The Robotic Hand Rehabilitation Device

PURPOSE:

THIS PAPER SERVES AS AN ANALYSIS OF RESEARCH CONDUCTED ON THE CONCEPT AND DESIGN OF THE ROBOTIC HAND REHABILITATION DEVICE AND HIGHLIGHTS ITS VERSATILITY IN THE MARKETPLACE FOR EXTERNAL OCCUPATIONAL THERAPY DEVICES. IT IS WRITTEN WITH THE INTENT TO INFORM THE READER OF THE CONCEPT BEHIND A ROBOTIC GLOVE MEANT TO REHABILITATE INDIVIDUALS WITH FORMS OF HAND PARALYSIS AND DISABILITY SO THAT THEY CAN REGAIN MUSCLE AND NERVE CONTROL

INTENDED AUDIENCE:

THE INTENDED AUDIENCE FOR THIS PAPER IS THOSE WHO ARE INTERESTED IN LEARNING MORE ABOUT ALTERNATIVE MEDICAL DEVICES THAT CAN EXPAND THE AVAILABILITY OF FINANCIALLY VIABLE REMEDIES TO NOT ONLY HAND PARALYSIS BUT OTHER FORMS OF PHYSICAL DISABILITIES. THIS PAPER OFFERS ONLY ONE OF MANY POSSIBILITIES FOR INTRODUCING SOLUTIONS THAT ARE ACCESSIBLE, AFFORDABLE, AND EFFICIENT IN THEIR DESIGN

STYLE GUIDE:

I WILL BE TYPING OUT THIS FINAL PROJECT IN AN IEEE JOURNAL ARTICLE FORMAT. I WILL BE TYPING OUT MY FINAL PROJECT ON GOOGLE DOCS, NOT IN LATEX.

Jhovanny Uribe

jhuribe@ucsc.edu

Abstract— **This paper serves as an exhibition of current and recent research done on this subject and emerging technology. I will be exhibiting the research and findings done on the technology behind hand rehabilitation devices as well as their impacts on clients' medical circumstances and concluding whether or not they can function as viable medical alternatives. I will be including articles that present valuable conclusions on the effects of medical devices and the methods used to develop these solutions.**

I. Introduction

Hand paralysis and disability are medical conditions that severely hinder the livelihood of a person, especially their ability to interact with their environment and surroundings with the use of their hands. Currently, nearly 1 in 50 people live with paralysis while hand injuries account for ⅓ of chronic injuries and ⅕ of permanent injuries. It is, therefore, a condition that has had numerous different remedies and treatments, ranging from nerve transfer surgery, in which neurological connections in the hand are repaired, to hand therapy conducted by trained kinesiologists and physiologists. While these remain effective solutions to this condition, they can be extremely costly, both physically and financially. In fact, roughly 28% of households with a person who is paralyzed make less than $15,000 per year, and nearly half, roughly 42%, of people who are paralyzed say they are unable to work. This report indicates that those afflicted by some form of hand paralysis will be unable to afford treatment as expensive as surgery or physical therapy, leaving many to remain affected by this condition. However, one alternative solution involves the use of external occupational therapy appliances, devices classified by the FDA, Food and Drug Administration, as devices used to aid the process of rebuilding muscle and nerve control. This solution is often more financially viable for many patients and provides opportunities for consistent practice and exercises that work toward rehabilitation. In this case, the use of robotic therapeutical gloves specifically designed with the intent of being accessible, affordable, and efficient for the patient to regain muscle maneuverability proves to be a feasible remedy for these medical circumstances.

II. Background

A wearable robotic hand is one of the less-studied form factors compared to other types of anthropomorphic robotic hands. In the study of robot manipulation, most of the previously proposed anthropomorphic robotic hands have been developed to mimic the human hand's ability in terms of motion and tactile sensitivity. Many robotic hands could imitate a human hand' grasping motion and former researchers on the anthropomorphic hand demonstrated that the hand could manipulate an object so that its performance is similar to that of a human hand's dexterity. The main example of the robotic hand involves that of the exoskeletal hand, which has the advantage of accurate force and position control, but its rigid structure often increases the size and mass of the system, a fault that causes an increase in price for development and manufacturing. To overcome the limitations of the exoskeletal robotic hand, robotics researchers have developed the soft robotic hand, which consists of deformable structures and materials such as fluids and elastomers. A typical soft robot hand is in the form of a glove with elastic power transmission and has the strength of compact and light design, but it has a weakness in the force display compared to the rigid exoskeletal robotic hand. For our purposes, however, this design is suitable for the goal to provide a tool for muscle and nerve rehabilitation through consistent practice at an affordable cost.

III. Exoskeleton v. Robotic Glove

A. Differences in Approach

A wearable robotic hand is one of the less-studied form factors compared to other types of anthropomorphic robotic hands. Most wearable robotic hands have been developed in the form of an exoskeleton hand interface to be worn on a human user's hand. This distinction leads to a split approach to understanding the needs of the human hand and its flexibility for the purposes of this project as well as the general design of the apparatus.

B. Exoskeleton

The exoskeletal robotic hand has the advantage of accurate force and position control, but its rigid structure often increases the size and mass of the system. These factors cause both the features of accessibility as well as the cost of production to increase. The architectures of the exoskeleton robotic glove require the robotic glove and human joints to be accurately aligned, as misalignments would result in kinematic incompatibilities impeding the movement of the fingers or causing physical discomfort.

C. Robotic Glove

The robotic glove is a device that uses textiles to interface with the body in parallel with the muscles, using the bone structure, to support fingers' motion. Robotic gloves have merits in assisting individuals with hand pathologies to perform continuous exercises for hand-functions restoration, which could accelerate the rehabilitation process and reduce costs. The design of the robotic glove over the exoskeleton approach proceeds to largely inform the design philosophies of the numerous research conducted and projects developed in the articles I have elected to analyze.

IV. Research Findings

The following articles each provide a unique insight into the intricacies behind the development and progression of a therapeutical hand rehabilitation device, each with its own set of design requirements and objectives. While each provides a distinct perspective, they all collectively contribute to the advancement of this particular medical technology and are each tailored toward the same fundamental principles, which are maneuverability, efficiency, and financially viable. Each article will be divided into three sections covering each other periods of setting the foundations of the project, the development cycle, and their results and/or findings.

1) *Post-stroke Hand Rehabilitation Using a Wearable Robotic Glove*

A. *Foundations*

The research done on this project by teams at the University of Craiova and the University of Medicine and Pharmacy in Craiova, Romania is very engaging and provides a foundation for the design principles behind a versatile and viable option found in the rehabilitative hand device. They strived to create a lightweight and low-cost robotic glove that post-stroke patients can use to recover hand functionality. The rehabilitation aims to help stroke patients to relearn the skills that were lost when they suffered a stroke. Before developing their initial rendition of the glove's design, they established key characteristics that their design would have to embody:

1. Natural/intuitive to use and easy to wear.
2. Lightweight.
3. Not restricting the natural human kinematics or range motion.
4. Compliance and stability.
5. Sufficient adaptability to individual differences in patients' anthropometric dimensions (without mechanical regulation or tunings).
6. Reduced system costs.
7. Easy maintenance.
8. High power-to-weight density and reduced energy consumption.

B. *Development*

Once they began development on the project, they continued to establish the essential behaviors that the design needed to inhibit in order to function at a base level. In order to have sufficient grasping force, they needed to ensure that the glove 1) did not disturb human finger movement, 2) allowed a grasping force proportional to the human grasping force, and 3) allowed variable compliance as the human finger so that the dexterity and stability of the grasping are preserved. These foundations prove to be consistent standards that nearly all iterations of this concept exhibit at some stage in development as they serve as markers for efficiency as well as practicality. This team also utilized a data acquisition system to determine variation laws of kinematic parameters of human hand movement using software called SimiMotion, allowing them to create a teleoperated robotic hand that simulated these motions. The next step in development was producing a robotic glove that consisted of three parts: a mechanical exoskeleton or soft robotic glove, an actuation system, and embedded control with a minimum number of sensors.After creating and testing several mechanical solutions involving different motion transmission solutions and actuation systems, they developed two structures, which were an exoskeleton with mechanical phalanges and a soft robotic glove using a Bowden and flexible tendons. They continued to use an embedded control system based on an Arduino board to test teleoperation using a glove with flex sensors and program-based actions, through which clinically-approved or self-generated recuperative programs are pre-set, as can be seen in the following images:

Figure 1. Tele-operation glove with flex sensors

Figure 2. Wearable soft robotic gloves in action

Additionally, through repeated testing of the actuation systems, they found that while pneumatic and SMA actuators were difficult to get to work consistently or impractical, linear electric actuators were easy to drive the linear movement and were much easier to control, visible in Figure 1. During testing, the evolutions in time of the output of the index finger flex sensors were monitored and captured on the following graph:

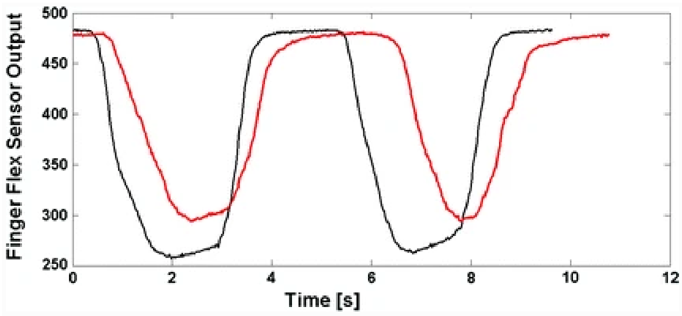


Figure 3. Output Timing Graph

The black line represents the teleoperated glove and the red line represents the robotic glove. As can be seen, there is a small delay and the flexion of the robotic glove is smaller than that of the teleoperation glove.

C. *Findings*

The findings of this project's development cycle concluded that wearable soft robotic gloves seem to be the better solution for human hand rehabilitation as these gloves are lightweight, portable, and compliant wearable systems that can still be further refined. They followed this up by stating, "The soft robotic gloves architectures will be more frequently used in assistive and rehabilitation robotics, due to their simplicity. Many development challenges and plenty of research remain to be done in actuator development, textile innovation, soft sensor development, human-machine interface (control), and biomechanics." Finally, and most significant for the objective of the project overall, it was concluded that the robotic glove not only shortens rehabilitation time post-stroke but also brings a higher level of recovery than is achievable with the current physiotherapy methods. This article serves as a crucial first step into understanding the potential reach and impact that a design such as this can have for the recovery and financial savings of a patient experiencing a need for this category of medical technology.

2) *Modeling and Control of a Soft-Rigid Hybrid Robotic Glove for Hand Rehabilitation and Assistance*

A. Foundations

This article, written by Yongkang Jiang from the Institute of Robotics, Beihang University, Beijing, China, proposes a soft-rigid robotic glove with new types of joint actuators as a response to the cumbersome and uncomfortable characteristics of previous rigid-framed designs. They present this concept through the use of a system view and working principle of the proposed robotic glove, followed by a comprehensive theoretical modeling of the novel actuator to describe the underlying principles when they deform, and finally by developing a robotic glove with the soft-rigid hybrid actuators and evaluating its performance in different conditions. Throughout the design portion of this article, they describe how silicone-based actuators perform when inflated and the faults that led them to develop a hybrid robotic glove that incorporates air pouches made of layers of TPU-fabric material together with rigid plates to fix the series of air pouches inside the joint actuators as well as length-adjustable connectors that are 3D printed with commercial PLA material. The use of descriptive models is very informative and does an excellent job of displaying the reasoning behind the hybrid design's philosophy, exhibiting the qualities of a healthy human hand's maneuverability and how critical it was in the process of developing a suitable apparatus for medical usage.

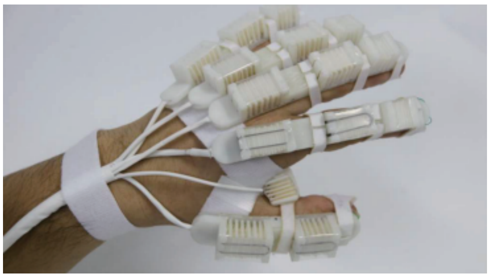


Figure 4. Proposed soft-rigid hybrid robotic glove design

B. Development

In Fig. 4(a), the single finger on the robotic glove consists of three soft-rigid hybrid joint actuators to help the bending motion of the related human finger joints, and length-adjustable connectors to link the joint actuators and benefit better fitting between the robotic glove and user's hand. Additionally, the related two joint actuators mounted on the are connected via air tubes.

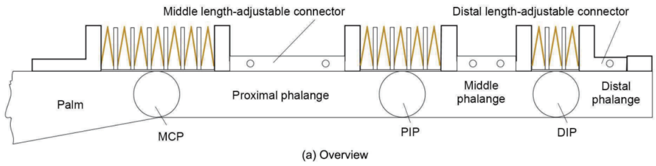


Figure 4(a). Finger System Overview

Similarly, illustrated in Fig. 2(b) is the main actuator, several arranged rigid plates, and a flexible strain-limiting layer to enable the bending of the soft-rigid hybrid actuator by restricting the elongation at the bottom:

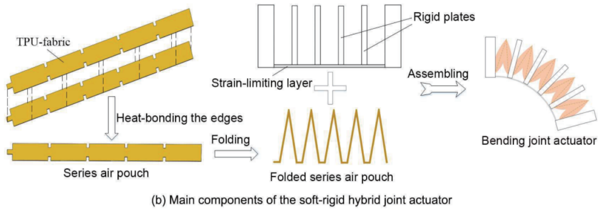


Figure 4(b). Proposed joint actuator

To better predict the interacting force between the joint actuators and the user's fingers, Jiang first analyzed the deformation theory of the air pouch itself, followed by the modeling of the force-pressure response of the joint actuator when mounted on an individual's hand. They then perform a deformation analysis of a single air pouch module at the distal end of the series air pouch, elaborating on the shape function of the layer's geometric symmetry as well as the large deformation theory and the virtual work principle. They continue to give an elaborate and well-thought-out study of the contour function of the contact area and the intersection equation between the air pouch layer and the plate. After these analyses, Jiang was able to find that "increasing the input air pressure, enlarging the contact area between the air pouch modules and the plates, and shortening the length of each air pouch module can all contribute to enhancing the output force of the joint actuator, which provides suggestions of the design and optimization of the proposed soft-rigid hybrid actuators." After further testing involving the joint actuator, they found that the pushing force increases along with the air pressure and that as the air pressure goes up, the analytical result predicted by the models matched well with the experimental one both in the trend and values, which validated the effectiveness of the models proposed in the glove's design

C. Findings

After extensive research, calculations, and modeling, the team developed a hand rehabilitation system including a robotic glove and a control box, with which they were able to develop a control framework that sent real-time commanding signals to the robotic glove. They proceeded to test the device by grasping various daily objects and evaluating its performance, as can be seen in the following figure:

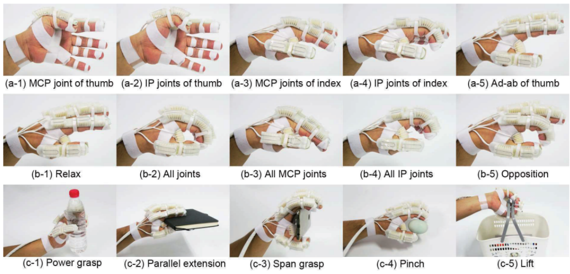


Figure 5. Demonstration of Glove Evaluations

They discovered that the glove was able to assist the human hand with single joint movement and other complex motions involving several joints at once. Additionally, the proposed robotic glove was able to assist the tested hand with multifarious common exercises including (1) all finger joints flexion simultaneously (2) all the MCP and IP joints bending (3) opposition movement between the thumb and other four fingers respectively. The test hand was also able to use various postures to grasp daily objects with different shapes, scales, and weights. The design was successful in what it set it out to prove and left room for optimization and improvement of its actuators and control precision. Jiang concluded that "the proposed glove could accelerate the process for impaired human hands to restore the correct hand postures and contributes to the design of novel soft robots as well as wearable devices."

3) *Wearable Robotic Glove Design Using Surface-Mounted Actuators*

A. Foundations

In this article, written by Jaeyoung Park, Inchan Hwang, and Woochan Lee from various Engineering institutes in South Korea, they propose a novel wearable robotic glove or exo-glove design scalable to the variation of the hand kinematics. This glove iteration exo-glove deforms a robotic finger's skin and, thus, the hand skeleton joints. Multiple tendons woven on the exo-glove's surface can make multi-DOF finger joint motions. This design of the robotic glove incorporates allocated tendons to mimic a hand's intrinsic and extrinsic muscles so that a robotic hand actuated with the exo-glove can perform natural finger motions, including abduction/adduction and flexion/extension of finger joints. Moreover, additional tendons for the thumb enable power grips and the robotic hand's human-like motion. This proposed design's approach places all the actuators on the surface without directly actuating any of the hand skeleton's joints and therefore, a random hand skeleton can work as a robotic hand by putting the wearable robotic glove on it. The article goes into extremely elaborate detail on the design process that the team experienced in order to develop a product that reflected the essential functionalities that they established early on in the paper.

B. Development

After an explanation of the history of research conducted on the concept of anthropomorphic robotic hands and wearable robotic hands, the authors continue to describe the wearable robotic glove with skin-mounted actuators and its design requirements, which bear a striking resemblance to the preexisting requirements (a) move five fingers independently and (b) mimic the functionalities of human hand motion, with the inclusion of one (c) the actuators of the tendon-driven system should not increase the length of the overall robotic hand. After using intricate CAD designs to illustrate the visual of the robotic hand's skeleton, its tendon configuration and maneuverability, and the mechanism of actuating the tendons to extend the finger, they built a dual-layer exo-glove robotic hand by combining the actuator units to a glove with tendon-sheath.

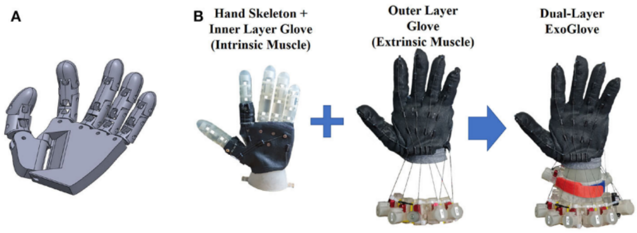


Figure 6. Design and assembly of the dual-layer exo-glove robotic hand

For the control of the robotic hand posture, the team utilized a synergistic control approach by controlling the posture of each finger to locate the end-effector (fingertip) to the desired position. To map the index finger control, they fixed the MCP joint angle and collected the end-effector position by rotating the PIP joint. Similarly, for the thumb control, the end-effector position by the thumb opposition angle is collected by rotating the thumb's IP joint. For other fingers, they implemented only extrinsic finger muscle movement so that only one end-effector trajectory could be collected, which was used for the finger pose control. Additionally, they integrated a tactile sensor to manipulate an object with the robotic hand actuated with the proposed exo-glove.

C. Findings

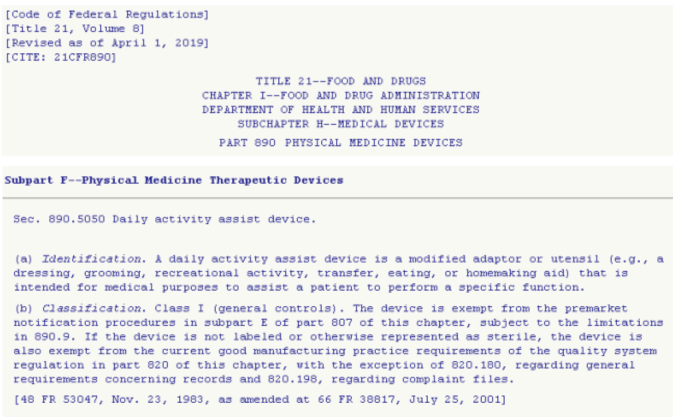
After all of these design implementations, the team tested and evaluated their products using standard grasp performance tests as well as in terms of position repeatability, and object grasping ability. The results of the tests indicated that the glove-worn robot hand can strike a number of poses and that the fingertip position tracking data shows that the finger position control can be repeated with no significant error. They also demonstrated that increasing fingertip stiffness could enhance the grip force when no gripping force is applied after the grip event. The design proved effective and the article displayed an extremely large quantity of valuable information and research that demonstrated that this robotic glove design could be a viable robot hand platform for variable manual tasks.

Figure 7. The glove grasping a bottle with precision grip

For future iterations, the team plans to continue to improve the robot hand platform by efficiently using rigid and soft structures, incorporating a flexible touch sensor for the robot hand to sense objects and conduct manual tasks effectively, and extending the exo-glove to applications such as prosthetic hand and power assist glove. For this application, they will need further implementation of the interface for intention cognition and they intend to conduct additional evaluations of the exo-glove in terms of device manipulability as well as apply lighter actuators to enhance the wearability of the exo-glove.

V. FDA Regulations

In addition to needing to ensure that the rehabilitative device is functional and efficient, the device would need to be regulated by the Food and Drug Administration in order to be listed as a rehabilitative medical device. The FDA classifies a "medical device" as "an instrument, apparatus, implement, machine, contrivance, implant, in vitro reagent, or another similar or related article, including a component part or accessory which is either intended for use in the diagnosis of disease or other conditions, or in the cure, mitigation, treatment, or prevention of disease in man or other animals." Below is an excerpt from the FDA's Title 21, Part 890 in which the identification of medical devices is specified:



[Code of Federal Regulations]
[Title 21, Volume 8]
[Revised as of April 1, 2019]
[CITE: 21CFR890]

TITLE 21--FOOD AND DRUGS
CHAPTER I--FOOD AND DRUG ADMINISTRATION
DEPARTMENT OF HEALTH AND HUMAN SERVICES
SUBCHAPTER H--MEDICAL DEVICES
PART 890 PHYSICAL MEDICINE DEVICES

Subpart F--Physical Medicine Therapeutic Devices

Sec. 890.5050 Daily activity assist device.

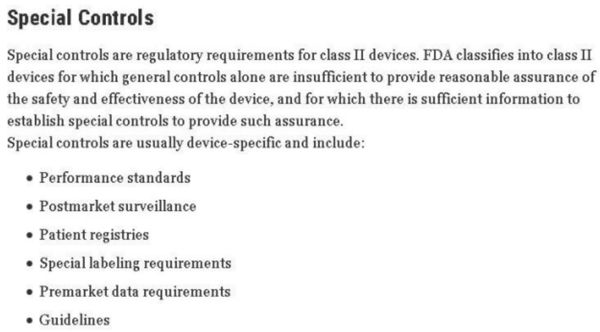
(a) *Identification.* A daily activity assist device is a modified adaptor or utensil (e.g., a dressing, grooming, recreational activity, transfer, eating, or homemaking aid) that is intended for medical purposes to assist a patient to perform a specific function.

(b) *Classification.* Class I (general controls). The device is exempt from the premarket notification procedures in subpart E of part 807 of this chapter, subject to the limitations in 890.9. If the device is not labeled or otherwise represented as sterile, the device is also exempt from the current good manufacturing practice requirements of the quality system regulation in part 820 of this chapter, with the exception of 820.180, regarding general requirements concerning records and 820.198, regarding complaint files.

[48 FR 53047, Nov. 23, 1983, as amended at 66 FR 38817, July 25, 2001]

Figure 8. FDA Regulations Excerpt

The FDA regulates three regulatory classes based on the level of control necessary to assure the safety and effectiveness of the device and this project falls under a class II device, which is described as follows:



Special Controls

Special controls are regulatory requirements for class II devices. FDA classifies into class II devices for which general controls alone are insufficient to provide reasonable assurance of the safety and effectiveness of the device, and for which there is sufficient information to establish special controls to provide such assurance.
Special controls are usually device-specific and include:

- Performance standards
- Postmarket surveillance
- Patient registries
- Special labeling requirements
- Premarket data requirements
- Guidelines

Figure 9. Special Controls Excerpt

VI. Conclusion

The Robotic Rehabilitation Device is a concept that has been proven to be effective as an individual and alternative form of treatment for patients dealing with paralysis in the hand. Through several iterations of the project, it has been found that the robotic glove is capable of interacting with daily objects as well as providing opportunities for constructive muscle rehabilitation through repeated usage. This category of medical hardware has the capability of being extremely accessible and financially viable for patients from a wide variety of backgrounds and experiences. The accessibility of medical appliances and hardware tools is a very important factor for many people who rely on affordable options for treatment and with the research and development done already, it is feasible for this design to be a practical and versatile tool for millions of people worldwide.

Acknowledgment

I want to acknowledge the various authors of these fascinating articles as well as the information provided by the Christopher and Reeve Foundation surrounding the prevalence of paralysis and its impacts. I also would like to acknowledge Professor Moulds for providing this template and providing helpful resources that helped me to write this cohesive paper

References

Below are the references I used for this paper

[1] Popescu, D., Ivanescu, M., Popescu, R., Petrisor, A., Popescu, L.-C., & Bumbea, A.-M. (2016). Post-stroke hand rehabilitation using a wearable robotic glove. *Innovation in Medicine and Healthcare 2016*, 259–268. https://doi.org/10.1007/978-3-319-39687-3_25

[2] Jiang, Y. (2022). Modeling and control of a soft-rigid hybrid robotic glove for hand rehabilitation and Assistance. *2022 12th International Conference on CYBER Technology in Automation, Control, and Intelligent Systems (CYBER)*. https://doi.org/10.1109/cyber55403.2022.9907229

[3] Park, J., Hwang, I., & Lee, W. (2020). Wearable robotic glove design using surface-mounted actuators. *Frontiers in Bioengineering and Biotechnology*, *8*. https://doi.org/10.3389/fbioe.2020

[4] *Topic resources: Living with paralysis: Reeve Foundation*. Christopher & Dana Reeve Foundation. (2023b, April 24).

https://www.christopherreeve.org/living-with-paralysis/free-resources-and-downloads/fact-sheets-a-z/topic-resources

[5] *The Federal Register*. Federal Register :: Request Access. (2023b, June 14). https://www.ecfr.gov/current/title-21/chapter-I/subchapter-H

[6] *CFR - Code of Federal Regulations Title 21*. accessdata.fda.gov. (2023, March 8). https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/CFRSearch.cfm?CFRPart=890&showFR=1&subpartNode=21%3A8.0.1.1.32.6

[7] *Hand paralysis: Orthopaedics*. Loyola Medicine. (n.d.-a). https://www.loyolamedicine.org/find-a-condition-or-service/orthopaedics/orthopaedic-conditions/hand-paralysis