Design and Implementation of a Pneumatically Actuated Soft Upper Limb Exoskeleton for Stroke Rehabilitation

The Socio-Technical Network of Exoskeleton Technology for Stroke Recovery

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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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General Research Problem:

How can recovery methods for stroke victims suffering from Post-Stroke Motor Dysfunction (PSMD) be improved?

Each year, around 16.9 million individuals experience stroke, leading to approximately 33 million stroke survivors and 5.9 million deaths a year. As one of the leading causes of death globally, strokes are a significant contributor to acquired disabilities in adults. Roughly 80% of stroke survivors face upper limb motor impairments, severely impacting their capacity to engage in daily activities (Kwakkel et al, 2015). It has been reported that over 80% of family members have to reduce working hours or even stop working to take care of patients with Post Stroke Motor Dysfunction (PSMD) (Zhang et al, 2023). Because of this, it is crucial for victims to receive timely care and rehabilitation.

There are many therapies in practice currently. A common recovery method is physical therapy, in which patients relearn how to move their bodies. A method known as constraint-induced motor therapy (CIMT) involves restraining unaffected limbs and having the patients practice moving the affected region (Clinic Staff, 2024). Studies have shown that adding CIMT to traditional recovery methods improves patient outcomes. (Zhang et al, 2023). In fact, CIMT or modified versions of it are considered the most effective treatment regimens in physical therapy to improve the outcome of PSMD (Kwakkel et al, 2015). However, CIMT methods are only accessible to certain ranges of the stroke victim spectrum. CIMT requires a baseline of motor control and physical strength that patients with severe symptoms do not possess.

In order to increase the range of PSMD afflicted individuals, this paper introduces a method of improving patient access to CIMT through a soft robotic exoskeleton that increases the patient's baseline strength and helps them perform movements they would be normally unable to do. The technical section will describe the methodology used to create the exoskeleton, laying out the mechanical structure and foundation of the system, and proposing a basic control scheme. Meanwhile, the STS portion will examine the socio-technical system involved in the formulation and integration of a new technology such as the rehabilitative exoskeleton.

Design and Implementation of a Pneumatically Actuated Soft Upper Limb Exoskeleton for Stroke Rehabilitation

How can current exoskeleton technologies be improved upon to be more comfortable and patient friendly?

Conventional rehabilitation treatments often depend on a patient's existing motor abilities, which can hinder comprehensive recovery. If a patient cannot move their arm more than a few inches, they cannot complete the full range of motion required for CIMT therapy. To address this, researchers have developed robotic exoskeletons that covers the difference in strength, allowing them to complete the motions required for rehabilitation.

Studies on patients outcomes found inconclusive evidence as to whether assistive exoskeleton rehab was even more effective than traditional CIMT, (Oliveira & Rose, 2019) but, the exoskeleton still enabled access to CIMT for patients who could not normally engage in it. Current assistive exoskeletons offer an enticing alternative for patients suffering from severe PMSD, but they can still be improved upon. Exoskeletons can be made cheaper, portable, and smaller to increase the accessibility of the technology. Patients require at least six hours per week for optimal recovery, so a portable exoskeleton allows patients to complete their therapy on a schedule that works for them (Yang et al, 2023).

To achieve these criteria, this paper proposes the design of a pneumatically actuated soft exoskeleton. Soft robotics, a recent advancement in robotics systems, distinguishes itself by utilizing soft and flexible materials like silicon rubber and prioritizing safety during human interaction (Elsamanty et al., 2023).

Several actuators are commonly used for the exoskeleton application, but the pneumatic artificial muscle (PAM) has proved to be the best due to its high power to weight ratio, compliance, and safe operation. The pneumatic muscle assembly consists of three main elements, the outer braided sleeve, the flexible inner bladder, and two end-fittings at either end. The primary operating concept of the PAM is that the bladder expands as a result of the pressured air input, causing an outward force on the surrounding braided sleeve, transforming the force into displacement of the muscle (Do Rosario Carvalho et al., 2022).

Braided sleeves can be easily purchased, and the interior bladder will be molded from silicon. Molds will be generated using CAD. Uncured silicone will be poured into the molds and left to sit. Once cured the outer sleeve is placed around the mold. The silicone bladder provides shape and the sleeve provides tensile strength. Then connector caps will be placed on the ends. Following this, a structure will be generated. Assistive exoskeletons aim to mimic human muscle contractions. When muscle fibers contract, they pull the two limbs together. The strong structure of the body determines which limb will move. Exoskeleton designs can take advantage of humans natural structure so when creating a structure, it is only necessary to create wearable connectors to attach the muscle to.

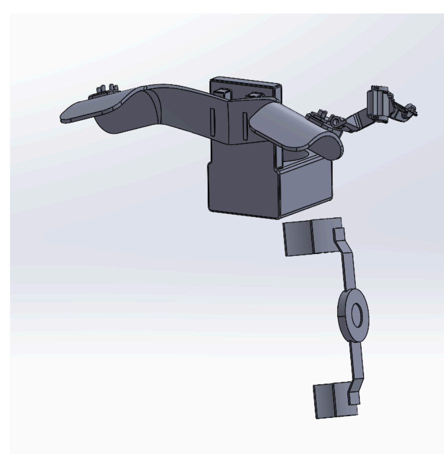

Fig 1. Proposed exoskeleton frame

To facilitate rapid prototyping and testing, 3D-printed connectors and supports will be utilized. Due to project time constraints, the proposed exoskeleton will feature only three degrees of freedom (DOF): one at the elbow and two at the shoulder. A fully functional exoskeleton typically has between six and nine DOF to replicate human ranges of motion. A "bicep" muscle can be simulated by contracting a pneumatic muscle between two arm cuffs, causing the arm to lift. Similarly, a pneumatic muscle connected to the shoulder can raise the arm, with the sockets protruding to generate additional torque.The final step is to generate a control scheme to control the movement. This is more difficult than a traditional exoskeleton because, unlike DC motors, pneumatic muscles do not have directly controllable positions. The only input is pump pressure. Therefore, in order to control the pump, a pressure force must be determined. Lagrangian dynamics will be performed, determining an equation for torque required to move a shoulder joint.

This equation can be derived into a force equation. From there, a PID controller will be generated. A PID controller enhances performance by continuously monitoring the PAM's output and comparing it to the desired setpoint. It adjusts based on proportional, integral, and derivative errors, allowing real-time modifications to pneumatic pressure for smooth, natural movements. Fine-tuning PID parameters optimizes PAM performance, effectively mimicking natural muscle behavior and enhancing assistive technologies in soft robotics.

The Socio-Technical Network of Exoskeleton Technology for Stroke Recovery

How does the means by which both patients and providers are educated on a new technology impact patient access and outcomes?

Increasingly complex technologies are becoming essential to modern healthcare, to the extent that medical devices are now considered "members" of the healthcare team. (Amoore & Ingram, 2002). In stroke rehabilitation, exoskeletons improve upon existing approaches and open new pathways for patients with severe disabilities, yet their effectiveness and accessibility are deeply influenced by how well, if at all, they are integrated into the socio-technical network —encompassing manufacturers, healthcare providers, patients, caregivers, and policymakers. This network, and the distribution methods within it, play critical roles in determining whether stroke survivors can access, benefit from, and ultimately regain functionality through these technologies.

Despite this, research found that training on medical equipment use receives minimal focus, accounting for less than 1% of department time (WHO, 2010). Failures in awareness and education among actors in the network decreases patients outcomes and hinders the adoption of a new technology.

Socio-technical systems analysis done on the healthcare system challenges the linear sequential approach to system design, implementation and use. It is now recognized that design, implementation and use activities overlap and interact with one other, forming a continuously interacting system (Carayon et al., 2011). This concept illustrates that a company's job does not end at the design of a product.

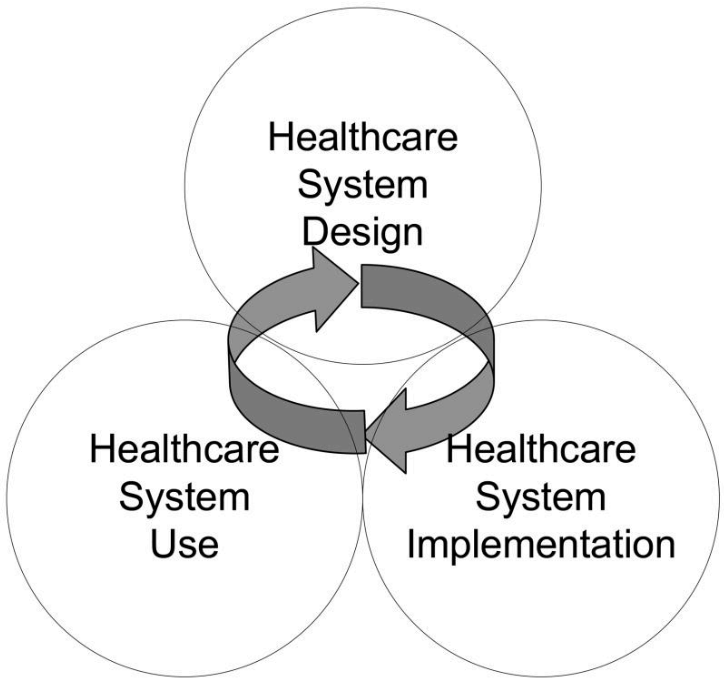

Fig 2. The STSA Cycle of Healthcare System Design, Implementation and Use

An example of such a phenomenon is the famously ongoing issues with insulin pumps. An insulin pump is a small computerized device worn on the body that delivers insulin to individuals with diabetes, providing an alternative to multiple daily insulin injections, closely mimicking the way a healthy pancreas releases insulin (Yao, 2023). Insulin pumps can improve blood sugar control and reduce the risk of complications associated with diabetes, such as neuropathy, kidney disease, and vision loss, putting the initiative back in patient hands. However, insulin pump technology has not been widely accepted, largely due to a lack of education among providers.

Despite being first manufactured in 1978, there are still no standardized national or international guidelines and only limited recommendations exist to outline the necessary education and training for starting insulin pump therapy. Education concerning the pump was so dismal that in 2015, thirty-seven years later, the American Nurses Association (ANA) published an article entitled ‘Boost your confidence in caring for patients with insulin pumps’ (Lampe, 2023), in which they describe a patient came to the hospital with their own pump, but the doctor and nurse turned it off because they didn't know how to use it, eventually leading to the patient experiencing diabetic ketoacidosis when the nurse couldn't continually check their sugar levels. This example shows what can happen when a failure in education prevents providers from engaging with a new, superior technology.

In order for rehabilitation to have the greatest effect, patients must receive it in a timely manner. Providers often describe this as the "golden window" for maximum recovery. Missing that window for any reason can cause the individual to become disabled in the long term, having disastrous impacts on the remainder of their life. If providers aren't comfortable using this new technology, the patient could miss out on the opportunity for improvement.

To research how provider and patient education influence patient outcomes involving exoskeletons, a study of current medical exoskeleton companies and practitioners will be completed. Training from leading companies will be compared to the training given for both successful and unsuccessful technologies to determine how effective the current training literature is. This research will determine how close to traditional medical training deemed "effective" the rehabilitation is. Then,reports from rehabilitation facilities actively using the technology will be examined to determine how effective they believe the training to be. Both of these factors will be compared to determine if proper steps are being taken to ensure meaningful patient and provider education.

Marketing also plays an important role in helping healthcare professionals to create, communicate, and provide value to their patients (Purcarea, 2019), so marketing material from top bionics companies will also be examined. Research will be done with a review of business literature to determine the most effective marketing practices and how current exoskeleton marketing strategies compare. Trends in medical marketing will be examined and compared to exoskeletons, as well as marketing that has failed historically. This can be compared to current usage rate over time to determine if marketing is effective based on the rate at which usage is increasing. These usage rates can be compared to the trends in usage of now commonly adapted technologies during their formative years. Exoskeletons can help patients, but only if the doctor and patient are aware of the technology in the first place.

Conclusion

With a critical "golden window" for rehabilitation, it is vital for healthcare providers to be equipped to deliver advanced therapies effectively. By improving educational and marketing initiatives, we can increase accessibility to exoskeletons.

The effective distribution of medical technologies, such as exoskeletons for stroke rehabilitation, is crucial for enhancing patient access and outcomes. The introduction of these innovative solutions requires a strong socio-technical network that encompasses education for providers, patient awareness, and community engagement. Research will be completed to determine methods to increase accessibility for patients. A new soft exoskeleton will be designed that will allow a greater range of patients access to Constraint Induced Movement Therapy. Then socio-technical impacts of patient and provider education and awareness will be examined to determine the current state of awareness on rehabilitative exoskeletons. By fully understanding the actors involved in these systems, new technologies for stroke rehabilitation can be successfully implemented, improving the lives of those affected by the disability.

References

A. C. d. Oliveira *et al*., "Exploring the Capabilities of Harmony for Upper-Limb Stroke Therapy," *2019 IEEE 16th International Conference on Rehabilitation Robotics (ICORR)*, Toronto, ON, Canada, 2019, pp. 637-643, doi: 10.1109/ICORR.2019.8779558.

Ahn, K. K., & Thanh, T. D. C. (2017, May 16). Nonlinear PID control to improve the control performance of the pneumatic artificial muscle manipulator using neural network - journal of mechanical science and technology. SpringerLink. https://link.springer.com/article/10.1007/BF02916109

Amoore J, Ingram P. Learning from adverse incidents involving medical devices. BMJ. 2002;325:272–275. doi: 10.1136/bmj.325.7358.272. . (3 August.) https://www.bmj.com/content/325/7358/272.short?casa_token=tIr1ssxpdgAAAAAA:hhrbSj1vkSLjqlXP5UDa44xwTi6U8YuDXJnMGYfKfR_rYcLKdpwYzp_RZlMoudkCPqdrLxXjTvdyfQ

Carayon, P., Bass, E., Bellandi, T., Gurses, A., Hallbeck, S., & Mollo, V. (2011). Socio-Technical Systems Analysis in health care: A research agenda. *IIE transactions on healthcare systems engineering.* https://pmc.ncbi.nlm.nih.gov/articles/PMC3351758/

Do Rosario Carvalho, A. D., Karanth, N., & Desai, V. (2022, June 5). Characterization of pneumatic muscle actuators and their implementation on an elbow exoskeleton with a novel hinge design. *Sensors and Actuators Reports.* https://www.sciencedirect.com/science/article/pii/S2666053922000364

Elsamanty, M., Hassaan, M. A., Orban, M., Guo, K., Yang, H., Abdrabbo, S., & Selmy, M. (2023, July 16). Soft pneumatic muscles: Revolutionizing human assistive devices with geometric design and intelligent control. *Micromachines.* https://pmc.ncbi.nlm.nih.gov/articles/PMC10383850/

Husseini, N. E., & Katzan, I. L. (2023, May 1). Cognitive impairment after ischemic and hemorrhagic stroke. *AHA Journal.* https://www.ahajournals.org/doi/10.1161/STR.0000000000000430

Kwakkel, G., Veerbeek, J. M., van Wegen, E. E., & Wolf, S. L. (2015). Constraint-induced movement therapy after stroke. *The Lancet Neurology*, *14*(2), 224–234. https://doi.org/10.1016/s1474-4422(14)70160-7

Lamp, J. S., (2023, August 22). *Boost your confidence in caring for patients with insulin pumps*. *American Nurse.* https://www.myamericannurse.com/boost-confidence-caring-patients-insulin-pumps/

Lorin Purcarea, P. Eng. (2019). The impact of marketing strategies in Healthcare Systems. *Journal of Medicine and Life*, *12*(2), 93–96. https://doi.org/10.25122/jml-2019-1003

Mayo Foundation for Medical Education and Research. (2024, April 17). *What to expect as you recover from a stroke*. *Mayo Clinic.* https://www.mayoclinic.org/diseases-conditions/stroke/in-depth/stroke-rehabilitation/art-20045172

Weiss, D., Rydland, H. T., Øversveen, E., Jensen, M. R., Solhaug, S., & Krokstad, S. (2018a). Innovative Technologies and social inequalities in health: A scoping review of the literature. *PLOS ONE*, *13*(4). https://doi.org/10.1371/journal.pone.0195447

World Health Organization. (2010, August). *Increasing complexity of medical technology and consequences for training and outcome of care/* https://www.mayoclinic.org/diseases-conditions/stroke/in-depth/stroke-rehabilitation/art-200451

Yang, Y.-K., Lin, C.-Y., Chen, P.-H., & Jhou, H.-J. (2023). Timing and dose of constraint-induced movement therapy after stroke: A systematic review and meta-regression. *Journal of Clinical Medicine*, *12*(6), 2267. https://doi.org/10.3390/jcm12062267

Yao, P. Y. (2023, August 28). *Insulin Pump*. *StatPearls*. https://www.ncbi.nlm.nih.gov/books/NBK555961/

Zhang, J., Feng, H., Lin, J., Zhai, H., & Shen, X. (2023). Influence of the constraint-induced method of constraint-induced movement therapy on improving lower limb outcomes after stroke: A meta-analysis review. *Frontiers in Neurology*, *14*. https://doi.org/10.3389/fneur.2023.1090808