiveness studies of workplace uses and worker acceptance will aid in developing appropriate consensus safety standards for the safe use of wearable exoskeletons in the workplace.

### DISCLOSURE BY AJIM EDITOR OF RECORD

John Meyer declares that he has no conflict of interest in the review and publication decision regarding this article.

### AUTHOR CONTRIBUTIONS

The authors conceived and drafted the work; revised it critically for important intellectual content; gave final approval of the version to be published; and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

### ETHICS APPROVAL AND INFORMED CONSENT

No ethics review nor informed consent was required as no human subjects research was involved.

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The findings and conclusions in this report of the authors do not necessarily represent the views of the National Institute for Occupational Safety and Health, the Centers for Disease Control and Prevention, or the U.S. Department of Health and Human Services.

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**How to cite this article:** Howard J, Murashov VV, Lowe BD, Lu M-L. Industrial exoskeletons: Need for intervention effectiveness research. *Am J Ind Med*. 2020;63:201-208. <https://doi.org/10.1002/ajim.23080>