PNEUMATICALLY ACTUATED SOFT WEARABLE EXOSKELETON FOR UPPER LIMB MUSCLE REHABILITATION

INVESTIGATING TELE-REHABILITATION AND THE FEASIBILITY OF WEARABLE REHABILITATIVE DEVICES IN A VIRTUAL ENVIRONMENT

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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: Ensuring Affordable Access to Rehabilitative Treatment for People with Reduced Upper Limb Muscle Control

How can limited access to portable, comfortable, and affordable rehabilitation medical devices and treatments for patients with upper limb mobility issues be mitigated?

Within the realm of the wearable medical device industry, there is a notable and distinct lack of upper limb rehabilitation devices that patients can use at home. Millions of people in the United States suffer from conditions that impact upper limb function, including stroke, arthritis, spinal cord injuries, and musculoskeletal disorders. Rehabilitation is essential for these patients to restore movement, strength, and coordination, enabling them to regain autonomy in daily activities. However, because upper limb movements often require complex and fine motor control, traditional rehabilitation treatments are often costly and reliant on stationary and rigid equipment found in clinical settings. For many patients in remote areas, underdeveloped countries or with limited financial means with upper limb mobility issues, frequent visits to specialized facilities are not feasible, resulting in decreased sessions of prescribed exercises and a slower recovery. More recently, though, wearable exoskeletons are being developed to provide powered upper body motion to patients. This device can be used at home and paves the way for more advanced and convenient at-home rehabilitation treatments.

In our technical project, my group and I focus on designing, testing, and manufacturing a pneumatically actuated (device powered by compressed air) soft wearable upper limb exosuit, specifically for patients recovering from strokes and neurodegenerative diseases like amyotrophic lateral sclerosis (ALS). Accessibility to this type of device has the potential to help patients recover without the hassle of travel and facility treatment expenses. Concurrently, my STS research seeks to investigate the concept of tele-rehabilitation with prosthetic/wearable devices and how it could bridge geographical and financial gaps when it comes to rehabilitation treatment access. This includes looking into how healthcare providers, private insurance and public healthcare policies, and patients adapt to tele-health platforms. The overarching goal of my technical and STS research projects is to explore ways to make rehabilitation devices and treatments convenient, affordable, and most importantly feasible. The technical aspect of building a portable wearable upper limb exosuit goes together with the sociotechnical component of finding ways healthcare workers and patients can use the exoskeleton as tool in a tele-communicative environment.

Technical Research: Pneumatically Actuated Soft Wearable Exoskeleton for Upper Limb Muscle Rehabilitation

How can wearable upper limb exoskeletons be made more comfortable, affordable, and convenient for stroke and neurodegenerative disease rehabilitation?

According to an article published in the Journal of Applied Physiology, about 80% of people who suffer from a stroke will experience motor impairment in their upper limbs (Ingram et al., 2021). Upper limb motility, in particular, is crucial to a patient's independence, self-esteem, and quality of life. While the loss of lower extremity function can be largely compensated for with a wheelchair or prosthetic device, there are very few options available for patients with reduced muscle ability in their upper body (Masia et al., 2018). More recently, wearable exoskeletons are being developed to provide powered motion to patients. This approach has many advantages including the potential for patient-controlled movement and assistance. Traditional exoskeletons often use rigid links parallel to upper limbs connected by joints and can achieve multiple degrees of freedom (DOFs) helping with a range of movements

(Dalas et al., 2019). Several drawbacks include bulkiness, weight, and power consumption. Remarkable soft exoskeletons have been developed in recent years using soft actuators and textile designs such as shape memory alloys (a material that conforms to a patient’s skin). However, there is still a noticeable lack of research on the use of other flexible actuators to create wearable technologies that move more naturally with a human arm, especially for medical applications. By creating a soft exoskeleton, patients can have more comfort when performing everyday tasks. The goal of our technical capstone project is to design and manufacture a soft wearable upper limb exosuit to assist patients with muscle rehabilitation, specifically those who have upper limb muscle mobility loss due to stroke. The objective is to make the exosuit light weight, portable, and affordable so that at-home rehabilitation is accessible for more people.

To actually produce motion in the arm, the exoskeleton relies on actuators that mimic muscle functions to help the patient regain mobility. Our group considered three types of actuation methods for our device - cable driven, shape memory alloy, and pneumatic. Cable driven actuation uses small, motor-powered reels to control cables (like a mechanized version of a fishing reel). Shape memory alloy (SMA) is a material that can "remember" and return to a pre-defined shape when heated. SMAs contract or bend in response to body heat and provide movement or force to assist the user's limb in activities. SMA actuation allows for lightweight and compact designs, but they have slow response time and limited force output.

We ultimately decided on pneumatic actuation for our design. Pneumatic actuators use compressed air to create a push and a pull effect. While this method does require a compressor to be mounted on the patient - which can be loud and uncomfortable - pneumatic actuators are lightweight, soft, and the actuation speed (which determines how fast a patient can move their arm) is controllable by how fast a compressor pumps air in and out. Besides our actuation method, we will implement a proportional-integral-derivative (PID) controller that will receive input data from a sensor placed along the patient's arm. This sensor tracks an electronic pulse that occurs in the muscle when their arm moves in a certain way (flexion in shoulder, rotation in the elbow, etc.). After reading and processing the data through an in-built algorithm, the PID controller will output power to the pneumatic actuators (the air pumps). The air will flow through cables and assist the patient with movement. To maximize the range of motion of the device (i.e. increase the number of DOFs the patient can move their arm) we created a rotating shoulder mount on the shoulder collar, on which the air pumps are connected to the cables. If a patient wants to move their arm side-to-side instead of up-and-down, they will move the mount so the cables run along the side of their arm instead of the front.

STS Research: Investigating Tele-Rehabilitation and the Feasibility of Wearable Rehabilitative Devices in a Virtual Environment

How does the relationship between healthcare providers, private and public healthcare policies, and patients influence the adoption of wearable rehabilitation devices into tele-rehabilitation?

The integration of wearable rehabilitation devices as a tool into tele-rehabilitation hinges on a complex relationship between healthcare providers, insurance policies, and patients. While there are other factors that influence this platform (such as access to wireless connections, home life, etc.), these are the three that will be focused on in my research. As wearable muscle rehabilitation devices become more advanced and better at improving patient outcomes, they can be implemented into virtual rehabilitation or physical therapy sessions. This, in turn, removes a barrier to access for people who live in remote areas and cannot travel to treatment facilities, as well as for people who cannot afford travel and in-person services. However, adoption of such platforms is strongly influenced by healthcare provider endorsement, the policies of private and public insurance providers, and patient perspectives.

Analyzing Healthcare Provider Opinions, Private & Public Insurance Policies, and Patient Attitude Towards and Tele-Rehabilitation through an Actor-Network Theory (ANT) Framework

To understand the players involved in the tele-health and tele-rehabilitation realm, my STS research paper will employ ANT, a social theory and research method that views everything as part of a constantly shifting network of relationships. Using the ANT framework, I will create a web of connections between three entities that play a role in this virtual sphere: healthcare practitioners, private and public insurance programs, and rehabilitative device users. My research will focus on the Appalachian states. These areas are remote, and most people work long laborious days in coal mines. I will use surveys from healthcare providers (physical therapists and doctors), coverage options of big insurance companies in that region, and interview statements from patients to understand the process of how each group influences the other. A brief introduction is provided in the following paragraphs.

Healthcare providers play a pivotal role in the adoption of wearable muscle rehabilitation devices. Their attitudes towards technology, willingness to incorporate new tools into practice, and ability to educate patients about the benefits of such devices are critical factors (Catalán et al., 2021). While muscle rehabilitation is typically seen as a hands-on discipline, providers recognize the efficacy of tele-rehabilitation and wearable technology in enhancing convenient, yet quality treatments for patients. Providers already use tele-health for initial consultations, education, and delivery of an orthosis/prosthesis. Implementing tele-health options for rehabilitation sessions is the next step that providers are generally in support of. In a 2024 survey of orthotics and prosthetic providers, they described several benefits of tele-rehabilitation for patients including access to a timely, convenient, and efficient service that works with the patients' demanding professional, personal, and social schedules. Given that this virtual platform helped improve access, providers noted there were fewer no-shows or last-minute cancellations. (Dillon et al., 2024). Appalachian Regional Healthcare in Barbourville, WV started offering tele-services to stroke patients. While these services focused on the neural instead of the rehabilitative aspect, providers said it gave "a better chance of stroke survival and recovery" and showcases positive provider response to tele-rehabilitation (Appalachian Regional Healthcare, 2021). My STS research will explore healthcare provider statements like this one to further gauge health care opinion on virtual rehabilitation options.

The relationship between healthcare providers and insurance companies is also critical in determining the adoption of wearable devices in tele-rehabilitation. Private insurance and public healthcare policies influence which technologies are covered and how they are reimbursed. If wearable rehabilitation devices like robot exoskeletons or prosthetics are not included in insurance coverage, both the patients and the providers may be less inclined to use them. Private insurance coverage for prosthetics and orthotics varies by plan and provider, but most plans offer some level of coverage for medically necessary devices. Patients may also still have to pay a deductible and co-pay depending on their coverage package. (*PrimeCare*, n.d.). My STS research paper aims to quantify exactly how much insurers in Appalachia are covering not only for the prosthetic or wearable device, but also for the tele-health sessions. This includes, first, researching healthcare infrastructure in this region and notable public or private plans the residents use. I will then investigate specific coverage plans offered to see what options patients have. This will help me identify if there is a monetary barrier to accessing rehabilitative tele-health treatment. In the past, Medicare coverage only applied to prosthetic devices and not remote rehabilitation sessions (Dobson et al., 2016). However, Medicare has begun to expand its coverage for telehealth services, which could include reimbursement for wearable rehabilitation devices, thereby incentivizing use among providers and patients (*Telehealth*, n.d.). However, disparities in coverage between private and public insurance can create barriers. Patients with private insurance may have more access to innovative technologies than those relying on public healthcare, leading to inequities in care.

Patients themselves are a vital component of this dynamic. Their acceptance and willingness to use wearable rehabilitation devices can significantly impact the success of tele-rehabilitation initiatives. Factors such as technological literacy, personal motivation, and previous experiences with rehabilitation technologies all play a role in patient engagement. In fact, patients with muscle mobility issues often yearn for family contact and frequently discontinue rehabilitation training sessions and return home to their local community. This emphasizes the value of home and community-based rehabilitation, where patients have the option to perform daily training with remote support from therapists (Sun et al., 2022). Additionally, patient advocacy and demand for better rehabilitation options can influence healthcare providers and insurance companies. When patients express a desire for innovative rehabilitation solutions, providers may be more inclined to adopt these technologies, and my STS research will discuss how insurers may expand coverage options to meet consumer demand. Using interview-style research papers and feasibility studies I will seek information regarding patient attitude towards wearable medical devices and tele-rehabilitative access in the Appalachian region.

Conclusion

The overarching hope and goal of the culmination of my technical and STS thesis is to investigate, understand, and analyze the ways in which wearable medical devices, in conjunction with quality tele-rehabilitation treatments, can be made more affordable and accessible. From my technical research, I hope to learn how to apply my engineering skills to solve the challenges involved with designing and manufacturing an innovative and affordable soft wearable upper limb exoskeleton. In my STS research, I hope to learn the nuances involved in creating a successful tele-health environment, specifically in the Appalachian region, where patients have the ability to effectively use their rehabilitative devices. By delving into both the technical and sociotechnical aspects, a wholistic review of this problem can be presented.

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