Exoskeleton Glove for Hand Rehabilitation

Chiamaka Akah
Northeastern University
Boston, USA

Harshith Nagaraj Chandrika
Northeastern University
Boston, USA

Kausalya Sankaranarayanan
Northeastern University
Boston, USA

Samyukta Ramesh
Northeastern University
Boston, USA

***Abstract*—Motor recovery is a critical component of rehabilitation for individuals with hand impairments caused by injuries, strokes, or neurological disorders. This project presents the design and implementation of an exoskeleton glove for hand rehabilitation, leveraging the principles of motor learning to promote recovery through repetitive, error-free movements. Neuroplasticity, the brain's ability to adapt and reorganize, is a cornerstone of motor recovery, and our exoskeleton glove is designed to exploit this principle by ensuring task accuracy and consistency—factors that are often difficult to achieve with traditional rehabilitation methods. It is important to highlight that the exoskeleton glove developed in this project is specifically designed for rehabilitative purposes rather than assistive functions. Unlike assistive devices that focus on aiding users in performing daily tasks, our glove facilitates recovery by enabling repetitive, controlled motion exercises that promote motor learning and neuroplasticity. This rehabilitative approach ensures that the device supports patients in regaining their motor function over time rather than compensating for lost abilities. The exoskeleton glove features a lightweight and ergonomic design that prioritizes user comfort, simplicity, and affordability to ensure accessibility for rehabilitation centers and patients with limited resources. Initial evaluations indicate that the glove achieves consistent execution of repetitive motion (Continuous Passive Motion) which is critical in triggering motor recovery. This work contributes to the advancement of assistive robotics by providing a practical, cost-effective solution for hand rehabilitation that leverages neuroplasticity and motor learning principles, addressing the need for accessible and scalable rehabilitation technologies.**

Keywords*—*Rehabilitation, Exoskeleton, Motor Recovery, Assistive Robotics

I. Introduction

Stroke, trauma, sports injuries, occupational injuries, spinal cord injuries, and orthopedic injuries are common prevalent occurrences in human life, often resulting in hand and finger impairment. In the United States alone, more than 610,000 people suffer strokes annually. Among stroke survivors, 50% are chronically disabled due to its high morbidity rate [1-3]. For most of these cases, partial or total loss of hand motor ability is observed. This significantly hinders an individual's ability to perform daily tasks; hence, functional recovery of the impaired hand is vital to regain independence and improve the quality of life. Rehabilitation programs are the primary method to promote active recovery in stroke and trauma survivors [4]. Conventional rehabilitation approaches which require extensive one-on-one sessions with physical therapists are well-established methods, but unfortunately, there is a constant shortage of trained therapists to treat patients requiring long-term rehabilitation. Also, most of these rehabilitation methods involve the patient being passive while the therapist does the active movements, but studies have shown that the active involvement of the patient can strengthen and improve their motor learning as well as their cognitive-motor skills, which can lead to a more rapid recovery [5]. Moreover, the cost of therapy over a prolonged period can get expensive, and the need for the patient to always go to the therapist can lead to a loss of interest. These issues have given birth to a need for active systems that can assist both therapists and patients.

Robotic systems can assist the therapy process by taking over the physical load of therapists, and longer and more intense training periods can be executed for a more rapid recovery [6]. It has also been shown by Lum et al. and Staubli et al. that highly repetitive task training can help the recovery of motor functions [7, 8]. Proof that robotic systems assisting therapists can improve the recovery of patients can be seen through the hand exoskeleton "HEXORR" and the clinical experiments that they have conducted in [9].

Motor learning, which plays a critical role in rehabilitation, involves the acquisition and refinement of motor skills through repeated practice and interaction with the environment. At the heart of this process lies neuroplasticity—the brain's remarkable ability to reorganize itself by forming new neural connections in response to repetitive activity. With regards to hand rehabilitation, one way of triggering neuroplasticity is through Continuous Passive Motion (CPM) of the impaired fingers over an extended period. Our exoskeleton glove leverages this principle by enabling patients to perform controlled movement tasks with precision and consistency, surpassing the accuracy achievable through traditional methods. It does not offer personalized or adaptive therapy. Instead, it adopts a standardized approach to deliver uniform continuous passive motion of the fingers for all users, with an emphasis on making the movements error-free, consistent, and extended, a critical factor for exploiting neuroplasticity and achieving motor recovery. We also focused on affordability to serve a broad range of patients, particularly in resource-constrained settings.

II. Literature Review

A. The role of the hand and its anatomy

The human hand is the most used external part of the human body for activities of daily living (ADL) [10, 11] and is an engineering marvel on its own. It plays a crucial role in the development of the brain's motor functions and skills and is

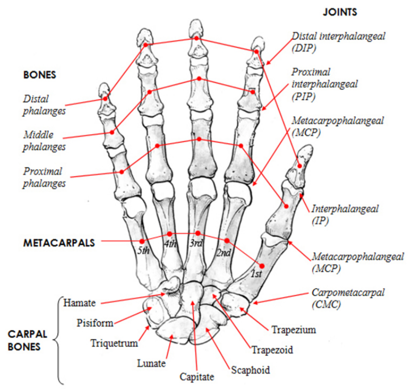


Fig. 1: Skeletal structure of the hand, showing various bones and joints [15].

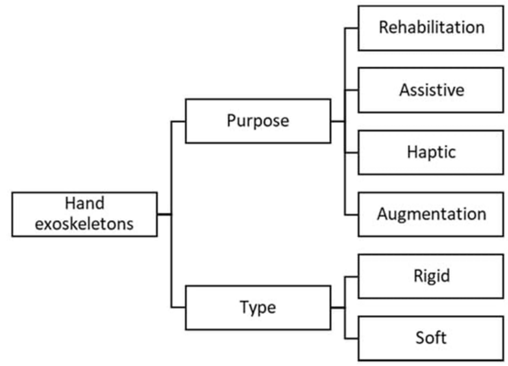


Fig. 2: Classification of Hand Exoskeletons [17].

used to communicate, express emotion, and manipulate the environment. The hand executes the commands given from the brain through neurons that travel through the nervous system to the respective areas, such as muscles, to articulate certain body parts [12]. The hand is one of the most complex structures in the human body due to its compact size (consisting of bones, joints, muscles, tendons, nerves, and blood vessels), large executable degrees of freedom (DOF), and range of motion (ROM). In total, there are 27 bones [13], 36 articulations [14], and 39 active muscles [14], which are all designed to make the hand the most versatile tool of the human body. The hand has four fingers and an opposing thumb and offers 21 DOF [14].

B. Hand Exoskeletons

Hand exoskeletons are wearable robotic devices that assist the fingers of the human hand to complete its range of motion (ROM), amplify power, or in rehabilitation. Since the word “exo” means ’outer’, robotic hand exoskeletons are designed to be fitted on the dorsal, palmar, or lateral side of the hand/fingers [16].

There are two types of robotic hand exoskeletons developed over the years, which are classified as rigid and soft exoskeletons (Figure 2). In rigid exoskeletons, the force or torque is transmitted to the required joints through a mechanical structure. The exoskeleton joints are aligned with the finger joints, usually on the lateral side of the fingers. This is the most intuitive design method, but it restricts the size due to the space between the fingers, and custom fits are usually required. On the other hand, soft (compliant) exoskeletons are designed in the form of gloves with flexible materials or elastic structures to transmit the forces to the joints of the fingers. These devices are lightweight and compact but usually require cables or air tubes situated remotely to the actuating unit. Special design care must be taken with soft exoskeletons because there is no rigid structure to guide the finger and transmit the required torques to the joint. The flexible structure usually relies on the rigid skeleton bone structure to guide the fingers in flexion and extension or abduction and adduction motions. Therefore, any misaligned forces may cause secondary injuries over time or cause discomfort to the users [17]. Many avenues have been and are still being explored in the field of robotic hand exoskeletons, such as artificial muscles [18], tendon-driven devices [19-22], and pneumatically actuated jointless structures [23-27].

According to purpose, robotic hand exoskeletons can be classified as Rehabilitative, Assistive, Haptic and Augmentative (Figure 2). Rehabilitative exoskeletons are designed to aid motor recovery by guiding repetitive and controlled hand movements, often used in therapy for patients with neurological or musculoskeletal impairments. Assistive exoskeletons enhance the user’s hand functionality; they provide support for daily activities in individuals with limited motor abilities. Haptic exoskeletons focus on delivering tactile feedback, enabling users to interact with virtual or remote environments with heightened sensory perception. Augmentative exoskeletons go beyond restoration; they enhance human capabilities for tasks requiring strength or precision. Each type of robotic exoskeleton addresses distinct needs, ranging from recovery to performance enhancement.

III. Materials & Methods

A. Design

The design of our rehabilitative hand exoskeleton focused on simplicity and affordability. For actuation, we utilized electric motors, selected for their precision and ability to deliver controlled, repetitive motion suited for rehabilitation. Power transmission is achieved through a rigid 3D-printed mechanical structure. Control is implemented through a low-level scheme designed to execute predefined motion patterns with accuracy and uniformity, making it ideal for repetitive motor exercises. A push button serves as the trigger signal, providing a straightforward and user-friendly way to initiate movement. The control type employed is Continuous Passive Motion (CPM), which guides the hand along a predefined trajectory without considering user intent. Sensing mechanisms were not included, as the focus was placed on a simplified control approach tailored to the project’s goal of Rehabilitation. See Fig. 3. for details.

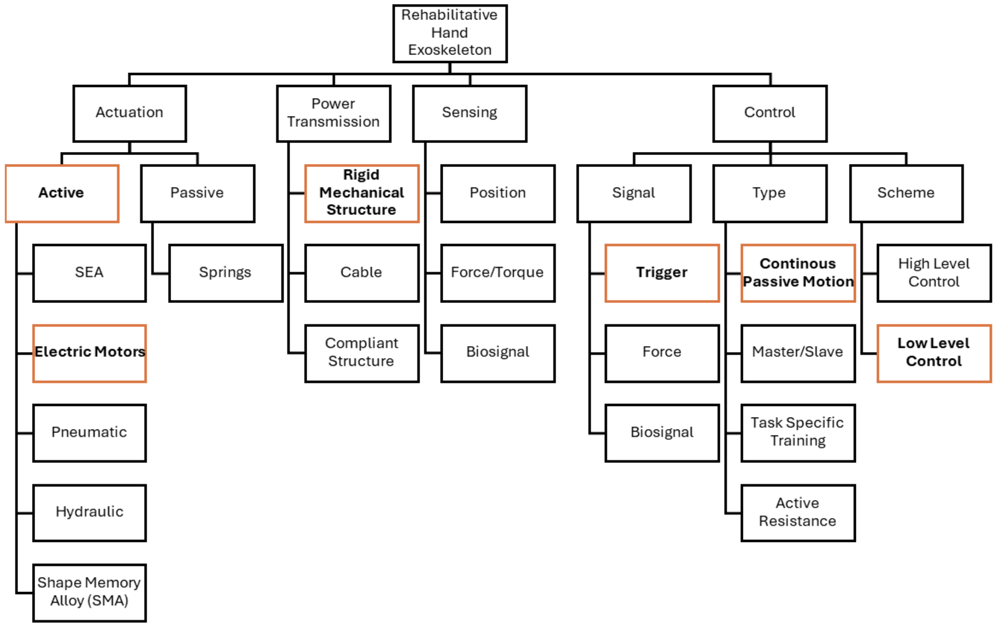


Fig. 3: Building Block of a Rehabilitative Hand Exo-Skeleton (The highlighted blocks are implemented in our project).

B. Materials

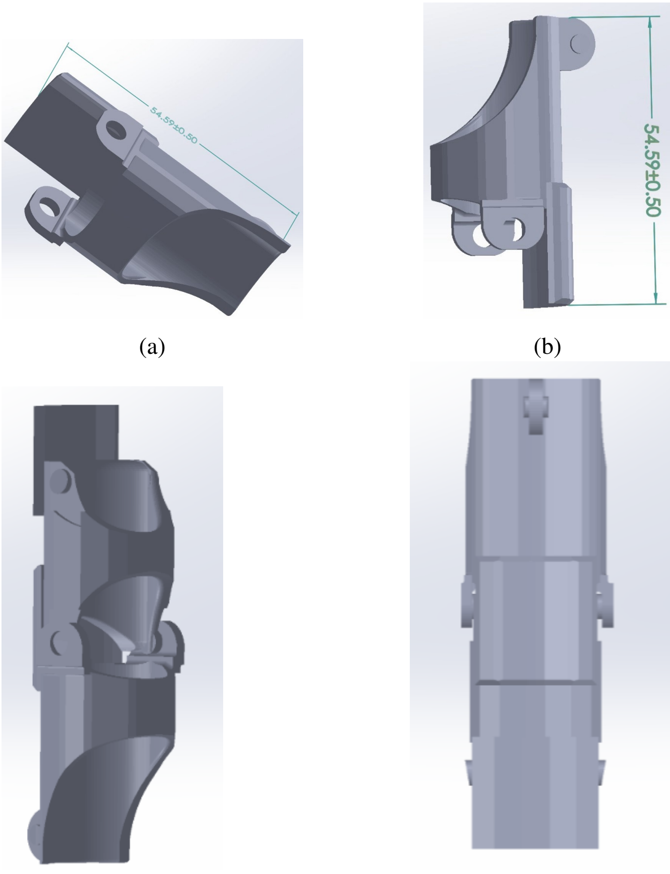
The materials selected for this exoskeleton glove project have been chosen for their reliability, precision, affordability, and ease of integration to create a functional system for hand movement control. The Round Push Button Switch (R13-507) is a 2-pin, single-pole, single-throw (SPST) momentary switch designed for manual input control. With a mounting hole size of 16mm, it supports an input voltage of 3A at 250V AC and 6A at 125V AC. The switch, rated for up to 500,000 cycles, provides a durable and efficient means to activate or deactivate the exoskeleton's hand-opening and closing mechanism. The MG90S Micro Servo Motor is a compact, high-torque actuator with metal gears and a coreless motor, delivering 2.0 kg/cm of torque at 4.8V and operating at a speed of 0.11 seconds per 60°. It has a voltage range of 4.8V to 6V and offers a 180° rotation range, enabling precise finger movements based on the user's input. This motor is responsible for driving the mechanical movements of the glove's fingers. The Arduino UNO R3 Controller Board, powered by the ATmega328P microchip, serves as the central control unit for the exoskeleton system. It features 14 digital I/O pins, 6 analog inputs, and supports USB communication for programming. It operates with a 5V regulated power supply and facilitates the control of the servo motors and other system components. The Breadboard offers a standard-sized platform for assembling circuits without soldering, enabling easy and flexible component placement for testing and prototyping. It ensures organized connections and facilitates rapid iteration during development. The Jumper Wires were used to establish electrical connections between the breadboard and various components, allowing for flexible and temporary connections in the circuit for easy experimentation and troubleshooting. Finally, the Power Supply Module ensured stable voltage regulation and provided consistent 5V/9V outputs to power the Arduino, servo motors, and other electronic components. These materials formed the core components required to design and implement a functional exoskeleton glove capable of providing Continuous Passive Motion (CPM) for hand rehabilitation.

C. Fabrication

TABLE I: Printing Parameters for Fabrication

Parameter	**Value**
Layer height	0.15 mm
Print speed	50 mm/s
Nozzle temperature	200°C
Bed temperature	60°C
Infill density	20%
Infill Pattern	Triangles
Shell thickness	0.8mm - 1.0mm
Adhesion	Enabled
Support structures	Enabled
Support type	Tree
Placement	Touching Buildplate
Total printing time	Approximately 22 hours

The hand exoskeleton was fabricated using 3D printing to ensure a cost-effective and adaptable design. An Ultimaker S3 printer was employed due to its high precision and reliability, and Polylactic Acid (PLA) was selected as the printing material for its durability, biodegradability, and suitability for wearable applications. The design was prepared in SolidWorks, with the model segmented into individual components for ease of printing, as shown in Figures 4(a)



(a) (b)

(c) (d)

Fig. 4: 3D Models of Exoskeleton Glove: (a) Separated components, (b) Assembled components.

and 4(b). These components were exported as STL files and processed using slicing software, where printing parameters, detailed in Table 1, were configured.

The printing process took approximately 22 hours to complete. Each component was carefully removed from the build plate shown in Figure 5 and cleaned to eliminate residual supports or imperfections. Once printed, the individual components were assembled to form the complete hand exoskeleton, as illustrated in Figures 4(b) and 4(c). Minor adjustments were made during assembly to ensure a secure fit and alignment of all parts.

D. Software Integration

Algorithm 1 controls the servo motor to actuate a mechanical finger based on commands received from the user. We utilize the Servo library, which provides the necessary functions for controlling the servo motor. A 'Servo' object is used to manage the servo motor responsible for the finger's movement. We defined the servo's target positions for opening (0 degrees) and closing (180 degrees) the finger, respectively.

The servo is attached to pin 9 of the microcontroller . This enabled the microcontroller to send control signals to the servo motor. A prompt was displayed to the user via the Serial Monitor, instructing them to input either the "open" or "close" command to control the finger.

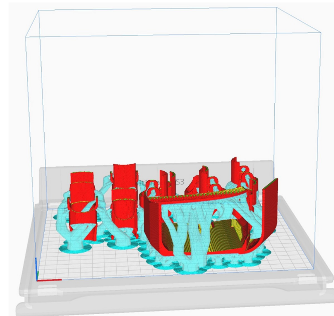


Fig. 5: Layout of individual 3D-printed exoskeleton glove components prior to assembly.

Algorithm 1 Servo Motor Control

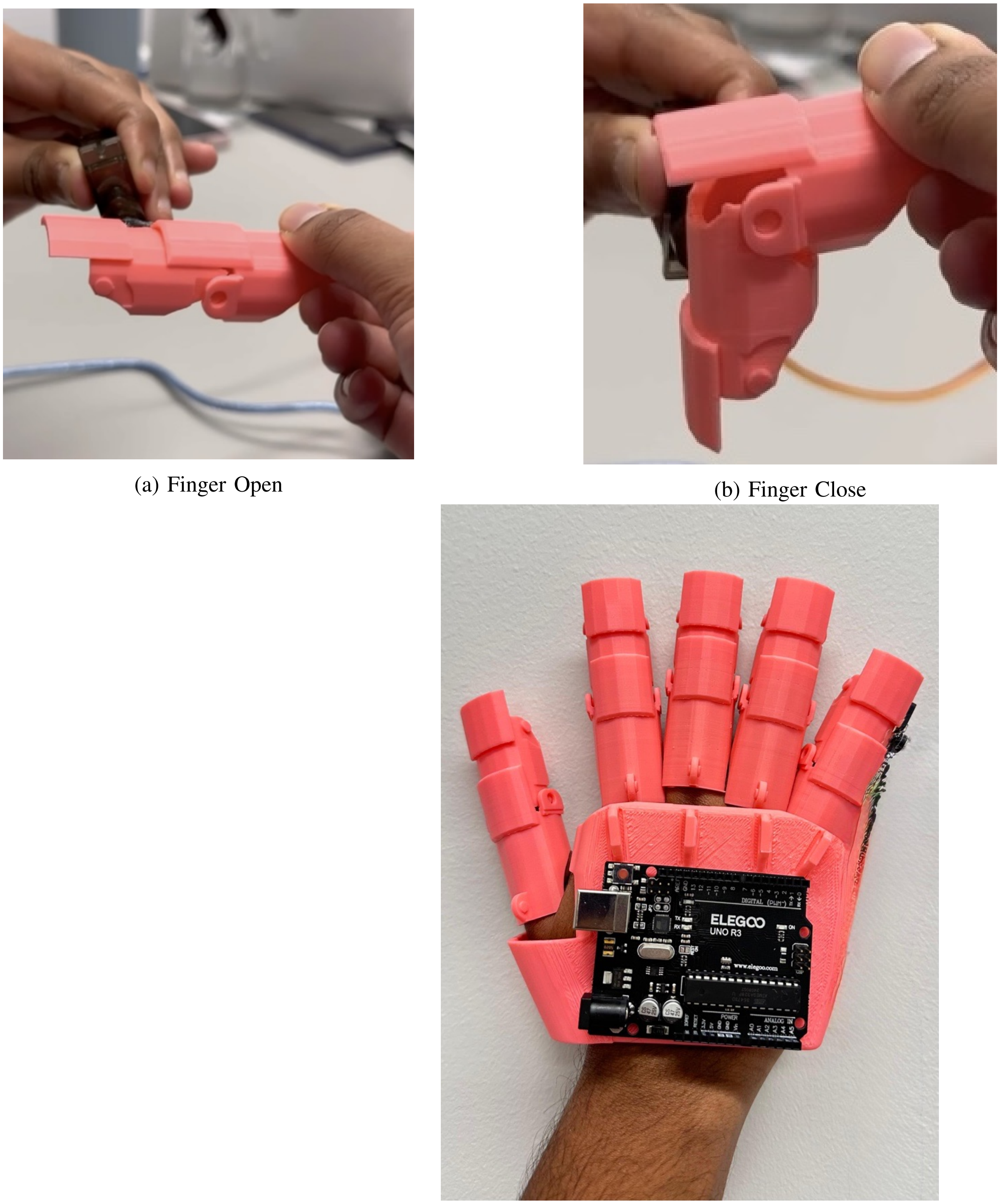
Require: Input command (open/close)
  Attach servo motor to pin 9
  while true **do**
    if Input command available **then**
      if command == "close" **then**
        Set servo motor angle to 180 degrees
      else if command == "open" **then**
        Set servo motor angle to 0 degrees
      else
        Print Invalid command. Type 'open' or 'close'.
      end if
    end if
  end while=0

The algorithm continuously checked for incoming data from the user. If data was available, it read the incoming command as a string until a newline character was detected. The command was then trimmed to remove any unnecessary whitespace. The system evaluated the received command: if the command was "close", the algorithm instructed the servo to move to the 'closeAngle' (180 degrees), closing the finger. If the command was "open", the servo was moved to the 'openAngle' (0 degrees), opening the finger. If the command was anything other than "open" or "close", an error message was displayed to prompt the user to input a valid command.

IV. Results & Discussion

The robotic finger was tested for its ability to open and close a total of 20 times in response to a single user input. During each cycle, the finger demonstrated consistent functionality, successfully completing the full range of motion from fully closed to fully open and vice versa as shown in Figure 6. The number of cycles (20) was chosen as a tunable parameter, and it can be adjusted according to user requirements for specific therapeutic applications, based on recommendations from therapists.

To evaluate the sensitivity and responsiveness of the system, we tested the communication baud rate settings by increasing



(a) Finger Open

(b) Finger Close

(c) Exoskeleton Glove

Fig. 6: Robotic finger operation: (a) Fully open and (b) Fully closed after one cycle. The finger completes 20 cycles per user input, with the cycle count adjustable for therapeutic needs.

the baud rate from 9600 bps to 19200 bps. However, no significant improvement in the sensitivity or operational response was observed under these conditions. The system's ability to accurately and repeatably execute finger movements remained unchanged across both baud rate settings.

This suggests that the performance of the finger's actuation mechanism is not significantly dependent on baud rate within the tested range, and that other factors, such as motor control or sensor resolution, may be more influential in determining the system's operational sensitivity.

The project faced several challenges during development. One significant challenge was related to the actuation system. The MG90S Micro Servo Motor that was selected for the glove could barely provide enough torque to move the exoskeleton's mechanical components, let alone the added weight of human fingers. According to its product specifications, the MG90S has a stall torque of approximately 1.8 kg·cm at 4.8V, which proved insufficient for driving the finger mechanisms effectively. This limitation likely arose due to the high torque demands of the exoskeleton's joints, which exceeded the motor's capacity. A more robust option, such as the MG996R Servo Motor, which has a stall torque of 10 kg·cm at 6V, could have been a viable alternative, as it would provide significantly more force. However, due to time constraints, switching to the MG996R was not feasible during the project's timeline.

Another potential solution would have been to explore alternative means of actuation, such as pneumatic or hydraulic systems. These methods are capable of generating significantly higher forces, making them ideal for applications like ours. However, implementing such systems would have altered our design and increased complexity, size, and cost. As a result, they were deemed incompatible with the project's core goals of affordability and compactness.

A second challenge arose from the scarcity of available printers in the EXP Marker Space. Due to high demand, printing the components was delayed until the last minute. This time limitation restricted opportunities for iterative testing and redesigns, which could have further improved the exoskeleton's performance and fit.

V. Ethical, Social, and Non-Technical Considerations

A. Safety

Safety is a fundamental priority for hand exoskeletons and exoskeletons in general, particularly for active systems, which pose potential risks to users if not carefully designed. To address this, our design emphasized user safety across mechanical, actuation, and control systems. The exoskeleton replicates natural finger movements, minimizing the risk of secondary injuries. The actuation mechanism was specifically chosen to prevent excessive range-of-motion movements, ensuring all motions remain within safe physiological limits.

Also, the software includes a safety feature that halts the device automatically after completing a predefined number of motion cycles. This feature requires a deliberate user trigger to resume operation, providing an added layer of control and mitigating risks associated with unintended prolonged use. These measures collectively enhance the safety profile of the exoskeleton while maintaining its functionality.

B. Comfort

We prioritized comfort in the design of the hand exoskeleton, recognizing that it is intended for extended wear. Every aspect of the design, from material selection to the overall fit, was tailored to ensure the device is lightweight and ergonomic. The exoskeleton's structure accommodates the natural contours of the hand, reducing pressure points and discomfort. These considerations ensure that users can focus on rehabilitation without being hindered by discomfort.

C. Affordability

Hand exoskeletons, like exoskeletons in general, are often prohibitively expensive due to the advanced technology, specialized materials, and the nascent stage of research in this field. To address this challenge, we focused on cost-effective strategies throughout the design process. Rapid prototyping, 3D printing, and software modeling were employed to streamline development and reduce production costs. Additionally, we opted for simple, off-the-shelf components and maintained a straightforward design approach. These measures not only kept the device affordable but also ensured that it remained accessible for broader use without compromising its core functionality.

D. Adaptability

Adaptability was another key consideration in the design of the hand exoskeleton. While designing and 3D printing, we ensured that the device could accommodate various hand sizes, making it suitable for a wide range of users without the need for extensive modifications.

VI. Conclusion

The exoskeleton glove for hand rehabilitation is an important step in developing affordable and accessible assistive technologies for people regaining lost motor function due to hand impairment.

The difficulties encountered during the project, such as the limitations of the MG90S servo motors and limited access to printing facilities, highlighted areas for development and emphasized the significance of meticulous resource planning. While alternate actuation technologies, such as pneumatic or hydraulic systems, could overcome the torque constraints, they would jeopardize the design's compactness and affordability—two key goals of this work. Addressing these problems in future versions will be critical for improving the device's performance and scalability.

Future development will center on improving the actuation system, doing comprehensive user testing, and incorporating feedback to guarantee that the glove satisfies the needs of its intended users.

Finally, the exoskeleton glove highlights the potential of technical solutions to address major healthcare concerns, providing optimism for more accessible and effective rehabilitation aids in the future.

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