IISE Transactions on Occupational Ergonomics and Human Factors

ISSN: 2472-5838 (Print) 2472-5846 (Online) Journal homepage: https://www.tandfonline.com/loi/uehf21

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To cite this article: Maury A. Nussbaum, Brian D. Lowe, Michiel de Looze, Carisa Harris-Adamson & Marty Smets (2019) An Introduction to the Special Issue on *Occupational Exoskeletons*, IISE Transactions on Occupational Ergonomics and Human Factors, 7:3-4, 153-162, DOI: 10.1080/24725838.2019.1709695

To link to this article: https://doi.org/10.1080/24725838.2019.1709695

Published online: 10 Jan 2020.

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IISE Transactions on Occupational Ergonomics and Human Factors, (2019), 7: 153–162
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ISSN: 2472-5838 print / 2472-5846 online
DOI: 10.1080/24725838.2019.1709695

INTRODUCTION

An Introduction to the Special Issue on *Occupational Exoskeletons*

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Welcome to this special issue of the *IISE Transactions on Occupational Ergonomics and Human Factors*! Our primary motivation in developing this issue was the rapid emergence of exoskeleton technologies for occupational use. While exoskeletons have been developed and tested for some time for rehabilitation and military applications, it is only recently that technologies designed for occupational tasks have become available. Indeed, the number of exoskeletons intended for occupational use is increasing rapidly, from vendors and labs around the world. There are diverse design approaches, intended to support specific body regions (e.g., arms, back, and legs), along with tool-holding devices and so-called "power gloves." Although these devices are now available, existing evidence on their effectiveness in the occupational context remains limited, and we aimed to help address this limitation. Specifically, we sought to compile new studies and evidence using user-centered approaches; such approaches are typical in ergonomics and human factors, though only recently have they been applied to occupational exoskeleton development, evaluation, or adoption/use.

Publications on the topic of occupational exoskeletons were relatively sporadic for over a decade, but have grown exponentially in recent years (Fig. 1); a similar trend was reported for the more general topic of "robotic exoskeletons" (Bao et al., 2019). While much has been learned and shared in existing literature on occupational exoskeletons, each of the 16 papers in this issue makes a new and important contribution toward understanding how best to facilitate the safe and effective adoption and use of this new technology. The papers in this issue address diverse topics, and include reviews, applications, and original research, described in more detail below.

Papers were solicited for this special issue starting in early 2018. A formal review process was used for all submissions, consistent with policies and procedures employed by the *IISE Transactions on Occupational Ergonomics and Human Factors*. Since each of the current editors was involved in one or more of the papers submitted, we clarify the specific procedures employed that ensured a fair review process (this information may also be of use to readers developing their own special issue in the future). First, an editor was not involved in any aspect of the review process or decisions for papers on which they were an author. Second, we relied in large part on the authors of submitted papers to review other submissions. Third, and given the relatively small community that is working on

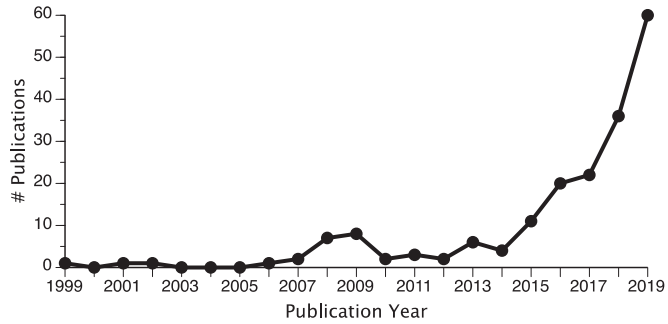

FIGURE 1 **Temporal trend in publications including material relevant to the occupational use of exoskeletons. These numbers were derived from the database of one of the authors (MN). Note that: (1) yearly numbers include both journal papers and extend conference papers; (2) judgement was used in deciding whether or not a given paper was occupationally-relevant; (3) the number for 2019 includes papers in this special issue.**

occupational exoskeleton at present, we were careful to ensure that reviewers were independent of the authors/teams involved in the papers they reviewed. Finally, no reviewers were solicited from among employees of exoskeleton manufacturers, to avoid potential conflicts of interest.

As noted, the contributions provided in this issue are quite diverse. As an approach to presenting these contributions, integrating them into the broader state of knowledge, and sharing our own collective impressions and opinions, we offer the following discussion on the broad topics of "The Past," "The Present," and "The Future" of occupational exoskeletons. In the former, we summarize some of the major historical developments in this area, as well as the specific contributions provided by review papers in this issue. Subsequently, we highlight the contributions of several of the papers here that have expanded the state-of-the art in terms of testing and evaluation methods, and that have provided important new evidence regarding the potential benefits and limitations of the occupational use of exoskeletons. Many of the authors here also provide interesting indications of where they think future developments can and should proceed. We conclude by offering our own thoughts on this, including suggestions for future research and important considerations in the future use of occupational exoskeletons.

THE PAST

Physically aiding, augmenting, or enhancing an individual using wearable, mechanical systems is not a new idea, with initial explorations documented in the 1960s. These early efforts appear to have focused on applications with substantial physical demands, mainly emphasizing powered (or active) devices for the entire body. The first patent application to include the word "exoskeleton" for human augmentation seems to have been filed in June, 1966 (US #3,449,769). As envisioned by the applicant, this "anthropomorphic" device, termed the "Man Amplifier," included articulated joints matching those of a human, with each joint powered by one or more servomotors that respond to sensor outputs included in the device. An implementation of a whole-body, powered exoskeleton was the "Hardiman," developed by General Electric, which included 28 joints and two robotic end-effectors. Any history of exoskeletons, though, would certainly be remiss to not mention the use (albeit fictional) of a powered loader by Sigourney Weaver in the film *Alien* (1979).

More recent history has seen the development, use, and evaluation of diverse exoskeleton technologies in healthcare. Applications in this context have sought to assist/enhance mobility or support rehabilitation, particularly through enhancing capacity in the lower extremity, upper extremity, and hand (see reviews by Bogue, 2015; Chen et al., 2016; Heo, Gu, Lee, Rhee, & Kim, 2012; Li et al., 2015; van der Heide, Gelderblom, & de Witte, 2015; Yan, Cempini, Oddo, & Vitiello, 2015; Yang, Zhang, Chen, Dong, & Zhang, 2008).

Exoskeletons have also been of interest for military applications for some time, and the Hardiman device noted above was commissioned by the US Military (Bogue, 2015). Among diverse physically-demanding tasks in the military, heavy and prolonged load carriage has garnered extensive attention due to the associated risks of musculoskeletal injuries. In this issue, Crowell, Park, Haynes, Neugebauer, and Boynton (2019)

summarize more than two-and-a-half decades of experience and research at the US Army Research Laboratory with exoskeletons and exosuits that have been designed to aid in military load carriage tasks. The authors describe a diverse set of design and evaluation challenges that have been identified in this work, including operating speeds, the effects of loads, the physical interface and adjustability, equipment compatibility, safety aspects, user controls, and environmental considerations. They also provide insights on several important aspects and associated challenges related to evaluating exoskeletons for the purpose of military load carriage.

Among the earliest reports on exoskeletons with specific emphasis on occupational tasks were those by Wehner (1992) and Umetami, Yamada, Morizono, Yoshida, and Aoki (1999), focusing respectively on the lower and upper limbs. These reports are also of interest in being among the earliest to use the term "exoskeleton" in their titles. In fact, an ongoing challenge in tracing the historical development and evaluation of occupational exoskeletons is that this term has only recently been in common use for this domain. Starting in the new millennium were an increasing number of reports on occupational exoskeletons, each involving custom devices with quite different technological approaches. Examples include reports by Barrett and Fathallah (2001), Yamamoto, Hyodo, Ishii, and Matsuo (2002), Kobayashi, Suzuki, Nozaki, and Tsuji (2007), Naito, Obinata, Nakayama, and Hase (2007), Kobayashi and Nozaki (2008), Rashedi, Kim, Nussbaum, and Agnew (2014), and Sylla, Bonnet, Colledani, and Fraisse (2014). Especially notable was a set of papers that assessed the "Personal Lift Augmentation Device" or PLAD (Abdoli-E, Agnew, & Stevenson, 2006; Abdoli-E & Stevenson, 2008; Frost, Abdoli-E, & Stevenson, 2009; Godwin et al., 2009; Graham, Agnew, & Stevenson, 2009; Graham, Sadler, & Stevenson, 2011; Graham, Smallman, Sadler, & Stevenson, 2013; Graham, Smallman, Miller, & Stevenson, 2015; Lotz, Agnew, Godwin, & Stevenson, 2009; Sadler, Graham, & Stevenson, 2011; Smallman, Graham, & Stevenson, 2013; Whitfield, Costigan, Stevenson, & Smallman, 2014). As a whole, these early papers laid the groundwork for future efforts in two areas. First, that diverse technological approaches are likely useful, and perhaps needed, to address the wide range of occupational task demands. Second, that a broad range of evaluative approaches are also useful, and perhaps needed, to assess the range of potential impacts of an exoskeleton on a user.

In the more recent past, a number of commercially-available exoskeletons have emerged on the market that are intended for occupational use. These devices include the Laevo (2015; en.laevo.nl), Skelex (2015; skelex.com), SuitX (2016; suitx.com), Levitate Technologies AirFrame (2017, levitatetech.com), and the EksoBionics EksoVest (2018; eksobionics.com), along with several others that have appeared in just the past few years from developers around the world. An ongoing compilation of exoskeletons for industrial and other applications is available at exoskeletonreport.com, and which at the time of writing lists no less than 21 "exoskeletons for work and industry."

The recent past has also seen an increase in field tests of occupational exoskeletons, particularly by real workers doing real jobs, in contrast to most existing evidence that was obtained in laboratory settings. According to the influential model of Rogers (1962), there are five sequential categories of adopters of new technologies, from "innovators" to "early adopters" and an "early majority," followed by a "late majority" and "laggers." We leave it to others to provide an authoritative history of those industries that were innovators in using occupational exoskeletons, though clearly in this category were several companies in heavy industry, especially manufacturing. Examples include BMW (Hetzner, 2016), Ford Motor Company (Krok, 2017), The Boeing Company (Wren, 2018), Hyundai Motor Group (Kim, 2018), Toyota (Selko, 2019), and Vermeer Corp. (Butler, 2016).

Papers in this issue include results from studies among several early adopters. Hensel and Keil (2019) provide results from a 4-week field trial of a low-back support exoskeleton (Laevo) among automotive manufacturing workers at AUDI AG. Tasks performed by the workers included both static trunk flexion and dynamic manual material handling. A major finding in their study was that workers overall reported a slight decrease in lower-back discomfort using the device, but that this benefit was only evident for the tasks requiring static postures. However, it is notable that this discomfort was only small-moderate to begin with (i.e., limited room for improvement). Evidence for a re-distribution of loads was also apparent, based on increased reported discomfort in the chest region. Finally, their analysis suggested that neither perceived usability or user acceptance

(or "intention-to-use") were particularly high, and that user acceptance was strongly influenced by both perceived usability and discomfort. Smets (2019) summarizes outcomes obtained from several phases of field trials involving prototypes of an arm-support exoskeleton (EksoBionics) for automotive assembly tasks at Ford Motor Company involving overhead work. Workers in this investigation wore the exoskeleton voluntarily for much of their shifts and noted that such use would continue if the exoskeleton were made available for them. Preliminary evidence was also found that suggested the exoskeleton could reduce exposure to risk factors for shoulder disorders. In the context of a multistage approach toward developing an acceptance model for occupational exoskeletons, Moyon, Poirson, and Petiot (2019) report on field trials of an upper extremity exoskeleton (Skelex) among workers at a boat manufacturer, BJ Technologies. From interviews among these workers, the authors identified key factors for the use of the exoskeleton, including the physical, cognitive, and occupational aspects. Gillette and Stephenson (2019) completed an ergonomic assessment of an arm-support exoskeleton (Levitate) among workers at two John Deere facilities whose tasks involved prolonged arm elevation. Reductions in shoulder muscle activation suggested the potential to reduce fatigue development during these tasks. While the workers in their study indicated that they would recommend use of the exoskeleton to others, they also noted concerns including the potential for task interference.

THE PRESENT

Broadly, exoskeletons can be categorized as passive or active. The former generate forces/torques in response to deformation, using un-powered mechanisms including springs or spring-like elements. Active devices, in contrast, involve powered force/torque generating elements (e.g., motors). At present, passive exoskeletons are predominant in the commercial market and in existing literature in the occupational domain.

Focusing first on passive exoskeletons, a fundamental aspect of these devices is the support (forces and torque) they provide as a function of the posture or movement of the user. Simply describing this support can be difficult, since many exoskeletons are complex, multi-link structures, and may include mechanisms that are not purely elastic (e.g., gas springs). An approach to quantifying the support generated by a passive arm-support exoskeleton is described in the current issue by de Vries, Murphy, Könemann, Kingma, and de Looze (2019), complementing earlier work by Koopman et al. (2019) that described a distinct approach for a back-support exoskeleton. The former authors emphasize that the support profile provided by an exoskeleton (e.g., moment vs. angle) should be a specific consideration in future investigations. Further, they note that there are likely benefits to adapting or customizing this profile on a task-specific basis, such that the support is consistent with the task demands that occur over a range of postures. Addressing this design aspect directly, Van Engelhoven et al. (2019) in this issue evaluated a passive arm-support exoskeleton in which the peak magnitude of the torque profiles could be adjusted. Participants in their study preferred varied levels of support, and excessive support was found to be potentially detrimental. The authors concluded that selecting the torque profile is an important consideration, to obtain maximal benefits (e.g., reduced muscle activity) while minimizing adverse impacts.

Active exoskeletons are also undergoing extensive development. As noted above, early efforts were made using powered technologies to augment human capacity, particularly for military application. More recent reports have documented a variety of approaches using active technologies to support most or all of the body, often for heavy material-handling activities (e.g., Fontana, Vertechy, Marcheschi, Salsedo, & Bergamasco, 2014; Kobayashi et al., 2007; Miura et al., 2018). A majority of existing research and evaluation of active technologies in the occupational domain, however, has emphasized support for the lower back. In this issue, Toxiri et al. (2019) provide a thorough overview of the diverse technological approaches that have been employed for this purpose. They note the particular challenge in developing effective control algorithms for exoskeleton actuation, and they suggest that active devices may be best applied for heavier and more dynamic tasks.

In much of the existing literature, including several papers in this issue, exoskeletons have been tested and evaluated under controlled laboratory conditions. The need for field studies is clear, however, since behaviors and outcomes found in the lab can differ substantially from those in field. Three papers in this issue involved field-based testing, thereby providing relatively stronger

ecological validity for the results obtained. Gillette and Stephenson (2019) emphasized the need to evaluate comfort and fit. These aspects were also highlighted by Hensel and Keil (2019), in that discomfort was strongly and inversely associated with user acceptance, and by Marino (2019), in that workers reported concerns about movement quality, task performance, and comfort. Comfort (and discomfort) was also emphasized by Luger, Cobb, Seibt, Rieger, and Steinhilber (2019) in this issue. Although completed in a laboratory, their study examined how comfort and discomfort are affected by the use of a passive lower-limb exoskeleton during a simulated assembly task with different task configurations. They found relatively low levels of discomfort, along with high ratings of comfort, which suggests the potential for such an exoskeleton in occupational application. However, increases in discomfort over time were found, and the authors recommended that the exoskeleton be used for brief periods. Authors of all four papers emphasized that future field studies are needed with larger samples, more diverse tasks, and longer-term evaluations.

Conclusions from research are clearly strengthened when there is converging evidence from different approaches and independent investigations. Several reports in this issue note the consistency of outcomes from exoskeleton use across multiple studies. In particular, there was general consistency found regarding decreases in muscle activity and perceived discomfort/exertion with the use of passive arm-support exoskeletons (de Vries et al., 2019; Gillette & Stephenson,2019; Kim & Nussbaum, 2019; Van Engelhoven et al., 2019). Notably, each of the four reports were based on experiments using different exoskeletons.

Contrasting this apparent convergence of evidence, however, two distinct reviews of existing literature included in this issue concluded that there is insufficient evidence to support that the use of exoskeletons will reduce the risk of work-related musculoskeletal disorders (WMSDs). Theurel and Desbrosses (2019) identified a critical gap in existing literature on occupational exoskeletons: an insufficient attention on the pathophysiological mechanisms that underly WMSDs of the upper limb and back. Focusing on the upper limb, McFarland and Fischer (2019) concluded that there was only limited-to-moderate evidence, to date, that exoskeletons reduce exposures to WMSD risk factors. Authors of both papers, however, helpfully provide specific suggestions for enhancing the body of evidence to address the issue of WMSD prevention. A similar conclusion regarding the insufficiency of existing evidence was made recently by Howard et al. (In Press), who also emphasized the need for intervention effectiveness studies in the workplace.

As noted earlier, the manufacturing sector has been a clear innovator with respect to occupational exoskeletons. It is quite likely, though, that many occupational sectors and jobs/tasks within these sectors could benefit from the use of exoskeletons. Two papers in this issue explore this directly, with a focus on barriers and facilitators to the adoption and use of exoskeletons. Kim et al. (2019) summarize the perspectives of stakeholders in the construction industry. Their results highlighted several expected benefits, including increased productivity, reduced injury risks, and better worker retention. Financial benefits and training were found to be important drivers to exoskeleton adoption, while safety, usability, and aspects inherent to the technology itself were drivers to continued exoskeleton use. Upasani, Franco, Niewolny, and Srinivasan (2019) completed an analogous investigation in the context of the agricultural sector. They found that critical adoption factors were related to affordability, durability, compatibility with farming equipment, and the ability to operate in diverse working conditions, while physical stress and several safety concerns were found as key barriers. Several tasks common in farming were also identified as likely to benefit from using an exoskeleton. Marino (2019) explored the use of exoskeletons in the wholesale and retail trade sector, finding indirect evidence of a decrease in metabolic demands. While the workers involved indicated both perceived benefits of exoskeletons and a willingness to use this technology in their jobs, several concerns that were raised were concluded as indicating more evidence is needed before large-scale deployment in this sector. The more general issue of the acceptance of exoskeletons, as a new technology, was investigated by Moyon et al. (2019). Using an ecological approach, these authors completed a case study involving several stages to identify important factors for the acceptance of an arm-support exoskeleton. Their final model included four aspects: physical, occupational, cognitive, and affective. All four of these reports clearly emphasize that exoskeleton adoption and acceptance is likely to be complex and driven by several diverse factors.

THE FUTURE

Suggestions for Future Research

Exoskeleton technologies are rapidly emerging, and the body of evidence regarding their potential and actual effects on workers in diverse applications is similarly expanding. Building on suggestions provided by several authors in this issue, we offer the following research topics as important to address in the near future:

1. Determine which exoskeleton designs are most effective for different types of task demands. Diverse exoskeleton design approaches and implementations exist, and there is substantial variability in the physical efforts required in occupational tasks. There is a clear need to determine if, and to what extent, specific exoskeleton designs are more or less effective for different task demands (e.g., static vs. dynamic or repetitive, forward vs. overhead reaching, single- vs. multi-axial movements). Further, there is a need to determine if and how active technologies can be used to create usable and effective occupational exoskeletons.
2. Understand and quantify the cognitive demands involved with using exoskeletons. Related needs are to describe the time required to learn how to effectively use an occupational exoskeleton, and to ascertain what training protocols will be most efficient. Each of these needs will likely be of particular importance when using active exoskeleton technologies.
3. Characterize the critical dimensions of adjustability in exoskeleton designs, to allow them to be applicable to and effective for use in a range of tasks, and to ensure fit, comfort, and usability for a broad set of users (e.g., of different sizes, genders, ages).
4. Identify potential adverse consequences of prolonged use of occupational exoskeletons and quantify the extent to which such consequences occur for different types of exoskeletons. Examples of such consequences include: a transfer of loads to different body parts (with subsequent increased risk of injury); an increased risk of a loss of balance (with resultant increased risk of a fall); and an altered neuro-muscular coordination (perhaps causing a loss of joint stability).
5. Identify environmental conditions that may contraindicate the use of an occupational exoskeleton (e.g., working in confined spaced or near physical hazards).
6. Explore important factors driving the adoption and use of occupational exoskeletons in diverse occupational sectors, in particular to identify key facilitators and barriers.
7. Complete large-scale field studies to better identify the benefits and limitations of exoskeleton use. Such studies should include a wide range of workers and tasks, involve diverse occupational sectors, and where possible should include health-relevant outcomes (e.g., musculoskeletal symptoms or disorders).
8. Develop and validate quantitative approaches for cost-benefit analyses of occupational exoskeletons (e.g., Todorovic, Constantinescu, & Popescu, 2018). Related to this, there is a need to better quantify the effects of exoskeleton use on occupational task performance (e.g., efficiency and quality).
9. Generate approaches to effectively simulate or predict important impacts of exoskeletons in a range of occupational applications (e.g., Constantinescu, Muresan, & Simon, 2016). Given the resource-intensive nature of lab- or field-based testing, such approaches, if sufficient valid, could substantially increase the efficiency with which exoskeletons are appropriately integrated into a workplace.

Considerations for the Future Use of Occupational Exoskeletons

As a new and rapidly emerging technology, the use of exoskeletons in different occupational applications will likely raise new and challenging questions and concerns. We discuss several here, from contexts including the exoskeleton manufacturer, the employer, and the employee. Starting with the exoskeleton manufacturer, many claims are made, such as on company websites and in other marketing materials. Often these claims are quite specific, in terms of benefits to musculoskeletal health, injury prevention, mitigation of fatigue, and enhanced performance. To our knowledge, though, few of these claims are supported by strong empirical evidence. Should there be oversight of such claims, and if

so by what oversight entity? In the near future, will this domain be one of *caveat emptor*, or, as suggested by Lowe, Billotte, and Peterson (2019), could device certification criteria be developed and implemented?

Rigorous field studies of occupational exoskeletons, as noted above, are clearly needed to demonstrate their effectiveness (e.g., in reducing the risk of WMSDs). Such studies, however, will inevitably be limited due to the extensive resources required. What alternatives might suffice, such as to support efficacy? What measures should be collected and in what contexts? Is a comprehensive set of measures (e.g., both subjective and objective) needed, or can efficiencies be gained (e.g., using one type of measure to predict the other)? Laboratory-based testing is obviously more efficient than field testing. But, do laboratory studies need to include high-fidelity task simulations, or might more general approaches be useful? The ASTM International F48 Standards Development Committee along with other potentially-relevant standards (ISO 13482 and ISO/DTR 23482-1), may help address some of the noted questions,. As noted by Lowe et al. (2019), standards will help overcome barriers to adoption and effective occupational application. Yet, it is easily envisioned that there will be situations not well covered by such a standard (e.g., new job demands, new exoskeleton technologies), suggesting an ongoing need for customized investigations.

Providing an occupational exoskeleton to a worker is clearly a type of workplace intervention. But, what type of intervention? Lowe et al. (2019) address the important issue of whether exoskeletons might be a new class of personal protective equipment (PPE). Authoritative U.S. occupational safety and health agencies do not currently consider exoskeletons as PPE, which otherwise would require employers to provide them to employees per regulatory authority. However, the U.S. National Science Foundation, National Robotics Initiative 2.0 has described the concept of "…wearable, prosthetic-like, exoskeletal, bionic, and other attachable human assistive robotic devices that can serve the workforce by functioning as (1) smart personal protective equipment (PPE) and/or (2) performance augmentation and amplification devices (PAADs)" (see NSF solicitation #18-518). Toyota (Selko, 2019) has established mandatory use of an arm-support exoskeleton when risk levels exceed exposure thresholds. There does not seem to be a current consensus about whether exoskeletons should be voluntary or mandatory, however, perhaps resulting from the lack of evidence about long-term effects.

Just a few decades ago, there was similar attention to a new workplace intervention at the time, so-called "back-belts." Back-belts were widely promoted as an effective intervention to reduce low-back problems, though their effectiveness was eventually questioned. While exoskeletons differ from back belts in the biomechanical aspects, they can be considered a similar mitigation approach with respect to the hierarchy of controls for injury prevention. Both are attempts to ameliorate the adverse consequences of exposure to physical demands, rather than reducing or eliminating the source of exposure. A back-belt, however, primarily provides support to the spine, rather than a reduction in physical loads. Exoskeletons, in contrast, use diverse approaches, redistributing these loads to other body regions, redistributing loads away from the body (e.g., to the ground), and/or reducing the physical effort required for a given task. Whether the use of an exoskeleton is considered an administrative or engineering control may depend on the specific use scenario (task demands + exoskeleton technology). Caution may be warranted, given the relative ineffectiveness found using administrative controls for injury prevention (Goggins, Spielholz, & Nothstein, 2008) and that eliminating the source of exposure(s) is commonly accepted as the more effective approach within the hierarchy of controls.

From a larger perspective, one can ask how occupational exoskeletons should fit within a more general ergonomics program. Such programs typically consider the full hierarchy of controls for safety and health, targeting those with higher likelihoods of effectiveness (e.g., elimination or substitution vs. administrative controls or PPE). Consistent with the hierarchy of controls, and given the discussion immediately above, we suggest that exoskeletons should not be used in place of or to circumvent ergonomics analysis and improvement efforts. We suggest further that exoskeletons should be used as a means for risk reduction, not to increase task demands. Additional questions remain, though, and others are likely to arise. As examples: Might exoskeletons be considered a form of "reasonable accommodation" to meet essential job functions, such as during a hiring decision? Could an exoskeleton be effective in assisting an injured worker in returning to work? Will there be adverse psychosocial effects of using an occupational exoskeleton (e.g., a worker being

perceived as being "weak"), and how might these effects influence workplace and employee acceptance?

An example framework for occupational exoskeleton deployment in a manufacturing context is provided Smets (2019) in this issue. Agreement was first reached between management and employees regarding the specific health/safety objectives of exoskeleton deployment, limiting how the technology might otherwise be used to increase productivity (and thereby potentially negate the benefits of reducing fatigue and enhancing musculoskeletal health). This example perhaps serves as a basic aspect of an ethical framework for exoskeleton deployment in the occupational domain. As occupational exoskeletons advance, however, we believe there will be an increased need for a more formal and comprehensive ethical framework. Many traditional manufacturing environments are undergoing a digital transformation made possible by the Industrial Internet of Things. Instrumented manufacturing assets feed extensive data streams, from which real-time insights can be obtained to support manufacturing efficiencies and productivity. If similar trends emerge in the context of occupational exoskeletons, ethical considerations on the use of wearable sensors for decision-making in the workplace may be applicable. For example, Morley, DeBord, and Hoover (2017) provide the following as critical components:

- Individual autonomy of employees (consent and disclosure, including future disclosure of data, is described along with its purpose)
- Employer consideration of whether initial or continued employment implies consent
- Cultural sensitivity and the engagement of stakeholders from varying cultural perspectives
- Individual control of information by protecting against intrusions into informational privacy
- Promotion of the employer's legitimate interest in organizational security, productivity, and favorable reputation
- Clarification of information ownership and accountability, including conditions for mandated external reporting (e.g., law enforcement), possible punitive actions, and responsibility and liability for inaccuracies

CONCLUSIONS

By combining the abilities of humans and machines, occupational exoskeletons may help overcome the limitations of each, and thereby positively impact the future workplace by reducing injury risks and enhancing performance. What do we envision for the future? As the famous saying goes, "It's difficult to make predictions, especially about the future" (attribution unknown: https://quoteinvestigator.com/2013/10/20/no-predict/). Nonetheless, and to paraphrase from one of the papers in this issue (Kim et al., 2019), we foresee exoskeletons eventually emerging as another useful tool in a worker's "toolbox." But many questions remain, and much evidence is still needed, before we know how best to match a given exoskeleton to a particular worker doing a specific task. However, the set of papers in the current issue has made important contributions to this end and will serve as a strong foundation for future contributions. As suggested in Fig. 1, such contributions are emerging at a rapidly-increasing rate, providing confidence that the potential benefits of occupational exoskeletons will be beneficially realized on a larger scale in the not-to-distant future.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DISCLAIMER

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of company names or products does not necessarily constitute endorsement by the Guest Editors.

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