The W.E.A.R. Bot: Engineering an Upper Limb Exoskeleton for Rehabilitation

How Ableism Influences the Design of Wearable Assistive Technology

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
Madeleine Deadman

Fall 2023

Technical Team Members:

Clara Bender, Addison Hall, Hannah Rigby, Kristen Pettit-Pokora

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

Rider Foley, Department of Engineering and Society

Sarah Sun, Department of Mechanical Engineering

INTRODUCTION

The control of one's bodily movements relies on the neuromuscular system, particularly the transmission of signals from the brain to the muscles through the nervous system. Motor neurons originating from the motor cortex in the brain extend down to the spinal cord, and then further extend to skeletal muscles throughout the body. Through this pathway, each muscle fiber is innervated by a motor neuron at a synapse referred to as the neuromuscular junction (NMJ). Upon receiving an excitation signal at the NMJ, a neurotransmitter is released, triggering a chemical reaction that prompts the muscle fiber to contract. The dynamic interplay of muscle contraction and relaxation actuates the bodily movement itself (Pathirana et al., 2021).

Damage or weakness at any point within the intricate neuromuscular system can result in a loss of voluntary motor ability, or paralysis. The location and severity of paralysis can vary widely, manifesting as constant muscle contractions (spastic paralysis) or the inability to contract muscles (flaccid paralysis) (Ropper et al., 2023). Paralysis may be caused by congenital neuromuscular disorders, or be the consequence of various possible triggers, such as a cerebrovascular accident (stroke), spinal cord injury, infection, or autoimmune disorder (Bertorini, 2022; Pathirana et al., 2021). In addition to numerous secondary physical health risks, the loss of voluntary motor control significantly impacts the ability to perform activities of daily living (ADLs), which has profound psychosocial effects.

Passive movement therapy (PMT), a physiotherapeutic approach involving moving the joints of a patient without their active participation, has demonstrated potential benefits for paralyzed individuals. These include improved blood circulation, prevention of muscle atrophy, and maintenance or enhancement of joint flexibility and range of motion (ROM) (Hosseini et al., 2019). It is crucial to acknowledge that the responses to PMT will vary greatly based on the specific conditions causing the paralysis, as well as the intensity and frequency of the PMT movements. For instance, in cases where paralysis stems from a stroke affecting the motor cortex, extensive rehabilitation incorporating passive movements can foster neural plasticity, potentially leading to partial or full restoration of motor control (Lin et al., 2021). PMT remains valuable in cases where motor recovery may not be possible, helping delay progression and treating symptoms like edema and muscle spasticity (Borbeni et al., 2017; Hu et al., 2009). Paralysis is a complex and diverse condition, necessitating individualized, comprehensive treatment plans tailored to the specific underlying causes and the patient's unique needs.

The technical portion of this project aims to develop an affordable robotic exoskeleton for upper limb passive movement therapy, capable of accommodating a diverse range of patients in terms of anatomy and ability. Customizable features will enable the exoskeleton to cater to the patient's unique needs and adapt to changes in their condition, ensuring its seamless integration into personalized physiotherapy regimens. Considering that the project team comprises able-bodied engineering students without formal medical or physiotherapy training, it is essential to recognize the sociotechnical implications involved in designing assistive technology without the direct involvement of the end-users themselves. The STS portion of this project will investigate the complexities of designing technology for individuals with disabilities, emphasizing the importance of avoiding *technoableism*— the notion that technology should be employed to "fix" or eradicate disabilities.

DESIGNING AN UPPER LIMB EXOSKELETON

Traditional rehabilitation services face challenges of inefficiency and high costs due to one-to-one delivery, expensive equipment, and inadequate workforce (Pathirana et al., 2021).

The demands for consistency and high intensity in PMT contribute to its time-consuming nature for both patients and therapists (Harvey, 2016). To address these issues, Robot-Assisted Therapy (RT) has emerged as a promising solution, aiming to facilitate therapists in delivering precise passive movements and potentially allowing patients to continue treatment independently at home (Hsieh et al., 2012; Onose et al., 2018). While existing RT devices primarily focus on shoulder and elbow movements, there is a notable absence of devices catering to wrist and hand movements, indicating a gap in upper limb rehabilitation technology (Hatem et al., 2016). Despite their potential, upper limb exoskeletons for RT remain novel devices and have yet to be widely adopted in clinical settings (Morris et al., 2023). Further technical developments are still necessary to address challenges related to effective Human-Robot Interaction (HRI) and to improve the overall usability of robotic exoskeletons across a diverse patient population (Klamroth-Marganska, 2018).

The typical human arm has approximately seven degrees of freedom, and each joint has a limited ROM. The ROM of each joint will vary greatly from person to person, as well as the size and proportions of the arm overall (Gull et al., 2020). To ensure safe motion, an exoskeleton must anthropomorphically apply actuation forces to the upper limb, adhering strictly to physiological joint stiffness and respecting specific degrees of freedom (Borboni et al., 2017). Weight plays a crucial role, as heavier exoskeleton components will induce larger inertial forces and misalignment, leading to discomfort and unnatural motion. Rigid wearable exoskeletons are more prone to this issue (Capello et al., 2016). In response, there has been a shift in research toward soft exoskeleton designs in recent years. Despite inherent limitations, soft exoskeletons, being textile-based, offer a conformal interface with the human body, prioritizing comfort and usability while preserving the natural ROM (Pérez et al., 2021; Bardi et al., 2022).

The technical portion of the project will involve the design and development of the *W.E.A.R. Bot* (Wrist-Elbow Automated Rehabilitation Robot), a portable and affordable upper limb exoskeleton tailored for physiotherapy, specifically targeting flexion and extension of the elbow and wrist. This exoskeleton aims to automate PMT techniques, catering to individuals with complete paralysis and severe mobility impairments.

To facilitate passive limb movements, it will be an active exoskeleton, requiring a power supply and mechanical actuators. To achieve elbow flexion and extension, the W.E.A.R. Bot will be equipped with pneumatic artificial muscles (PAMs). PAMs are lightweight, flexible, biomimetic actuators that contract upon being filled with pressurized air (see Figure 1). For wrist flexion and extension, a servo motor will serve as the actuator since it

Figure 1. PAM prototype in expanded state (above) and contracted state (below)

allows for precise position control and is relatively small and lightweight. An Arduino will be used to control both the servo motor and a solenoid that will operate the pump for the PAMs and receive real-time goniometric data for feedback control from the potentiometers wired as rotary position sensors at both the elbow and wrist joints (see Figure 2).

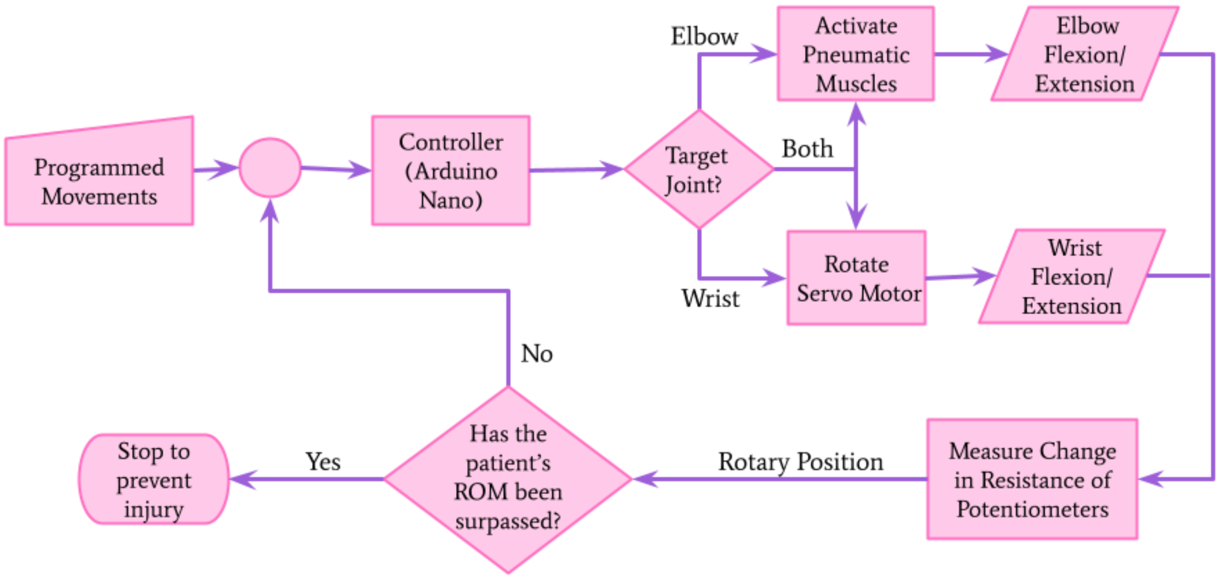

Figure 2. Control system flowchart of the W.E.A.R. Bot

To minimize unnecessary bulk directly attached to the arm, the pump, solenoid, Arduino, and power supply will be housed in a backpack. This backpack can be worn or conveniently hung on the back of a chair. While the design will necessitate the use of rigid components for structural support and proper alignment, the incorporation of soft materials will be prioritized to increase comfort and adjustability. A commercial elbow brace with an adjustable fit and comfortable padding will serve as the base for the elbow fixture of the W.E.A.R. Bot. The structure of the wrist portion will be designed and 3D printed, building off the *eWrist* exoskeletons developed by Lambelet et al (2017, 2020). In a wearability evaluation of one iteration of the *eWrist*, most subjects found that it was easy to don/doff using its ratchet mechanisms, but some expressed discomfort due to size mismatch and movement constraint (Lambelet et al., 2020). To address this, the wrist components of the W.E.A.R. Bot will include soft straps with Velcro closures and a ratchet lacing mechanism to easily adjust the fit of the wrist brace, as well as comfortable padding. (see Figure 3).

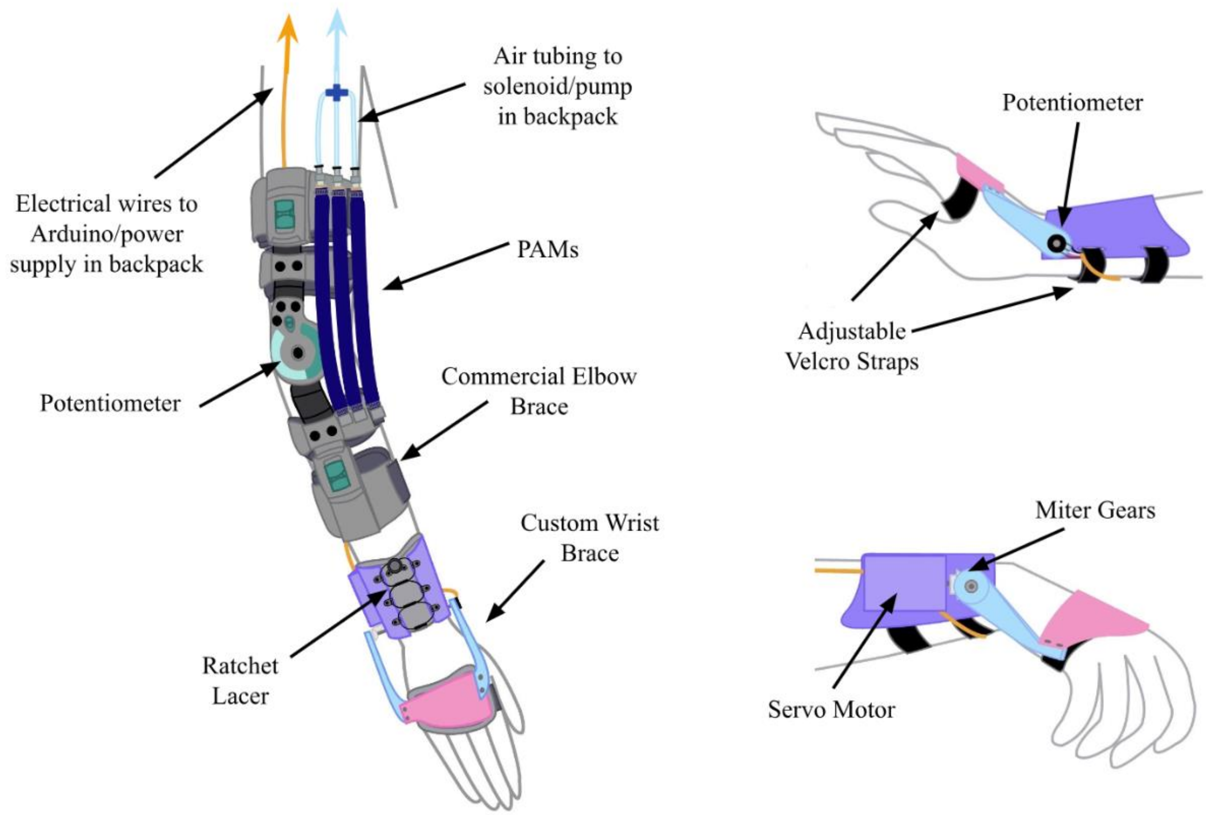

Figure 3: Overview of the W.E.A.R Bot Exoskeleton (backpack not pictured)

In a state-of-the-art review, Morris et al. (2023) highlighted limitations perceived by patients and physiotherapists in existing soft robotic exoskeleton technology, revealing a potential disconnect between the needs of exoskeleton users and the engineers designing them. The W.E.A.R. Bot project seeks to bridge this gap by introducing an innovative design that addresses these concerns, emphasizing a blend of technical innovation and user-centric design. In addition to being adjustable to fit a wide anthropometric range, the user will be able to set the ROM limits and desired movements to match their unique needs. The inclusion of customizable features underscores a commitment to individualized, patient-specific solutions and effective HRI. As the W.E.A.R. Bot is intended to cater to a wide range of patients with upper limb mobility impairments, it would behoove the designers to consider accessibility, usability, and societal perceptions of rehabilitative and assistive technologies. By investigating the broader societal implications, the project aims to contribute not only to technical innovation but also to the creation of RT devices that align with the diverse needs and preferences of end-users.

BEYOND THE MECHANICS: TECHNOABLEISM

A dual focus on technical functionality and societal awareness exemplifies a holistic approach to designing technology that interacts intimately with the lives of individuals with disabilities. Wearable robotics may be intended to be a new tool to assist in rehabilitation and promoting overall health in paralyzed individuals, but they could also be viewed as an attempt to force disabled bodies into the mold of “abled” bodies. Some non-disabled tech enthusiasts envision a future where assistive devices could be affixed to disabled bodies to provide ubiquitous assistance, seemingly eradicating the effects of disability. However, that “solution” is far from the true preferences and needs of disabled people (Ladau, 2015). Ableism distorts expectations of what disabled people want, framing disabilities as an individual’s problem rather than a social one. For instance, the requirement of making environments accessible (e.g. mandating the inclusion of ramps, elevators, subtitles, etc.) is sometimes viewed by non-disabled individuals as a hassle that limits design possibilities and compromises aesthetics and efficiency. They fail to realize that increasing accessibility ultimately enhances technologies and infrastructure for everyone (Shew, 2020).

To better understand the intersections between technology and disability, the framework of *technoableism*, a term coined by Virginia Tech STS professor Ashley Shew, can be applied. Technoableism describes the rhetoric of empowering disabled people through technologies, while still reinforcing harmful tropes about what is expected of a “good” or “normal” body and what abilities are needed to be worthy as a human. A key facet of avoiding technoableism is the rejection of the medical model of viewing disability, focusing instead on developments toward freedom and interdependence, not toward cures or normalization. Medicalized approaches to disability tend to define disabled individuals by their diagnostic defects and attempt to “remove” those defects (Shew, 2020). The social model of viewing disability, which critiques exclusive reliance on medical and rehabilitative interventions, emphasizes that disability is not solely a result of an individual’s impairment but also from social, cultural, and environmental barriers that restrict the full participation of disabled individuals in society (Shew, 2023).

Treatments for mobility disabilities will vary widely, even among people with the same medical diagnoses, encompassing a combination of physical therapy, medication, surgical intervention, psychosocial support, and assistive devices. The main goal of treatment is to enhance the quality of life and make the patient more comfortable (van Putten, 2020). While it is important to consider the perspectives of physiotherapists, doctors, nurses, and caregivers, it is imperative to recognize that the patient holds the ultimate right to determine the most suitable care and treatment that aligns with their preferences. To avoid perpetuating technoableism in the design of technology for individuals with disabilities, it is essential to actively seek out and prioritize the perspectives of disabled people.

Within the disability community, a prevalent sentiment is that the pursuit of technological “solutions" for mobility impairments neglects disabled peoples’ autonomy and may diminish the perceived need for accessible infrastructure and divert focus away from solutions to certain struggles that non-disabled people may not be aware of (Shew, 2020). Compared to able-bodied people, people with mobility disabilities do not have the same level of access to public environments they can traverse reliably, appropriate living conditions, transportation, employment, and financial stability (Harvey, 2016). Due to their lived experiences navigating a world where most things are designed without considering disability as a significant factor, disabled people are experts in designing everyday life and effective agents of change in building a more socially just world (Hamraie & Fritsch, 2019). Collaboration among designers, healthcare professionals, organizations, and government services directly with the disabled community is crucial for addressing these complex problems.

RESEARCH QUESTION AND METHODS

This research project seeks to answer the question: How do ableist ideals influence the design of wearable robotics for individuals with impaired mobility? It is essential to comprehend how ableism molds societal expectations of disabled individuals and impacts the design of assistive devices to develop technologies that genuinely meet the needs and preferences of those with mobility disabilities. The primary research method will be a multiple case study of wearable robotics designs from the past five years, focusing on their adherence to or deviation from principles of inclusivity and user-centric design. Furthermore, a comparative analysis of wearable robotics designed for ubiquitous assistance versus those intended for rehabilitation will be highlighted. Thematic coding will be employed for an in-depth examination, analyzing qualitative data to identify recurring themes related to technoableism and inclusivity.

With the technoableism framework in mind, literary sources directly conveying the experiences and viewpoints of disabled individuals will be prominently featured. Additionally, surveys will be conducted to gather insights from disabled individuals, designers, and healthcare professionals. Survey data will be quantitatively analyzed to provide statistical evidence of the impact of experiences and societal perceptions on design expectations and ethical considerations.

This mixed-methods approach will offer a comprehensive view of the factors influencing wearable robotics design, providing actionable insights for the creation of more inclusive and user-centered assistive technologies.

CONCLUSION

A main goal in designing the W.E.A.R. Bot is to work towards future technology that will enable widespread access to effective and customized rehabilitation treatment. A portable, affordable, and customizable rehabilitation device could help patients overcome logistical and financial barriers that hinder the effectiveness of physiotherapy for motor rehabilitation.

The multifaceted nature of paralysis, with its diverse manifestations and therapy approaches, presents a challenge that requires a robust exploration of user experiences. Prioritizing the perspectives of disabled individuals and challenging ableist ideals inherent to traditional treatment models, the project ultimately seeks to create an inclusive wearable robotic exoskeleton that is functional and attuned to the diverse needs and experiences of individuals with impaired upper-limb mobility.

REFERENCES

Bardi, E., Gandolla, M., Braghin, F., Resta, F., Pedrocchi, A. L., & Ambrosini, E. (2022). Upper Limb Soft Robotic wearable devices: A systematic review. *Journal of NeuroEngineering and Rehabilitation*, *19*(1). 87. https://doi.org/10.1186/s12984-022-01065-9

Bertorini, T. E. (2022). Introduction: Evaluation of Patients with Neuromuscular Disorder. In *Neuromuscular disorders: Treatment and management* (2nd ed., pp. 2–39). Elsevier.

Borboni, A., Villafañe, J. H., Mullè, C., Valdes, K., Faglia, R., Taveggia, G., & Negrini, S. (2017). Robot-assisted rehabilitation of hand paralysis after stroke reduces wrist edema and pain: A prospective clinical trial. *Journal of Manipulative and Physiological Therapeutics*, *40*(1), 21–30. https://doi.org/10.1016/j.jmpt.2016.10.003

Cappello, L., Binh, D. K., Yen, S.C., & Masia, L. (2016). Design and preliminary characterization of a soft wearable exoskeleton for upper limb. *2016 6th IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob)*. 623–630. https://doi.org/10.1109/BIOROB.2016.7523695

Gull, M. A., Bai, S., & Bak, T. (2020). A Review on Design of Upper Limb Exoskeletons. *Robotics*, *9*(1), 16. http://dx.doi.org/10.3390/robotics9010016

Hatem, S. M., Saussez, G., della Faille, M., Prist, V., Zhang, X., Dispa, D., & Bleyenheuft, Y. (2016). Rehabilitation of motor function after stroke: A multiple systematic review focused on techniques to stimulate upper extremity recovery. *Frontiers in Human Neuroscience, 10*, 442. https://doi.org/10.3389/fnhum.2016.00442

Hamraie, A., & Fritsch, K. (2019a). Crip Technoscience Manifesto. *Catalyst: Feminism, Theory, Technoscience, 5*(1), 1–33. https://doi.org/10.28968/cftt.v5i1.29607

Harvey, L. A. (2016). Physiotherapy rehabilitation for people with spinal cord injuries. *Journal of Physiotherapy*, *62*(1), 4–11. https://doi.org/10.1016/j.jphys.2015.11.004

Hosseini, Z.-S., Peyrovi, H., & Gohari, M. (2019). The Effect of Early Passive Range of Motion Exercise on Motor Function of People with Stroke: a Randomized Controlled Trial. *Journal of Caring Sciences*, *8*(1), 39–44. doi:10.15171/jcs.2019.006

Hsieh, Y., Wu, C., Lin, K., Yao, G., Wu, K., & Chang, Y. (2012). Dose-response relationship of robot-assisted stroke motor rehabilitation. *Stroke*, *43*(10), 2729–2734. https://doi.org/10.1161/strokeaha.112.658807

Hu, X. L., Tong, K., Song, R., Zheng, X. J., & Leung, W. W. (2009). A comparison between electromyography-driven robot and passive motion device on wrist rehabilitation for chronic stroke. *Neurorehabilitation and Neural Repair, 23*(8), 837–846. https://doi.org/10.1177/1545968309338191

Klamroth-Marganska, V. (2018). Stroke rehabilitation: Therapy robots and assistive devices. *Advances in Experimental Medicine and Biology*, 579–587. https://doi.org/10.1007/978-3-319-77932-4_35

Ladau, E. (2015, April 8). Fix Discriminatory Attitudes and Broken Sidewalks, Not Humans. *Vice*. https://www.vice.com/en/article/d73947/fix-discriminatory-attitudes-and-broken-sidewalks-not-humans

Lambelet, C., Lyu, M., Woolley, D.G., Gassert, R., & Wenderoth, N. (2017). The eWrist — A wearable wrist exoskeleton with sEMG-based force control for stroke rehabilitation. *2017 International Conference on Rehabilitation Robotics (ICORR)*, 726-733. https://doi.org/10.1109/ICORR.2017.8009334

Lambelet, C., Temiraliuly, D., Siegenthaler, M., Wirth, M., Woolley, D. G., Lambercy, O., Gassert, R., & Wenderoth, N. (2020). Characterization and wearability evaluation of a fully portable wrist exoskeleton for unsupervised training after stroke. *Journal of NeuroEngineering and Rehabilitation*, *17*(1), 132. https://doi.org/10.1186/s12984-020-00749-4

Lin, Y., Qu, Q., Lin, Y., He, J., Zhang, Q., Wang, C., Jiang, Z., Guo, F., & Jia, J. (2021). Customizing Robot-Assisted Passive Neurorehabilitation Exercise Based on Teaching Training Mechanism. *BioMed research international*, *2021*, Article ID 9972560. https://doi.org/10.1155/2021/9972560

Morris, L., Diteesawat, R. S., Rahman, N., Turton, A., Cramp, M., & Rossiter, J. (2023). The state-of-the-art of soft robotics to assist mobility: A review of physiotherapist and patient identified limitations of current lower-limb exoskeletons and the potential soft-robotic solutions. *Journal of NeuroEngineering and Rehabilitation*, *20*(1), 18. https://doi.org/10.1186/s12984-022-01122-3

Onose, G., Popescu, N., Munteanu, C., Ciobanu, V., Sporea, C., Mirea, M.-D., Daia, C., Andone, I., Spînu, A., & Mirea, A. (2018). Mobile Mechatronic/robotic orthotic devices to assist–

rehabilitate Neuromotor impairments in the upper limb: A systematic and Synthetic Review. *Frontiers in Neuroscience*, *12*. 577. https://doi.org/10.3389/fnins.2018.00577

Pathirana, P. N., Li, S., Lee, Y. S., & Pham, T. (2021). *Human Motion Capture and Identification for Assistive Systems Design in Rehabilitation* (1st ed., pp. 1-22). Hoboken, NJ: John Wiley & Sons Ltd. https://doi.org/10.1002/9781119515104.ch1

Pérez Vidal, A. F., Rumbo Morales, J. Y., Ortiz Torres, G., Sorcia Vázquez, F. de J., Cruz Rojas, A., Brizuela Mendoza, J. A., & Rodríguez Cerda, J. C. (2021). Soft Exoskeletons: Development, Requirements, and Challenges of the Last Decade. *Actuators*, *10*(7), 166. https://doi.org/10.3390/act10070166

Ropper, A. H., Samuels, M. A., Klein, J., & Prasad, S. (2023). Paralysis and Weakness. In K. J. Davis & T. Y. Hiscock (Eds.), *Adams and Victor's Principles of Neurology* (12th ed.). New York: McGraw Hill.

Shew, A. (2020). Ableism, Technoableism, and Future AI. *IEEE Technology and Society Magazine, 39*(1), 40–85. https://doi.org/10.1109/MTS.2020.2967492

Shew, A. (2023). Disorientation. In *Against Technoableism: Rethinking Who Needs Improvement* (pp. 14–33). W. W. Norton & Company, Inc.

van Putten, M., Hmeljak, J., Aartsma-Rus, A., & Dowling, J. J. (2020). Moving neuromuscular disorders research forward: From novel models to Clinical Studies. *Disease Models & Mechanisms*, *13*(2). https://doi.org/10.1242/dmm.044370