Designing a Soft Upper-limb Exoskeleton for Amyotrophic Lateral Sclerosis Patients

Relationships Between Designers and Users During the Exoskeleton Design Process

A Thesis Prospectus
In STS 4500
Presented to
The Faculty of the
School of Engineering and Applied Science
University of Virginia
In Partial Fulfillment of the Requirements for the Degree
Bachelor of Science in Mechanical Engineering

By
Priti Patel

October 27, 2022

Technical Team Members:
Ellianna Bailey
Patrick Evans
Willis Williams
Dongmei Xu
Nicholas Yantiss

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.

ADVISORS

MC Forelle, Department of Engineering and Society

Sarah Sun, Department of Mechanical and Aerospace Engineering

Introduction

According to the CDC, one in seven adults in the United States suffer from limited mobility and have serious difficulty with daily activities such as walking and climbing up stairs (Centers for Disease Control and Prevention, 2016). These disabilities become more common amongst the older generation, and tend to target those living in poverty. They can result in reduced strength and endurance, affecting both the physical and emotional qualities of living. Recently, many engineers have been developing technologies that aim to allow people with limited mobility to utilize their joints, as well as boost their strength. Several companies have developed exoskeletons which are wearable robotic devices that integrate human sensing, an actuator, mechanical design, and feedback control that provide extra support to a person's muscle and enhance physical performance.

Despite the fact that this industry is rapidly growing, there are many unknown variables when designing these devices, causing an increase in prices which have made them inaccessible for the average person in the United States. Furthermore, these devices are often times very rigid and uncomfortable, defeating the overall intention to provide comfort for people that suffer from mobility disabilities. According to research done by the Wyss Institute, devices that are rigid can, "impede a wearers' natural joint movements, thus causing fatigue and exacerbating the very problems they are attempting to fix", for people with less severe mobility issues (Wyss Institute, 2019). The technical portion of my capstone project involves designing and producing a soft upper-limb exoskeleton for Amyotrophic Lateral Sclerosis (ALS) patients to assist them with raising and lowering their forearms, while lifting a small weight such as a glass of water or a book. ALS is a progressive neurodegenerative disease that affects the brain and spinal chord, resulting in the brain losing the ability to initiate and control muscle movements (The ALS

Association, 2021). According to the National Institute of Neurological Disorders and Stroke, there is no cure for ALS patients to regain this ability, and many of them require rigid joint support, so we thought they would be a good candidate for our design (National Institute of Neurological Disorders and Stroke, n.d.). By designing a soft exoskeleton as opposed to a rigid exoskeleton, my group hopes to allow ALS patients to utilize their elbow joint without causing discomfort.

As engineers it is important to constantly evaluate the devices created so that there are no negative unintended consequences that the users have to endure, including both the technical aspects and the social implications. Closely coupled with the technical portion of my capstone project, my STS portion will attempt to gain insight on the benefits and risks of exoskeletons by researching how designers engage with the disability community and the workplace in the design process. It will explore the development of exoskeletons over time, including the standards that have been created, as well as the impact that they have had on society.

Technical Portion

As a new era of modern neuromuscular rehabilitation has emerged, exoskeletons have been utilized as assistive technologies for a variety of uses including medical uses, rehabilitation, exosuits for hazardous working conditions, and military uses. They have proved to be promising for allowing patients to perform daily tasks. However, there are many design difficulties involved because it is challenging to replicate the kinematics and dynamics of a human musculoskeletal structure, leading to many problems with mechanical design, actuation, and control strategies. The field of exoskeleton technologies lacks standards and a unanimous kinematic model for the upper limb due to the design parameters weighing heavily on the targeted user (Gull et al., 2020).

The two major types of exoskeletons are rigid and soft. The environment, purpose, and conditions the device is used in greatly impact which type of exoskeleton is used (Tiboni et al., 2022). Rigid devices are more traditional and they have produced promising results for horizontal precision tasks and overhead pointing tasks, as found by a study performed by Harvard University about a soft exoskeleton that assists the shoulders of industrial workers, however they come with disadvantages (Zhou et al., 2021). They can result in discomfort and can place a heavy load on the body, producing additional risks. Soft exoskeletons have recently emerged, presenting an alternative to rigid devices that, "offer the promise of limited mass on the limb, better comfort, and less kinematic restriction from joint misalignment" (Zhou et al., 2021), and are more practical to implement due to their flexible nature.

Our capstone group aims to design and produce a soft wearable exoskeleton for ALS patients. Our goal is to give the device the ability to be used in unstructured environments by making the device battery powered and fabricating the device with primarily soft components. When designing a soft upper limb exoskeleton there are many factors that have to be considered such as the application of the device, number of degrees of freedom, and the types of sensors, actuators, and controllers utilized. The upper limb has seven degrees of freedom: three in the shoulder, two in the elbow, and two in the wrist (Gull et al., 2020). Our group aims to achieve one degree of freedom (DOF) in the elbow, specifically flexion/extension. We will be using a bowden cable actuator which is a cable consisting of an inner wire surrounded by an outer housing that stays stationary, creating a push and pull effect (Childree, 2022). This actuator is a widely employed solution used for designing exoskeletons where kinematic transparency is required due to its durability, safety, weight, and flexibility (Dihn et al., 2017). In 2006, a research team concluded that the cables had good force-feedback performance and contact stability, aligning well with our technical requirements (Schiele et al., 2006). A design that accomplished seven degrees of freedom with a rigid exoskeleton used a bowden cable actuator, displaying that it able to achieve high levels of actuation (Herbin & Pajor, 2021). Control strategies impact how the user and exoskeleton interact. Our design will be passive, meaning the decisions will be patient controlled and will relieve force even when the actuators are not engaged (Rehmat et al., 2018).

One of the main challenges that my group will face is that there is a lack of unanimous standards for exoskeletons because pre-existing industrial robotic metrics do not typically include humans (Bostelman & Hong, n.d.). Although there are pre-existing designs that incorporate bowden cables, control strategies are still being developed because there are many nonlinearities involved such as friction and backlash so we will have to perform a lot of experimentation to create a working prototype (Hosseini et al., 2020). Our goal is to have a completed CAD design by the end of the fall semester and will assemble and test the device in the spring semester.

STS Portion

The first exoskeleton was designed in 1936 and was used as a foot-operated mechanical feeder for serving food to the user, while remaining attached to a wheelchair (Gopura et al., 2016). Since then, exoskeletons have evolved immensely over the years, and have been integrated as medical devices to assist with rehabilitation, in the workplace to prevent injuries, and in the military. The importance of assistive robotics has increased heavily to assist the elderly population and those that have experienced neurological injuries. Neurological injuries do not have a cure, placing immense pressure on exoskeleton devices to help those with limited mobility regain functionality with daily tasks. Patients with neurological injuries often times require a caregiver, and exoskeletons have the potential to decrease reliance on them and foster independence (Gorgey, 2018). In the workplace, industrial exoskeletons aim to reinforce the performance of workers that have healthy limbs.

Exoskeletons carry a lot of potential for society and they have proved to beneficial, however due to adoption barriers such as a lack of commercialization, general discomfort, and added risks, the use of these technologies has been very limited. According to a study performed with wearable robotics for Spinal Chord Injuries (SCI), there have been improvements in ,"performance, such as balance, walking distance, velocity, and duration", however only a small number of patients choose to use these devices because they can be challenging to use (Forte et al., 2022). Similarly in the workplace, lifting and handling heavy materials accounts for 30% of all workplace injuries, and exoskeletons are able to alleviate some of the muscle loading; however, workers have expressed concerns about hygiene, the risks for pressure wounds from prolonged use, and safety measures (Howard et al., 2019).

Society will not be able to benefit from these technologies if they are not implemented in an accessible and safe manner. In order to analyze the societal enactment of these devices, I will determine how designers interact with their intended users during the design process and what ergonomic and safety metrics they follow. I will research the impacts of rigid and soft exoskeletons, specifically in the medical field and in the workplace. My research will follow the devices from their design process to their implementation in society, studying the relationships between the designers, exoskeletons, and their users.

The deliverable will be a literary analysis which presents awareness towards adoption barriers and the associated risks and benefits of these devices and will provide solutions from credible research sources. One of the main limitations of this analysis is that there is a lack of resources available to research from due to exoskeletons being a relatively novel technology. A study done in 2019 revealed a number of obstacles with testing exoskeletons due to, “a lack of tangible testing objectives, too few subjects, [and] a lack of portable evaluation methods”, demonstrating that there is a need for more research to be done in this field (Howard et al., 2019). Engineers that work on wearable electronics should be committed to protecting the health and well-being of the users, so that as many people as possible can benefit from them, and while it is important to perform ample research on the technical aspects of mechanical design, it is equally as important to research the social implications of the devices.

Research Question and Methods

I will research the question, “how do designers engage with the disability community and the workplace in the process of designing exoskeletons?”, which will reveal more information about design strategies for the development of exoskeletons. These devices will not be beneficial to their users if the risks outweigh the benefits, so it is important to evaluate the social and technical impacts that they have on society. The two frameworks that will be compared in my study are configuring the user by Woolgar (1990) and design justice by Costanza Chock (2022). Configuring the user establishes an understanding of how devices are created to ‘configure’ their users and will be used to show how users can contribute to designs and its uses based on their interactions with them (Woolgar, 1991). Design justice explores the relationship between design, power, and social justice and shows how universal design principles can erase certain groups of society (Costanza-Chock, 2022). I will be using this framework to analyze the impact of exoskeletons on different groups in society and compare it to my findings from configuring the user.

Wearable robotics is relatively novel field, so most of my research will be performed using a literary analysis that will compile previous research describing the design process and implementation of exoskeletons used for rehabilitation, neuromuscular disorders, and injury prevention in the workplace. Performance and safety standards are still being developed, so I will carry out a policy analysis that will trace policies about ergonomics and safety, and the success of their implementation in designs. These methods and frameworks will lay out the foundation of my research project.

Conclusion

There is a significant lack of soft exoskeletons on the market and research performed in the exoskeleton field. Creating a device that is fabricated with soft materials, portable, wearable on a daily basis, and effective at assisting human muscles at low loads will be a crucial step for the industry and will be able to help patients that need assistance with moving their limbs. Our current design is focused on ALS patients, however if it is successful it may be implemented to help other neuromuscular disease patients as well. Along with my technical deliverable,my STS deliverable will reveal information about how the designers of exoskeletons interact with their users, the benefits and risks of the devices, and possible solutions for adoption barriers. The findings from my research can inform designers about concerns and the impacts of their devices, leading to designs that empower their users.

Resources

Bostelman, R., & Hong, T. (n.d.). *Test Methods for Exoskeletons – Lessons Learned from Industrial and Response Robotics*. https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=922383

Centers for Disease Control and Prevention. (2016, August 18). *CDC: 1 in 4 US adults live with a disability*. CDC: 1 in 4 US Adults Live with a Disability. https://www.cdc.gov/media/releases/2018/p0816-disability.html

Costanza-Chock, S. (2022). *Design Justice Community-Led Practices to Build the Worlds We Need*. The MIT Press. https://mitpress.mit.edu/9780262043458/design-justice/

Childree, T. L. (2022, November 30). *What is a Bowden Cable?* Wiki Motors. https://www.wikimotors.org/what-is-a-bowden-cable.htm

Dinh, B. K., Xiloyannis, M., Cappello, L., Antuvan, C. W., Yen, S.-C., & Masia, L. (2017). Adaptive backlash compensation in upper limb soft wearable exoskeletons. *Elsevier*, *92*, 173–186. https://doi.org/10.1016/j.robot.2017.03.012

Forte, G., Leemhuis, E., Favieri, F., Casagrande, M., Giannini, A. M., Gennaro, L. D., & Pazzaglia, M. (2022). Exoskeletons for Mobility after Spinal Cord Injury: A Personalized Embodied Approach. *Journal of Personalized Medicine*, *12*(3), 380. https://doi.org/10.3390/jpm12030380

Gopura, R. A. R. C., Bandara, D. S. V., Kiguchi, K., & Mannc, G. K. I. (2016). Developments in hardware systems of active upper-limb exoskeleton robots: A review. *Robotics and Autonomous Systems*, *74*, 203–220. https://doi.org/10.1016/j.robot.2015.10.001

Gorgey, A. S. (2018). Robotic exoskeletons: The current pros and cons. *World Journal of Orthopedics*, *9*(9), 112–119. https://doi.org/10.5312/wjo.v9.i9.112

Gull, M. A., Bai, S., & Bak, T. (2020). *A Review on Design of Upper Limb Exoskeletons*. https://doi.org/10.3390/robotics9010016

Herbin, P., & Pajor, M. (2021). Human-robot cooperative control system based on serial elastic actuator bowden cable drive in ExoArm 7-DOF upper extremity exoskeleton. *Elsevier*, *163*. https://doi.org/10.1016/j.mechmachtheory.2021.104372

Hosseini, M., Meattini, R., San-Millan, A., Palli, G., Melchiorri, C., & Paik, J. (2020). A sEMG-Driven Soft ExoSuit Based on Twisted String Actuators for Elbow Assistive Applications. *IEEE Robotics and Automation Letters*, *5*(3), 4094–4101. https://doi.org/10.1109/LRA.2020.2988152

Howard, J., Murashov, V. V., Lowe, B. D., & Lu, M.-L. (2019). Industrial exoskeletons: Need for intervention effectiveness research. *American Journal of Industrial Medicine*. https://doi.org/10.1002/ajim.23080

National Institute of Neurological Disorders and Stroke. (n.d.). *Amyotrophic Lateral Sclerosis (ALS) Fact Sheet*. https://www.ninds.nih.gov/amyotrophic-lateral-sclerosis-als-fact-sheet

Rehmat, N., Zuo, J., Meng, W., Liu, Q., Xie, S. Q., & Liang, H. (2018). Upper limb rehabilitation using robotic exoskeleton systems: A systematic review. *International Journal of Intelligent Robotics and Applications*, *2*, 283–295.

Schiele, A., Letier, P., van der Linde, R., & van der Helm, F., (2006, October) *Bowden Cable Actuator for Force-Feedback Exoskeletons*. https://ieeexplore.ieee.org/document/4058962/

The ALS Association. (2021, April 26). *What is ALS?* https://www.als.org/understanding-als/what-is-als

Tiboni, M., Borboni, A., Vérité, F., Bregoli, C., & Amici, C. (2022). Sensors and Actuation Technologies in Exoskeletons: A Review. *MDPI*. https://doi.org/10.3390/s22030884

Woolgar, S. (1990). *Configuring the user: The case of usability trials.* (Vol. 38). The Sociological Review. https://doi.org/10.1111/j.1467-954X.1990.tb03349.x

Wyss Institute. (n.d.). *Soft Exosuits for Lower Extremity Mobility*. https://wyss.harvard.edu/technology/soft-exosuits-for-lower-extremity-mobility/

Zhou, Y. M., Hohimer, C., Proietti, T., O'Neill, C. T., & Walsh, C. J. (2021). Kinematics-Based Control of an Inflatable Soft Wearable Robot for Assisting the Shoulder of Industrial Workers. *IEEE Robotics and Automation Letters*, *6*(2). https://ieeexplore.ieee.org/document/9361252