Introduction to the *Human Factors* Special Issue on User-Centered Design for Exoskeleton

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Wearable technologies, such as smart watches, head-mounted displays, wearable sensors, electronic textiles, exoskeletons, and exosuits, are examples of an emergence of disruptive technology. These technologies are iteratively pushing our society through a paradigm shift—one that is closer toward the bionic human interfaces that until now were the stuff of Hollywood movies and comic books.

Beyond interface considerations are the questions of how we will don, doff, wear, or implant these types of technology and what will be the short- and long-term implications of their usage. Recent publications looking at the barriers to acceptance and utilization of wearable technology noted that a wearable product must not only be safe, comfortable, useful, and usable, but just as importantly, must be desirable to the end user (Jacobs et al., 2019; Schall et al., 2018; Reid et al., 2017). To help explore these concerns, journals and conferences around the world have been producing publications and events centered on how these new technologies should be designed. The limiting factor with these events and publications, however, is that they primarily focus on functional product design such as material science, motor control theory, servomechanism design, or energy sources (essentially how to make the system work). There are few public sources of empirical data available for designers, end users, and third-party organizations that can be used for design that is properly centered around and for the human end user.

In the fall of 2017, ASTM International formed the Exoskeleton and Exosuits Standards Committee, known as ASTM F48. This committee endeavors to develop standards for safety, reliability, and effectiveness of the technology designs: from design and manufacturing, to human factors and ergonomics, to information technology (IT) and cyber security. More recently (2019), ASTM formed the Exo Technology Center of Excellence (https://www.etcoe.org/), a research and funding arm of ASTM International geared toward working hand in hand with the ASTM F48 standards developers. Outside of ASTM, other international standards organizations such as the International Organization for Standardization (ISO), as well as national standards organizations, such as in Japan and France, are actively deciding for their populations how the bar should be set for designing, assessing, and interfacing with exoskeletons and exosuits.

In 2018, the Human Factors and Ergonomics Society, in collaboration with ASTM International, developed a partnership through the ErgoX Symposium that focused on user-centered design of exoskeletons. The year 2020 marks the third year for this symposium, which has brought together academic, private industry, and government experts from around the world to discuss and identify major human system interface gaps and solutions in an annual iterative fashion. This *Human Factors* special issue journal is a

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product of the 2018 and 2019 ErgoX Exoskeleton Symposiums.

So what is exoskeleton and exosuit wearable technology? Exoskeletons and exosuits are wearable technology designed to enable, augment, or assist with physical activities (ASTM F3323-19a, 2019). Exoskeletons are primarily made up of rigid or hard components, whereas exosuits are primarily made up of soft and malleable components, similar to clothing textiles.

Known colloquially as exosystems or exos for short, they are increasingly found in the military, industrial, rehabilitation, and even athletic settings. As exos become more prevalent globally, the science and technology behind exos become more complex, requiring a better understanding of both the short-term and long-term impacts. Over the last two decades, this evolution of exos has been rapid and expansive. Whether attempting to protect a worker from the demands of the job or enhancing the performance of worker, athlete, patient, or soldier, there are many aspects about the design of the exos that need to be understood to optimize these efforts for its human user. This special issue aims to provide insight into several key aspects of this expanding field of wearable technology.

First, as exos become more widespread and complex, several studies have investigated the key factors into user acceptance of exos in order to design better ones. If designers and engineers don't understand why workers accept or reject the devices, and specifically why they don't use them properly, exos will fail to accomplish the goals of protecting the worker or patient. In this issue, three different studies investigated the importance of end user involvement in the design phase and the factors that contribute to user acceptability (Baltrusch et al., 2020; Elprama et al., 2020; Ármannsdóttir et al., 2020). The three most important factors for workers to use exos were (1) ease of use, (2) how many others use exos, and (3) how well the exo performed (Elprama et al., 2020). In evaluating the user-centered design approach, Ármannsdóttir et al. (2020) found a need for standardization and validated methods to evaluate exos. Furthermore, exos for low back rehabilitation will need a strong implementation strategy and oversight by coaches to ensure success in returning the injured patient to work (Baltrusch et al., 2020). As exos are introduced into new industries, special considerations must be undertaken, as many industries offer unique obstacles. Cha et al. (2020) discuss one such industry, healthcare, where the potential benefits of exos are immense, given healthcare workers' physical demands, long hours, and frequent injuries. Another emerging opportunity for exos is in industries with large populations of older workers. To achieve widespread acceptance and adoption, exo designers and researchers must understand how older workers will engage with exos. Shore et al. (2020) discuss the Exoscore tool which is designed specifically for understanding acceptance of older workers for lower leg exos.

Second, there is a huge potential for exos to impose both physical and mental demands that require the user to accommodate simultaneously to these demands. Oftentimes, dual demands result in increased stress, more errors, and poorer performance. Two research groups (Bequette et al., 2020; Stirling et al., 2020) investigated the impact of exos on dual demands (e.g., mental and physical) on the user. Bequette et al. (2020) provided evidence that powered exos of the lower extremity negatively impact performance (e.g., slowed reaction times and increased workload). Stirling et al. (2020) revealed that in order for an exo to fit a worker and the workplace requirements, it must account for both physical and cognitive demands. Insights from these two studies should lead to a broader range of scientific investigation for exos and serve as a starting point for multidisciplinary studies.

Third, impact of exos on performance frequently depends on design features that affect the level of muscle exertions and the overall amount of biomechanical effort. Two studies investigated the biomechanical responses in the lower back when wearing exos (Alemi et al., 2020; Madinei et al., 2020). Three studies investigated the impact of lower extremity exos during various manual handling tasks (Bequette et al., 2020; Kermavnar et al., 2020; Pillai et al., 2020). Together, these studies provide some insight into the complex relationship between the exo and the human musculoskeletal system. Ultimately, we need a better understanding of how an exo designed for one part of the body may affect whole body mechanics. It is important to recognize that benefits to one body region could be partially or completely negated by the exo's effect on another body region.

Overall, this special issue on the user-centered design of exos represents a broad look into many of the critical issues that must be addressed before exos can be fully adopted at the global societal level. Our understanding of exos must investigate not only the physical biomechanics but also the mental demands that are imposed by them. Furthermore, as designs evolve (e.g., lighter materials, smaller devices, more integrated devices, wearable computing, artificial intelligence), users will continue to provide the best input into whether a device is acceptable and more importantly, whether it will be used. The articles in this special issue lay the foundation for future exo human user research and provide critical insights that will ensure that exos and their many potential benefits are here to stay instead of becoming the next ergonomic fad.

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