Factors Influencing Societal Acceptance of Exoskeletons

A Research Paper submitted to the Department of Engineering and Society

Presented to the Faculty of the School of Engineering and Applied Science
University of Virginia • Charlottesville, Virginia

In Partial Fulfillment of the Requirements for the Degree
Bachelor of Science, School of Engineering

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Spring 2024

On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Introduction

Wearable technology has evolved over many centuries, as individuals have donned these items that provide functionality and aesthetic properties. Wearable technology is prolific in modern society, as the most popular contemporary example is the Apple smartwatch. (Wilson & Laing, 2018). In the 13th century, English friar Roger Bacon invented wearable technology with the creation of spectacles, long before the development of the Apple watch. Since Bacon placed the roots for wearable technology, there has been an emergence of various inventions. The most rapid development pace has occurred in the last half-century with the advancement of electronics-based wearable technology (Ometov et al., 2021). This convergence of fashion and function has integrated wearable technology as commonplace in today's society (Babič et al., 2021). As this integration becomes more evident, it is necessary to delve into the dynamics between these technological advancements and society.

Exoskeletons are a form of wearable technology that works in tandem with the user to either transfer load off or augment joint torque. A misconception portrayed by the media is that exoskeletons are advanced robots that provide their users with superhuman capabilities. A deeper dive into this type of technology suggests that the media's perception is far off. In reality, while some exoskeletons are robots equipped with sensors and actuators, many of them are also passive wearable devices that reduce physical load, enhance strength, or improve task performance (Crea et al., 2021). The blue-collar, military, and medical industries have used exoskeletons since the 2000s (Bengler, 2023). The military in particular is a pioneer in the development of exoskeletons. With their current development, exoskeletons can become devices incorporated into daily life, extending beyond their current sectors. Based on this expansion, the exoskeleton market is expected to increase from a worth of $68 million in 2014 to $1.8 billion in 2025 (Golabchi et al., 2022).

Exploring the potential limitations that may impact the use and effectiveness of exoskeletons can provide valuable insights into their acceptance and adoption within various contexts. In this paper, I delve into the factors affecting exoskeleton utilization in society and how their integration into social systems is accepted. Rehabilitation, disability, occupational, and military are the main sectors analyzed.

Methods

To understand the current acceptance of exoskeletons, in-depth research into their influence and limitations is necessary. Identifying and exploring the factors that limit exoskeleton effectiveness gains valuable insight into how different contexts embrace these devices. This information helps develop strategies and solutions to overcome limitations and foster widespread acceptance. Notably, the advancement of wearable technology and ethical usage is a concern.

I use the Social Construction of Technology (SCoT) framework to understand the societal acceptance of exoskeletons. Wiebe Bijker developed SCoT and it explores how human actions and experiences shape technological development. Within SCoT there are several central concepts, including the relevant social group, interpretive flexibility, closure, stabilization, technological frame, and inclusion (Bijker, 2001). These core concepts analyze the safety, efficacy, cost-effectiveness, wearability, and ethical implications of exoskeletons.

To effectively gather data and analyze the interactions between the various actors and factors and the effect of exoskeleton acceptance, a literature review collects evidence. This literature includes an array of published research papers and narrative books. Exoskeletons involve the human experience, so it is pertinent to look into subjective perceptions and not only pure statistics.

Exoskeletons for individuals with disabilities or rehabilitation needs are a key part of the discussion. An integral part of the literature review is exploring disability works. Published research papers discuss the use of exoskeletons for limb replacement or rehabilitation. These provide insight into a medical perspective of exoskeletons. Narratives that explore the thoughts of people with disabilities gain a subjective perspective. Beyond the realm of disability support, exoskeletons are gaining prominence for occupational and military use (Bengler, 2023).

Results and Discussion

Rehabilitation

The medical field is the application of technology and methods to improve human health and well-being. Medical technology and devices cater to diverse health needs and treat various ailments. Preventive or curative efforts are a large part of medical care. Medical care is not only limited to treating existing diseases but also includes crucial efforts toward preventing and minimizing factors that lead to chronic diseases. Chronic diseases can significantly impact one's quality of life and focusing on reducing risks and promoting healthy lifestyles is essential (Bunker, 2001). Rehabilitation is a subset in the medical field developing wearable technologies, like exoskeletons, to improve patient recovery. Many social groups interact within this sector including patients, healthcare professionals, researchers, and policy-makers/insurance companies. Rehabilitation exoskeletons aid individuals with mobility impairments and provide the patient with preventive care. A technique used in physical therapy is passive movements. The therapist will manually move the targeted limb of the patient to induce the brain to learn and adapt the movement (Onishi, 2018). An exoskeleton can take the place of the therapist to move the targeted limb through passive movement or aid the patient with other rehabilitation methods such as constraint-induced movement therapy, where the stronger limb is constrained to force the use of the weaker limb. A goal with rehabilitative exoskeletons is that one day patients will be able to use them at home without the supervision of a physical therapist to complete their routines. Exoskeletons provide a pathway for patients to have more control over their rehabilitation process and improve their independence.

There are FDA-approved exoskeletons like the ReWalk, Ekso, and Rex. This increase in regulatory approvals and awareness of exoskeleton systems is driving up the demand and acceptance rate. This demonstrates exoskeleton usage as a current rehabilitation tool. However, there are technical downsides to these exoskeletons such as having slow dynamic performance in comparison to human capabilities, heavy battery packs that require specific requirements/conditions, comfortability, and wearability. Social issues of these exoskeletons include high capital costs which in turn lowers accessibility and general hesitation from patients to use such highly assistive technology as an everyday part of their routine (Rupal et al., 2017). The current price tag on a rehabilitative exoskeleton starts in the tens of thousands, which decreases accessibility in both developed and less developed countries. Developing countries often rely largely on importing medical equipment, which further raises costs and limits access to exoskeleton technology, restricting the expansion of the exoskeleton industry. Policy-makers can increase exoskeleton production and decrease the cost of production through funding and regulation to remedy this problem. Further, the price may drop as more competitors enter the market (Gorgey, 2018).

In the rehabilitation sector, exoskeletons are generally viewed in a positive light and primarily interpreted as a tool for physical therapy by social groups. They are assistive devices with daily routine activities as well. In general, they offer an innovative solution for mobility impairments. A concern with exoskeletons is visibility and how it impacts user perception. Clinical or private settings use rehabilitative exoskeletons as a temporary addition to the user which suggests there aren't overarching negative perceptions associated with them.

Disability

Exoskeletons designed for individuals with mobility impairments function similarly to rehabilitation exoskeletons. They replicate biomechanical movements for paralyzed, atrophied, or missing limbs, enabling users to perform daily tasks with ease. The key difference between these exoskeletons and those used for rehabilitative purposes is the design focus. Rehabilitation exoskeletons are used in controlled environments and focus on performing repetitive movements to aid patients in regaining mobility and strength. Whereas exoskeletons for disability purposes require a more advanced design to perform various tasks and endure continuous operations raising concerns about practicality. This requires far more research, time, and resources from designers resulting in a hefty price tag. Much like rehabilitative exoskeletons, policy-makers, and insurance companies have a role in affecting the accessibility of these exoskeletons and impact acceptance.

In the medical realm, it is often assumed that people with disabilities want to be "cured." In her essay *Disabled People Don't Need To Be "Fixed" - We Need A Cure for Ableism*, Wendy Lu (2018) describes herself as a proud disabled activist. She describes how the idea of a cure in disability communities is a complex issue that perpetuates that people have a negative relationship with their disability. For some people with disabilities, they see a cure as a rejection of who they are and an ableist view. Cures set forward a notion of what a normal body should be and promote ideas that disabled people's bodies are less valuable. Rather than focusing on cures, society should work towards dismantling ableism and improving accessibility for all disabled people. Lu does go on to state that while cure-focused narratives can be harmful, access to treatment is still important. There is a distinction between a "cure" that satisfies ableist views and treatments that provide relief.

Liz Moore (2020) in her essay *I'm Tired of Chasing a Cure* shares a perspective common among disabled individuals. Moore suffers from chronic pain and longed for a "cure." She was first diagnosed with fibromyalgia and recounts how she spent many years hating herself for not being able to overcome her disability. Unsolicited advice and constant redirection to new cures amplified her disappointment. An antibiotic prescription relieved her chronic pain from Lyme disease. But, when the prescription expired, the pain was worse than before. She goes on to have a constant stream of various antibiotic prescriptions that almost led to her death when she contracted *C. difficile,* a deadly gut bacteria common in long-term antibiotic users. The conventional medication wasn't working, however, Moore was able to live thanks to an experimental fecal transplant. Her story is an example of how chasing a cure is not always what's best for disabled individuals. Moore concludes that the relentless pursuit for cures can overshadow living life fully, stating, "I will still take a cure if it's presented to me, but I am so tired of trying to bargain with the universe for some kind of cure. The price is simply too high to live chasing cures, because in doing so, I'm missing living my life."

In contrast to the narratives of Lu and Moore, there are stories like Amanda Boxtel's. In her story, *Exoskeleton Technology Could Redefine Disability*, Boxtel (2015) illustrates how a bionic exoskeleton suit turned her life around for the better after a freak incident at the age of twenty-four fully paralyzed her from the waist down. Adaptive technology enabled her to keep doing the activities she loved after the incident, but she maintained a deep yearning to one day be able to walk again. Sixteen years post-incident, she volunteered to be the first person in the U.S. to have human embryonic stem cell treatments. While it did not enable her to walk, it did aid her in regaining trace muscle power and sensation. While she tried many experimental treatments, she realized that all of the given therapies were missing some component of walking. She didn't let discouragement stop her from dreaming of using a robotic suit to stand up and walk. This dream came true when the CEO of Ekso Bionics reached out to her and asked if she would test-pilot an exoskeleton prototype that covered her legs and feet. With some practice, Boxtel was able to walk on her own using the exoskeleton. Today, she has acquired her own personal suit and has walked more than 130,000 steps with it. For some wheelchair users it is part of who they are and not seen as a negative aspect in their life. For Boxtel, she says the wheelchair can be disempowering and hopes that exoskeletons can become an alternative.

There are conflicting perspectives on whether exoskeletons are a "cure" that would perpetuate ableist views or if it's an innovative alternative that can greatly improve disabled people's lives. Ultimately, the disabled community is not a monolith and does not need to share the same ideals. The cost associated hinders how available exoskeletons are to the disabled community, especially if they are battling with other medical-related expenses. Much like with the wheelchair, if exoskeletons were to have a widespread application in the disability community, it would create a perception that a 'normal' person shouldn't use them (Kapeller et al., 2020). Furthermore, users would see disability exoskeletons as a permanent or semi-permanent addition, creating psychological effects or perceptions that would further affect acceptance. Exoskeleton design and usage are improving as companies are including disabled people in the design and experimental process, however, they remain from being a piece of mainstream equipment still.

Occupational

In blue-collar industries, physically demanding work leads to musculoskeletal disorders (MSDs). Employers see MSDs as costly due to their relation to compensation claims or indirect expenses like production losses. Companies are looking towards occupational exoskeletons (OEs) as a remedy for the physical risks causing MSD. Developers designed most OEs to increase strength and reduce the physical load on the upper limbs or the lumbar region. OE classification is based on kinematic structure and type of actuation. For kinematic structure, OEs fall under rigid structure: anthropomorphic or non-anthropomorphic, or soft exosuit. Actuation types are passive, semi-active, and active. Active OEs use powered actuators and sensors to sync with human motion and assist torque. Passive OEs do not have a power source but rather use springs or elastic material to store and release energy during lifting work. Semi-active OEs are a middle ground between the two. Active OEs tend to have greater adaptability and passive OEs have greater usability however, active OEs require far more accurate control algorithms making them difficult to implement in field scenarios. The environments employing OEs have complex interactions and routines that make it difficult to measure the biomechanical effectiveness of OEs. The effectiveness of OEs requires a more holistic approach determined by psychological and usability factors (Crea et al., 2021).

The study "Exoskeleton acceptance and its relationship to self-efficacy enhancement, perceived usefulness, and physical relief: A field study among logistics workers", surveyed logistic workers of a vehicle manufacturing company and their work-related self-efficacy using a passive exoskeleton. A baseline self-efficacy was established before use and then compared to self-efficacy with the use of the exoskeleton. On average wearing a passive exoskeleton decreased self-efficacy beliefs. Workers reported that they felt constrained rather than relieved and that the function of the exoskeleton did not correspond well with their work tasks. However, a small subset of workers who did perceive the usefulness of the exoskeleton and greater physical relief showed an increase in self-efficacy and overall positive association with exoskeleton acceptance. While this study focused on passive exoskeleton use, it does show that both passive and active exoskeletons could continue to gain relevance in this field if designs turn to focus more on human-centric and ergonomic structures to increase usability.

Sandra Siedl and Martina Mara (2023) conducted another study where they formed a focus group of workers in food retail and corporate logistics to discuss occupational exoskeletons. The focus group was designed to gain an understanding of workers' willingness to wear OEs and explore more social and emotional aspects of OEs. Participants showed concern about exoskeletons harming work performance due to perceived reductions in flexibility, work speed, and additional cognitive load. Furthermore, there was more focus on preventing a drop in work performance than achieving an increase. Participants also showed an assumption that exoskeletons would have a lack of physical strain relief and ease of pain, leading to a decreased intention to use exoskeletons. Some participants even vocalized fears about harmful physical side effects. The focus group revealed concerns about the visibility of exoskeletons which hasn’t been explored significantly in other research. The sight of an exoskeleton on a worker would provoke a reaction from coworkers or customers that can affect work performance, effort, and psychological well-being. Implementing measures to avoid negative social dynamics is crucial to further exoskeleton acceptance.

Occupational exoskeletons are still in the early development and adoption stages. Significant deployment of exoskeletons is currently unlikely as workers must have a willingness to wear them and there are several hurdles to overcome to achieve this. Additionally, there is little knowledge about the effectiveness of OEs in preventing MSDs which is the original intention of employing OEs (Monica et al., 2020). Beyond these factors, several other stakeholders are involved in the process like health and safety, human resources and production department, unions, and policymakers. Additionally, there would need to be an in-depth cost-benefit analysis (Crea et al., 2021).

Military

The military pioneered exoskeleton applications and is a specialized subgroup within occupational exoskeleton usage. The military first began researching and developing exoskeletons to provide strength and endurance to service members working in logistic settings and dealing with heavy loads. Much like occupational exoskeletons, the military wants to decrease the amount of MSDs occurring in soldiers. While this maintains to be one goal of militaristic exoskeletons, a new focus on soldiers in combat and special operations forces has arisen. These soldiers carry anywhere from 96 to 140 pounds of equipment on their backs for several hours or days. The military exoskeletons switched gears to augment soldiers' physical capabilities, improve endurance, and reduce fatigue during missions and other tasks. The ultimate goal is to create superhuman soldiers with better endurance and strength than their non-exoskeleton-donning counterparts. (Yeadon, 2020).

Implementing military exoskeletons would follow a roadmap similar to that of occupational exoskeletons. Extensive research and development is needed to create exoskeletons that are adaptive to the environment and have a human-centric design to increase user willingness to wear them. However, with military exoskeletons, there is more concern with the ethics surrounding them. Mehlman, Lin, and Abney (2013) proposed ethical and legal conditions that need to be met for enhanced soldiers to be morally acceptable which included legitimate military purpose, objective must be reasonably necessary, benefits outweigh risks, burdens on soldier must be minimized, accountability of superior officers coercing soldiers into illegal decisions, and transparency with the public. If the military follows these rules, it would allow them to maintain an ethical approach to exoskeleton use and neutral or positive societal acceptance.

Safety and Efficacy

The safety and efficacy of exoskeletons constitute a critical aspect of their integration into society. Research findings and case studies of successful iterations of exoskeletons provide valuable insight into the capabilities and limitations of exoskeletons. Some industries have already begun to integrate exoskeletons into their environment and different industries are looking into adopting exoskeletons as a part of their everyday routine, however, a wide-scale adoption is limited due to the challenges and risks involved. While the study by Siedl and Mara (2021) discussed OEs and the self-efficacy of the user, the efficacy of the exoskeleton itself is crucial as well. The efficacy of exoskeletons is dependent on the intended goal of the context and task, such as reducing physical load, improving joint torque, or rehabilitation. The metrics used to evaluate efficacy in these situations can be subjective or objective. Subjective metrics include user perception, satisfaction, and comfort. Objective measures include measurements such as electromyography, heart rate, energy expenditure, and joint angle and torques. Additionally, other metrics like productivity and accuracy are considered. The metrics can provide a comprehensive evaluation of an exoskeleton's safety and efficacy (Golabchi et al., 2022). A challenge of exoskeletons is to assess any potential risks and hazards that arise from their use and mitigate them. Risks are categorized as sources of possible harm or adverse effects the exoskeleton causes to the user. There are technical reports from the International Organisation of Standardization (ISO) that guide the risk assessment and risk reduction process for a personal care robot, which exoskeletons fall under.

A study by Stefano Massardi et al. (2023) in the Journal of NeuroEngineering and Rehabilitation conducted a risk assessment of exoskeletons by surveying anonymous participants from exoskeletons, human biomechanics, and robotics communities. The survey received 65 answers and all participants had experience in creating or operating an exoskeleton. The survey asked participants to evaluate the frequency and severity of seven causes: unintended shutdown, unintended/unexpected motion, misalignments, skin and soft tissue injury, electrical fault, vibrations, and use error. The authors set parameters to evaluate a hazard relevance score for each cause. This hazard relevance score was calculated using a table with a frequency score of 1 to 3 on the columns and a severity score of 1 to 3 on the rows. Scores were then crossed and multiplied to get a relevance score. These scores were grouped into three combinations. A score of 1 to 2 was low relevance, 3 to 4 was moderate relevance, and 6 to 9 was high relevance. The results were broken down into percentages of the participant's responses that resulted in a specific score. The relevance scores collected showed no high relevance for most causes except skin injury and misalignment. The high relevance for these causes was 6.3% and 12.5%

respectively. The moderate relevance ranged from 18.8% for unintended shutdown to 56.3% for misalignment. The low relevance ranged from 31.3% for misalignment to 81.3% for unintended shutdown. In all causes except misalignment, the percentage of low relevance scores was higher than moderate relevance scores.

The results of these surveys show that there isn't a high risk/hazard associated with exoskeletons, but there is nuance in that the number of participants in the survey was relatively limited and they typically operated exoskeletons in very controlled clinical settings. This study also had to work with generalizations as not all hazards and risks are applicable in the same way to all exoskeletons. While this study is not a catch-all that clears exoskeletons from being harmful in any way, it provides adequate insight into the potential risks and hazards that can stem from exoskeleton use.

Conclusion

Several key conclusions can be drawn from the analysis of the factors influencing the acceptance of exoskeletons across the various sectors of rehabilitation, disability, occupational, and military. In the rehabilitation sector, exoskeletons have shown promise as aids for physical therapy and improving patient independence. The market for exoskeletons in this sector has grown immensely over the years and continues to show potential. Some challenges exist such as high cost, wearability, and user perception. These limiting factors are beginning to diminish as more exoskeletons with improved designs are entering the market. This leads to the conclusion that rehabilitative exoskeletons are on a path to widespread acceptance.

Exoskeletons navigate a complex landscape in the disability sector. Exoskeletons offer innovative solutions for mobility impairments, however, there are contrasting perspectives within the disabled community regarding the concept of a "cure." Some people find the idea of an exoskeleton to be a great tool that will enhance accessibility and quality of life whereas others may find it a symbol of ableism. Including disabled people in the design, testing, and feedback process will improve exoskeleton acceptance however, the perceptions associated with exoskeletons in the disability community, along with high costs, further complicate exoskeleton acceptance. Widespread acceptance of exoskeletons does not appear to be happening soon.

Occupational exoskeletons have not been proven to mitigate musculoskeletal disorders or improve work performance significantly. Concerns about usability, ergonomic design, and social perceptions among workers highlight the need for more human-centric design approaches. A lack of evidence of the effectiveness of occupational exoskeletons hinders companies from funding or purchasing exoskeleton products.

Military exoskeletons were initially developed for logistical support. This is still a focus of military research, but a focus has evolved to augment soldiers' capabilities in the field. Ethical considerations surrounding the transparency and risk of using militaristic combat exoskeletons are crucial for the acceptance of exoskeletons in the military and a broader social perspective.

The safety, efficacy, cost-effectiveness, wearability, and ethical implications of exoskeletons are central to their societal acceptance. Ways to improve these factors can be addressed in various ways within each sector. Promoting awareness of exoskeleton benefits, limitations, and ethical considerations amongst stakeholders within each sector and the general public is beneficial to the integration of exoskeletons.

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