WEARABLE HAND REHABILITATION SYSTEM FOR POST-STROKE PATIENTS

By

Upama Adhikary
20321001
Zafira Tahseen Hoque
20310002
Rifat Rahman Rafi
20321010
Md Rifat
19121021

A Final Year Design Project (FYDP) submitted to the Department of Electrical and Electronic Engineering in partial fulfillment of the requirements for the degree of B.Sc. in Electrical and Electronic Engineering/ Electronic and Communication Engineering

Academic Technical Committee (ATC) Panel Member:

Prof. Dr. AKM Abdul Malek Azad

(Professor, Department of EEE, BRAC University)

Ms. Sabrina Saima

(Lecturer, Department of EEE, BRAC University)

MD Rafiqul Islam Rafi

(Lecturer, Department of EEE, BRAC University)

Department of Electrical and Electronics Engineering
Brac University
October 2024

Declaration

It is hereby declared that

1. The Final Year Design Project (FYDP) submitted is my/our own original work while completing degree at Brac University.
2. The Final Year Design Project (FYDP) does not contain material previously published or written by a third party, except where this is appropriately cited through full and accurate referencing.
3. The Final Year Design Project (FYDP) does not contain material which has been accepted, or submitted, for any other degree or diploma at a university or other institution.
4. I/We have acknowledged all main sources of help.

Student's Full Name & Signature:

Zafira Tahseen Hoque (20310002)	**Upama Adhikary** (20321001)
Rifat Rahman Rafi (20321010)	**Md Rifat** (19121021)

Approval

The Final Year Design Project (FYDP) titled "Wearable Hand Rehabilitation System for Post-Stroke Patients" submitted by

1. Zafira Tahseen Hoque (20310002)
2. Upama Adhikary (20321001)
3. Rifat Rahman Rafi (20321010)
4. Md Rifat (19121021)

Summer, 2024 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of B.Sc. in Electrical and Electronic Engineering/ Electronic and Communication Engineering on 24th October, 2024.

Examining Committee:

Academic Technical Committee (ATC): (Chair)

____

Prof. Dr. AKM Abdul Malek Azad
Professor, Department of EEE
Brac University

Final Year Design Project Coordination Committee: (Chair)

____

Abu S.M. Mohsin, PhD
Associate Professor, Department of EEE,
Brac University

Department Chair:

____

Md. Mosaddequr Rahman, PhD
Professor and Chairperson, Department of EEE,
Brac University

Ethics Statement

We confirm that the project titled "Wearable Hand Rehabilitation System for Post-Stroke Patients" has successfully met the requirements for the Final Year Design Project (FYDP). The content presented is the result of our independent work, with all external sources appropriately cited where applicable. The project has been developed and implemented by our team, with valuable support and guidance from our supervisor and the university. Additionally, we have adhered to all ethical guidelines throughout the project. A Turnitin check was conducted, and the plagiarism percentage is only 10%.

Abstract

Stroke is a leading cause of long-term disability, significantly affecting hand mobility and strength among survivors. Traditional rehabilitation methods are often inaccessible due to high costs, limited availability, and patient engagement challenges. Therefore, this research introduces a wearable hand rehabilitation system designed to address the specific needs of stroke survivors, offering an affordable, efficient, and portable alternative to conventional therapy. The system leverages modern technology to enhance hand mobility, allowing patients to independently perform rehabilitation exercises while enabling doctors to remotely access and monitor exercise data for personalized feedback. By comparing the system's effectiveness against standard rehabilitation techniques, this study highlights its superior potential for improving recovery outcomes in stroke patients. positioning it as a promising tool for facilitating comprehensive and efficient stroke recovery.

Keywords: Hand Rehabilitation; Stroke; IoT app, Pressure, Flex Sensor, Force Sensor.

Dedication

We dedicate this project to the unknown laborers who were martyrs of the July Movement in Bangladesh.

Acknowledgement

We would like to express our sincere gratitude to our committee chair, Dr. AKM Abdul Malek Azad, and our panel member, Md. Rafiqul Islam Rafi, for their invaluable support and continuous review of our project throughout its development. We are also profoundly thankful to the dedicated lab assistant Shakil Ahmed of Brac University, whose continuous support and commitment made the journey smoother.

Table of Contents

Chapter 1: Introduction

1.1 Introduction

1.1.1 Problem Statement

Stroke is a severe, widespread health crisis both nationally and internationally, remaining one of the most prevalent life-threatening conditions. Despite significant advances in stroke treatment, many patients still rely solely on physical interventions[1]. Stroke causes brain cell death, resulting in disabilities such as paralysis and aphasia in 55% to 75% of survivors [2]. Hemiparesis, the loss of ipsilateral motor function, is a common after-effect, severely impacting quality of life and posing a significant burden on families and society[3], [4]. Although recent medical advances have increased stroke survival rates, there remains a high demand for rehabilitative treatments to enhance motor recovery. Assistive devices have been effective for paralysis in limb disorders, particularly for large motions and extremity function [5]. However, the rehabilitation of fine motor skills, such as finger movement and coordination, compared with lower limbs, remains challenging and time-consuming, with 21% of stroke patients unable to achieve full recovery of upper limb motor function [5]. Therefore, the rehabilitation of upper limb motor function after a stroke remains an urgent problem to be addressed [5]. Traditional rehabilitation techniques, while beneficial, often fall short in addressing the multifaceted needs of stroke patients, being time-consuming, resource-intensive, and lacking in patient engagement. This highlights the urgent need for innovative, patient-centered approaches to provide more efficient, effective, and personalized care.

1.1.2 Background Study

Stroke occurs when the blood supply to part of the brain is interrupted or reduced, depriving brain tissue of oxygen and nutrients. This interruption can be caused by either a blockage in the blood vessels (ischemic stroke) or a rupture of blood vessels (hemorrhagic stroke). Ischemic strokes, which account for about 85% of all strokes, are more common.

When an individual experiences a stroke, the immediate consequences can be severe, including paralysis or weakness on one side of the body, difficulty speaking or understanding speech, vision problems, and loss of coordination and balance. The extent and severity of these symptoms depend on the area of the brain affected and how quickly treatment is administered.

When someone experiences a stroke, it results in the interruption of blood supply to their brain. This occurrence can give rise to various complications, including weakness, numbness, and paralysis. Sometimes these symptoms affect patients' upper limbs and make it difficult for them to use them properly. Due to this stroke survivors often face substantial challenges in regaining mobility and strength in their upper limbs, hindering their independence in daily activities. According to recent data, Bangladesh records a daily stroke prevalence of 11.39 cases per 1000 population, with a mortality rate of 54% [6].

These challenges highlight the critical need for effective rehabilitation strategies tailored to address the specific impairments faced by stroke survivors, particularly in the upper limbs. Hand rehabilitation becomes essential for post-stroke patients to regain functionality and improve their overall quality of life. However, many survivors struggle with the traditional rehabilitation process, finding it time-consuming, costly, and sometimes inconvenient due to travel constraints. The reported cost of conventional rehabilitation can be as high as US $328 per month per patient, making it inaccessible for many. Additionally, only 22% of stroke patients follow through with rehabilitation services, leaving a significant gap in care[7].

This project aims to develop a cost-effective, portable, and efficient wearable hand rehabilitation system designed to address the challenges faced by stroke survivors in regaining hand mobility. With 65% of chronic stroke patients experiencing difficulties with hand movement, the need for accessible rehabilitation solutions is critical. By utilizing modern technology and targeted therapeutic strategies, the system seeks to accelerate recovery, promote patient engagement, and enhance the overall quality of life for stroke survivors.

Research highlights the barriers stroke patients encounter in accessing and completing traditional rehabilitation programs, often resulting in limited progress in restoring hand function. This project addresses these challenges by introducing an innovative wearable rehabilitation system, providing a more accessible, personalized, and effective alternative. The solution aligns with the growing demand for technologically advanced, patient-centric rehabilitation tools within the healthcare industry. By focusing on the specific needs of stroke survivors, this project offers a meaningful contribution to the field of rehabilitation, with the potential to significantly improve recovery outcomes and empower patients on their journey to regain independence.

Hand rehabilitation plays a crucial role in the recovery journey of individuals who have experienced a stroke. A notable advancement in this rehabilitation domain is the emergence of smart gloves, which present varied design approaches. These gloves vary in functionality, with one approach centered around exercise mechanisms, while another utilizes electrical pulses for rehabilitation purposes. Recent technological advancements have led to the integration of IoT elements and wearable technology within these smart gloves, emphasizing their potential to enhance stroke rehabilitation processes. This literature review critically evaluates and consolidates findings from key research papers centered on the efficacy of smart gloves in stroke rehabilitation.

A significant advancement in stroke rehabilitation with the introduction of robotic gloves was done by the author A. Arivarasi [8]. These gloves leverage wearable technology, incorporating flex sensors, pneumatic muscles, and IoT elements to revolutionize the rehabilitation process for stroke survivors. Unlike traditional hospital-based methods, this approach offers cost-effective and portable solutions, empowering patients to undergo rehabilitation in their own homes or community settings.

One of the key strengths of this research lies in its integration of hardware and software components. By utilizing software platforms such as Autodesk Fusion 360, Android Studio, Arduino IDE, and AWS Cloud, the study seamlessly combines hardware design with software development. This integration enables real-time data collection, analysis, and transmission using the MQTT protocol, facilitating remote monitoring and feedback from healthcare professionals.

The study’s findings highlight the significant impact of the proposed robotic gloves on stroke rehabilitation, with patients achieving a recovery rate of 90.23% within four weeks of using the device. Prior to treatment, the recovery rate among patients stood at 28.48%. After four weeks of treatment, the existing system yielded a recovery rate of 70.22%, while the proposed system outperformed it with a recovery rate of 78.12%. A follow-up assessment conducted three months later showed continued improvement, with the existing system reaching a recovery rate of 77.39% and the proposed system demonstrating a rate of 86.68%. Upon subsequent evaluation, the recovery rate for the existing system increased to 83.48%, whereas the proposed system maintained its superior performance with a recovery rate of 90.23%. [8]

These results emphasize the effectiveness of the proposed rehabilitation approach in enhancing hand mobility and muscle strength among stroke survivors. The study further provides comparative insights, revealing that the robotic glove system offers greater efficiency and cost-effectiveness than conventional hospital-based rehabilitation methods. This research marks a significant advancement in the field, showcasing a promising alternative to traditional rehabilitation strategies.

The development of a portable smart glove also represents a major step forward in stroke rehabilitation. This wearable device supports stroke survivors in independently regaining lost muscle memory by integrating sensors and soft robotics. By facilitating continuous muscle contraction and release, the smart glove accelerates muscle memory recovery, thereby optimizing the rehabilitation process and improving patient outcomes.

A key feature of the smart glove is its user-friendly interface, which allows healthcare professionals to monitor patient statistics in real-time. This capability enables doctors to track the progress of individual patients remotely, providing timely feedback and adjustments to their rehabilitation regimen as needed. By promoting personalized and adaptive rehabilitation strategies, the smart glove addresses the diverse needs of stroke survivors, ultimately leading to improved outcomes.

The development of the smart glove underscores the growing demand for effective and cost-efficient rehabilitation tools in the healthcare industry. By offering a portable and accessible solution, the device has the potential to significantly reduce healthcare expenses associated with traditional rehabilitation methods while enhancing recovery rates among stroke survivors.

A notable aspect of the paper is the evolution from cotton-based to 3D-printed exoskeleton structures in the design of the smart glove. This transition signifies a trend toward durability and ergonomic design, ensuring optimal comfort and functionality for users. Additionally, the integration of advanced technologies such as Arduino IDE, the Blynk app, and the ESP32 MCU further enhances the usability and functionality of the smart glove. Overall, the development of the portable smart glove represents a promising advancement in stroke rehabilitation technology. By combining innovative design principles with cutting-edge technologies, the smart glove offers stroke survivors a versatile and effective tool for regaining lost muscle memory and improving overall mobility and function.

Researchers introduced a smart glove designed to enhance post-stroke motor recovery by incorporating resistive flex sensors and a Lightblue bean microcontroller **[9]**. This innovative device leverages wireless communication via Bluetooth 4.0, enabling seamless real-time transmission of data between the processing unit and the display module. By utilizing advanced sensor technology, the smart glove is capable of detecting wrist and finger extensions with high precision and accuracy.

The efficacy of the Smart Glove was evaluated through rigorous testing involving stroke patients and individuals with traumatic brain injuries. Results from the study demonstrated the glove's ability to effectively detect and monitor wrist and finger movements, providing valuable insights into the progress of motor recovery among participants. Notably, the smart glove showcased adaptability by allowing sensitivity adjustments tailored to individual patients' spasticity levels, ensuring optimal functionality and user experience.

To further enhance usability and user comfort, the researchers introduced modifications such as additional Velcro straps to ensure a secure fit for users of varying hand sizes. These enhancements address common challenges associated with wearable rehabilitation devices, such as ensuring proper alignment and minimizing movement during use.

One of the key highlights of the study is the affordability of the Smart Glove, with a fabrication cost of $68.24. This cost-effective solution holds significant potential for clinics and patients seeking accessible rehabilitation tools for post-stroke motor recovery. By offering an affordable alternative to traditional rehabilitation methods, the Smart Glove opens up promising prospects for improving hand function recovery among neurologically impaired individuals, ultimately enhancing their quality of life and independence.

An innovative approach to stroke rehabilitation is done by integrating wearable technology with electrostimulation[10]. A unique electric stimulation system is embedded within a five-finger glove, strategically targeting specific finger segments to improve motor functions in stroke patients. This system comprises two independent electric circuits designed to stimulate the median and ulnar nerves, strategically placed on the glove's fingers. One of the key advancements is the fabrication of electrodes using Optisana bandages, featuring a thin electroconductive layer produced through physical vapor deposition. This fabrication method ensures continuous electroconductivity while maintaining user comfort, addressing challenges encountered in previous electrode designs.

Microscopic analysis validates the electrode structure and confirms the feasibility of the innovative fabrication process, demonstrating promising potential for practical application. A case study involving a 36-year-old stroke patient further supports the effectiveness of the electrostimulation glove. After completing a four-week rehabilitation program that incorporated fingertip electrostimulation, the patient showed significant improvements in motor function. These findings highlight the potential of electrostimulation gloves in enhancing post-stroke mobility and motor functions, paving the way for personalized and effective rehabilitation strategies.

1.1.3 Literature Gap

In the field of stroke rehabilitation, there is a notable gap in the development of integrated systems that effectively combine multiple rehabilitation techniques into a single cohesive design. Current rehabilitation methods often rely on isolated approaches such as physical therapy, occupational therapy, and speech therapy, which may not adequately address the comprehensive needs of stroke survivors. While individual technologies such as robotics, virtual reality, and exoskeletons have shown promise in improving motor functions, there is limited research on how these technologies can be effectively integrated to provide a more holistic rehabilitation experience.

Moreover, the current literature lacks detailed studies on the design and implementation of such integrated systems that are both user-friendly and scalable. This gap is particularly evident in the context of creating systems that are accessible and cost-effective, which is crucial for widespread adoption in various healthcare settings. The proposed design aims to address this gap by developing a systematic approach that combines advanced technologies into a unified rehabilitation system. This system will be designed to enhance patient engagement, provide real-time feedback, and facilitate more efficient recovery processes, thereby overcoming the limitations of existing rehabilitation methods.

By focusing on the design phase, this project seeks to lay a foundation for future development and implementation, ensuring that the proposed system can be effectively translated into clinical practice. This approach will not only bridge the gap in current rehabilitation practices but also pave the way for more innovative and effective solutions in the future.

1.1.4 Relevance to current and future Industry

The rehabilitation industry is rapidly evolving with the integration of advanced technologies such as virtual reality, robotics, and artificial intelligence. These innovations are reshaping how rehabilitation services are delivered, making them more personalized, effective, and engaging for patients. The emergence of smart hand devices, controlled by brainwave signals rather than traditional electrical stimulation, presents new opportunities for enhancing neuroplasticity and supporting functional recovery in stroke patients. This shift reflects a broader trend within the healthcare sector, where technology-driven, patient-centered care models are becoming the standard for improving outcomes and overall patient well-being.

1.2 Objectives, Requirements, Specification and constraints

1.2.1. Objectives

The field of rehabilitation therapy continually seeks innovative solutions to address the diverse needs of individuals recovering from stroke, a leading cause of long-term disability worldwide. As traditional methods of rehabilitation often present limitations in accessibility, cost-effectiveness, and patient engagement, there exists a pressing need for novel approaches that offer enhanced mobility, convenience, and efficacy. In response to this challenge, the development of a wearable hand rehabilitation system is a promising solution, leveraging advancements in technology to deliver personalized, efficient, and accessible therapy for stroke survivors.

a. Develop an innovative wearable hand rehabilitation system tailored to address the distinctive needs of stroke survivors, with the primary goal of enhancing hand mobility and strength.
b. Design an affordable wearable system that caters to stroke survivors across all economic backgrounds, ensuring accessibility and inclusivity.
c. Evaluate the efficiency of the developed system in comparison to traditional rehabilitation methods, showcasing its superior ability to facilitate stroke recovery.
d. Assess the portability of the system in contrast to traditional rehabilitation methods, highlighting its convenience and ease of use in aiding stroke recovery efforts.

1.2.2 Functional and Nonfunctional Requirements

Functional Requirements:

1. Soft Robotics Implementation:
   - Utilizing soft robotics technology, the gloves will mimic natural hand movements, providing an intuitive and effective rehabilitation experience.
2. Replicate Human Muscle Functionality:
   - Developing a muscle replication system that considers the gloves to emulate the strength and coordination of human muscles
3. Control the pneumatic muscle:
   - Implement a robust pneumatic control system using a mcu to regulate the pressure within the soft robotic muscles accurately.
4. Signal transmission:
   - Seamless transmission of signals from a microcontroller to the robotic hand
5. Tracking hand movements and joint analysis using sensors:
   - Integrate a comprehensive sensor array, including flex sensor and force sensor, to precisely track hand movements and provide detailed joint analysis.
6. Power Management:
   - Develop an efficient power management system to optimize the energy consumption of the soft robotic gloves, ensuring extended use without frequent recharging.
7. Software Integration:
   - Integrate software platforms like Fusion 360, Arduino IDE, Android Studio, Flutter, and Blynk app to create a user-friendly interface and enable seamless interaction between hardware and data.

Non-Functional Requirements:

1. Reliability:

   - The gloves must work reliably over time, providing uninterrupted support for rehabilitation.

2. Scalability:

   - The design will allow for efficient mass production and deployment in healthcare facilities, meeting a wide range of patient needs.

3. Safety Certifications:

   - The system will meet strict safety standards and certifications for medical devices, ensuring confidence for healthcare professionals and patients alike.

4. Durability:

   - We'll use high-quality materials to ensure the gloves withstand regular use and last a long time.

5. Cost-Efficiency:

   - The production process will be optimized to strike a balance between cost-effectiveness and quality, ensuring accessibility for a wide range of patients seeking rehabilitation solutions.

6. User friendly Interference:

   -The interface of the smart glove system will be intuitively designed, ensuring that users can quickly understand how to operate the system without the need for extensive training. Clear and straightforward design elements, such as buttons, controls, and indicators, will contribute to the overall ease of use.Moreover, controls and commands will be easily accessible and logically organized, promoting a seamless user experience.

1.2.3 Specifications

Design specifications according to components:

According to the design specifications, it was chosen to fulfill the goal. The component-wise specification is as follows:

Table 1: Specifications of the components

Design	List of Material	Model	Attributes
Design Approach 1	Microcontroller	Arduino Uno	● Low-cost, lightweight ● Bluetooth and WiFi modules for wireless communication
	Battery	Li-ion battery of 3.7 Volt	● Lightweight:16g each ● Rechargeable batteries can be recharged up to 500 times ● The battery size is 1.5*1.5*5cm to make the system compact
	Pneumatic muscle	Hose clamp/ Lock Nut	● Lightweight, contractile. ● To mimic hand movements.
		Nylon Braided sleeving	
		Latex tube	
		Pneumatic Tube	
	Pneumatic Pump	DC 12V 380mA 500mmHg Micro Air Pump	● Lightweight with adjustable pressure settings. ● Low Noise Operation ● Durable and Longer Lasting ● Small in Size ● Manifold Valve is included to ensure consistent and equal airflow to every finger

	Sensors	4.5-inch Flex Sensor, Force Sensor	● 4.5-inch Flex sensors for precise tracking of hand movements. ● Force sensors to assess hand strength and muscle engagement.
	Motor Driver	L298n motor driver	● To control muscle movement precisely ● Dual H-bridge configuration which allows for bidirectional control of a motor
	User Interface	Mobile App	● Collect patients' data from the device ● Store data for the doctor to review
	Wires	Jumper wires	● To connect the components
	Gloves	Textured Cotton Gloves	● Enhanced flexibility and grip
	Solenoid Valve	5 way 1/4 inch Valve	● Distribute air evenly to the fingers
Design Approach 2	Gloves	Textured Cotton Gloves	● Enhanced flexibility and grip
	Electrode	Carbon Rubber Electrodes	● Offer flexibility and durability ● Suitable for wearable applications
	Substrate	Optisanal Bandage	● Highly flexible and lightweight
	Conduction Layer	High-Purity Silver	● Highly Conductive ● Biocompatible ● Exhibit low tissue impedance
	Electrical Stimulator Device	DC Battery DC-DC boost converter H-bridge module	● Stimulate controlled electrical pulses to the fingers through the electrodes ● Show previous records

		Arduino Uno	
		LCD display	
	Wires	For Electrodes	• Facilitate the transmission of electric pulses generated by the electrical stimulator

Design Specifications Aligned with Device's Key Features:

In accordance with the recommendations, we have chosen the following specifications for the device, aiming to enhance the range of motion[11] and actuation force while keeping the weight and size to a minimum for ease of training[12]. Human hand size is also mentioned in the table[13].

Table 2: Design Specifications Aligned with Features

Design	**Feature**	**Design Specification**
Design 1	Weight	150-190 gram
	Size	Designed with scalability, accommodating a range of hand sizes from 6" to 8" for enhanced customization
	DOFs	Bidirectional actuation
	ROM	>70° for metacarpophalangeal (MCP) joint, >61° for proximal interphalangeal (PIP) joint, >39° for distal interphalangeal (DIP) joint
	Output force	> 20 N in total for gripping; maximizing extension force
	Functionality	Passive ROM/Multi-finger synergic motion/Single-finger independent movement
Design 2	NMES Waveform	Asymmetric Biphasic PC
	Frequency	30–40 Hz
	Pulse Duration	200 µs or 300 µs

	Current Amplitude	Individual Maximum Tolerated Intensity
	Work–Rest Cycle	10–60 s
	Treatment Duration	Average 30 min/day
	Session Frequency	5 days/week
	Treatment Duration	4–8 weeks

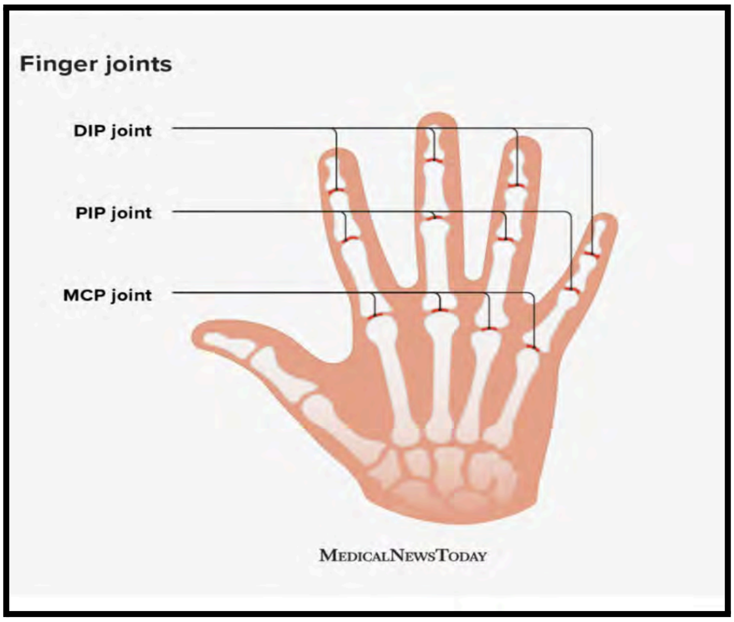


Fig 1 : Finger Joints [13]

1.2.4 Technical and Non-technical consideration and constraint

Constraints

1. Challenge to Wear the Glove: The current design of the smart rehabilitation glove may pose challenges for individuals with high spasticity, as the process of putting on the glove may be difficult for them. This constraint arises from the lack of features such as a modular design or assistive mechanisms that could facilitate easier application for users facing these challenges.

2. Data Security and Privacy Concerns: Given that the system transmits medical information through the Blynk app, security becomes a critical consideration. Any lapse in security could potentially lead to a violation of HIPAA laws, compromising patient privacy and confidentiality.

3. Risk of User Discomfort: The use of electrodes and electrical stimulation poses a risk of discomfort or irritation for some users, affecting the overall user experience.

4. Cost Implications: The integration of Neuromuscular Electrical Stimulation (NMES) and conductive layers incur higher expenses, impacting the overall budget.

1.2.5 Applicable compliance, standards, and codes

1. ISO 13485: Medical devices - Quality management systems. This standard is applicable to the entire system, as it outlines the requirements for a quality management system specific to the medical devices industry.

2. ISO 14971: Medical devices - Application of risk management to medical devices. This standard applies to the entire system as well, as it provides guidance on identifying and mitigating risks associated with medical devices.

3. IEC 60601 series: Medical electrical equipment. These standards apply to any electrical components within the system, ensuring their safety and performance in a medical environment.

4. EN 62133 For Lithium Ion battery. This standard covers requirements for the safe operation of lithium-ion batteries, ensuring they meet safety and performance criteria for portable applications.

5. IEC 62366-1- This standard applies to the design and development of the user interface in the mobile app, ensuring it is user-friendly and safe for medical use.

1.3 Systematic Overview/Summary of the Proposed Project

This project addresses the critical need for effective rehabilitation solutions for stroke survivors, focusing specifically on enhancing hand mobility and functionality through innovative wearable technology. Stroke remains a leading cause of long-term disability worldwide, necessitating advanced approaches that surpass traditional rehabilitation methods in accessibility, cost-effectiveness, and patient engagement.

Technological Foundation:

Drawing from extensive research and technological advancements, this project centers on the development of smart rehabilitation gloves. These gloves integrate soft robotics and sensor technologies to simulate natural hand movements and provide personalized rehabilitation experiences. By leveraging microcontroller (MCU) integration and pneumatic air muscles (PAMs), this system enables precise control over muscle rehabilitation, enhancing motor function recovery.

Integrated Digital Twin Model:

This system incorporates a digital twin model that bridges physical rehabilitation activities with virtual monitoring and analysis tools. This model facilitates real-time data collection from the gloves' sensors, empowering both patients and healthcare providers with actionable insights for personalized rehabilitation plans. Through IoT-based web dashboards and mobile application connectivity, patients can monitor their progress, while healthcare professionals gain comprehensive insights for informed decision-making and treatment adjustments.

Benefits and Impact:

Enhanced Rehabilitation Outcomes: By integrating advanced technologies and real-time data analysis, this system aims to improve hand mobility and functional recovery for stroke patients.

Personalized Care: Tailored rehabilitation programs based on real-time data enable personalized treatment plans, enhancing patient engagement and adherence.

Medical Professional Support: Access to comprehensive data facilitates informed decision-making and adjustments to rehabilitation protocols, ensuring optimal patient care.

1.4 Conclusion

In summary, the project introduces a transformative approach to stroke rehabilitation through smart rehabilitation gloves. By merging cutting-edge technology with personalized care, we aim to set a new standard in post-stroke rehabilitation, offering accessible, effective, and patient-centric solutions. This innovation not only addresses current gaps in traditional rehabilitation methods but also paves the way for future advancements in neurorehabilitation technologies.

Through rigorous design, integration of state-of-the-art components, and adherence to medical standards, the smart rehabilitation gloves represent a significant advancement in improving the quality of life for stroke survivors worldwide.

Chapter 2: Project Design Approach

2.1 Introduction

This report explores two innovative design approaches for hand rehabilitation gloves. The first approach utilizes soft robotics and integrated physical-virtual interfaces to mimic natural hand movements, enabling real-time monitoring and data analysis via IoT and mobile applications. The second design employs neuromuscular electrical stimulation (NMES) to restore motor function and muscle strength in stroke survivors. Both approaches aim to restore hand function in post-stroke patients in two different ways. The work is to analyze them and find the best among them. The following sections provide an in-depth examination of the components, operational methodologies, and the potential impact of each design.

2.2 Identify multiple design approach

The two design approaches presented in this report mark significant strides in the evolution of rehabilitation glove technology. Design Approach 1 centers on the development of a digital twin model, utilizing pneumatic air muscles (PAMs) to replicate hand gestures, flex sensors to monitor speed and pressure, and a web-based dashboard for comprehensive patient monitoring. This approach prioritizes precise control over hand movements and real-time feedback, thereby enhancing the effectiveness of rehabilitation. In contrast, design approach 2 introduces Neuromuscular Electrical Stimulation (NMES) gloves, which employ electrodes to directly stimulate muscle contractions. By targeting specific nerve pathways, this method aims to improve muscle strength and mobility, making it especially beneficial for post-stroke recovery. Both designs aim to bridge the gap between traditional rehabilitation methods and advanced technological solutions, promising to redefine therapeutic outcomes in rehabilitation medicine.

2.3 Describe multiple design approach

Smart Rehabilitation Gloves with Digital Twin Model

Design Approach 1:

Smart Rehabilitation Gloves with Digital Twin Model

The proposed smart rehabilitation gloves offer an advanced solution to support stroke patients experiencing limited hand mobility. This system operates on the foundation of a digital twin model, seamlessly integrating both physical and virtual interfaces to establish a strong connection between the user and cloud-based services.

Initially, in the Physical Interface Layer, the foundational components have been focused. The glove design involves the utilization of textured cotton gloves with raised dots. It is a lightweight glove with enhanced grip which can be incorporated with soft robotics technology to mimic human hand movement. To enable seamless signal transmission, the microcontroller has been employed, benefiting from its low cost, high efficiency, and dual Bluetooth capabilities. The integration of Bluetooth connections ensures wireless communication seamlessly which will be connected to a mobile app. Now, to replicate human muscle functionality, pneumatic air muscles (PAMs) are implemented with the MCU, alongside a pneumatic pump with dual pistons. The pneumatic air muscles (PAMs) used in this design can replicate human muscle functionality by contracting and expanding. It enables precise control of force and movement in the glove **[1].** The pneumatic air pump with dual pistons is connected to the PAMs which ensure accurate and responsive air pressure adjustments. It provides fine-tuned control over the glove's movements during rehabilitation exercises. To control the pneumatic pump's motion precisely using the microcontroller, an L298 motor driver will be incorporated in between the pump and MCU. Additionally, a manifold air regulator valve is implemented with the pump to evenly distribute air pressure to multiple actuators, thus allowing the pressure to be even on every finger **[9]**. The design also features flex sensors integrated with the pressure points like MCP, PIP, and DIP points of the gloves to measure stress in specific areas, facilitating joint stress analysis **[14].** The microcontroller will also enable the user to determine the rotation of different pressure points. The maximum force and range of motion of different pressure points have been set in the MCU to protect users from excessive motion in joints **[11]**. It makes the system more efficient than conventional methods and user-friendly.

A tentative interface layer of the smart glove is shown in Figure 2.

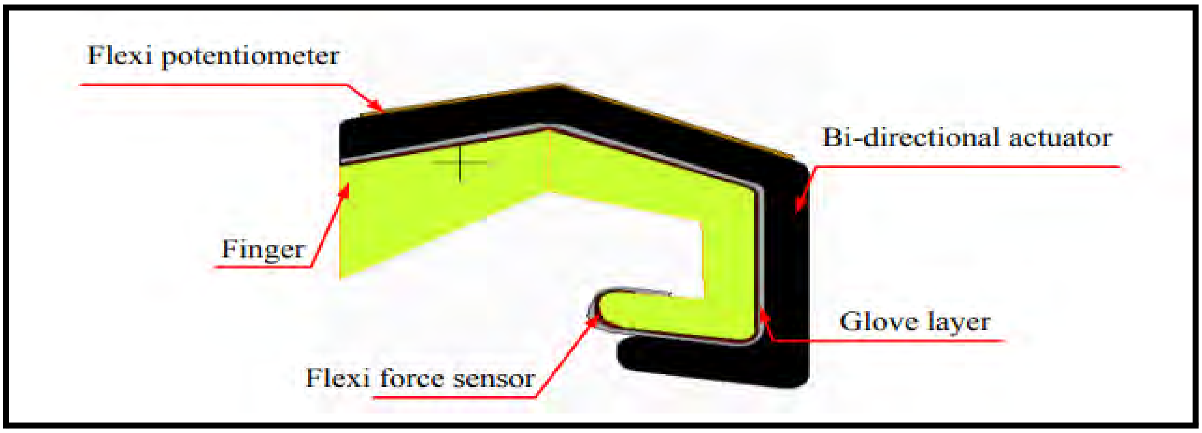


Fig 2: Tentative design of smart glove [11]

In the Virtual Interface Layer, the system utilizes a web dashboard in the mobile phone to receive data seamlessly. It's an IoT-based software that can be paired with the microcontroller via Bluetooth module, and a user interface can be built into the web dashboard according to the requirements. For the web dashboard, Node-RED is used. It enables remote monitoring and analysis, ultimately enhancing patient care and rehabilitation outcomes. By incorporating the dashboard, physicians can gain real-time access to a user-friendly dashboard displaying vital information, including their use time, force and pressure data of patients, and other parameters. This immediate insight facilitates the doctor's ability to assess a patient's progress effectively, adjust treatment plans, and ensure optimal care.

The working procedure of design 1 is shown in Figure 3.

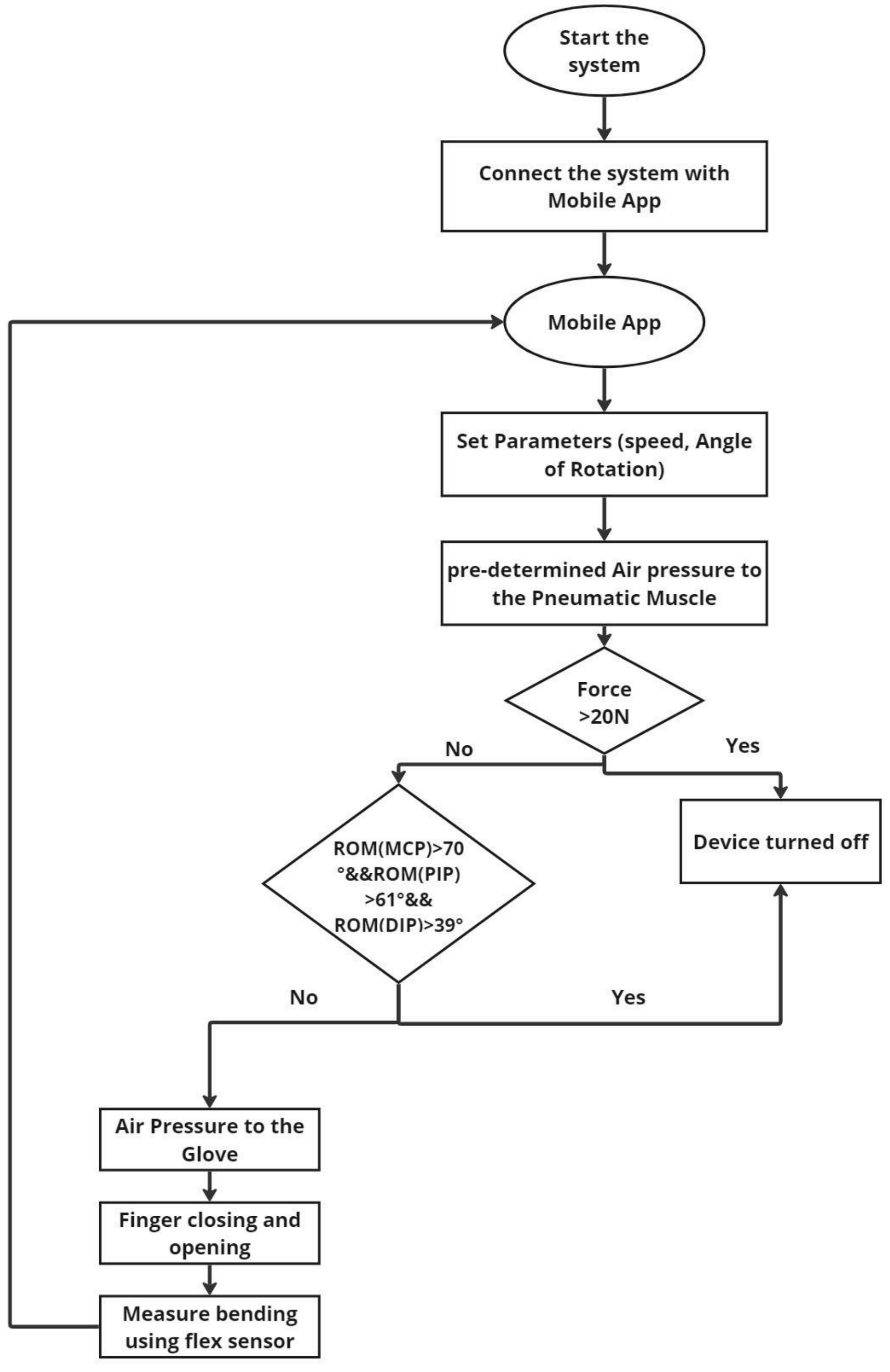


Fig. 3: Flow Chart for Design 1 (Smart Rehabilitation Gloves with Digital Twin Model)

Design Approach 2:

Neuromuscular Electrical Stimulation (NMES) based Gloves

In this design approach, we will implement Neuromuscular Electrical Stimulation (NMES) in the glove to stimulate muscles with electric pulses.[15] Neuromuscular Electrical Stimulation (NMES) is a device that sends electrical impulses to nerves, which cause muscles to contract. The electrical stimulation increases strength and range of motion. It is often used to "re-train" or "re-educate" a muscle to function and build strength after a period of disuse. NMES plays a vital role in muscle rehabilitation following neurological injuries like strokes [16]. In the NMES system, electrodes deliver electrical pulses mimicking nervous system signals, which induce muscle contractions. This external stimulation effectively activates muscles, bypassing impaired neural pathways and aiding muscles that might not respond to brain signals. As [12] described, it can increase strength and range of motion and retrain muscles. First of all, this method utilizes a five-finger glove equipped with electrodes on each fingertip for the electrical pulses and will be layered with a thin film of high-purity silver. This layer will act as a conductor for electrical pulses to flow from the electrodes to the nerves in the fingers. Stimulation is accomplished by sending controlled pulses of current with the aim of inducing changes in the neural cells of the patient's brain, potentially benefiting various medical conditions. The glove features two separate electrical circuits: one for stimulating the median nerve in the thumb, index, and middle fingers. The median nerve supplies motor innervation to the first and second lumbrical muscles Another for the ulnar nerve in the ring finger and small finger. The ulnar nerve provides motor innervation to part of the forearm and majority of the hand. It supplies sensory cutaneous innervation to the medial forearm, medial wrist, and medial one-and-one-half digits. The currents used for stimulation will be adjusted according to guidelines provided by rehabilitation professionals. Fig. 4 shows the tentative interface layer of the smart glove proposed by [15].

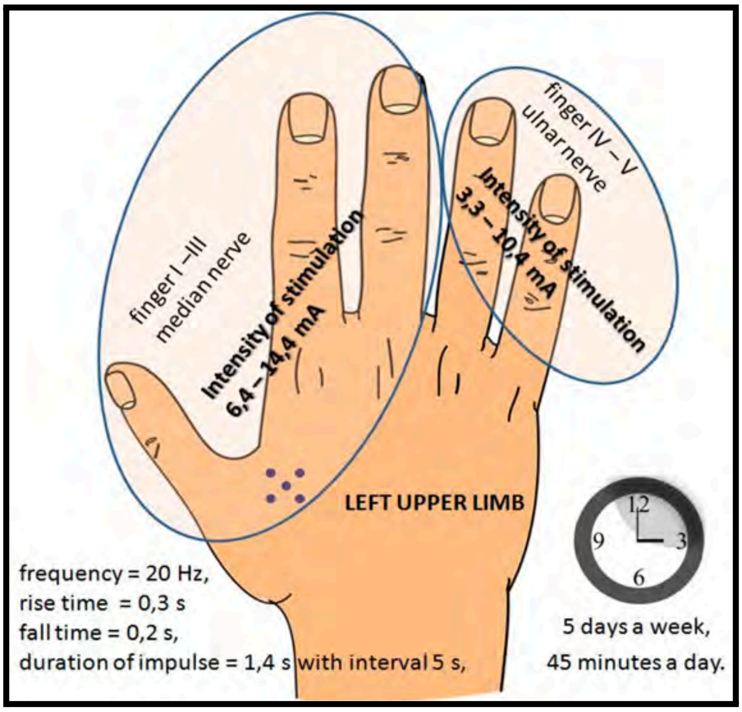


Fig. 4: Electrodes of Design Approach 2 [10]

To enable this design approach to function, four essential units will operate as follows:

Pulse Monitor: This unit is responsible for monitoring the current pulse at the load during electrical stimulation. It provides feedback on the current levels, which is crucial for ensuring safe and effective stimulation.

Control Unit: This unit controls various aspects of the stimulation process. It manages the stimulation pattern, communicates with external devices (such as servers), and samples the output of the voltage and current monitors. It also handles tasks related to data acquisition and processing.

Power Management Unit: Responsible for managing the power supply voltages required for the operation of the control unit and other components. It regulates the voltages supplied to different parts of the system, ensuring stable and reliable operation.

Stimulation Unit: This unit delivers electrical stimulation to the target tissue or muscles. It includes components such as the voltage transconductance amplifier and the power operational amplifier, which generate the necessary voltage and current pulses for stimulation.

The working procedure of design 2 is shown in Fig:5

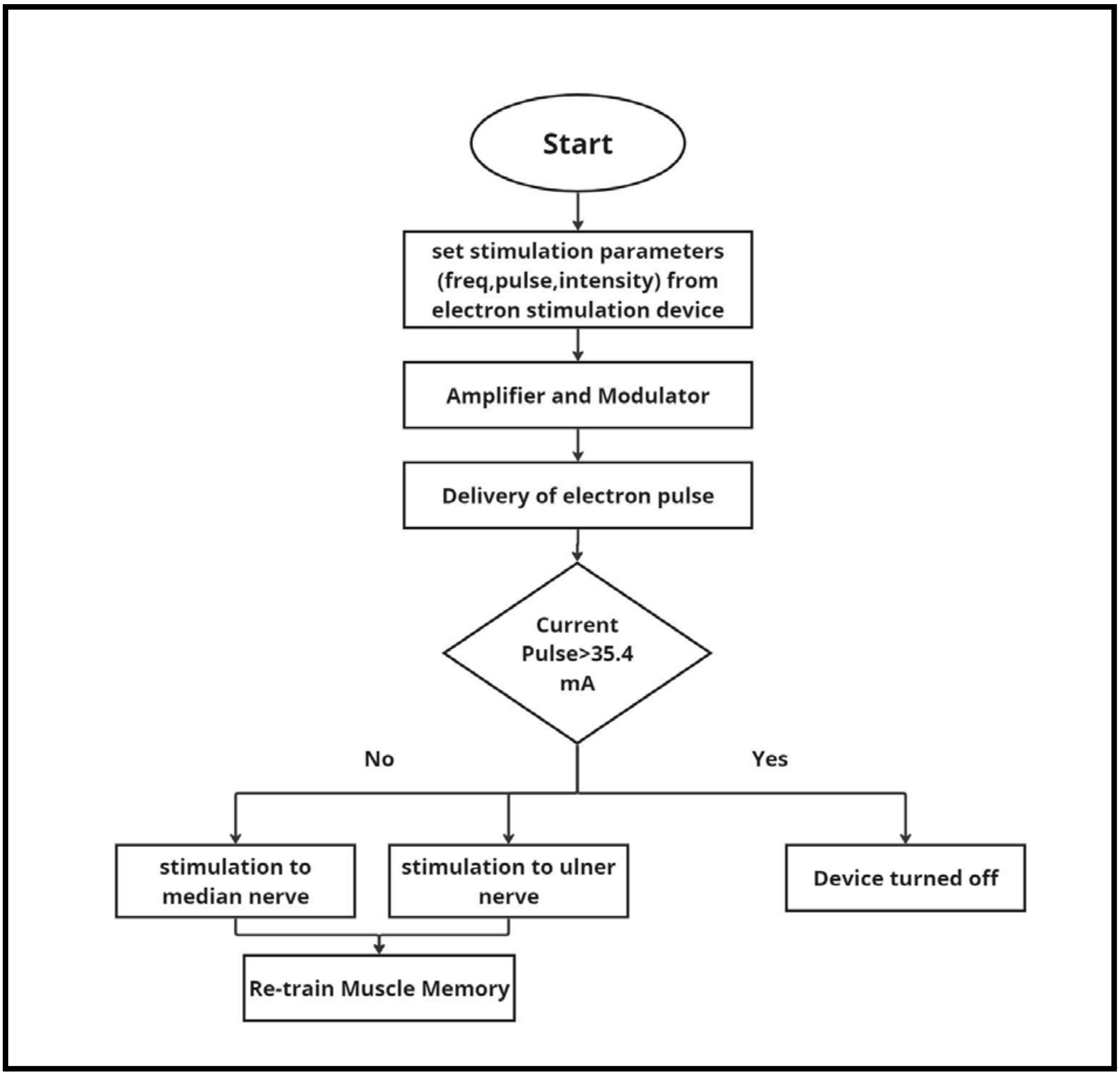


Fig. 5 : Flow Chart for Design 2 (NMES based system)

2.4 Analysis of multiple design approach (functional)

In order to optimize multiple design approaches, simulation of the two design approaches were conducted to evaluate their performance.

Design 1: The first design was simulated using Proteus software to assess its functionality and performance. Figure 6 presents the schematic diagram of the circuit layout.

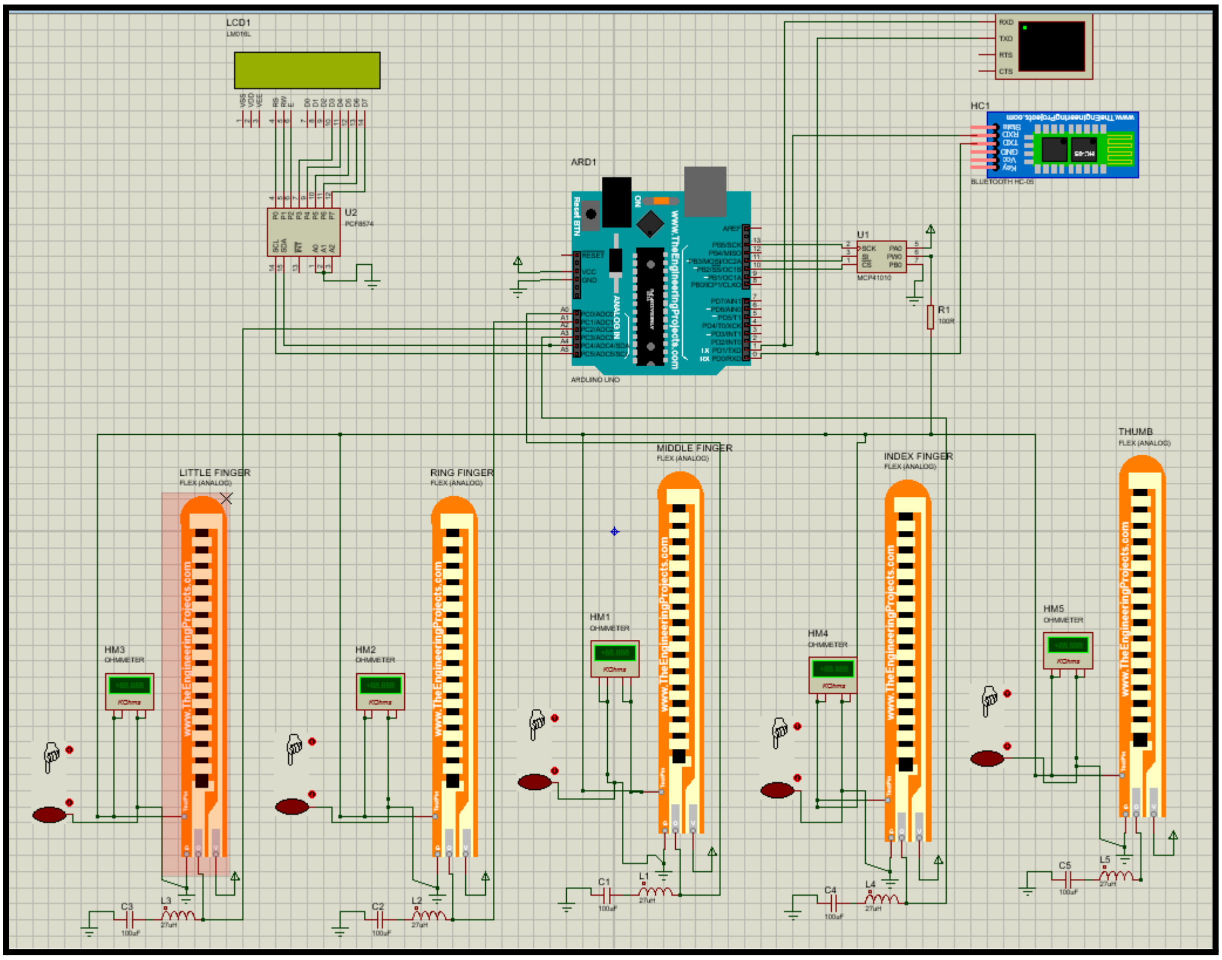


Fig. 6: Simulation Diagram for Design Approach 1

The complete design integrates five flex sensors, with the resistance controlled by the MCP41010 Digital Potentiometer to replicate the functionality of a pneumatic muscle. Each flex sensor is strategically positioned to detect bending movements in each finger, while the pressure sensor measures the applied force. These sensors transmit data to the microcontroller, which processes the information and adjusts the resistance of the MCP41010 accordingly. Here, The IC serves as a controllable variable resistor, mimicking the behavior of the pneumatic muscle. By adjusting its resistance value, the system can replicate the bending and pressure exerted by the muscle in response to external stimulation. The microcontroller interfaces with the IC and sensors, facilitating real-time monitoring and control of the system's behavior. The results of the sensor readings and resistance adjustments are displayed in the Node-RED web dashboard, providing users with visual feedback on the pneumatic muscle's actions. Users can monitor the flex sensor readings, pressure levels, and resistance values in real-time through the user interface, enabling precise control and observation of the system's behavior. Overall, this design offers a comprehensive solution for replicating the functionality of a pneumatic muscle using flex and pressure sensors, coupled with the MCP41010 Digital Potentiometer. With the ability to monitor and control the system remotely via the Node-RED web dashboard, it provides a versatile platform for various applications in robotics, prosthetics, and rehabilitation engineering.

Pneumatic Muscle:

In the design, the MCP41010 Digital Potentiometer serves as a pivotal component for emulating the behavior of a pneumatic muscle. Its integration into the system enables precise manipulation of resistance, a critical factor that directly influences the stimulated muscle's actions and responsiveness. By dynamically adjusting resistance levels, we can accurately replicate the bending and pressure exerted by a pneumatic muscle in a controlled fashion.

The MCP41010 is strategically connected to various pins within the circuit: VCC to the +5V supply, CS to a dedicated digital output pin for communication, SCK to the SPI clock output, and SI to receive data input from the microcontroller. Furthermore, the A, B, and W terminals of the MCP41010 are linked to the circuit where resistance modulation is required, typically in series with the pneumatic muscle or its equivalent.

To mimic the movements and pressure variations of a pneumatic muscle, the system incorporates sensors capable of detecting changes in bending and pressure. These sensors translate physical stimuli into corresponding data signals, which are then relayed to the MCP41010's variable resistor pin. Through this mechanism, the microcontroller gains real-time insights into resistance fluctuations, allowing for precise control over the simulated muscle's behavior. By harnessing this configuration, the system effectively replicates the nuanced movements, flexibility, and pressure dynamics of a pneumatic muscle in a programmable and controllable manner.

Library MCP41010:

To create a custom library for the MCP41010 dual high-performance digital potentiometer within Proteus design software, users can follow a systematic approach outlined in the provided steps. Begin by initiating library creation through the Library Manager window, selecting a descriptive name such as "MCP41010_Library" to aid in identification. Subsequently, add individual components using the "New Part" button and define their specifications using the "New Component Wizard." Assign properties, including names, descriptions, pins, and graphical representations, ensuring accurate reflection of the MCP41010's characteristics. Configure component pins, draw clear symbols using Proteus's drawing tools and select suitable package options for physical footprints. Save each component after configuring its properties, repeating the process until all necessary components are added. Finally, save the entire library to preserve changes. This systematic approach facilitates the creation of a comprehensive library for the MCP41010, enabling efficient integration into Proteus projects.

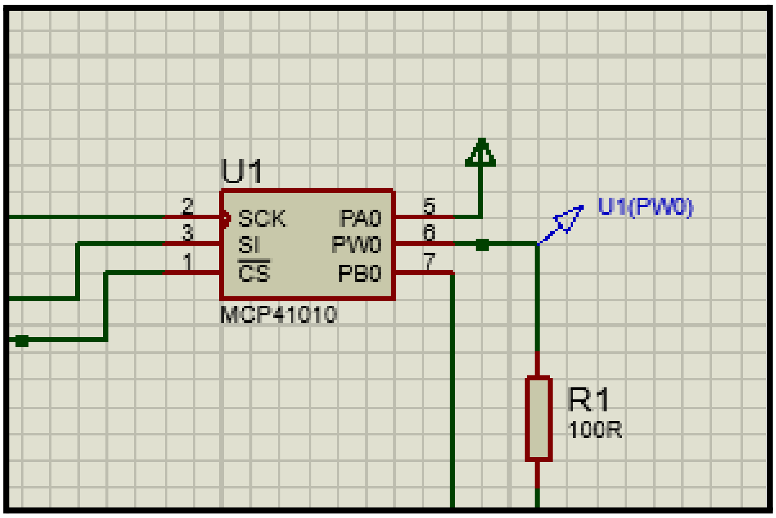


Fig. 7: Digital Pot as pneumatic muscle

Communication Unit:

The smart glove system utilizes a dedicated communication unit to seamlessly interact with external devices, such as a web dashboard, enabling effortless control and monitoring of its functionalities remotely. Node-RED serves as the backbone for observing the outcomes of Proteus within a user-friendly platform.

For controlling and monitoring the glove functionalities, a mobile application acts as a versatile interface. It connects to an Arduino microcontroller via Compim and a virtual terminal. Users have precise control over the glove's bending within a range of 90 to 270 degrees and can adjust the exerted force from 0 to 30 Newtons using intuitive controls provided by the app. Real-time data from integrated force and flex sensors is displayed comprehensively, allowing users to monitor bending and force exertion closely for informed adjustments and optimizations.

Furthermore, the app stores monitored data for later analysis, enabling users to review their progress over time and make informed decisions about their rehabilitation regimen. Overall, the mobile application offers a user-friendly and efficient platform for controlling, monitoring, and analyzing glove functionalities, empowering users to enhance their rehabilitation experience effortlessly.

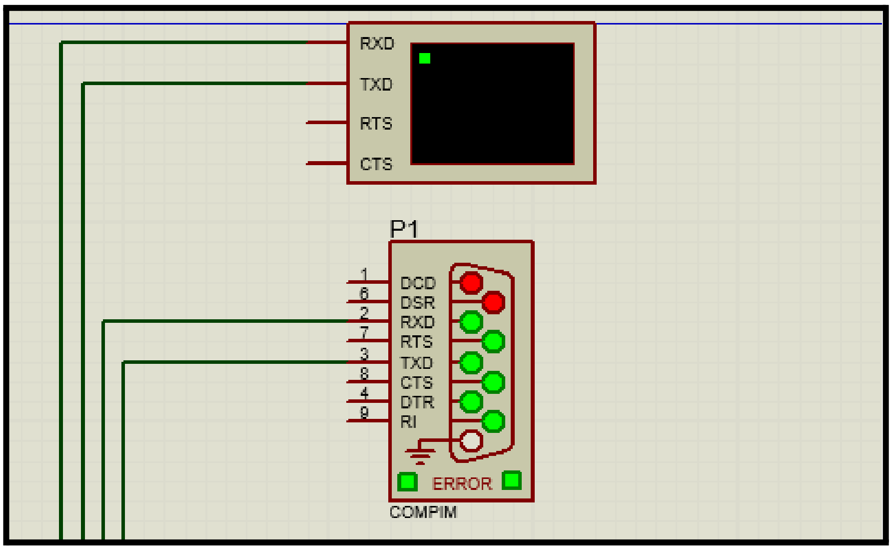


Fig. 8: COMPIM Module and virtual serial Monitor for communication

Virtual Terminal:

Fig. 9: Virtual Serial Port

Here Virtual Serial Port Kit facilitates seamless communication between COM 28 and COM 29 within Proteus and Node-RED environments. By establishing a virtual connection between these COM ports, data transmission between simulated hardware and Node-RED flows is enabled with ease. This integration allows for efficient interaction between virtual devices and external systems, facilitating the exchange of information for various applications such as simulation, testing, and prototyping. With Virtual Serial Port Kit, developers can streamline their development process and ensure smooth communication between Proteus simulations and Node-RED workflows, enhancing productivity and effectiveness in their projects.

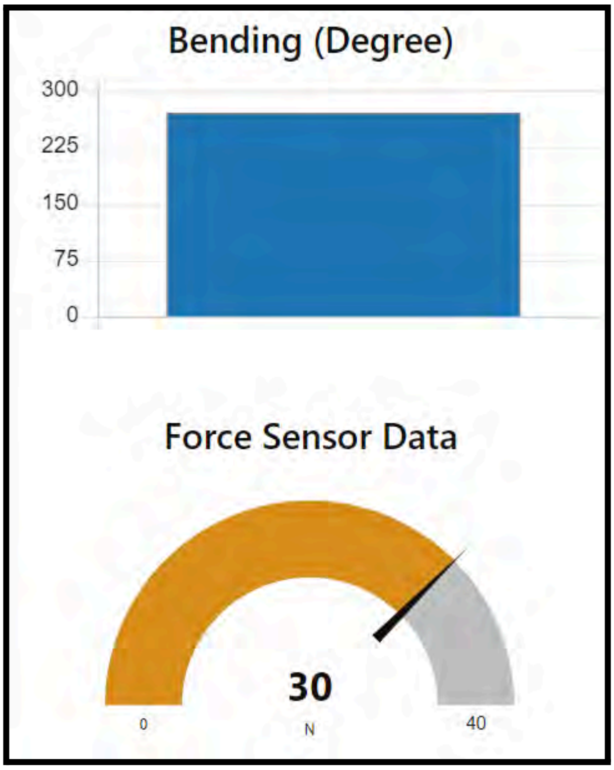


Fig. 10: Graphical User Interface

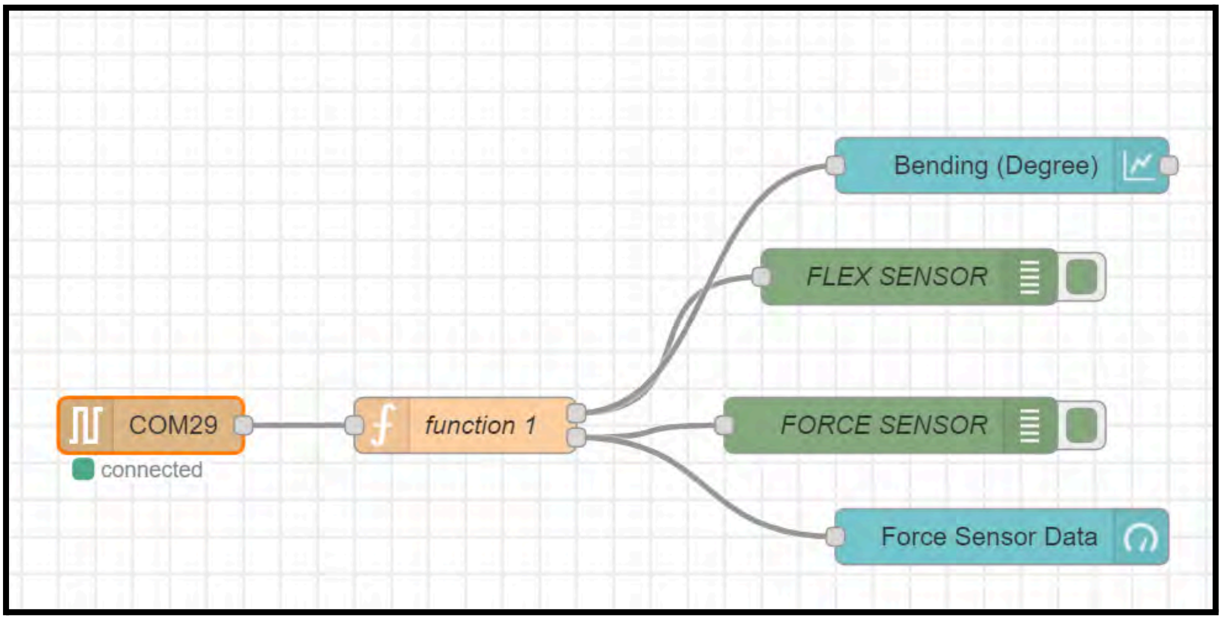


Fig. 11: Block designing for the Mobile Application

Flex Sensor:

Flex sensors are essential components in the system, serving as sensitive detectors of bending or flexing movements. Positioned strategically within the fabric of the glove, these sensors precisely capture the angles of finger and hand joints during rehabilitation exercises or gestures.

The flex sensors operate based on the principle of resistance variation, where their resistance values change proportionally with the degree of bending applied to them. As the user flexes their fingers or hand, the flex sensors detect these movements and dynamically adjust their resistance accordingly.

Once the flex sensors register changes in resistance, they generate corresponding electrical signals. These signals are then transmitted to the microcontroller unit (MCU) for processing. The MCU plays a vital role in interpreting the data received from the flex sensors, converting it into meaningful feedback or control commands.

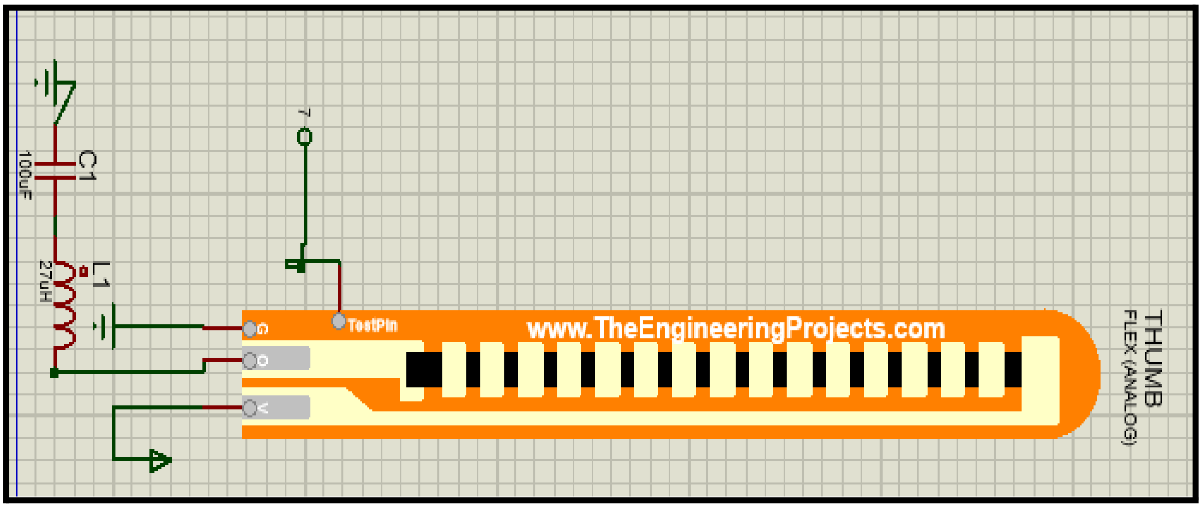


Fig. 12: Flex Sensors

LCD display:

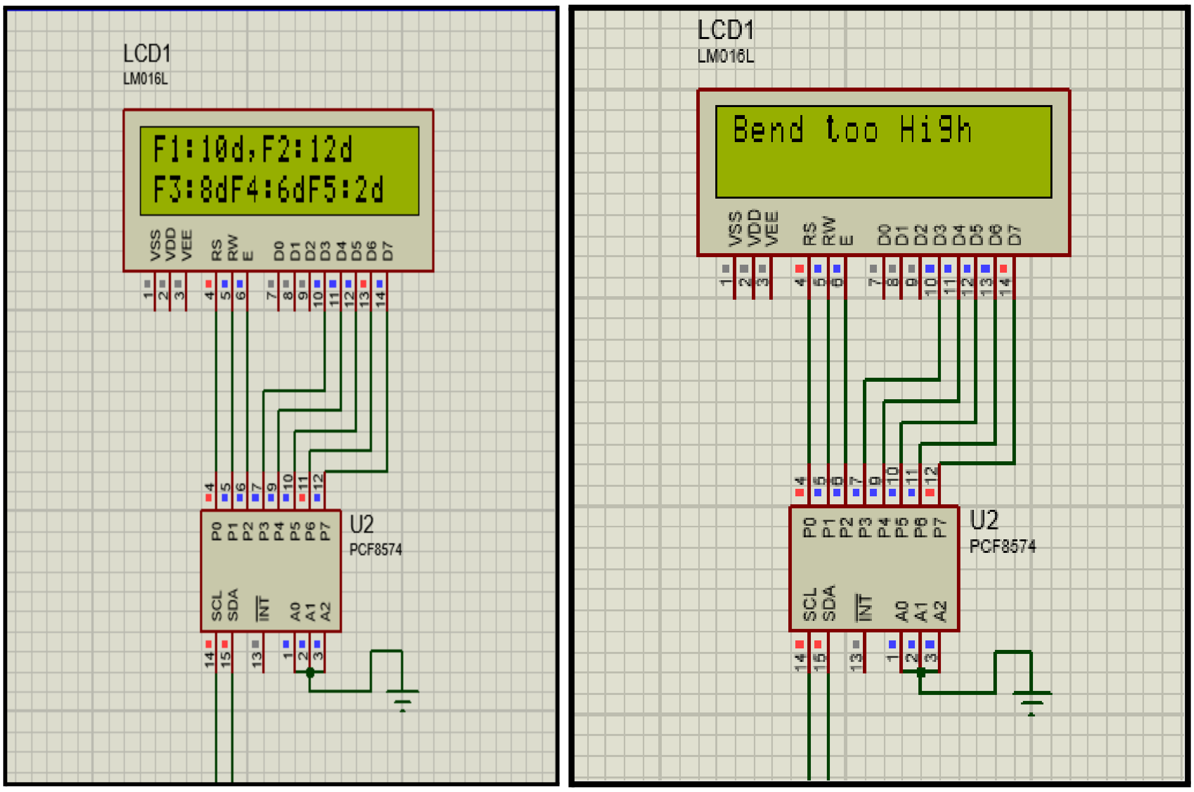


Fig. 13: LCD display showing the result

The design Utilizes an LCD with an I2C interface (LCDi2c), an Arduino Uno microcontroller regulates a digital potentiometer, adjusting its resistance to modify voltage levels applied to five flex sensors. These flex sensors are connected to the Arduino's analog pins (A0 to A4), each representing the bending degree of a specific finger. The Arduino reads the analog voltage output by each flex sensor and translates it into a bending degree using the map() function. The bending degree values are then displayed on a Liquid Crystal Display (LCD) with an I2C interface, commonly known as LCDi2c. The LCDi2c offers the advantage of simplified wiring and reduced pin usage, enhancing the overall system's efficiency and simplicity. On the LCD screen, each finger's bending is visualized with labels F1 to F5 alongside their respective bending degrees. Additionally, to ensure user safety and provide immediate feedback, if any of the fingers reach a bending degree of 255 degrees, indicative of maximum bend, the LCD displays a cautionary message indicating that the bend is too high, prompting the user to adjust their finger position. The monitoring of five fingers bending is crucial for hand dexterity and movement analysis. accurately measuring and visualizing the bending degrees of all five fingers is paramount for understanding hand movements comprehensively and facilitating the development of advanced applications that rely on precise hand gestures and control. This real-time monitoring and warning mechanism enhances the usability and safety of the system during operation.

Design Approach 2:

This design involves a five-finger glove with electrodes on the fingertips, utilizing NMES to stimulate muscle. The glove targets the median nerve in the thumb, index finger, and middle finger and the ulnar nerve in the ring and small finger using precisely controlled current pulses. Two electrodes will transmit the current to the nerves. The adjustment of current pulses will follow guidelines from rehabilitation professionals, ensuring an effective approach. The functional block diagram of the necessary units of this approach is as below:

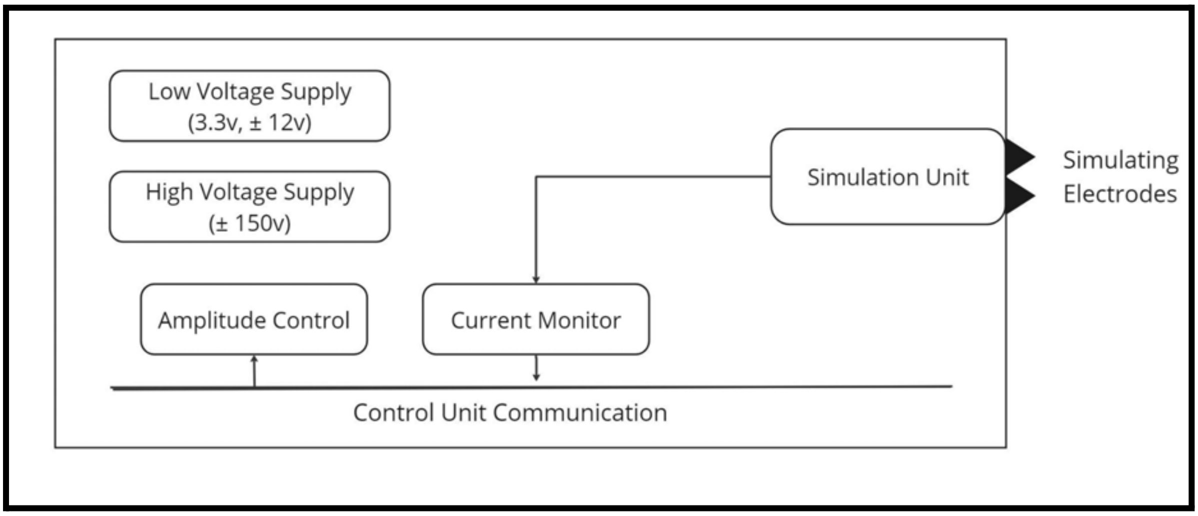


Fig. 14: Block Diagram for Design 2 (NMES based system)

Each units are explained with a simulation below:

Stimulation Unit:

We use a Microstim Pulse(MP) stimulator for generating the current pulses.MP stimulators generate symmetrical biphasic waveforms. The MP stimulator uses a 56.53-to-1 turns ratio transformer to convert the 9-volt battery voltage to a higher output voltage pulse. A PNP Darlington transistor (TIP107) turns on the current to the primary winding of the transformer[17]. The timing of pulses was controlled through a 555 timer. The secondary winding is connected to a user controlled potentiometer of measured value 23.85 kilo ohms in order to regulate the intensity of the output stimulus. The high side red labeled terminal is connected to the center tap of the potentiometer. 10 major intensity settings, labeled 1 through 10, are marked on the potentiometer dial.

Here using R7 and R8 as voltage dividers are set to output current. For that, using 10 settings for getting 10 different intensities of electrical pulses as discussed by [17].

Table 3: Different resistor values for different settings

Setting	1	2	3	4	5	6
R7(ohm)	23.8k	23.73k	19.35k	14.5k	10k	7k
R8(ohm)	33.75	120	4.5k	9.35k	13.85k	16.85k

PNP Darlington Transistor: The PNP Darlington configuration allows for small base currents to control significantly larger collector currents, ensuring adequate amplification of the input signal. This feature is crucial for driving the primary winding of the transformer and delivering appropriately amplified output pulses for effective stimulation. Moreover, the transistor's reliable performance and stability contribute to the overall durability and longevity of the device, essential for medical and research applications. Additionally, the efficiency of the PNP Darlington configuration optimizes energy utilization, a key consideration in battery-powered devices like the MP stimulator.

Stimulator Drive Stage: The stimulator drive stage plays a vital role in electrical stimulation devices by generating and regulating the electrical pulses delivered to target tissues or neural pathways. This process begins with a step-up isolation transformer connected to a transistor on the primary winding to initiate stimulation. A DC voltage source is connected to the other terminal of the primary winding. When activated by a 5V signal, the transistor allows current from the voltage source to pass through the primary winding. In an ideal scenario, the transformer increases the voltage from the primary to the secondary winding by a ratio of N2/N1, where N2 and N1 represent the number of turns in the secondary and primary windings, respectively [17]. However, non-idealities such as leakage and core losses are unavoidable.

A diode placed across the primary winding helps dissipate back electromotive force (EMF) that results from sudden current withdrawal, protecting the transistor from voltage spikes that could exceed its tolerance. The voltage across the secondary winding is then applied to the load, and following the pulse, the secondary winding facilitates skin discharge to reduce potential tissue damage. The transformer also provides electrical isolation between the DC power source and the subject, ensuring safety. Since the secondary winding acts as a short circuit at the output terminals after stimulation, it further aids in reducing tissue damage by allowing the skin to discharge.

Despite these advantages, transformers present some challenges. They are mechanically larger and heavier compared to silicon-based components, and electromagnetic emissions from transformers can complicate compliance with medical device regulations, such as IEC 60601-1-2, if not properly grounded. Additionally, the output waveform to the skin load lacks closed-loop control, meaning that the output pulses depend on the load across the secondary winding. Another limitation is core saturation, where the magnetic flux density in the transformer's core reaches its limit. As the magnetizing force increases with higher current, the magnetic moments within the core align with the magnetic field. Once fully aligned, the core cannot contribute further to the magnetic flux density, resulting in saturation. In this state, increasing the winding current has little impact on the transformer's output current.

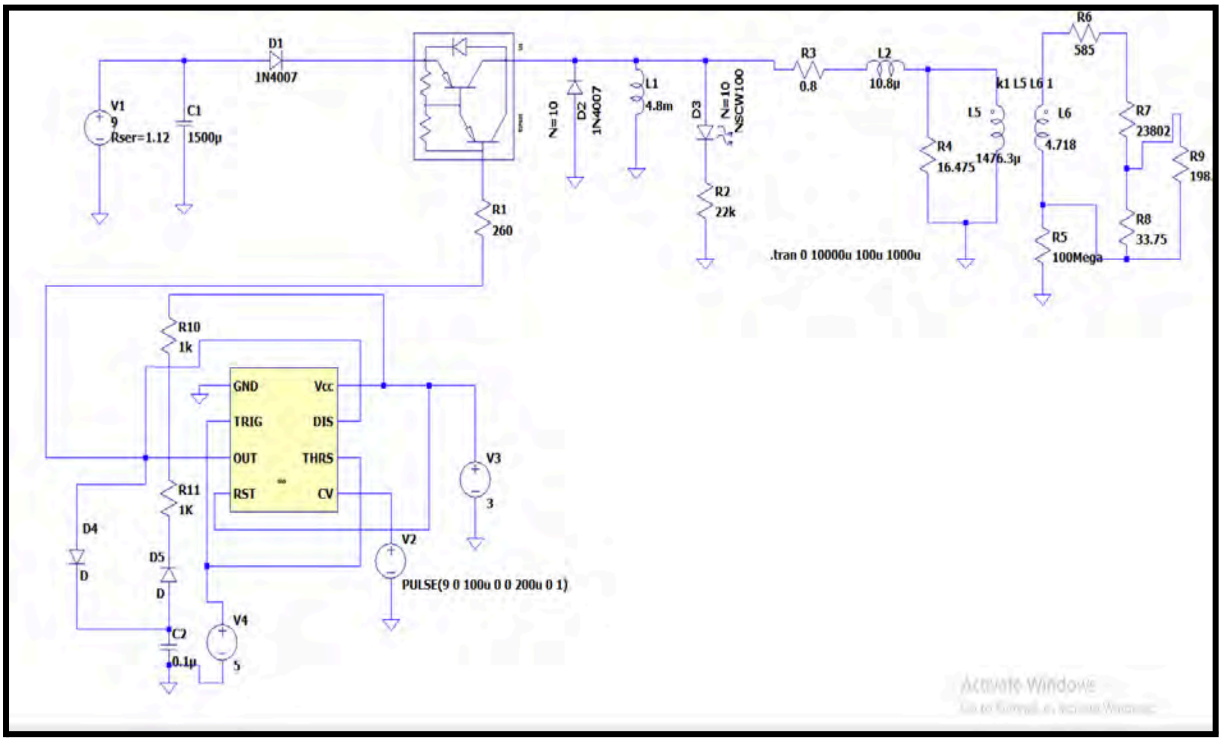


Fig. 15: Simulation Diagram of Stimulation Unit of Design Approach 2

In the fig16, there is a current across L6 inductor(mA) Vs Time(μs) graph where we can see that the stimulation unit generates a 15 mA symmetrical biphasic waveform for setting 1.

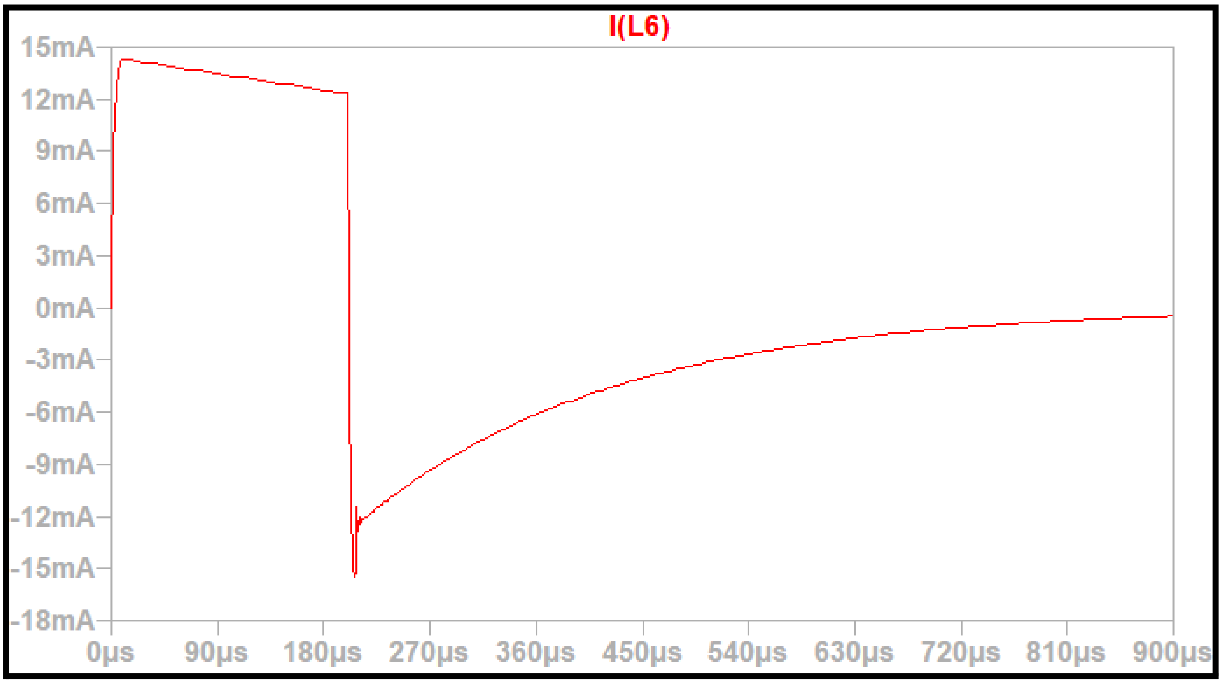


Fig. 16: Stimulation unit result of Design Approach 2

Control Unit: The control unit allows doctors to regulate the intensity of the current pulses. To achieve this, the input voltage (Vin) must be determined for each equivalent load resistance across the eight settings. For that, we replace the load resistors with R9=781.53ohm resistors and measure the corresponding input voltages.

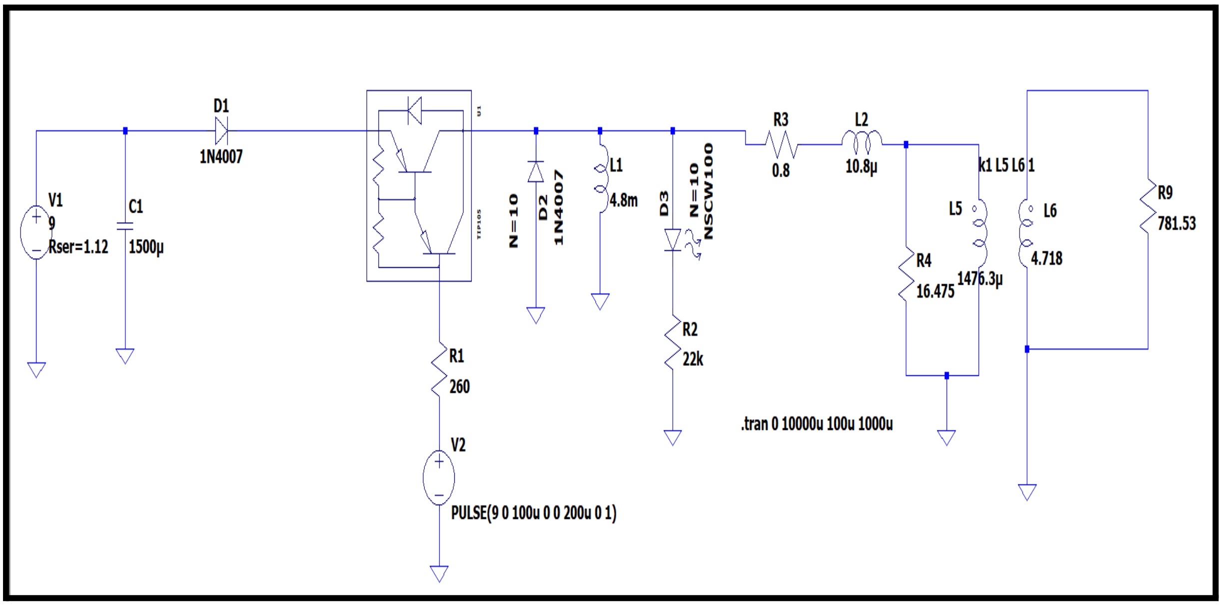


Fig. 17: Circuit diagram for stimulation unit with equivalent load resistance

In Fig 17,, the load side receives stimulation primarily through resistors R7 and R8. By adjusting R7 and R8, we can modify the current pulse value at the output, thereby providing different stimulation settings. However, manually changing the load resistance repeatedly for different pulses is challenging. Alternatively, the same outcome can be achieved by adjusting the voltage input, represented by V1 in diagram 18. Initially, we calculated the equivalent resistance for various unit settings, as detailed in Table 4.

Subsequently, we conducted simulations as shown in Figure 20, by varying the equivalent resistance to determine the desired current pulses. With this understanding of which settings yield specific current pulses, we maintained the load resistance as R9=781.53Ω and adjusted the voltage input to achieve the desired current pulses.
In the simulation, we only altered the voltage input V1 to observe the output.

The voltage input, V1, will be received from the output of the control unit depicted in Figure 21. By determining which digital pin needs to be active to achieve the desired output from the control unit, we calculated the value of Vin. This value is provided below.

The Vin value will be the output of DAC. It will be measured by the formula [17]:

Vin = Vref(A1/2 + A2/4+ A3/8+ A4/16 + A5/32 +A6/64 + A7/128 + A8/256)
Here, we set Vref=15V.
Here, A1-A8 is the digital pins that need to be active for the desired voltage.

Here, we set V_{high} as 10V and V_{low} as -5V. Therefore, Vref is (10-(-5))=15 V.

Setting 1:

Here, to get 2.6V voltage, we need to send digital 1 input to 3,5 and 6 pins. Because,

$V_{theoretical}$ = 15(0/2 +0/4+ 1/8+ 0/16 + 1/32 +1/64 + 0/128 + 0/256)=2.578~2.6

Setting 2:

To get 2.7V voltage, we need to send digital 1 input to 3,5,6 and 7 pins. Because,
$V_{theoretical}$ = 15(0/2 +0/4+ 1/8+ 0/16 + 1/32 +1/64 + 1/128 + 0/256)=2.695~2.7

Thus we calculated all the voltages we would get from the DAC and calculated the error for the corresponding current. The values are as below:

Table 4: Equivalent Load Resistance for the required current

Setting No.	Eq. Load Resistance(Ω)	$V_{theoretical}$ (V)	$I_{theoretical}$ (load)(mA)
1	24415.83	2.6	13.2mA
2	24389.74	2.7	14.4mA
3	20124.80	2.9	17mA
4	15279.047	3.2	21.5mA
5	10780.36	3.7	28mA
6	7780.857	4.2	35.4mA

The control unit will consist of the following subunits:

1. Digital Input: The control unit incorporates 6 buttons that enable users to provide digital inputs for setting the intensity of the current pulse. These buttons serve as intuitive interfaces, allowing users to easily adjust the parameters of the stimulation according to their preferences.
2. Microcontroller: A microcontroller serves as the central processing unit of the control unit. It is responsible for interpreting the inputs received from the buttons and converting them into corresponding digital values. This conversion process ensures that user commands are translated into a format compatible with the subsequent stages of the system. In this control unit, the Arduino Nano microcontroller is used because it has 16 digital I/O pins.
3. Digital-to-Analog Converter (DAC): The control Unit has DAC0808. The DAC plays a pivotal role in the control unit by converting the digital input signals received from the microcontroller into analog outputs. These analog outputs represent the desired intensity levels of the current pulse. The DAC's precision and accuracy are crucial in maintaining the fidelity of the stimulation parameters, ensuring that the output closely matches the user's specified settings.

Upon receiving input from the user through the buttons, the microcontroller processes this information and generates digital values reflective of the desired current pulse intensity. These digital values are then forwarded to the DAC, which translates them into analog signals suitable for driving the stimulation unit. The analog outputs generated by the DAC are directed to the stimulation unit, where they serve as control signals for modulating the intensity of the current pulse. Through this seamless integration, the control unit facilitates real-time adjustments to the stimulation parameters, enabling precise customization according to the user's requirements.

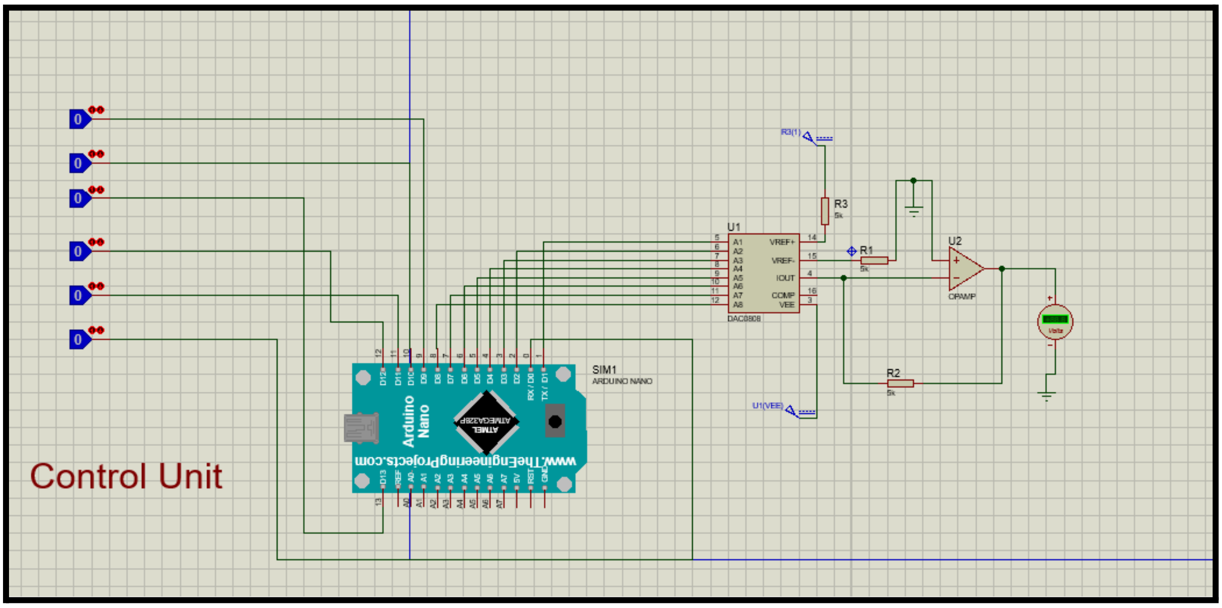


Fig. 18: Control Unit of design 2

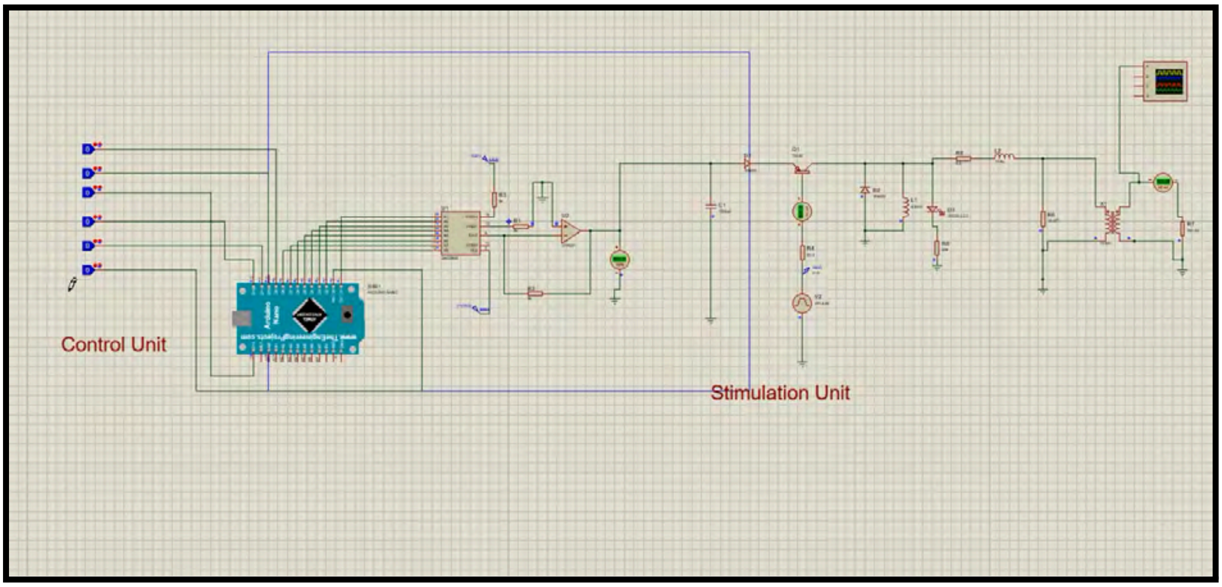


Fig. 19: All units together in design 2

2.5 Conclusion

The exploration of two distinct design approaches for rehabilitation gloves underscores the transformative potential of advanced technology in enhancing rehabilitation outcomes. Design Approach 1, centered around Smart Rehabilitation Gloves with a Digital Twin Model, showcases innovations like pneumatic air muscles (PAMs) and IoT-based monitoring systems. This approach not only mimics natural hand movements with precision but also empowers clinicians with real-time data for personalized patient care. On the other hand, Design Approach 2, utilizing Neuromuscular Electrical Stimulation (NMES)-based Gloves, focuses on targeted muscle stimulation through electrodes, aiding in muscle re-education and strength recovery post-neurological injury.

Both designs represent significant strides in rehabilitation technology, catering to diverse patient needs and conditions. Design Approach 1 emphasizes versatility and adaptability through its integration of soft robotics and comprehensive sensor systems, enabling tailored rehabilitation programs and remote monitoring. Meanwhile, Design Approach 2 targets specific neurological pathways, offering specialized treatment for conditions such as stroke rehabilitation. By bridging the gap between traditional therapies and cutting-edge innovations, these designs pave the way for more effective, personalized rehabilitation interventions.

In conclusion, the future of rehabilitation gloves lies in the seamless integration of physical and virtual interfaces, empowering both patients and healthcare providers with enhanced functionalities and data-driven insights. Continued research and development in this field promise to further refine these technologies, ultimately improving the quality of life and recovery outcomes for individuals undergoing rehabilitation worldwide.

Chapter 3: Use of Modern Engineering and IT Tool

3.1 Introduction

In the development of the Smart Rehabilitation Glove with Digital Twin Model, the integration of modern engineering and IT tools is paramount. These tools facilitate the design, simulation, and optimization processes, ensuring that the final product is both effective and reliable. This chapter explores the selection and application of various advanced tools employed in the project, highlighting their roles in achieving the project's objectives.

3.2 Selection of Appropriate Engineering and IT Tools

MIT App Inventor: The MIT App Inventor tool has been developed and used in this project in order to control the device remotely and store data of the performance to keep the doctors updated with the patient's medical condition.

Arduino IDE: Arduino IDE has been used to program the microprocessor which will allow the application to connect with the device. It will also enable monitoring the sensor data in the mobile application in real time.

LTspice: LTspice has been utilized in the project for its advanced simulation capabilities, allowing precise analysis and optimization of the electronic circuits. Its ability to model complex components and provide real-time waveform visualization ensured accurate circuit behavior assessment.

Proteus: Proteus was utilized for its capability to accurately simulate and evaluate sensor-driven circuits in a virtual environment. It has been used to simulate the project in software, allowing for the verification of results before implementing the design in a physical prototype.

Altium Designer: The Altium Designer has been used in the project in order to design the PCB circuit of the device. It enables to design the circuit in an efficient and optimized manner.

3.3 Use of Modern Engineering and IT Tools

Proteus: Proteus Design Suite, crafted by Labcenter Electronics Ltd., stands out as a premier electronic design automation (EDA) tool, renowned for its prowess in circuit design and simulation. Boasting an expansive component library, it offers a diverse range of sensors, including flex sensors and force sensors, crucial for numerous electronic applications. With

Proteus, designers can seamlessly integrate these sensors into their circuit designs, accurately simulating their behavior and performance across various scenarios. This capability allows designers to thoroughly evaluate their sensor-driven circuits virtually, preempting issues and reducing the need for physical prototypes. Moreover, Proteus empowers users to fashion custom devices, enabling the emulation of tailored sensors and microcontrollers to suit specific project demands. By harnessing Proteus' user-friendly interface and robust simulation features, designers can refine their designs with ease, fostering the development of optimized electronic systems.

LTspice: LTspice is a robust and widely-utilized analog electronic circuit simulator computer software, rooted in the SPICE (Simulation Program with Integrated Circuit Emphasis) framework. It is an essential tool for engineers, researchers, and students involved in electronic circuit design and analysis. The software offers a comprehensive suite of features tailored to meet the demands of modern circuit design, simulation, and optimization. At its core, LTspice provides a user-friendly interface facilitating the design, simulation, and analysis of electronic circuits. With a built-in schematic capture tool and an extensive library of electronic components, including resistors, capacitors, inductors, diodes, transistors, and more, circuit design becomes an intuitive and straightforward process. Its advanced simulation engine supports various analysis techniques such as transient, AC, DC, and parameter sweep analysis, employing sophisticated numerical methods for accurate results. LTspice's interactive simulation capabilities allow real-time visualization of circuit waveforms, with virtual probes enabling monitoring of voltage, current, and other parameters. Supporting Monte Carlo analysis and parameter sweeps for statistical and sensitivity analysis, LTspice seamlessly integrates with external tools, enhancing its versatility and making it a preferred choice for electronic circuit design and analysis across industries.

Arduino IDE: Arduino IDE, short for Integrated Development Environment, is a user-friendly software tool used for programming Arduino microcontroller boards. It provides a simple yet powerful platform for writing, compiling, and uploading code to Arduino boards, making it accessible to both beginners and experienced users. It supports various programming languages like C and C++, making it versatile for a wide range of applications. Arduino IDE simplifies the process of writing code for interacting with sensors, actuators, and other electronic components connected to Arduino boards. It also facilitates debugging and testing of code, ensuring smooth operation of projects. In the design approach 1, an Arduino Nano is utilized as the microcontroller platform. As a result, Arduino IDE serves as the primary software tool for coding and programming tasks.

MATLAB Simulink: MATLAB Simulink played a pivotal role in analyzing the relationship between electrical stimulation and hand extension movement dynamics. By utilizing Simulink, it was possible to model and simulate the behavior of the system with different models, including linear, non-linear, and linearized approaches. Simulink provided a graphical environment where the transfer function representing the system dynamics could be implemented and tested. Additionally, Simulink facilitated the integration of controllers, such as the PID controller, allowing for the implementation and tuning of control strategies to optimize the system's performance. The software enables it to simulate the response of the system to various inputs and parameter configurations, providing valuable insights into the system's behavior and aiding in the refinement of rehabilitation strategies. Furthermore, Simulink's compatibility with MATLAB allowed for seamless data analysis, visualization, and interpretation of simulation results, enhancing the overall understanding of the relationship between electrical stimulation and hand movement dynamics.

MIT APP INVENTOR: MIT App Inventor is a free, open-source web-based platform developed by the Massachusetts Institute of Technology (MIT) that allows users to create mobile applications for Android and iOS devices without needing extensive programming knowledge. It uses a visual programming approach, where users drag and drop blocks to design the app's functionality and interface, rather than writing code manually. Instead of writing code, users piece together visual blocks that represent different programming constructs (like loops, conditions, or events). Additionally this makes it easier for beginners to understand programming concepts.Users design the app's user interface by dragging and dropping components (such as buttons, text fields, and images) onto a virtual screen. Users can test their apps on a connected device or an emulator in real-time, allowing for immediate feedback and adjustments.There is a large community of users and a wealth of tutorials, guides, and sample projects available to help new developers get started. Moreover it’s designed to be accessible to a wide audience, including students, educators, and hobbyists, making it a popular tool in educational settings for teaching programming and app development.

Altium Designer: Altium Designer plays a crucial role in ensuring the smooth integration of electronic components, helping to create a compact and efficient device layout. In this project, the software was used to seamlessly connect the Arduino Nano, Bluetooth module, and sensors, streamlining the overall design. By organizing all components within a single printed circuit board (PCB), the device minimizes wiring, reduces the chances of signal interference, and enhances reliability. This compact configuration not only improves performance but also increases the device's portability, making it practical for use in various rehabilitation environments.

3.3 Conclusion

The integration of modern engineering and IT tools such as Proteus Design Suite, LTspice, Arduino IDE, Node-RED Dashboard, and MATLAB Simulink played a pivotal role in the development of the Smart Rehabilitation Glove. These tools facilitated the design, simulation, optimization, and visualization processes, ensuring the creation of a cost-effective, reliable, and user-friendly rehabilitation device. Through the systematic application of these advanced tools, the project achieved its objectives, providing an innovative solution for post-stroke rehabilitation.

Chapter 4: Optimization of Multiple Designs and Finding the Optimal Solution.

4.1 Introduction

In addressing the challenge of hand rehabilitation, two distinct design approaches have been proposed: Smart Rehabilitation Gloves with Digital Twin Model (Approach 1) and Neuromuscular Electrical Stimulation (NMES) based system (Approach 2). Approach 1 focuses on integrating sensor technology and digital modeling to track and enhance finger movement, while Approach 2 utilizes electrical stimulation to target muscle memory and motor function. To determine the optimal solution, a thorough comparison of these approaches is essential, considering factors such as cost, efficiency, usability, manufacturability, impact, sustainability, and maintainability. Through systematic analysis and optimization, the most suitable design solution can be identified and refined to meet the specific needs of hand rehabilitation effectively.

4.2 Optimization of multiple design approach

To identify the optimal design approach for hand rehabilitation, the efficiency of both design approaches needs to be calculated and compared. This involves analyzing various performance metrics for each design to determine which one provides better overall results.

4.2.1 Design 1 Efficiency:

In the simulation setup, a 5k ohm variable digital potentiometer has been chosen to control the bending of the flex sensor. This potentiometer serves as a variable resistor whose resistance can be adjusted electronically. As the resistance in the potentiometer changes, it directly influences the bending angle of the flex sensor. The flex sensor, capable of bending up to 1023 degrees, exhibits a linear relationship between its bending angle and the resistance applied to it. Therefore, the theoretical change in bending angle for each ohm of resistance variation in the potentiometer can be calculated as the maximum bending angle (1023 degrees) divided by the maximum resistance of the potentiometer (5000 ohms). This relationship allows for precise control over the bending angle based on the resistance settings of the potentiometer.

Let, $\nabla\theta$ is the the change in bending angle per ohm of resistance variation, θmax denotes the maximal bending angle of the flex sensor and Rpot signifies the uppermost resistance of the digital potentiometer.

So, $\nabla\theta = \frac{\theta max}{Rpot}$ degree per ohm of resistance variation. **[11].**

In consideration of patient safety, the device has been designed to limit the rotation of the flex sensor to a maximum of 270 degrees. Excessive rotation beyond this threshold may pose a risk of discomfort or injury to the patient. Consequently, the range of resistance values in the digital potentiometer has been adjusted to ensure that the corresponding bending angle of the flex sensor does not exceed this limit. By carefully calibrating the resistance settings within this constrained range, the device can provide controlled and safe rehabilitation exercises for the patient, optimizing both effectiveness and safety.

Now, calculating bending angle for different resistance in the digital potentiometer and comparing it with the simulated result,

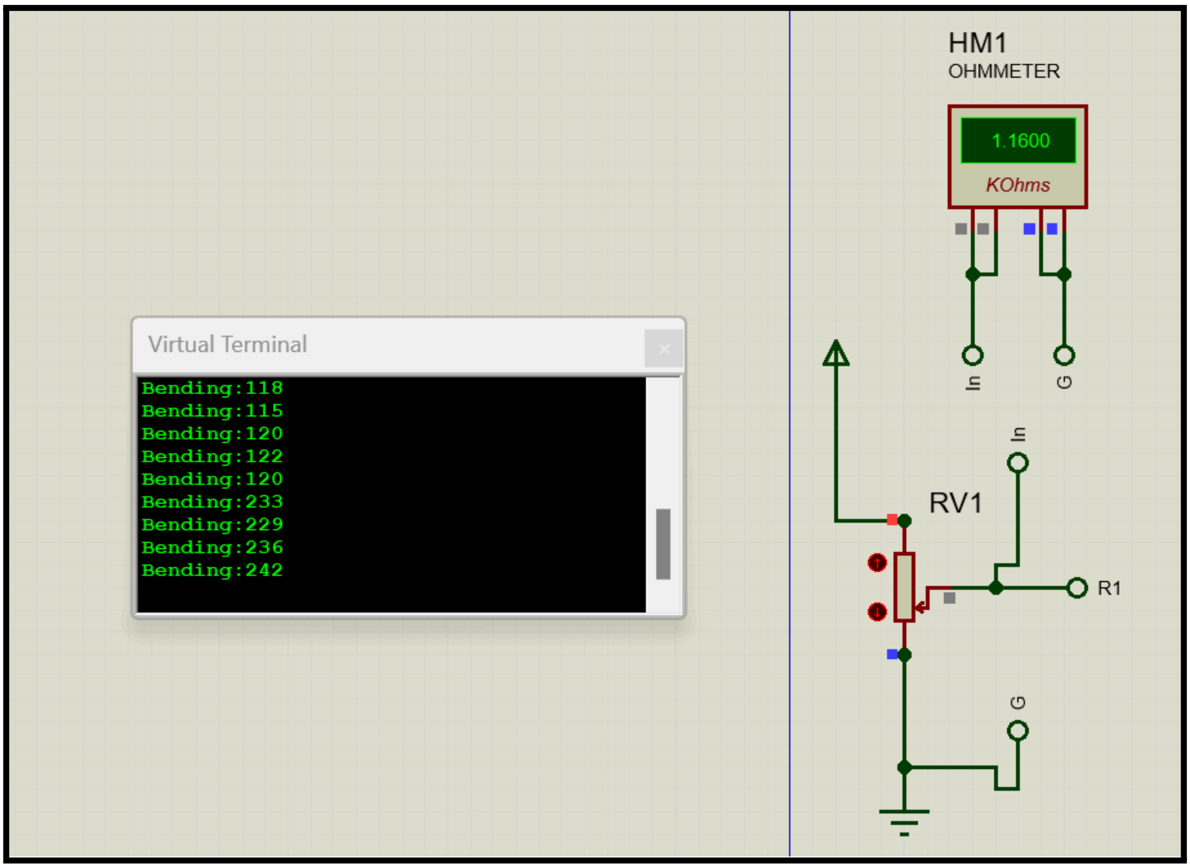


Fig. 20: Change in bending angle for different resistance

Table 5: Comparison of Theoretical and Simulated Bending Angles for Different Resistance Values

Resistance (ohm)	Theoretical Bending Angle (degrees)	Simulated Bending Angle (degrees)	Efficiency (η)	Error percentage (e)
600	121.24	120	98.96%	1.04%
700	143.22	141	98.44%	1.56%
800	163.68	162	98.93%	1.07%
900	184.14	188	97.91%	2.09%
1000	204.60	208	98.22%	1.78%
1150	233.29	229	98.16%	1.84%
1300	265.98	266	97.41%	2.59%
			Average Efficiency=98.28%	Average error= 1.71%

Design 2 Efficiency calculation:

For efficient calculation in design 2, we measured the percentage error.

Table 6: Percentage Error Calculation for the Peak Current Pulse of Design 2

Setting No.	Eq. Load Resistance(Ω)	$V_{theoretical}$ (V)	$I_{theoretical}$ (load)(mA)	$V_{experimental}$ (V)	$I_{experimental}$ (load)(mA)	Error $\lvert \frac{I_{experimental} - I_{theoretical}}{I_{theoretical}} \rvert$
1	24415.83	2.6	13.2mA	2.578	12.7	3.78%
2	24389.74	2.7	14.4mA	2.695	14.36	0.27%
3	20124.80	2.9	17mA	2.93	17.9	5.29%
4	15279.047	3.2	21.5mA	3.22	22	2.32%
5	10780.36	3.7	28mA	3.69	27.5	1.78%
6	7780.857	4.2	35.4mA	4.22	36.1	1.9%
Average Error: 2.26%						

In this experiment, it is aimed to measure the percentage error for the peak current obtained. Initially, it determined a theoretical value of the peak current (I(Theoretical)) at the load. However, due to limitations with the setup, specifically with the Digital-to-Analog Converter (DAC) it was unable to obtain exact voltages as required.
The primary reason for this limitation lies in the nature of the DAC utilized, which in this case is an 8-bit DAC. In the context of an 8-bit DAC, the resolution of voltage output is determined by the number of bits, which directly influences the granularity or precision of voltage levels that can be generated. With an 8-bit DAC, there are 2^8 = 256 possible output voltage levels.

After obtaining the experimental values of load voltage, we proceeded to measure the experimental current corresponding to these voltages in LTspice. This experimental current, denoted as $I_{experimental}$, was then compared to the theoretical value of the current $I_{theoretical}$ previously determined. The percentage error for each experimental measurement was calculated using the formula **[13]**:

$$\text{Error}=\left|\frac{I_{experimental}-I_{theoretical}}{I_{theoretical}}\right| \times 100$$

This formula computes the absolute difference between the experimental and theoretical currents, normalized by the theoretical current and expressed as a percentage.
Subsequently, the individual errors calculated for each experimental measurement were summed, and the average error was computed by dividing the total error by the number of measurements. This averaged error provides a consolidated measure of the overall deviation between the experimental and theoretical values of current, allowing for a comprehensive assessment of the accuracy of the experimental results.

Degree of motion for NMES of design 2:

Three models, linear, non-linear, and linearized, were employed to analyze the relationship between an electrical stimulus and hand extension movement dynamics. The linear model utilized a transfer function with two poles and no zeroes. Parameter identification for this model was conducted through experimental tests involving a 40-year-old volunteer. The volunteer underwent electrical stimulation while with electrodes placed on the flexor carpi radialis muscle. The electrical stimulation comprised a balanced, biphasic, rectangular waveform with a pulse width of 220 μs and a frequency of 50 Hz. The pulse amplitude was adjusted to induce finger extension, reaching a maximum angle of 150°. After acquiring input and output signals simultaneously, the parameters of the transfer function were determined using LabVIEW software **[18].** This function served as a reference for relating the electrical stimulus (input) to the position of the volunteer (output).

Design of the controller and linear model:

The initial controller employed was the PID (Proportional-Integral-Derivative) controller, a widely utilized method for controlling diverse processes and plants.

K_p =0.02685, K_i =0.077938, and K_d =0.000457

Transfer function:

$$\frac{\theta_v(s)}{u(s)} = \frac{45.59}{0.06803s^2+0.5265s+1} \quad [18]$$

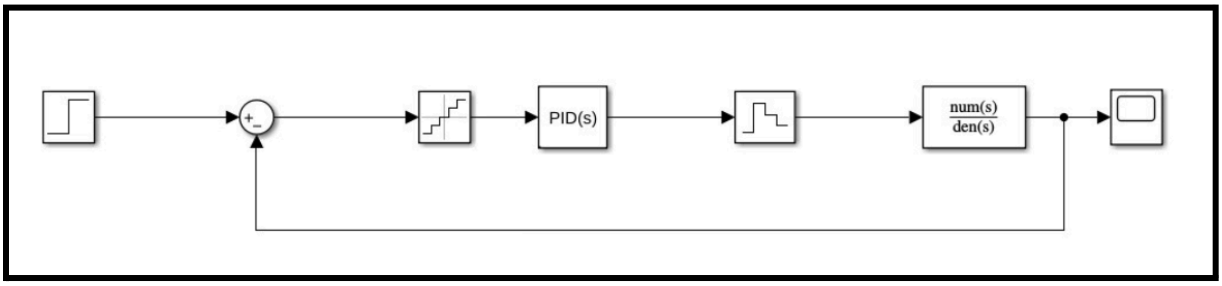


Fig. 21: Controller and plant simulated in Matlab

After examining the graph within the scope, we obtained the plot depicting the degree of finger motion in radians over time.

Degree of motion(rad) vs time(μs):

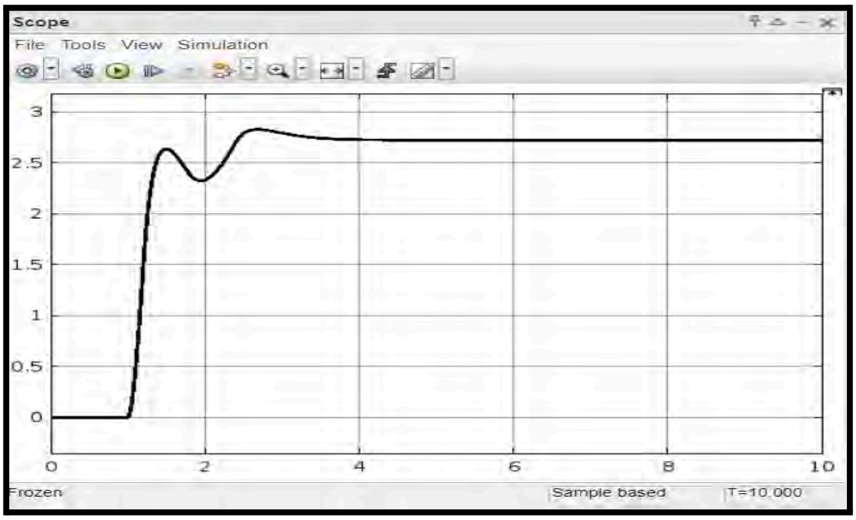


Fig. 22: Graph of degree of motion vs time

Here we get the value of output in radians,

$\theta_v = 2.7rad = 150^{\circ}$

So we can see that in design 1 there is a huge range of degree of motion available for the hand to retrain and regain its muscle memory whereas for design 1, we only have a handful of degree of range of motion due to electromyostimulation-induced contraction.

4.3 Identify optimal design approach

To identify the optimal design approach for hand rehabilitation, a comprehensive comparison between the two proposed designs—Smart Rehabilitation Gloves with Digital Twin Model (Design 1) and Neuromuscular Electrical Stimulation (NMES) based system (Design 2)—was conducted. The evaluation criteria included efficiency, budget, range of motion, user convenience, power consumption, and portability.

Efficiency: Design 1 showed higher efficiency with an average error of 1.71%, compared to Design 2's average error of 2.26%. This indicates that Design 1 provides more accurate and consistent performance.

Budget: Design 1 is more cost-effective, with a total budget of 17,834 Tk, whereas Design 2 requires a higher budget of 20,670 Tk. This difference in cost makes Design 1 more affordable and accessible.

Range of Motion: Design 1 offers a broader range of motion, which is crucial for effective hand rehabilitation and muscle memory recovery. In contrast, Design 2 has a limited range of motion due to the constraints of electromyostimulation-induced contraction.

User Convenience: Design 1 scores higher in terms of user convenience. It is designed to accommodate a wider range of patients, including those with higher spasticity levels, whereas Design 2 may not be as suitable for patients with severe spasticity.

Power Consumption: Design 1 consumes less power, using a lithium battery as its power source. In comparison, Design 2 requires both a battery and a USB connector for the Arduino Uno, leading to higher power consumption and less sustainability.

Portability: Design 1 is more portable, enhancing its practicality for use in various rehabilitation settings. Its compact and lightweight design allows for easy transportation and use outside clinical environments, unlike Design 2, which is less portable.

Based on these criteria, Design 1—Smart Rehabilitation Gloves with Digital Twin Model—emerges as the optimal design approach for hand rehabilitation. It excels in efficiency, cost-effectiveness, range of motion, user convenience, power consumption, and portability, making it the most suitable solution for addressing the needs of patients requiring hand rehabilitation.

4.4 Performance evaluation of developed solution

To get the optimal design we need to compare the two design approaches. Below is the comparison table for the corresponding comparison matrix:

Table 7: Comparison between the two design approaches.

Comparison Matrix	**Design 1**	**Design 2**
Average Percentage Error in Output	1.71%	2.26%
Budget	17,834 Tk	20,670 Tk
Range of motion	More	Fewer
User-convenience	Higher	Lower for high spasticity
Power consumption	Lower	Higher

Portability	More	Less

In conclusion, after a thorough comparison of the two design approaches for hand rehabilitation, Design 1 emerges as the optimal choice:

4.5 Conclusion

In conclusion, the comprehensive evaluation of the two design approaches for hand rehabilitation has revealed that the Smart Rehabilitation Gloves with Digital Twin Model (Design 1) is the superior solution. This design offers several advantages, including higher efficiency, lower cost, greater range of motion, enhanced user convenience, lower power consumption, and better portability.

Design 1's ability to accurately track and enhance finger movement through integrated sensor technology and digital modeling makes it a highly effective tool for rehabilitation. Its cost-effectiveness ensures that it is accessible to a broader range of users, while its wide range of motion facilitates comprehensive hand retraining and muscle memory recovery. The user-friendly nature of Design 1 makes it suitable for a diverse patient population, including those with varying levels of spasticity.

Furthermore, the lower power consumption of Design 1, achieved through the use of a lithium battery, contributes to its sustainability and cost-effectiveness. Its portability ensures that it can be used in various settings, from clinical environments to home-based rehabilitation, providing flexibility and convenience for users.

Overall, the systematic analysis and optimization of the two design approaches have led to the identification of the Smart Rehabilitation Gloves with Digital Twin Model as the optimal solution for hand rehabilitation. This design meets the specific needs of patients effectively, offering a comprehensive, efficient, and user-friendly solution that can significantly enhance the rehabilitation process.

Chapter 5: Completion of Final Design and Validation.

5.1 Introduction

This chapter presents the final design of the smart rehabilitation glove, achieved by systematically integrating all the core components. The project was divided into five subsystems to incorporate the sensor integration, circuit design and programming, power management, and base station with the robotic hand structure. This division allowed each subsystem to be optimized individually before being integrated into the final design. Each subsystem underwent testing using simulation tools like Proteus and LTspice.

By combining these subsystems, the overall performance of the glove is assessed, enabling final refinements in both efficiency and usability. The result is a user-friendly and impactful therapeutic device, designed to support post stroke recovery of the upper limb. The final prototype provides real-time, accurate feedback through an intuitive interface, transforming the concept into a functional device ready for real-world rehabilitation applications.

5.2 Completion of Final Design

This system is designed around a digital twin model, having both physical and virtual interfaces to create a connection between the user and cloud-based service. The block diagram of the workflow of the system is shown in fig 23.

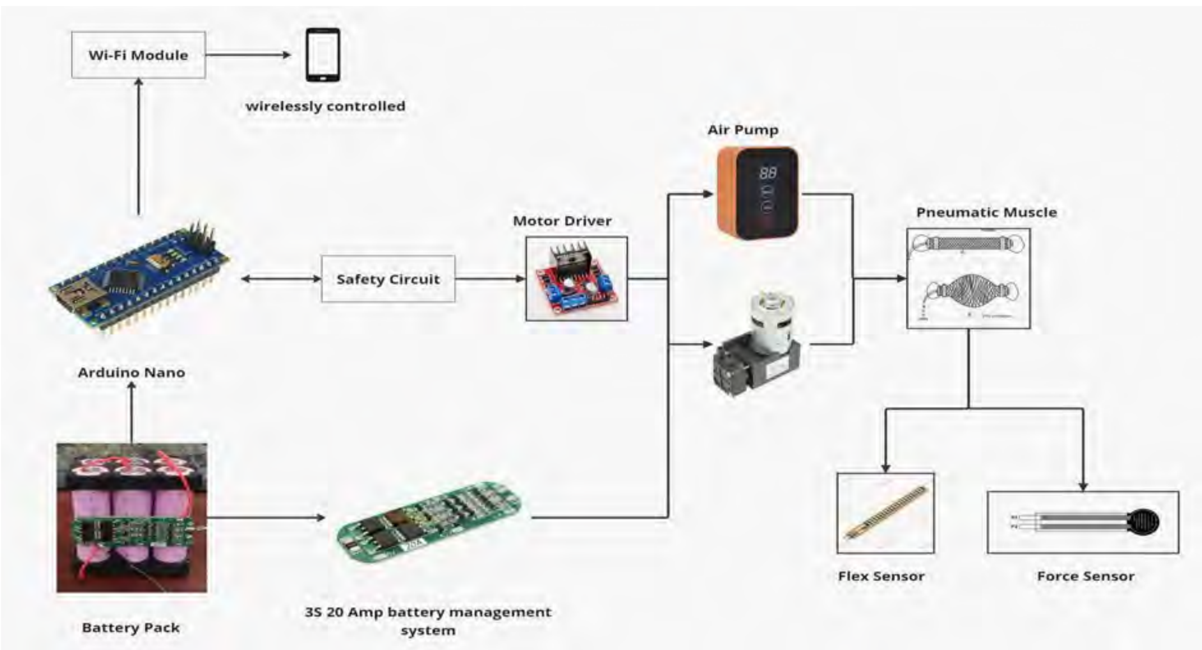


Fig. 23: Block diagram of design Approach 1

To improve workflow and simplify development, the design has been organized into five essential subsystems:

Physical Interface:

- Control Unit
- Power Unit
- Structure
- Communication Unit

Virtual Interface:

- Base Station

5.2.1 Virtual Interface:

Base Station: The base station serves as the core of the virtual interface, utilizing a web dashboard on a mobile device to manage and monitor the system. The primary purpose of this subsystem is to enable patients or doctors to set the glove's pressure and movement through an IoT-based app, allowing for remote control of the glove. This setup facilitates remote monitoring and analysis, ultimately improving patient care and rehabilitation outcomes.

With the dashboard, doctors can access real-time data, such as usage time, force, pressure, and other important details. The instructions set on the base station are crucial, as they ensure that the pressure levels align with the doctor's prescriptions. These instructions are then transmitted to the control unit for execution.

Therefore, the base station consists of two parts. Graphical User Interface and Bluetooth module.

Graphical User Interface Design: The IoT app, developed using MIT App Inventor, allows patients or doctors to remotely control key parameters such as pressure and movement. The app's dashboard offers real-time monitoring, providing insights into critical metrics like usage time, applied force, and pressure. These data points are particularly valuable for doctors, enabling them to continuously analyze patient progress and adjust treatment plans as needed. By allowing doctors to set the glove's pressure and movement remotely, the base station ensures that rehabilitation exercises align with prescribed protocols, enhancing patient care and outcomes.

The interface includes buttons for scanning available Bluetooth devices, connecting, and disconnecting the Bluetooth module, making it easy to pair the glove system with a mobile device. Additionally, the interface provides buttons to turn the glove's functionalities "On" and "Off." A key feature of the interface is the sensor value display, which shows real-time data from the glove's sensors, including flex and force measurements. These values are essential for monitoring the effectiveness of the rehabilitation process, giving patients and healthcare professionals precise feedback on the glove's performance. The user interface is shown in fig24.

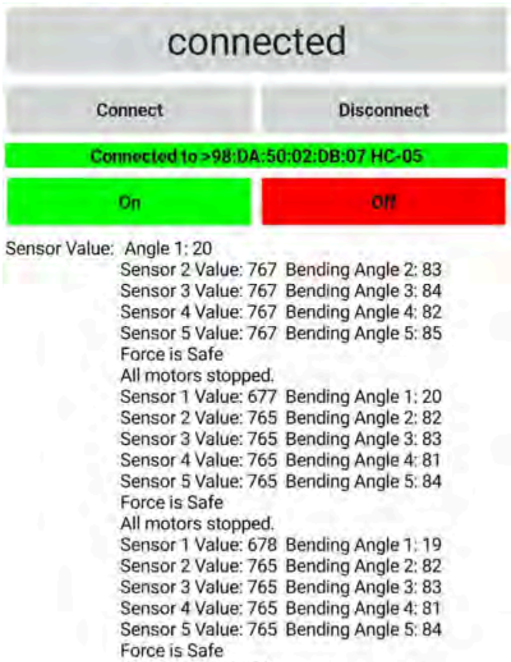


Fig. 24. User Interface of the mobile application

To build the mobile application, block design was implemented in the backend of the application. The backend development involved creating a set of logical blocks that define how the system interacts with the hardware components via Bluetooth. Using MIT App Inventor, the app's functionality was programmed through visual block-based coding. This design allows the app to scan for nearby Bluetooth devices, establish connections, and send control signals to turn the glove's components on or off. The backend also handles data transmission, where sensor values from the glove, such as pressure and flex readings, are sent back to the app for real-time monitoring. This block-based approach ensures smooth communication between the app and the glove, efficiently managing data flow, user inputs, and system responses. The block diagram is shown in fig25.

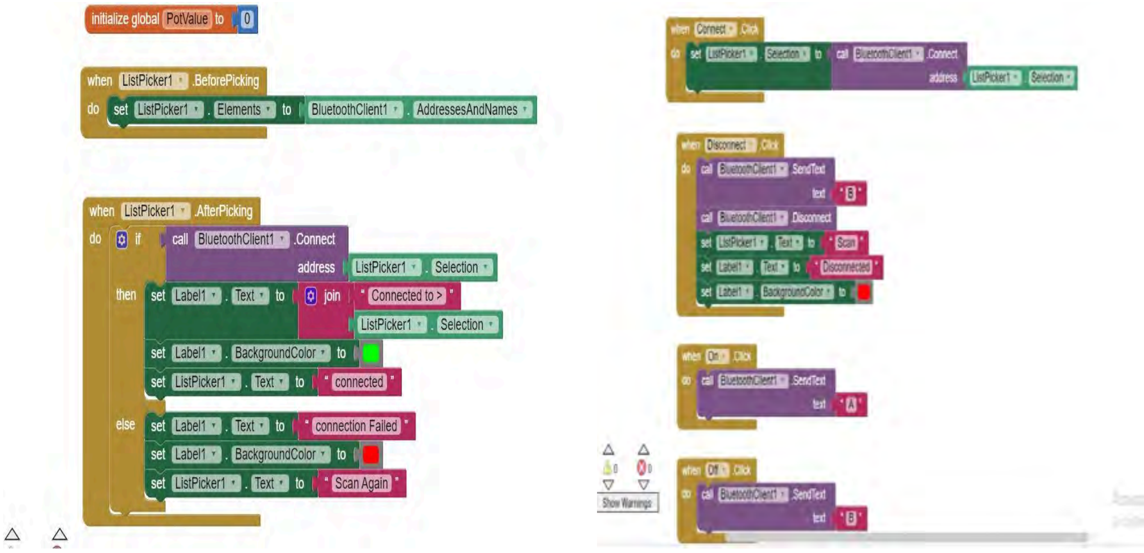


Fig25. Backend block development of the application

Bluetooth Module: The second critical component is the Bluetooth module, which is integrated with the microcontroller of the control subsystem. This module serves as the communication bridge, allowing the app to connect to the control system and manage the glove's functionalities. Here, the HC-05 Bluetooth module is used which facilitates wireless communication between the glove and a mobile application, enabling remote control and performance monitoring. The connection between the Bluetooth module and the control unit is depicted in fig26.

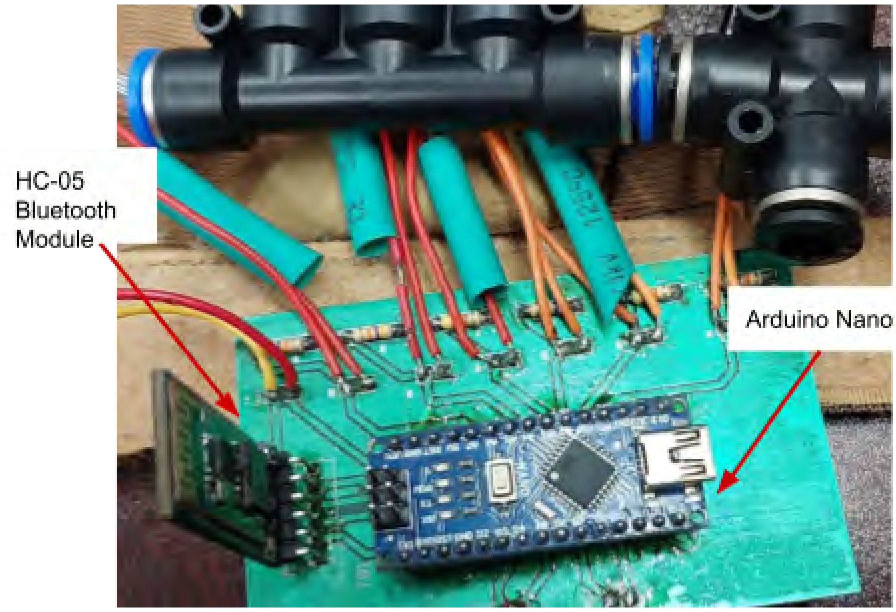


Fig26: Arduino Nano connected with HC-05 Bluetooth module for wireless connection

5.2.2 Physical Interface:

5.2.2.1 Control Unit

The control unit is a vital component of the rehabilitation system, responsible for translating rehabilitation instructions from the base station into precise actions. Instructions are transmitted to the microcontroller (Arduino Uno), which processes them to generate Pulse Width Modulation (PWM) signals. These signals are then sent to the motor driver to manage both the air pump and the vacuum pump as needed.

The system features a 12V vacuum pump with a flow rate of 12 liters per minute and a maximum current of 1.5A. This vacuum pump generates sufficient negative pressure to actuate the pneumatic muscles or structures within the glove. In contrast, the air pump is a 12V DC motor with a power rating of 20W, delivering air at a flow rate of 15 liters per minute, capable of reaching a maximum pressure of 350 mmHg. Both pumps are controlled by an L298N motor driver, which is managed by an Arduino Nano microcontroller.

The primary function of the control unit is to coordinate the operation of the pneumatic pumps based on instructions received from the dedicated application running on the base station subsystem. When the vacuum pump is activated, the air pump remains off, creating negative pressure that causes the pneumatic muscles to contract, resulting in the opening of the patient's hand. Conversely, when the vacuum pump is deactivated and the air pump is activated, the air pump inflates the pneumatic muscles, causing them to expand and close the patient's hand. This alternating actuation mechanism enables precise control over hand movements, effectively mimicking natural hand motions and aiding in the rehabilitation process.

Furthermore, the speed of the motors can be adjusted through the motor driver by varying the PWM signals sent from the microcontroller [19]. PWM allows for efficient control of the average power delivered to the motors by rapidly switching their power on and off at a high frequency. By changing the duty cycle of the PWM signal—the ratio of time the signal is high versus low—it's possible to control the effective voltage and, consequently, the motor speed. For instance, a higher duty cycle results in a higher average voltage, leading to faster motor speeds, while a lower duty cycle reduces the voltage and slows the motor down. This method of speed control is crucial for ensuring smooth adjustments and achieving precise control over the pneumatic actuation of the rehabilitation glove, ultimately enhancing the rehabilitation experience for post-stroke patients. The control unit is shown in fig27.

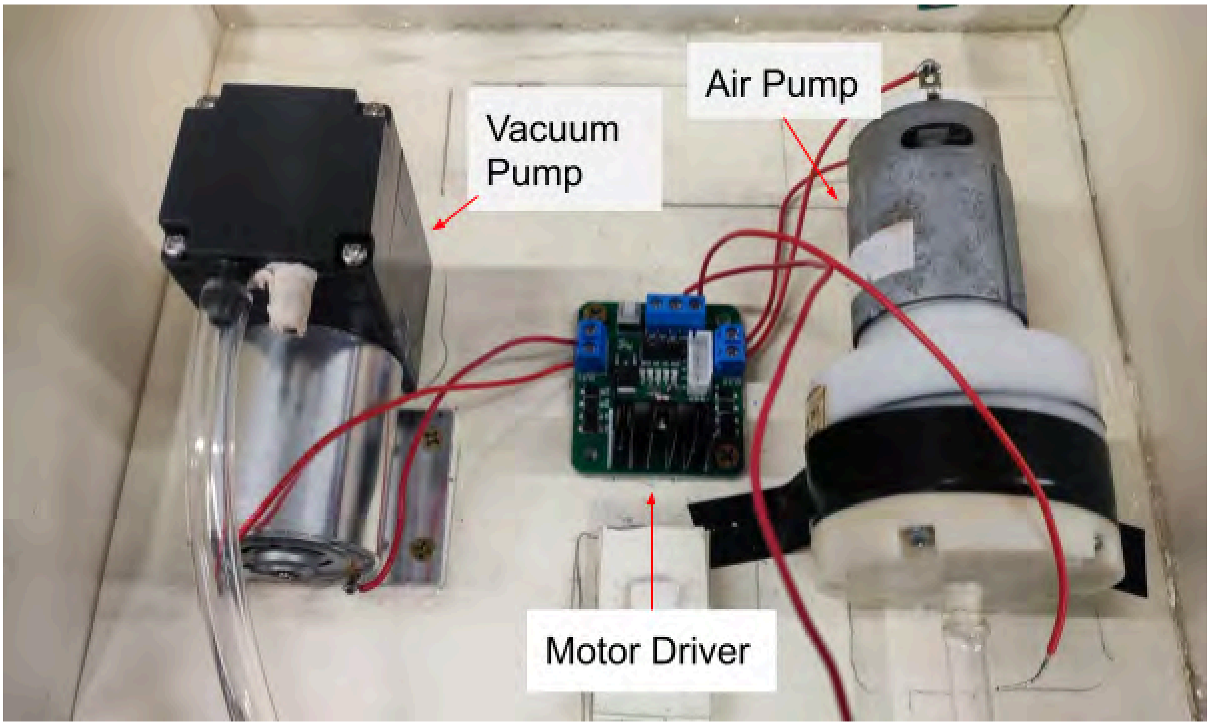


Fig. 27: Control Unit

5.2.2.2 Power Unit:

The power unit is a critical subsystem of the design as it is responsible for supplying energy to both the control unit and the communication unit. It provides 11.7V of power to the control unit for motor operation and 5V to the microcontroller. The sensors of the communication unit also receive 5V power from this unit.

The power unit has a battery pack consisting of six 3.7V, 2 Amp lithium-ion batteries arranged in a 3S (3-series) configuration [20]. This setup delivers a nominal voltage of 11.7V and a capacity of 7500mAh, making it well-suited for powering the system reliably [20]. The choice of lithium-ion batteries is based on their high energy density, reliability, and rechargeability, which are essential for portable electronic applications that demand energy efficiency and longevity.

To ensure safe and reliable operation, a 3S 20 Amp battery management system (BMS) is integrated into the design [21]. The BMS plays a vital role in monitoring the voltage levels of each individual battery cell during both charging and discharging cycles. This monitoring prevents overcharging or excessive discharging, which could compromise the health and performance of the batteries over time. Additionally, the BMS provides protection against overcurrent, undervoltage, and short circuits, safeguarding both the battery pack and the connected electronic components.

The integration of the BMS not only enhances safety but also optimizes the operational efficiency of the battery pack [21]. By actively balancing the charge among individual cells, the BMS helps maintain uniform cell voltages, which prolongs the lifespan of the batteries. The power unit is shown in fig28.

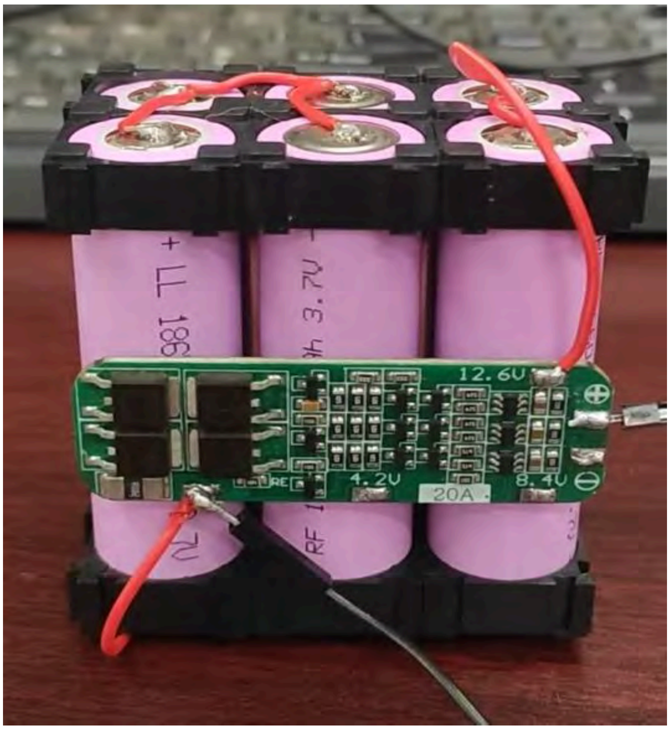


Fig. 28 : Power Unit

5.2.2.3 Communication Unit:

The Communication Unit is equipped with flex sensors and a force sensor placed at the fingertips. These sensors are designed to detect finger movements and communicate this information directly to the base station. This real-time data transmission allows the base station to monitor the rehabilitation process closely and make necessary adjustments, ensuring that treatment remains accurate and effective.

For the sensor integration within the glove, five flex sensors are employed to monitor the bending angle of each finger. These sensors measure the degree of movement, and the collected data is transmitted to the microcontroller [22]. Additionally, a force sensor detects the overall force exerted by the hand's muscle movements. The Bluetooth module receives data from the microcontroller and sends it to the mobile application via Bluetooth, enabling real-time visualization of the bending angles and force values on the app's interface.

In addition to real-time monitoring, the application will maintain a record of weekly updates on the bending angles. This feature allows healthcare providers to track the patient's progress over time. With these detailed reports, doctors can prescribe personalized adjustments to the therapy, thereby enhancing its effectiveness. The communication unit is shown at fig29.

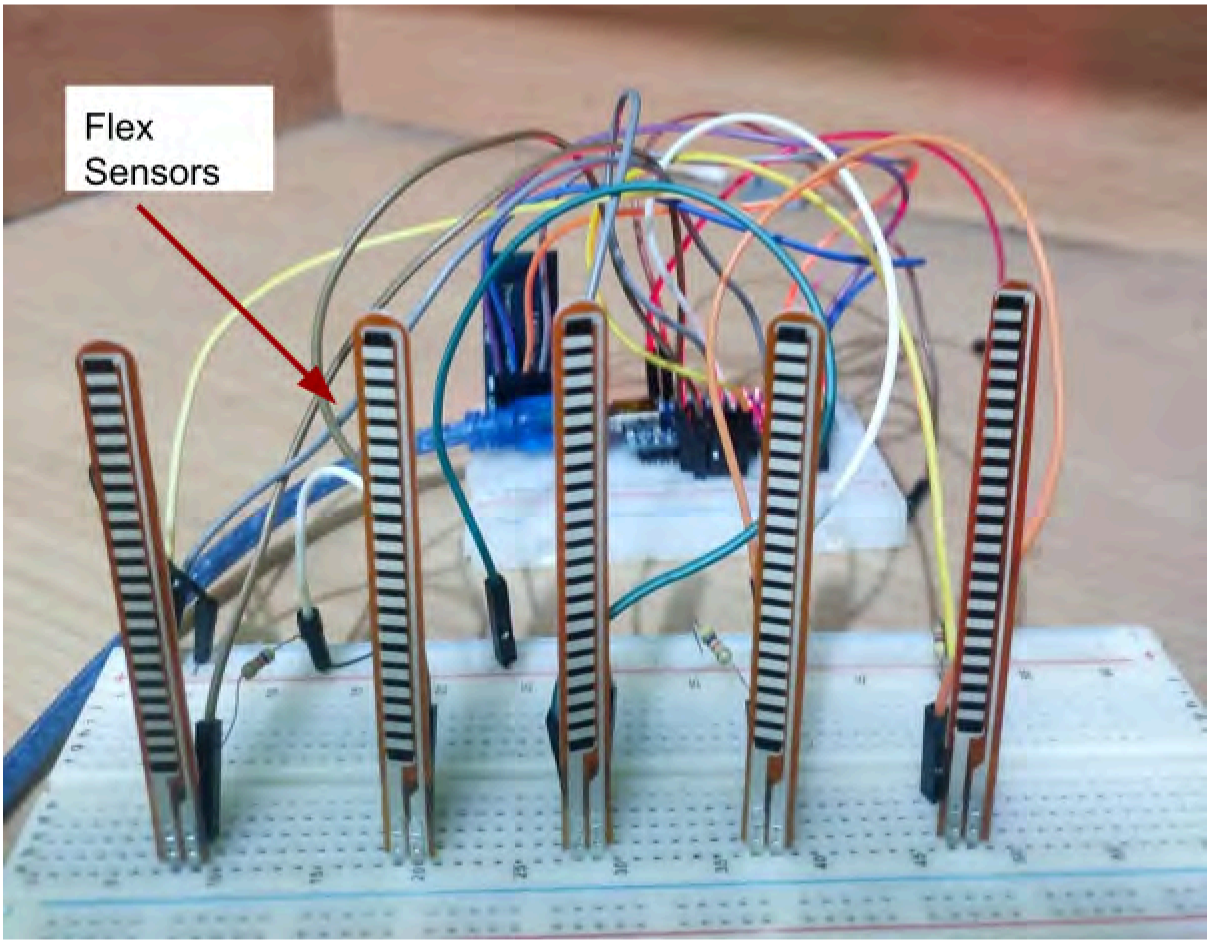


Fig. 29: Flex sensors connected with communication unit

5.2.2.4 Structure

The structure serves as the primary physical interface that directly engages with the patient. It comprises two main components: the Pneumatic Artificial Muscle (PAM) and the Manifold Valve [23]. The PAM is designed to replicate hand gestures for patients with paralysis, offering a lightweight and flexible solution that generates the necessary force and movement for effective rehabilitation. Meanwhile, the Manifold Valve ensures even pressure distribution across the muscles, enhancing their operational efficiency. This coordinated system provides precise control and balanced support, contributing to positive therapeutic outcomes.

The glove features a core structure constructed from flexible and durable materials, allowing it to conform to the user's hand comfortably. Within this base layer, pneumatic muscles are embedded to replicate the movement and functionality of human fingers. The pneumatic muscle inflates and deflates, mirroring the natural flexion and extension of the fingers.

The microcontroller of the control unit controls the pneumatic muscles of the structure, managing the timing and pressure of the air supplied to each muscle. Meanwhile, the sensors of the control unit are embedded over the glove, which provide real-time feedback on finger position and movement. Thus, the structure is connected with the other subsystems and controlled as needed. The structure is shown at fig 30.

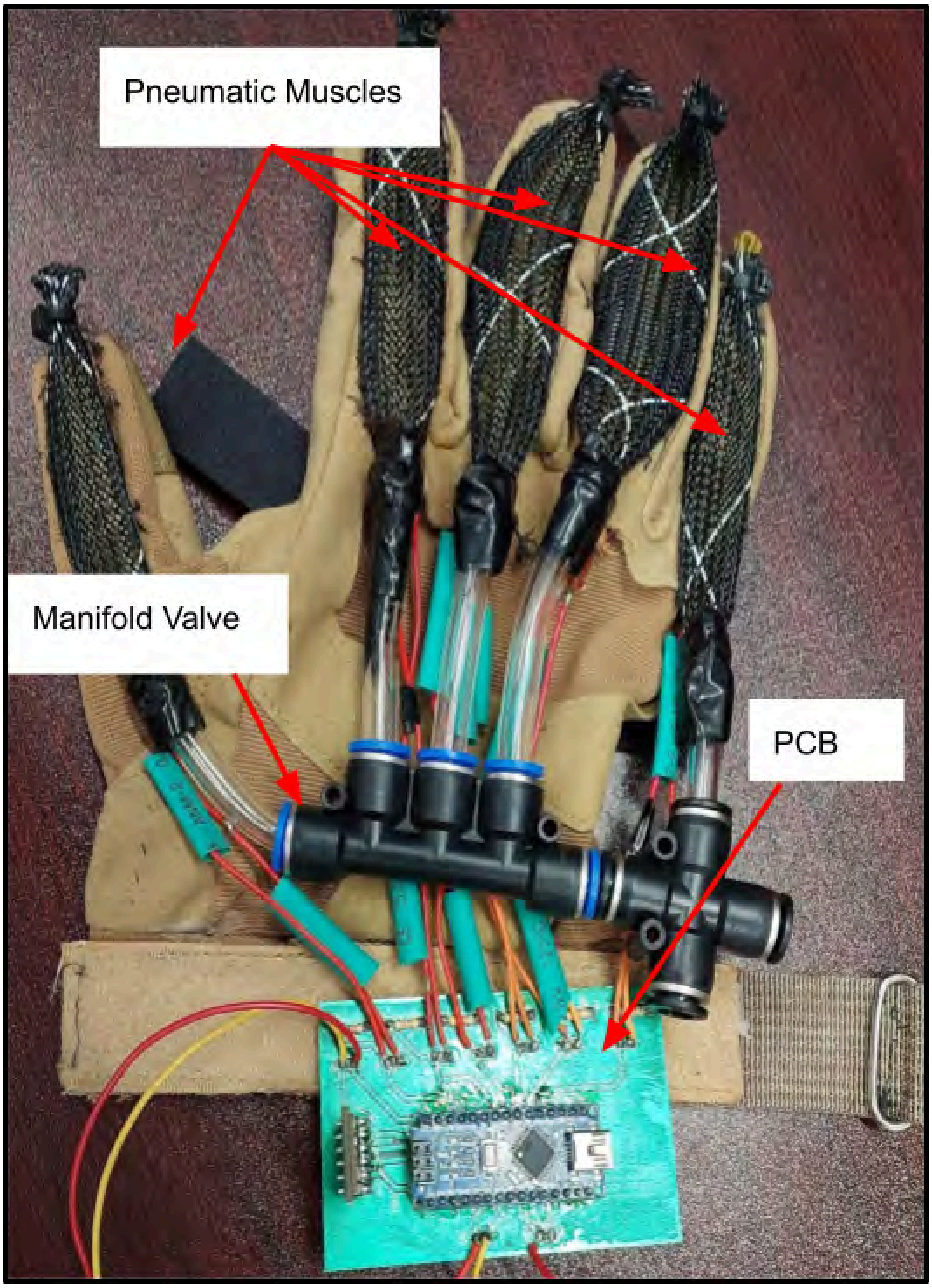


Fig 30: Pneumatic muscle with the Manifold Valve

5.2.2.5 PCB designing of the subsystem

The Printed Circuit Board (PCB) design for this project is essential for integrating the components of the control unit, base station, and communication unit within the structure of the glove.The Arduino Nano of the control unit is at the core of the PCB. It is responsible for managing the system's functions, processing data from external sensors. The flex and force sensors, of the communication unit, are connected to the PCB through precisely routed signal pathways, ensuring accurate data transmission while minimizing signal degradation. In addition, the PCB also incorporates the HC-05 Bluetooth module of the base station subsystem. The PCB is designed for careful placement of components and routing of traces to ensure stable connections and reliable performance. Therefore, the compact footprint of the PCB is a critical design consideration, balancing the need for a small, portable solution with the requirement for robust functionality. Overall, the PCB design effectively combines the functionality of the control unit, base station, and communication unit, ensuring that all components work harmoniously within the smart rehabilitation glove. The 3D layout of the PCB is shown in Figure 31.

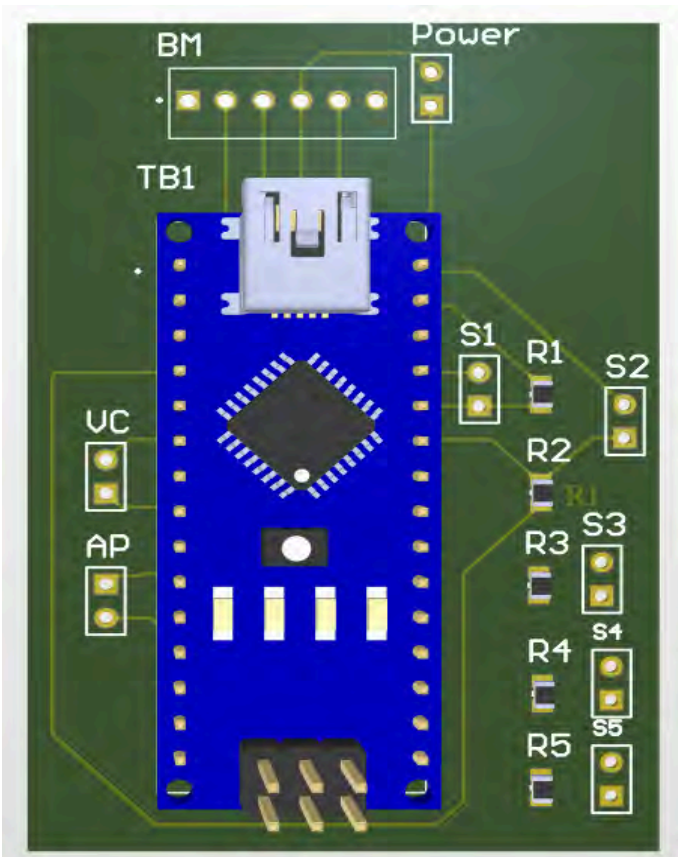
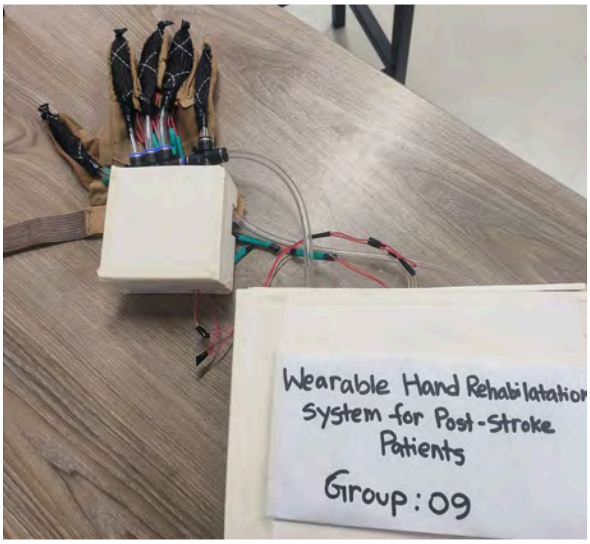


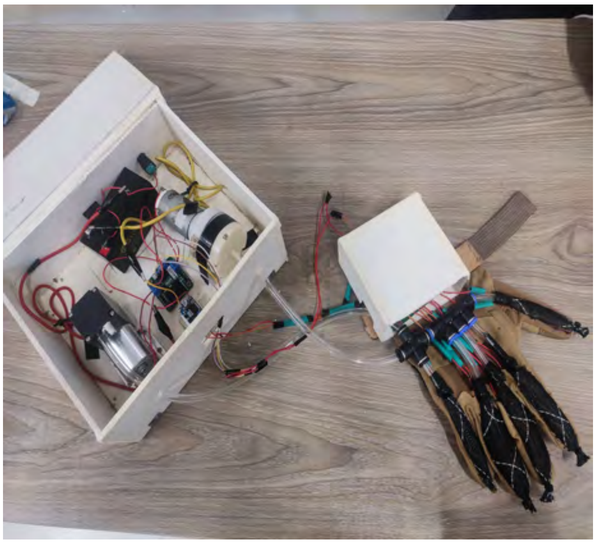
Fig 31. PCB Design

5.2.3 Final Prototype of the Device

The final prototype of the wearable hand rehabilitation system for post-stroke patients represents the culmination of thoughtful design and engineering efforts. This innovative device uses pneumatic muscles to replicate natural hand movements, helping patients engage more effectively in rehabilitation exercises. Equipped with flex sensors, the system provides real-time tracking of finger bending angles, delivering meaningful feedback to both patients and healthcare providers.

Housed within the control box are essential components, including the air and vacuum pumps, and a power management system, ensuring smooth operation. With IoT integration, the system supports remote monitoring and personalized therapy sessions, improving both accessibility and efficiency in rehabilitation. Its compact, user-friendly design encourages patient compliance, making it easier to incorporate into daily routines. This project bridges the gap between traditional rehabilitation methods and advanced technological care, offering stroke survivors a practical, affordable, and effective path to recovery.





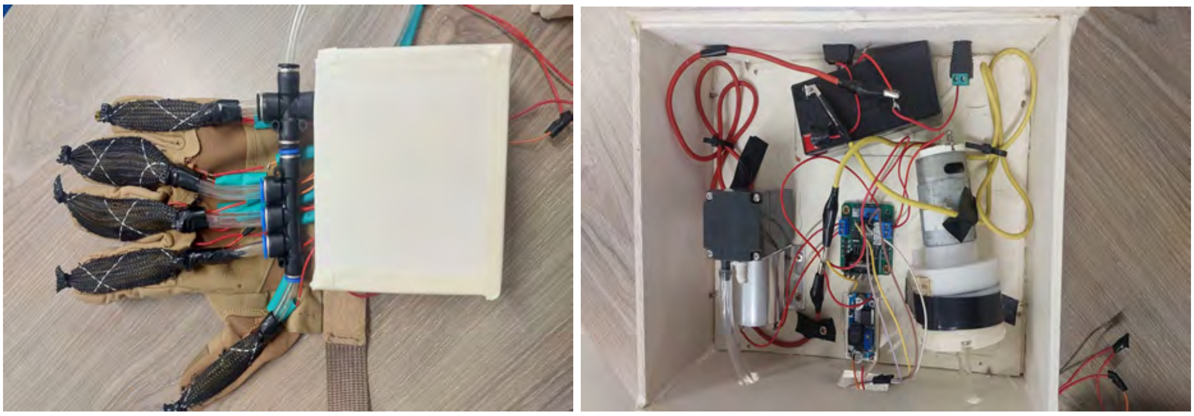


fig. 32: Final Prototype of the Wearable Hand Rehabilitation System for Post-Stroke Patients

5.3 Evaluate the solution to meet the desired need

This chapter presents the evaluation of the wearable hand rehabilitation system developed for stroke survivors, focusing on its performance metrics concerning hand rotation accuracy and error percentages. The results are analyzed to determine the system's effectiveness in meeting the rehabilitation needs of patients.

Sensing Accuracy Across Multiple Trials for Finger Bending Angles

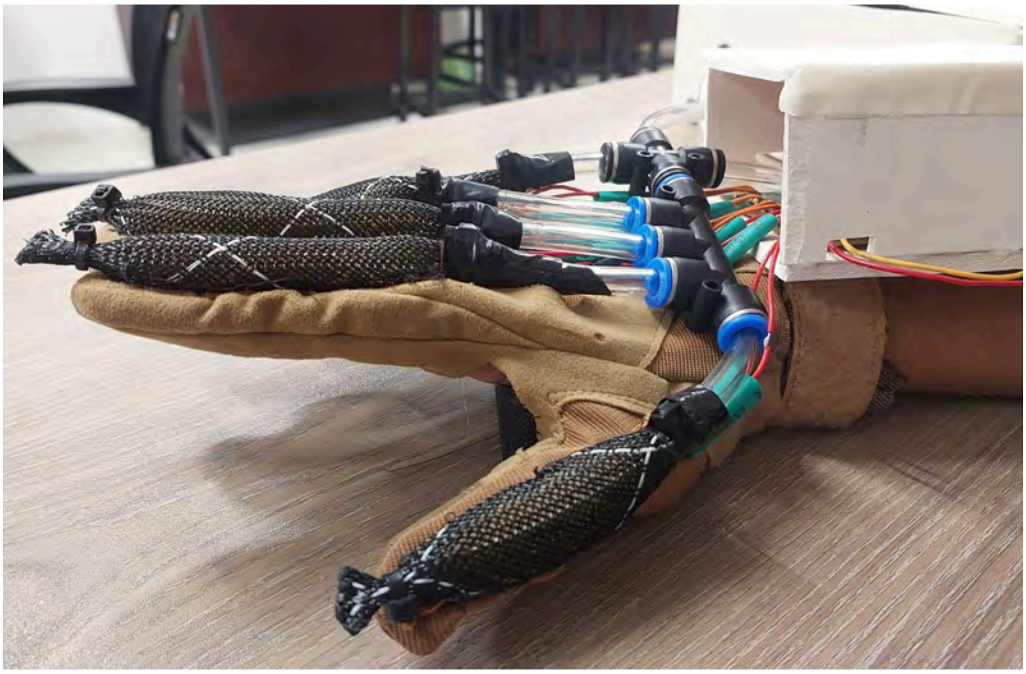
To measure sensing accuracy, several trials have been run, during which the performance of the flex sensors was evaluated across different input rotations (30°, 45°, 60°, and 90°). In each trial, the bending angles of five fingers (Thumb, Index, Middle, Ring, and Pinky) were recorded and compared with the expected input angles. The results from these trials were used to calculate the sensing accuracy for each input angle, indicating how effectively the sensors replicate the intended rotations. The sensing accuracy percentage reflects the average performance across all fingers for each input angle. Additionally, the overall accuracy, derived from individual trials, provides a comprehensive view of the system's reliability. This detailed analysis highlights the consistency of the sensors and helps identify any deviations or areas that may require further calibration.

Table 8: Sensing Accuracy Across Multiple Trials for Finger Bending Angles

Input (degree)	Trial 1					Trial 2					Trial 3					Sensing Accuracy
	Fin 1	Fin 2	Fin 3	Fin 4	Fin 5	Fin 1	Fin 2	Fin 3	Fin 4	Fin 5	Fin 1	Fin 2	Fin 3	Fin 4	Fin 5	
30	28	32	33	36	31	24	31	33	28	30	32	27	26	33	34	91.25%
45	43	46	45	41	49	44	47	48	47	45	41	46	48	51	52	93.48%
60	63	58	56	59	60	66	67	65	68	64	63	64	66	58	63	92.21%
90	96	92	88	86	94	80	81	79	82	85	90	92	91	96	89	95.47%
											Overall accuracy= 93.10%					

Here in the table fin 1, fin 2,fin 3,fin 4,fin 5 represents thumb finger, index finger, middle finger,ring Finger and little finger respectively. And the input denotes the given angle on the sensors.

(i)



(ii)

Fig33: Testing of the gloves. i. Closing the glove ii.Opening the glove

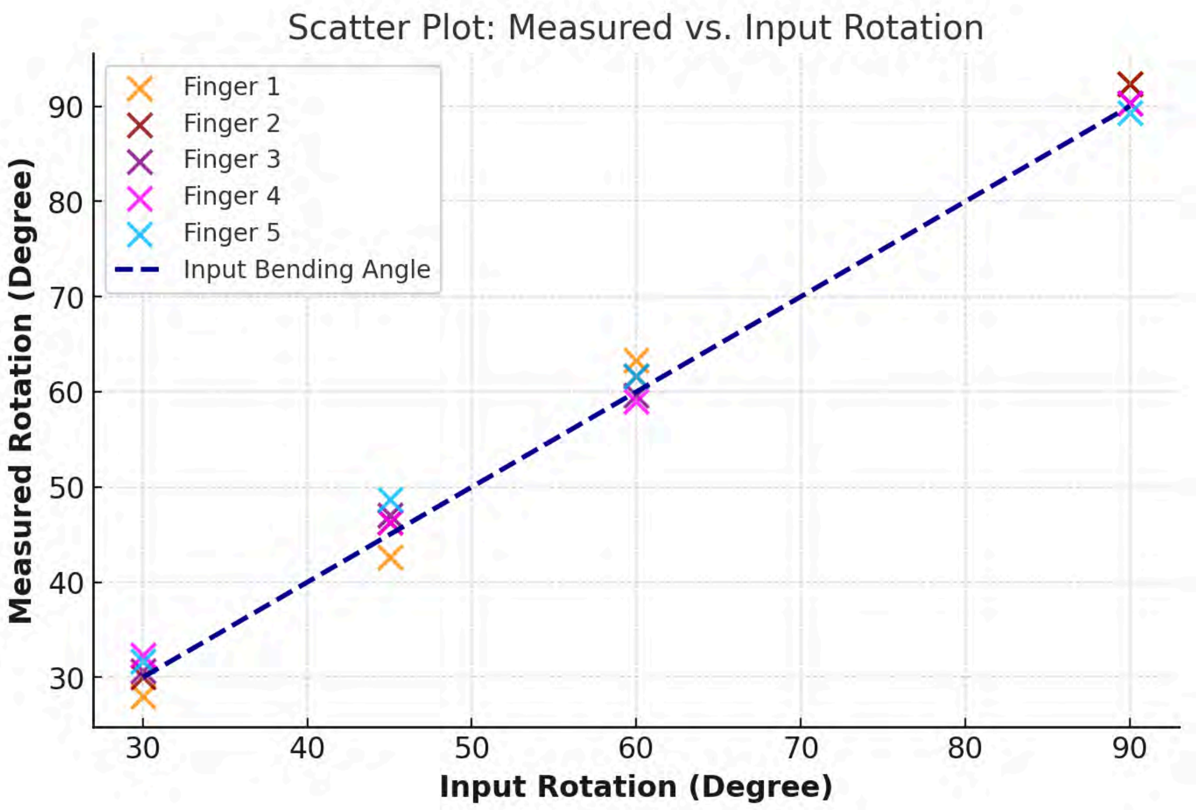


Fig 34: Comparison of Input Bending Angle vs. Measured Rotation Across Fingers

This plot illustrates the relationship between the input rotation angles (expected bending angles) and the measured rotations from five flex sensors across multiple trials. Each cross represents the average measured rotation for a specific finger (Thumb, Index, Middle, Ring, and Pinky) at given input angles. The dark blue dashed line marks the ideal scenario, where measured values perfectly align with the input angles. Most data points closely follow this line, indicating good sensor accuracy. Minor deviations from the line suggest slight inconsistencies in some measurements, highlighting areas for potential improvement. As the input angle increases (from 30 to 90 degrees), the measured rotations remain consistent, reflecting reliable performance at higher angles. The enhanced marker visibility and gridlines improve readability, making it easier to interpret the data and assess the system's overall sensing performance.

Performance Metrics of Hand Rotation

The following table summarizes the expected and resulted hand rotation angles, along with their corresponding accuracy and error percentages measured at different time intervals as [24] described:

Table 9: Performance Metrics of Hand Rotation (Accuracy and Error by Interval)

Expected Hand rotation		**Resulted Hand rotation**		**Accuracy**	**Error percentage**
Time (sec)	**Bending Angle (Degree)**	**Time (sec)**	**Bending Angle (Degree)**	$\eta=\frac{n1}{n2} \times 100\%$	**e=100%-η**
0	0	0	0	N/A	N/A
0.5	15	0.5	12	80%	20%
1	30	1	31	96.47%	3.53%
1.5	45	1.5	40	88.88%	11.12%
2	60	2	64	93.75%	6.25%
2.5	75	2.5	78	96.42%	3.58%
3	90	3	97	92.73%	7.27%

	Average Accuracy=91.38%	Average error= 8.2%

As demonstrated in Table 7, the wearable hand rehabilitation system shows a commendable range of accuracy across various time intervals, with an overall average accuracy of 91.38%. This suggests that the device effectively meets the expected hand rotation during rehabilitation exercises. This is happening because of a time delay.

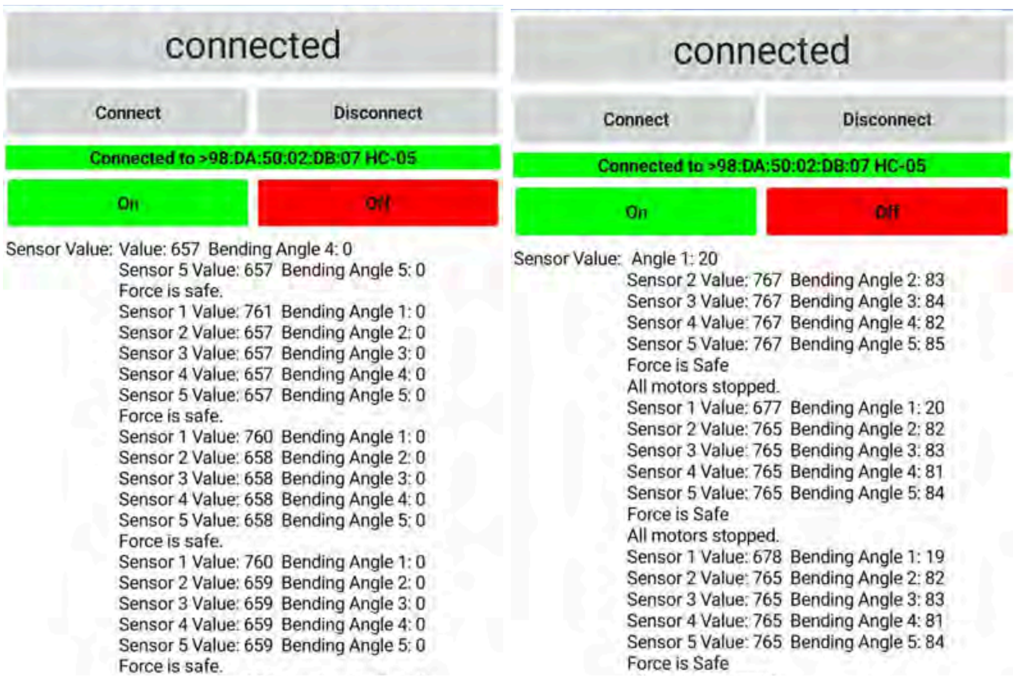


Fig. 35: Bending Result in the mobile App

Error Analysis

The error percentages provide critical insights into the system's reliability. The system exhibited the lowest error percentage of 3.58% at the 2.5-second mark, indicating optimal performance during this interval. Conversely, the highest error percentage of 20% occurred at the 0.5-second mark, highlighting the need for further refinements to enhance performance during shorter durations.

Graphical Representation

As shown at [25], figure 35 illustrates the expected hand rotation compared to the resulted hand rotation over time, providing a visual representation of the device's performance:

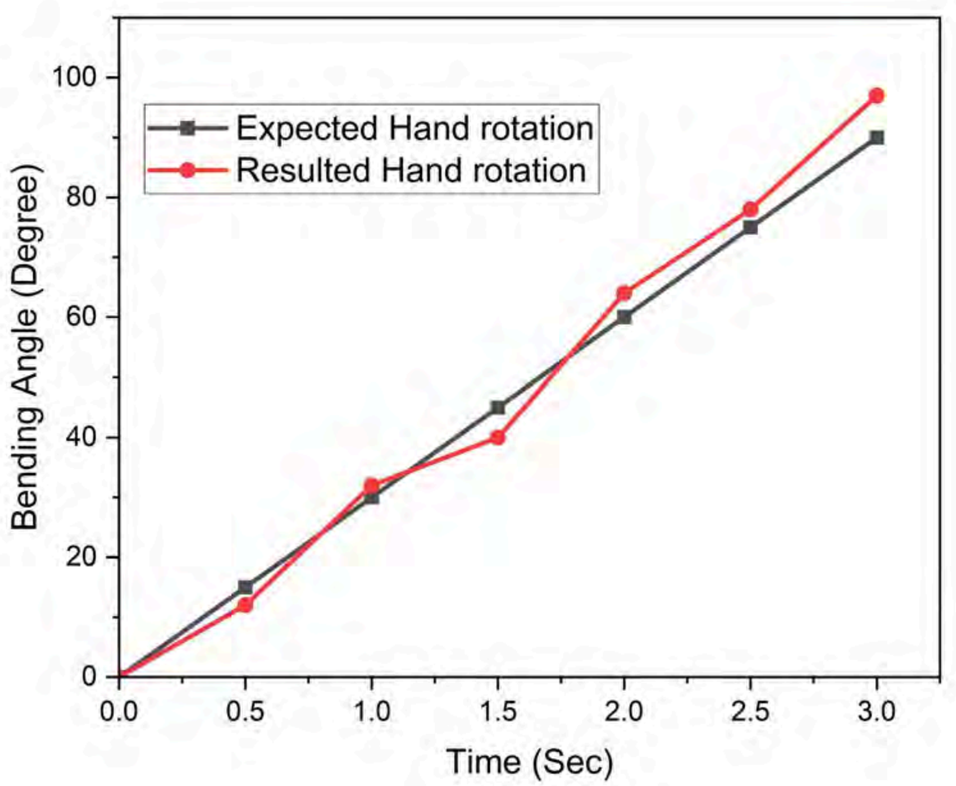


Fig. 36: Expected Degree of Hand Rotation & Resulted Hand Rotation by the device vs Time (sec)

As shown in [26], Figure 36 illustrates the accuracy and error percentages at different time intervals, providing a visual representation of the device's performance:

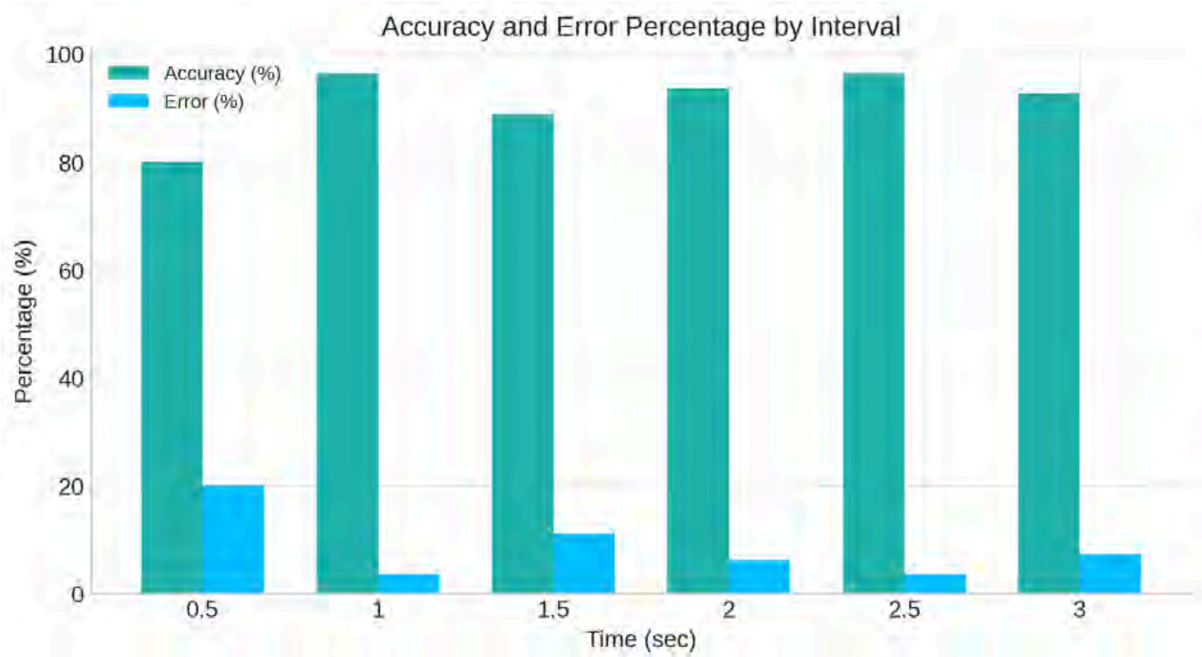


Fig. 37: Accuracy and Error Percentage by Interval

The graph depicts the accuracy and error percentages across various time intervals, highlighting the fluctuation in accuracy, particularly at the 0.5-second interval where the error percentage is notably higher. As the time interval increases, the accuracy stabilizes and the error percentage decreases, suggesting improved performance of the device with longer durations.

Power Consumption Analysis:

The device is powered by a 12V 1.3Ah rechargeable lithium-ion battery, which supplies energy to two motors: an air pump motor (12V, 200 mA) and a vacuum pump motor (12V, 500 mA). Additionally, the battery is connected to a buck converter, which regulates the voltage to 4.7V for the microcontroller, ensuring stable operation. Now calculating the power consumption,

The air motor consumes power of, $P_{air} = V \times I = 12 \times 0.2 = 2.4$ W

The Vacuum motor consumes power of, $P_{vacuum} = V \times I = 12 \times 0.5 = 6$ W

The power consumption of Arduino nano, $P_{nano} = V \times I = 4.6 \times 0.04 = 0.184$ W so, the total consumption of power, P_{device} = 2.4 W+ 6 W+ 0.184 W = 8.58 W

Now, the energy available in the battery, $E_{battery}$= 12V×1.3 Ah= 15.6 Wh

So, total run time, Run time=$E_{battery}$ ÷ P_{device} = 15.6 Wh ÷ 8.58 Wh = 1.82 hours

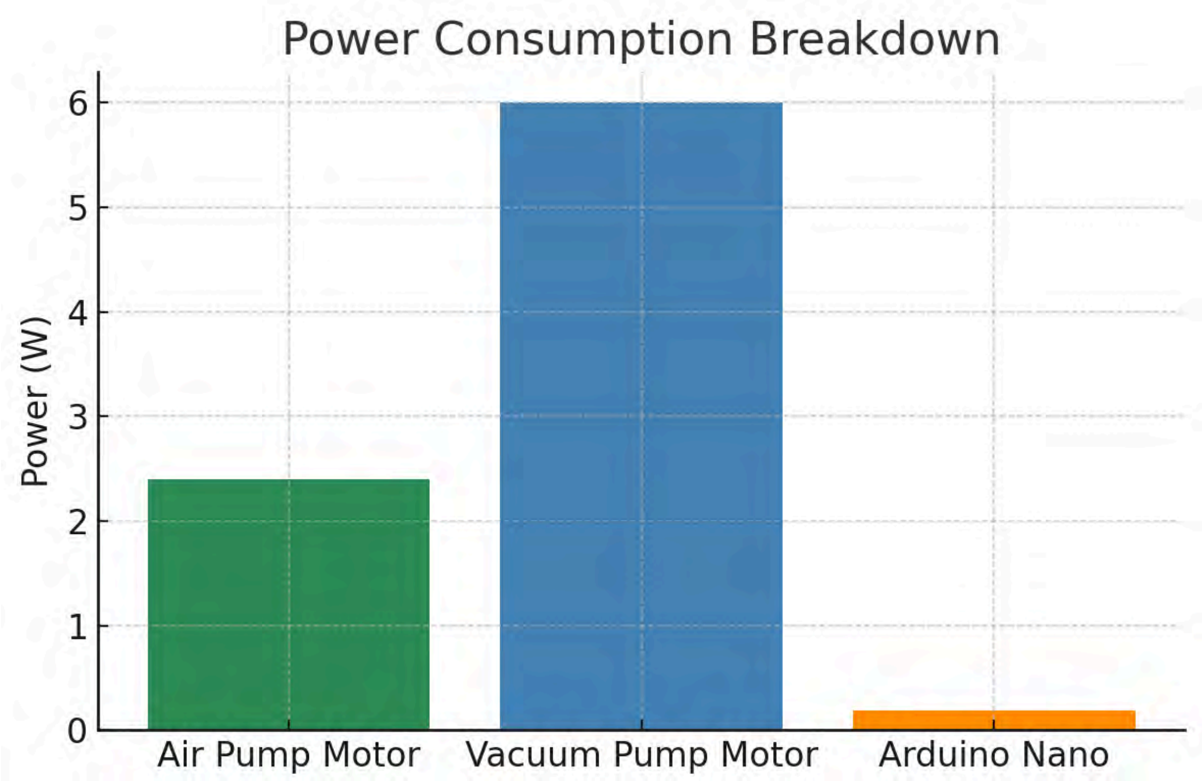


Fig. 38: Power consumption breakdown of system components

Performance Analysis of the device in Hardware and Software:

Software Efficiency:

In the simulation setup, a 5k ohm variable digital potentiometer has been used to control the bending of the flex sensor. This potentiometer serves as a variable resistor whose resistance can be adjusted electronically. As the resistance in the potentiometer changes, it directly influences the bending angle of the flex sensor. The flex sensor, capable of bending up to 1023 degrees, has a linear relationship between its bending angle and the resistance applied to it. Therefore, the theoretical change in bending angle for each ohm of resistance variation in the potentiometer can be calculated as the maximum bending angle (1023 degrees) divided by the maximum resistance of the potentiometer (5000 ohms). This relationship allows for precise control over the bending angle based on the resistance settings of the potentiometer.

Let, $\nabla\theta$ is the the change in bending angle per ohm of resistance variation, θmax denotes the maximal bending angle of the flex sensor and Rpot signifies the uppermost resistance of the digital potentiometer.

So, $\nabla\theta = \frac{\theta max}{Rpot}$ degree per ohm of resistance variation [11].

In consideration of patient safety, the device has been designed to limit the rotation of the flex sensor to a maximum of 270 degrees. Excessive rotation beyond this threshold may pose a risk of discomfort or injury to the patient. Consequently, the range of resistance values in the digital potentiometer has been adjusted to ensure that the corresponding bending angle of the flex sensor does not exceed this limit. By carefully calibrating the resistance settings within this constrained range, the device can provide controlled and safe rehabilitation exercises for the patient, optimizing both effectiveness and safety.

Now, calculating bending angle for different resistance in the digital potentiometer and comparing it with the simulated result,

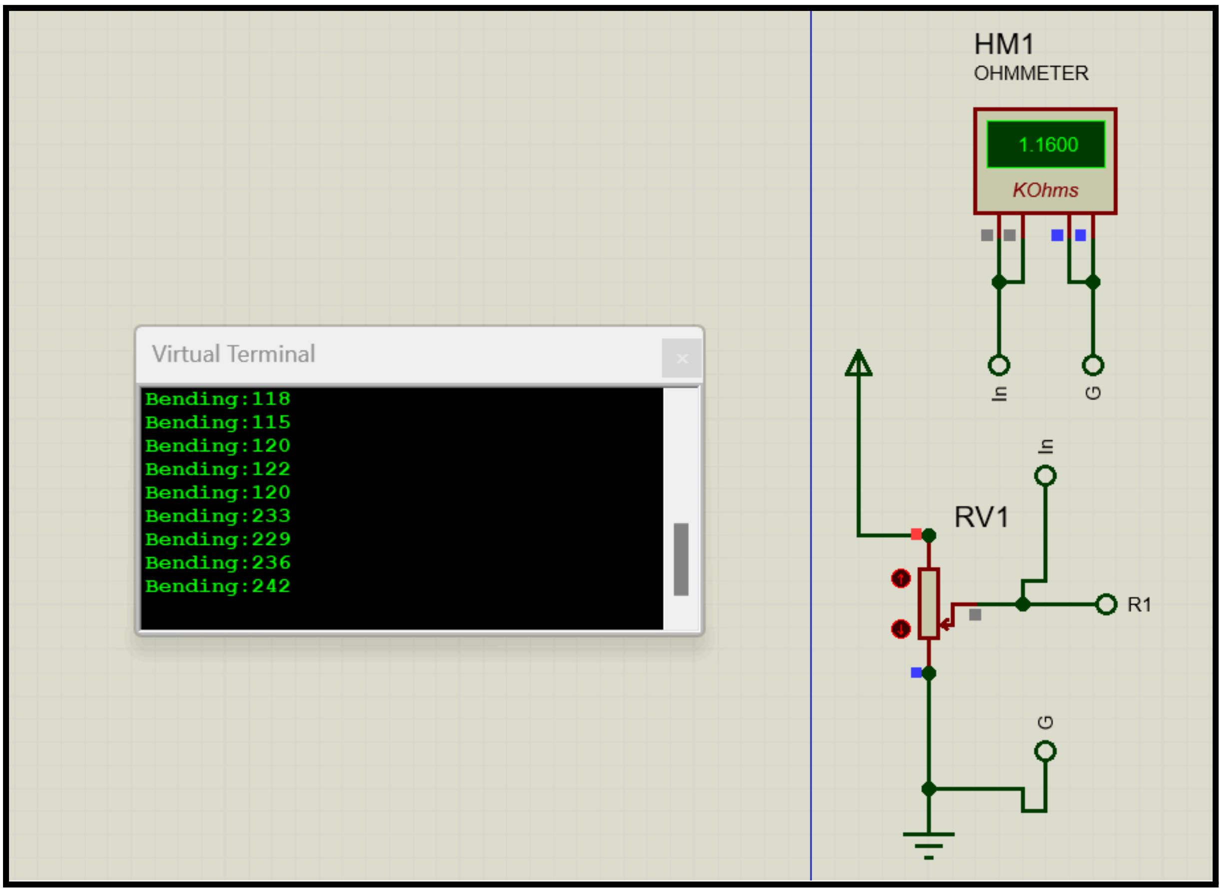


Fig. 39: Change in bending angle for different resistance

Table 10: Comparison of Theoretical and Simulated Bending Angles for Different Resistance Values

Resistance (ohm)	Theoretical Bending Angle (degrees)	Simulated Bending Angle (degrees)	Efficiency (η)	Error percentage (e)
600	121.24	120	98.96%	1.04%
700	143.22	141	98.44%	1.56%
800	163.68	162	98.93%	1.07%
900	184.14	188	97.91%	2.09%
1000	204.60	208	98.22%	1.78%
1150	233.29	229	98.16%	1.84%
1300	265.98	266	97.41%	2.59%
			Average Efficiency=98.28%	Average error= 1.71%

Efficiency Analysis and Comparison:

The hardware efficiency was evaluated by comparing the expected hand rotation with the resulting hand rotation. The hardware trials showed a range of accuracies across different bending angles, with an average accuracy of 91.38% and an average error of 8.2%. As the angles increased, slight discrepancies between the expected and actual angles emerged, suggesting that factors such as mechanical alignment, sensor precision, or signal noise may affect performance. The highest observed error percentage was 11.12% at a 45-degree bending angle, while the lowest error was 3.53% at a 30-degree angle.

The software efficiency was assessed by comparing the theoretical bending angle (calculated based on resistance values) with the simulated bending angle from software models. The software exhibited high accuracy, with an average efficiency of 98.28% and an average error of only 1.71%. Across multiple trials, the maximum error was 2.59% for a resistance value of 1300 ohms, and the minimum error was 1.04% for 600 ohms. These results indicate that the simulation model is highly reliable in predicting bending behavior, suggesting precise calculations and well-defined mathematical models.

While both the hardware and software systems demonstrate good performance, the software efficiency (98.28%) surpasses the hardware efficiency (91.38%). This discrepancy can be attributed to several factors:

1. Environmental Variables: Hardware performance is influenced by mechanical losses, sensor data inaccuracies, and potential interference, which are absent in the software simulation.

2. Ideal Conditions in Software: Software models operate under controlled, ideal conditions without the unpredictability of the physical systems, which leads to more precise results.

3. Calibration Issues: Hardware errors may reflect limitations in sensor calibration, mechanical wear, or signal degradation that reduce measurement precision.

5.4 Conclusion

The development of the smart rehabilitation glove has successfully culminated in a functional design that integrates all critical subsystems. We optimized the individual components, including sensor integration, circuit design, programming, power management, and the base station, ensuring each element performs effectively within the overall system..

Ultimately, the completed prototype not only meets the technical requirements but also transforms the initial concept into a practical therapeutic device tailored to support upper limb recovery for post-stroke patients. With its intuitive interface providing real-time, accurate feedback, the smart rehabilitation glove stands poised for real-world rehabilitation applications, promising to make a meaningful impact in the lives of users.

Chapter 6: Impact Analysis and Project Sustainability.

6.1 Introduction

The development of a smart hand for post-stroke patients represents a significant advancement in rehabilitation technology, addressing the challenges faced by individuals striving to regain motor function in their hands. Stroke survivors often experience difficulties in performing essential daily tasks, which can compromise their independence and reduce their quality of life. This project introduces a wearable device equipped with advanced sensor technology to facilitate personalized rehabilitation exercises. The system provides real-time feedback and adaptive therapy programs tailored to the patient's progress, focusing on improving hand dexterity and functional skills required for everyday activities. By supporting stroke survivors in regaining independence, the smart hand aims to enhance recovery outcomes and foster long-term improvements in quality of life.

6.2 Assess the impact of solution

The introduction of the smart hand technology offers the potential to transform post-stroke rehabilitation outcomes across several dimensions, including societal, health, safety, legal, and cultural aspects. The system leverages sensors and AI to monitor hand movements precisely, enabling customized rehabilitation exercises that adapt to individual needs at different stages of recovery. The provision of real-time feedback enhances patient engagement and motivation, which are essential for sustaining long-term adherence to therapy. By focusing on restoring abilities such as gripping, writing, and self-care, the device aims to improve the overall quality of life for stroke survivors, positively influencing health and societal outcomes. Additionally, adherence to established safety standards and legal guidelines ensures ethical implementation within healthcare settings, reinforcing the responsible deployment of the technology.

6.3 Evaluate the sustainability

Ensuring the sustainability of the smart hand project requires careful evaluation of both its environmental impact and societal benefits. The ongoing development of sensor technology enables continuous refinement of rehabilitation strategies to meet evolving patient needs. Environmental considerations are addressed through responsible manufacturing processes and appropriate disposal methods for the device. The ergonomic design and user-friendly interface promote adoption within healthcare settings, facilitating accessibility and scalability. Furthermore, affordable pricing strategies enhance market penetration, ensuring equitable access to advanced rehabilitation technologies. By integrating technical innovation with environmental, social, and legal responsibility, the project establishes a sustainable model that aims to support long-term rehabilitation outcomes and foster patient independence.

6.4 Conclusion

The smart hand project exemplifies a commitment to addressing complex engineering challenges while aligning with health, safety, legal, cultural, and environmental considerations. Through the use of advanced technology, the device delivers personalized rehabilitation therapy with real-time feedback, empowering stroke survivors on their path to recovery. Collaboration with healthcare professionals and the integration of continuous feedback loops ensure that the system evolves in response to patient needs. By prioritizing sustainability and responsible innovation, the project aims to redefine post-stroke rehabilitation outcomes and establish new standards for engineering practices in the healthcare field.

Chapter 7: Engineering Project Management.

7.1 Introduction:

Effective project management is critical to the success of engineering projects, ensuring tasks are completed efficiently, objectives are met, and resources are used optimally. It involves a range of activities, such as defining project scope, planning tasks, coordinating resources, and monitoring progress. In the Smart Rehabilitation Glove project, the objectives included developing a cost-effective and user-friendly rehabilitation glove for post-stroke patients. The project was divided into manageable tasks with specific timelines to ensure smooth execution. Regular meetings were held to address potential challenges and keep tasks aligned with the project schedule. Resource management was essential to ensure materials, tools, and personnel were available when needed, while risk management strategies helped identify and mitigate potential obstacles. Continuous progress evaluations allowed for comparison between planned and actual performance, enabling timely corrective actions. This structured approach ensured that the project met its objectives efficiently and contributed to advancements in rehabilitation technology.

7.2 Define, plan and manage engineering project

A structured methodology is essential for the successful completion of engineering projects within defined timelines and constraints. This section outlines the key phases of defining, planning, and managing the Smart Rehabilitation Glove project.

Defining the Project

The first phase of the project involved establishing clear objectives, scope, and deliverables. The primary objective was to develop a user-friendly and affordable device for post-stroke rehabilitation. The scope of the project included integrating sensor technology, creating an interface for visualizing data, and ensuring the device's safety and comfort for users. The key deliverables consisted of a working prototype, a detailed project report, and a final presentation of the project outcomes.

Planning the Project

Effective planning requires breaking the project into smaller, manageable tasks, setting deadlines, and allocating resources to cover all aspects of the project. A detailed project plan ensured that risks were identified and mitigated in advance. The following table provides an overview of the project schedule, highlighting specific tasks, their start and end dates, and the duration required for completion. This planning process ensured that the project stayed on track and that each component was completed within the allocated time.

EEE499P:

FYDP-P

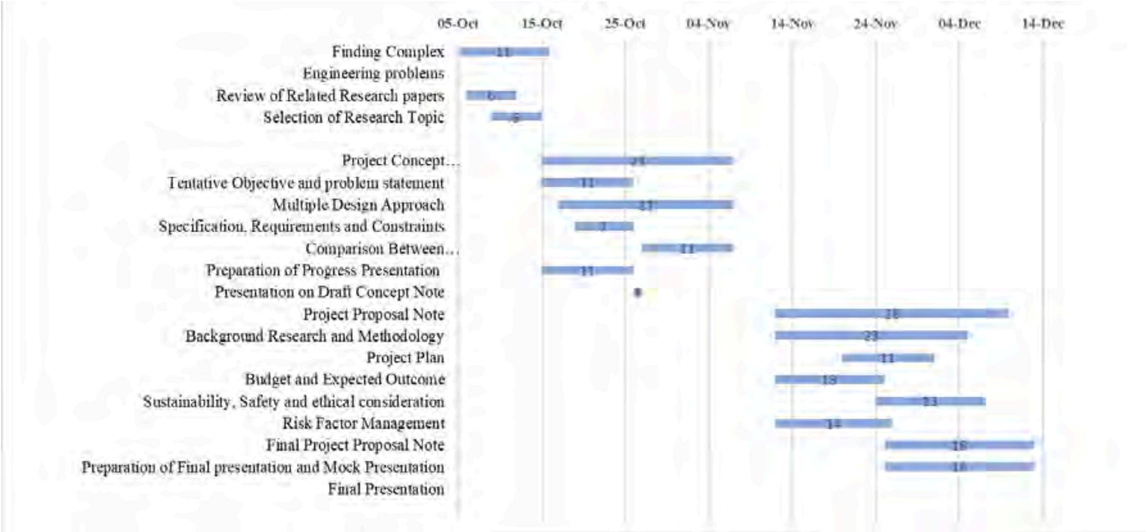


Fig. 40: Gantt Chart for EEE499P

Table 11: EEE499P Project Plan

Task	Start date	End date	Duration
Topic Selection	**5 October, 2023**	**15 October 2023**	**11 Days**
Finding Complex Engineering problems	5 October, 2023	10 October, 2023	6 Days
Review of Related Research Papers	6 October, 2023	12 October, 2023	7 Days
Selection of Research Topic	9 October, 2023	15 October, 2023	6 Days
Project Concept Note	**15 October, 2023**	**8 November, 2023**	**23 Days**
Tentative Objective and problem statement	15 October, 2023	26 October, 2023	11 Days

Multiple Design Approach	17 October, 2023	8 November, 2023	21 Days
Specification, Requirements and Constraints	19 October, 2023	26 October, 2023	7 Days
Comparison Between Design Approaches	27 October 2023	8 November, 2023	11 Days
Preparation of Progress Presentation Progress	15 October, 2023	26 October, 2023	11 Days
Presentation on Draft Concept Note	26 October, 2023	26 October, 2023	1 Day
Project Proposal Note	**12 November, 2023**	**14 December, 2023**	**28 Days**
Background Research and Methodology	12 November, 2023	5 December, 2023	23 Days
Project Plan	20 November, 2023	30 November, 2023	11 Days
Budget and Expected Outcome	12 November, 2023	24 November, 2023	13 Days
Sustainability, Safety, and Ethical consideration	24 November, 2023	7 December, 2023	13 Days
Risk Factor Management	12 November, 2023	25 November, 2023	14 Days
Final Project Proposal Note	25 November, 2023	13 December, 2023	18 Days
Preparation of Final presentation and Mock Presentation	25 November, 2023	13 December, 2023	18 Days
Final Presentation	14 December, 2023	14 December, 2023	1 Day

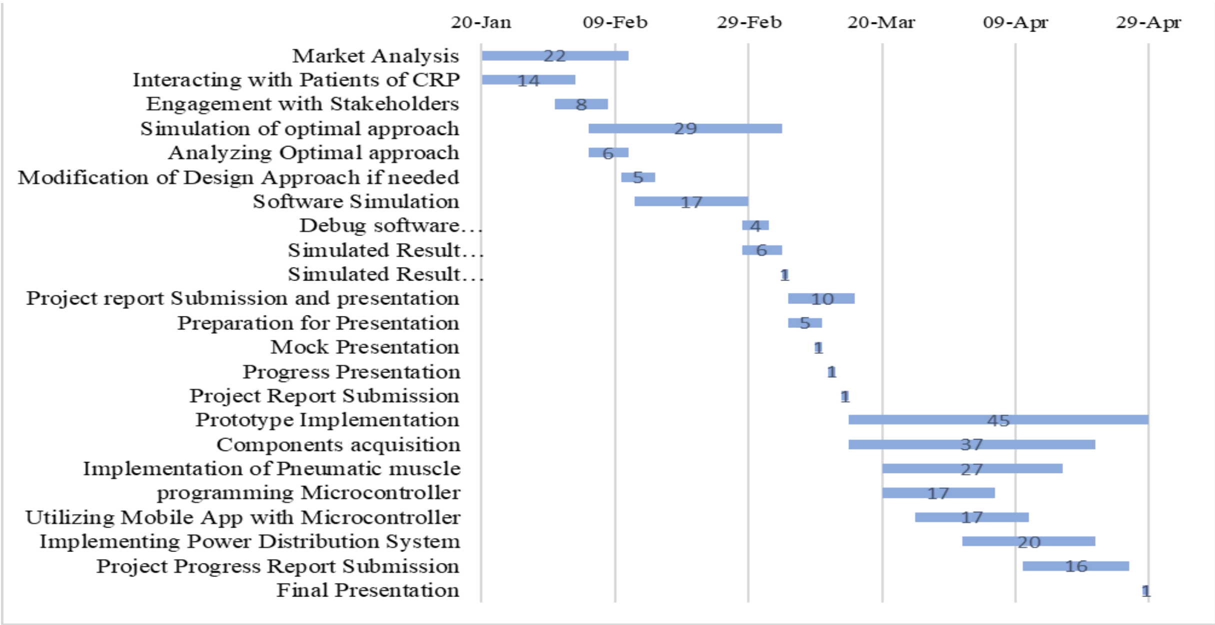


Fig. 41: Gantt Chart for EEE499D

Table 12: EEE499D Project Plan

Task	Start date	End date	Duration
Market Analysis	**20 January, 2024**	**10 Feb, 2024**	**30 Days**
Interacting with Patients of CRP	20 January, 2024	2 February, 2024	12 Days
Engagement with Stakeholders	31 January, 2024	7 February, 2024	7 Days
Evaluation of Similar products available in market	31 January, 2024	7 February, 2024	7 Days
Simulation of optimal approach	**5 February, 2024**	**4 March, 2024**	**23 Days**
Analyzing Optimal approach	5 February, 2024	10 February, 2024	5 Days
Modification of Design Approach if needed	10 February, 2024	14 February, 2024	4 Days
Software Simulation	12 February, 2024	28 February, 2024	16 Days
Debug software simulated	28 February, 2024	2 March, 2024	4 Days

results			
Simulated Result Analysis	28 February, 2024	4 March, 2024	6 Days
Simulated Result Analysis	5 March, 2024	5 March, 2024	1 Day
Project report Submission and presentation	**6 March, 2024**	**15 March, 2024**	**9 Days**
Preparation for Presentation	6 March, 2024	10 March, 2024	4 Days
Mock Presentation	10 March, 2024	10 March, 2024	1 Day
Progress Presentation	12 March, 2024	12 March, 2024	1 Day
Project Report Submission	14 March, 2024	14 March, 2024	1 Day
Prototype Implementation	**15 March, 2024**	**28 April, 2024**	**43 Days**
Components acquisition	15 March, 2024	20 April, 2024	5 Days
Implementation of Pneumatic muscle	20 March, 2024	15 April, 2024	35 Days
programming Microcontroller	20 March, 2024	5 April, 2024	25 Days
Utilizing a Mobile App with a Microcontroller	25 March, 2024	10 April, 2024	15 Days
Implementing a Power Distribution System	1 April, 2024	20 April, 2024	20 Days
Project Progress Report Submission	10 April, 2024	25 April, 2024	15 Days
Final Presentation	28 April, 2024	28 April, 2024	1 Day

EEE499C:

FYDP(C):

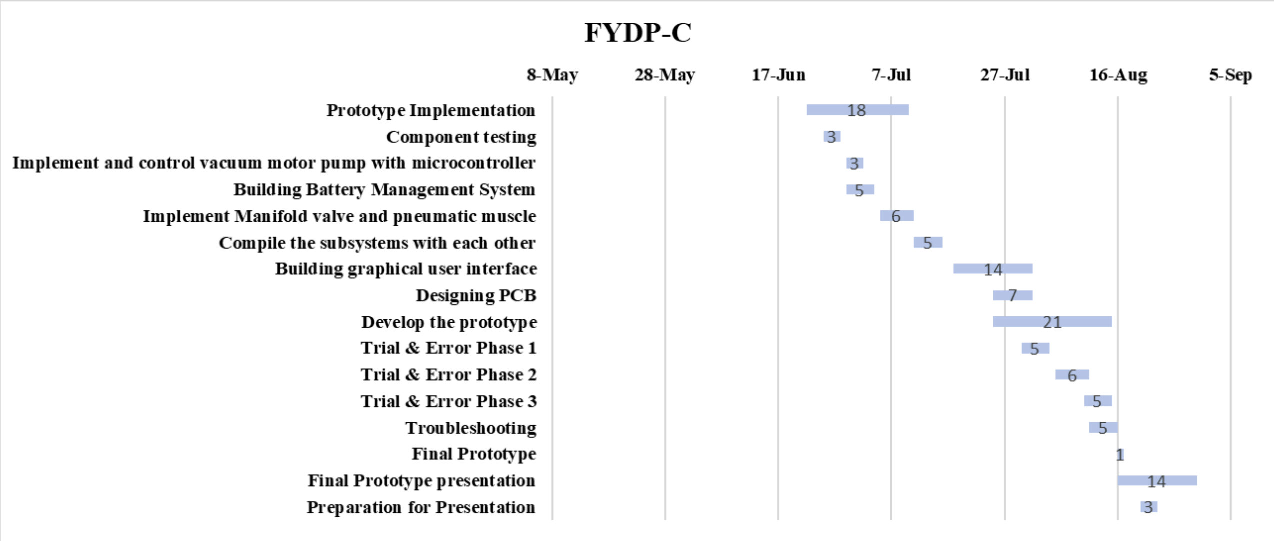


Fig 42: Gantt chart for FYDP(C)

Table 13: project plan for the FYDP(C)

Task	Start date	End date	Duration
Prototype Implementation	**22 June, 2024**	**10 July, 2024**	**18 Days**
Component testing	22 June, 2024	25 June, 2024	3 Days
Implement and control vacuum motor pump with microcontroller	25 June, 2024	28 June, 2024	3 Days
Building Battery Management System	29 June, 2024	04 July, 2024	5 Days
Implement Manifold valve and pneumatic muscle	29 June, 2024	05 July, 2024	6 Days
Compile the subsystems with each other	05 July, 2024	10 July, 2024	5 Days
Building graphical user interface	11 July, 2024	25 July, 2024	14 Days
Designing PCB	18 July, 2024	25 July, 2024	7 Days

Develop the prototype	**25 July, 2024**	**15 August, 2024**	**21 Days**
Trial & Error Phase 1	25 July, 2024	30 July, 2024	5 Days
Trial & Error Phase 2	30 July, 2024	05 August, 2024	5 Days
Trial & Error Phase 3	05 August, 2024	10 August, 2024	5 Days
Troubleshooting	10 August, 2024	15 August, 2024	5 Days
Final Prototype	11 August, 2024	11 August, 2024	1 Day
Final Prototype presentation	**16 August, 2024**	**30 August, 2024**	**14 Days**
Preparation for Presentation	16 August, 2024	19 August, 2024	3 Days
Mock Presentation	20 August, 2024	20 August, 2024	1 Day
Final Presentation	22 August, 2024	22 August, 2024	1 Day
Project Report Submission	30 August, 2024	30 August, 2024	1 Day

Managing the project

Managing the project involves coordinating tasks, monitoring progress, and making necessary adjustments to stay on track. This includes regular progress meetings, resource allocation, risk management, and ensuring quality control. Throughout the project, progress is evaluated against the planned timeline to identify any deviations and implement corrective actions promptly. Effective communication among team members and stakeholders is crucial to address issues and ensure alignment with project goals.

Conclusion

The application of engineering project management principles was instrumental in the successful execution of the Smart Rehabilitation Glove project. By defining clear objectives, planning meticulously, and managing resources effectively, the project stayed on track and met its goals within the allocated time frame. Regular progress evaluation ensured timely identification and resolution of issues, contributing to the development of a functional and optimized rehabilitation device. The systematic approach to project management not only enhanced the project's efficiency but also ensured its alignment with the broader objectives of post-stroke rehabilitation.

Chapter 8: Economical Analysis.

8.1 Introduction:

A thorough product analysis must include an economic evaluation, as it provides critical insights into the practicality and profitability of the project. Economic analysis helps developers assess the potential benefits and limitations of their product, offering a realistic view of its market feasibility. This process also involves anticipating consumer response and evaluating the product's value to the community, as well as the level of demand it may generate. One of the key objectives of this analysis is to estimate the potential for profitability, providing a clearer picture of the product's expected business performance and sustainability.

8.2 Economic Analysis:

The economic analysis of the smart rehabilitation glove is conducted by comparing its features, performance, and pricing with commercially available rehabilitation gloves. This comparative evaluation sheds light on the market positioning and competitiveness of the proposed design.

Tista Rehabilitation Robotic Hand Gloves: The Tista Rehabilitation Robotic Hand Gloves, manufactured in China (Model No. TB-104), are intended for the rehabilitation of individuals recovering from strokes, hand burns, or other hand disorders, including hemiplegia. As of June 21, 2024, the retail price of these gloves is approximately BDT 20,000. Designed to support recovery, the Tista gloves feature a central frequency of 3.5 MHz and are covered by a six-month warranty. Weighing 1.1 kg, with dimensions of 300×280×70 mm, the gloves are recommended for use two to four times daily. The demo picture provided by [27] for the glove is shown below:

Fig. 43 : Tista Rehabilitation Robotic Hand Gloves available in Bangladesh

According to available documentation [27], the Tista gloves offer several notable features:

- **Lightweight and Comfortable:** Constructed from soft, breathable materials to ensure comfort during extended use.
- **User-Friendly Interface:** Equipped with simple buttons or switches to facilitate ease of use, even for patients with limited hand mobility.
- **Customizable Programs:** Allows users to adjust intensity, duration, and type of exercises to suit individual rehabilitation needs.
- **Precise Hand Movement Tracking:** Incorporates multiple sensors to accurately monitor hand movements, providing targeted and effective therapy.

Also, [27] also mentioned about the single finger mode which is shown in Fig 43 .

Fig. 44: Single Finger Mode of the Tista Rehabilitation glove [15]

The Syrebo Hand Rehabilitation Robot Gloves E10 model:

The Syrebo Hand Rehabilitation Robot Gloves E10 model is a self-training device designed to support finger and hand recovery, particularly for individuals recovering from strokes [28]. Equipped with a user-friendly interface, the gloves facilitate targeted rehabilitation by combining pneumatic power with intelligent control systems, enhancing finger mobility and hand strength. To accommodate different users, the E10 model is available in multiple sizes, ensuring a comfortable fit. It also offers customizable training modes, allowing users to tailor rehabilitation exercises to their specific recovery needs.

Lightweight and portable, the E10 model is designed for easy use in both home and clinical settings, promoting convenience and accessibility. Although the Syrebo gloves are not manufactured in Bangladesh, they are available through international shipping, making them accessible to users within the region. Priced at approximately BDT 46,129, these gloves provide an advanced rehabilitation solution by integrating innovative technology with practical functionality, offering an effective option for individuals seeking personalized hand therapy. The demo picture provided by [28] for the glove is shown below:

Fig. 45: Syrebo Hand Rehabilitation Robot Gloves E10 model

Comparison : From the research conducted, it has been determined that, as of 2024, no rehabilitation gloves are manufactured locally in Bangladesh; all currently available products are imported. The proposed design approach, referred to as Design 1, sets itself apart by offering a comprehensive user interface, a feature not present in existing models such as the Tista Rehabilitation Robotic Hand Gloves and the Syrebo Hand Rehabilitation Robot Gloves E10. Furthermore, the inclusion of flex and force sensors in the design enables precise measurement of pressure and movement speed, providing enhanced therapeutic benefits for users. Although the Tista Hand Glove highlights several features, they are presented without specific details, leaving room for improvement in clarity and functionality. Priced at approximately BDT 20,000, the proposed glove aligns with the cost of imported alternatives, ensuring affordability. With its advanced features and the integration of a mobile application for seamless user interaction, this design represents the first locally manufactured rehabilitation glove in Bangladesh, delivering both innovation and value at a competitive price point.

8.3 Cost Benefit Analysis

Determining the feasibility of a project requires a comprehensive cost-benefit analysis, carefully assessing the advantages and limitations of each economic factor. This analysis goes beyond minimizing expenses; instead, it emphasizes balancing effectiveness, performance, and durability to ensure the overall viability of the project. Benefits are quantified based on reliable assumptions, offering precise guidance during product development and facilitating informed decision-making.

An economically viable project does not necessarily mean achieving the lowest cost but rather ensuring that the selected components contribute to the system's optimal functionality and long-term reliability. With an overwhelming variety of components available on the market, it can be challenging to find the right balance between cost and performance. Engineers must make thoughtful decisions to select components that are both cost-effective and capable of meeting the project's technical requirements.

In evaluating multiple design alternatives, it became clear that some higher-priced components offer distinct advantages in specific applications. Therefore, effective decision-making requires careful consideration of trade-offs, ensuring that each component selected delivers the best value for the intended purpose. This approach not only ensures efficient resource utilization but also strengthens the overall performance and sustainability of the project.

8.4 Evaluate Economic and Financial Aspects

Below is a detailed breakdown of the components required for Design 1, along with their respective quantities, prices, and associated costs for the project.

Table 14: Component Wise Budget For Design 1

Elements	Unit	Product Link	Unit Price	Total Price
Arduino Nano	1	https://www.electronics.com.bd/Arduino-Nano-Arduino-Nano-V3-0-China-Boards-nano-arduino-Arduino-Nano-ATmega-328p-ATmega-328p-micro-controller-microcontroller-price-in-online-BD-Bangladesh?route=product/product	410 Taka	410 Taka
Li-ion battery of 3.7 Volt	6	https://store.roboticsbd.com/battery-charger/1687-37v-18650-rechargeable-battery-solderable-robotics-bangladesh.html	84 Taka	336 Taka
Hose clamp/ Lock Nut	10	https://machineandtoolsbd.com/shop/tools-hardware-supplier-in-bangladesh/1-inch-ss-hose-clamp-fit-rubber-pipes-with-garden-taps-supplier-in-bangladesh/	15 Taka	150 Taka
Nylon Braided sleeving	6	https://www.electronics.com.bd/Nylon-6mm-Expandable-Braided-Sleeve-for-Wire-Protection-1feet-Length-Nylon-6mm--Expandable-Braided-Sleeve-cable-Sleeve-price-in-online-BD-Bangladesh?route=product/product	40 Taka	240 Taka
Latex tube	5	https://www.daraz.com.bd/products/natural-latex-rubber-band-tube-elastic-2x5mm-yellow-i198559103.html	70 Taka	355 Taka
Pneumatic Tube	5	https://www.dunia.com.bd/product/pneumatic-tube-high-pressure-pu-pipe/	80 Taka	400 Taka
DC 12V Air Pump	1	https://bdpromart.com/product/dc-12v-air-pump-555/	650 Taka	650 Taka

DC 12 V Vacuum pump	1	https://techshopbd.com/detail/3151/Vacuum_Pump_-_12V_12L_min_techshop_bangladesh	2521 Taka	2521 Taka
4.5 inch Flex Sensor, Force Sensor	5	https://store.roboticsbd.com/robotics-parts/169-flex-sensor-bangladesh.html	1250 Taka	3,750 Taka
Force Sensor-0.5″ Force Sensitive Resistor Sensor	1	https://techshopbd.com/detail/1308/Force_Sensitive_Resistor_-_Small_techshop_bangladesh	525 Taka	525 Taka
L298n motor driver	1	https://store.roboticsbd.com/motor-driver/376-l298n-h-bridge-dual-motor-driver-stepper-motor-driver-robotics-bangladesh.html	195 Taka	195 Taka
Glove	1		200 Taka	200 Taka
5 way 1/4 inch manifold Valve	1	https://www.daraz.com.bd/products/5-way-manifold-block-splitter-quick-connect-air-hose-splitter-coupler-air-compressor-splitter-pneumatic-air-compressor-manifold-fitting-i187919287.html	1405 Taka	1405 Taka
Bluetooth Module				
Total component Price:				11137 Taka
Prototype cost				1000 Taka
PCB Cost				830 Taka
Testing Cost				1,000 Taka
Delivery Cost				1,000 Taka
Unforeseen Emergency				2000 Taka
Total Price				**16,967 Taka**

Below is a detailed breakdown of the components required for Design 2, along with their respective quantities, prices, and associated costs for the project.

Table 15: Component Wise Budget for Design 2

Elements	Unit	Product Link	Unit Price	Total Price
3D printed texture cotton Gloves	1	https://www.facebook.com/groups/1059526854173512/	1,130 Taka	1,130 Taka
Carbon Rubber Electrodes	2	https://www.totaldiabetessupply.com/products/carbon-rubber-electrode-1-75-x-4-pin-4-pk	2,500 Taka	5,000 Taka
Pure Silver	1	https://www.ubuy.com.bd/en/product/R6836MC-ten-one-gram-999-pure-silver-bars-with-random-designs-in-a-jewelry-pouch-original-version	5,499 Taka	5,499 Taka
Dc Battery	2	https://store.roboticsbd.com/robotics-parts/652-battery-9v-robotics-bangladesh.html	75 Taka	150 Taka
DC-DC boost converter	1	https://store.roboticsbd.com/components/730-xl6009-dc-dc-booster-robotics-bangladesh.html	130 Taka	130 Taka
H-bridge module	1	https://store.roboticsbd.com/motor-driver/2389-l298n-dual-h-bridge-motor-driver-module-robotics-bangladesh.html	420 Taka	420 Taka
Arduino Uno	1	https://store.roboticsbd.com/arduino-bangladesh/94-8-arduino-uno-r3-robotics-bangladesh.html	1,100 Taka	1,100 Taka
LCD display	1	https://store.roboticsbd.com/display/661-lcd-16x2-yellow-backlight-robotics-bangladesh.html	240 Taka	240 Taka
Electrode wire	2	https://technohealth.com.bd/tens-unit-lead-wires-cable-1-set-1-pair/	500 Taka	1,000 Taka
Total Component price				14,770 Taka
Prototype cost				1,000 Taka
PCB cost				2,000 Taka
Testing Cost				1,000 Taka

Delivery Cost	1,000 Taka
Unforeseen Emergency	1,000 Taka
Total Price	**20,670 Taka**

8.5 Conclusion:

In conclusion, the economic and budget analysis demonstrates that design one is the most economical and practical option among the evaluated alternatives. This design distinguishes itself through its efficiency, achieving a lower average error rate of 1.71%, and offering cost-effectiveness with a total budget of 17,834 Taka. It provides an extensive range of motion, facilitating effective hand retraining and muscle memory recovery. Additionally, Design One offers enhanced user convenience, as supported by insights from the literature review, and promotes sustainability through low power consumption powered by a lithium battery, further reducing operational costs. Its lightweight and portable design also ensures greater usability across various rehabilitation settings, adding to its practicality.

As the first rehabilitation glove designed and manufactured in Bangladesh, this solution integrates advanced features along with a mobile app interface for seamless user interaction, matching the price point of imported alternatives. Conducting a thorough economic analysis has been essential in evaluating the trade-offs necessary to enhance both sustainability and accessibility. Continuous assessment throughout the project's development has ensured that the design achieves optimal functionality while maintaining cost-efficiency. This comprehensive approach lays a strong foundation for the project's long-term success and its impact on rehabilitation outcomes.

Chapter 9: Ethics and Professional Responsibilities

9.1 Introduction

The development of medical devices, particularly those aimed at improving the lives of vulnerable populations such as stroke survivors, necessitates a thorough examination of ethical issues and professional responsibilities. Upholding ethical standards is crucial not only to protect patients but also to foster trust and credibility within the healthcare community. As such, addressing issues like informed consent, data privacy, equity, and intellectual property is essential in ensuring that the device is not only effective but also safe and accessible for all potential users.

9.2 Identify ethical issues and professional responsibility

Several ethical issues are crucial to consider in the development and use of medical devices, especially one intended for stroke rehabilitation. First, informed consent is paramount. Patients need to be fully aware of how the device works, the risks involved, and their rights to discontinue use at any time. Second, data privacy and security are essential, as patient data will be collected and monitored. This data must be handled with confidentiality, ensuring that only authorized personnel can access it. Third, equity and access must be prioritized to guarantee that all patients, regardless of socioeconomic background, can benefit from the device. Finally, avoiding plagiarism and respecting intellectual property is essential to maintain academic and professional integrity throughout the project.

9.3 Apply ethical issues and professional responsibility

The ethical issues were addressed during the project are as below:

Data Privacy and Security: All patient data, including device usage duration, is securely encrypted in the mobile app. This ensures that personal information remains confidential and is only used to improve patient care.

Equity and Access: The wearable system is designed to be affordable and accessible to all stroke survivors. This inclusivity ensures that no patients are excluded based on factors such as age, gender, race, or socioeconomic status.

Plagiarism: All journal papers from which ideas were taken for the project were diligently cited, ensuring proper credit was given to the original sources. There was no plagiarism in the report writing, and no part of the project was copied. The entire development process was original and adhered to intellectual property standards.

Safety and Environmental Responsibility: In developing the device, user safety was prioritized. For example, the power unit includes a 4s Battery Management System (BMS) to protect against overcharging, over-discharging, overheating and short circuits. The structural materials chosen for the device were selected to be safe for human use, avoiding any harmful substances. Additionally, efforts were made to use environmentally friendly materials wherever possible, ensuring that the device is both safe and sustainable for long-term use.

Also a risk response matrix was done to address unwanted risk events.

Table 16: Risk Response Matrix

Risk Event	Likelihood	Impact	Risk Level	Response Strategy
Component Failure	Low	High	Medium	Protecting compotants from Overcharging or Short Circuit by using 4s BMS.
Compatibility Issues between software and hardware	Low	High	High	Ensuring thorough compatibility testing and proactive communication channels between software and hardware to promptly address any compatibility issues.
Power Outage	Medium	Medium	Low	Introducing an easy option to charge the battery.
Sensor data error /Data Quality Issues	Low	High	High	Ensure data accuracy through validation checks.

9.4 Conclusion

Considering ethical issues and professional responsibility throughout the development and implementation of the wearable hand rehabilitation system is paramount. By prioritizing informed consent, data privacy, equity of access, and safety, the project aligns itself with the highest ethical standards. This commitment not only enhances the integrity of the project but also ensures that the device can effectively and responsibly serve the needs of stroke survivors, ultimately contributing to their recovery and well-being. A strong ethical foundation fosters trust among users and stakeholders, reinforcing the project's mission to provide an innovative and inclusive solution to rehabilitation therapy.

Chapter 10: Conclusion and Future Work.

10.1 Conclusion

Stroke, a leading cause of long-term disability worldwide, often results in significant challenges for individuals trying to regain functionality in their upper limbs. Traditional rehabilitation methods can be costly, time-consuming, and inconvenient, leading to a low adherence rate among patients. In response to these challenges, the project is designed as a cost-effective, portable, and user-friendly rehabilitation glove that empowers stroke survivors to engage in their recovery independently. This glove allows patients to perform exercises at home while enabling healthcare professionals to monitor their progress remotely. The system's design emphasizes inclusivity, ensuring accessibility for stroke survivors across all economic backgrounds.

This wearable hand rehabilitation system not only addresses the pressing need for effective rehabilitation tools but also strives to improve the quality of life for stroke survivors. By harnessing technology and prioritizing user engagement, this project can make a meaningful impact in the field of stroke rehabilitation.

10.2 Future work

Future developments of the wearable hand rehabilitation system will focus on enhancing its functionality and improving user experience. Key areas for future work include:

1. **Incorporation of Force Sensors**: The system may integrate force sensors for each finger, allowing for more precise measurements of grip strength and finger movements.
2. **Improved Mobile Application**: The mobile app will undergo significant upgrades to create a more organized interface that efficiently manages larger volumes of data. Enhanced data storage capabilities will allow for comprehensive tracking of patient progress over time, while advanced analytical tools will enable detailed performance evaluations and personalized feedback.
3. **Expanded Range of Motion**: To increase the range of motion for the fingers, the design may incorporate DC motors. This addition will allow for more dynamic movements, simulating various rehabilitation exercises that closely mimic real-life hand functions.

Chapter 11: Identification of Complex Engineering Problems and Activities.

11.1: Identify the attribute of complex engineering problem (EP)

	Attributes	**Put tick (√) as appropriate**
P1	Depth of knowledge required	√
P2	Range of conflicting requirements	
P3	Depth of analysis required	
P4	Familiarity of issues	√
P5	Extent of applicable codes	
P6	Extent of stakeholder involvement and needs	√
P7	Interdependence	√

11.2: Provide reasoning how the project address selected attribute (EP)

P1. Depth of knowledge required: This project goes into several fields of engineering that require in-depth knowledge of various fields. It involves knowledge in biomechanics to comprehend hand movement control, robotics for integrating technology, signal processing for successfully transmitting signals from the device to the app and programming for seamless transmission of signals and precise control over the glove's functions. In-depth analysis and expertise in these domains is necessary for creating an optimal solution.

P4. Familiarity of issues: The concept and technical details of the rehabilitation system are unfamiliar in the context of Bangladesh. Advanced technologies like soft robotics, sensors, pneumatic muscle, and so on into a wearable rehabilitation device might pose unique challenges not commonly encountered in traditional glove manufacturing or healthcare device development.

P6. Extent of stakeholder involvement and needs: This project requires a diverse group of people including medical professionals, rehabilitation experts, post stroke patients who require a rehabilitation system for getting back to normal life. Involving these stakeholders ensures that the smart gloves meet the specific needs of rehabilitation, considering user experiences, functional requirements, and clinical efficiency.

P7. Interdependence: This project includes different subsystems such as power distribution, Control processing unit, software implementation, sensor integration, communication Interface, User Interface which are interdependent of each other. The seamless integration of these subsystems optimizes the glove's functionality, usability, safety, and data analysis capabilities, ultimately ensuring that the smart rehabilitation glove system significantly contributes to effective rehabilitation outcomes for individuals in need.

11.3 Identify the attribute of complex engineering activities (EA)

	Attributes	Put tick (√) as appropriate
A1	Range of resource	√
A2	Level of interaction	√
A3	Innovation	
A4	Consequences for society and the environment	
A5	Familiarity	√

11.4 Provide reasoning how the project address selected attribute (EA)

A1. Range of Resources: The development of the smart gloves requires a diverse range of resources, including specialized sensors for hand motion tracking, flexible conductive materials for electrode integration, software tools for data analysis, prototyping kits for hardware development, and user friendly materials for glove fabrication. Moreover, it has a diverse group of people as the stakeholder.

A2. Level of interaction: This project requires the seamless integration of various sensors within the smart glove framework, necessitating the creation of a cohesive system that interfaces with an IoT platform for real-time data transmission and analysis, ensuring comprehensive functionality and connectivity. Also, a good level of interaction is needed among the students, the health professionals and the stakeholder.

A5. Familiarity: This project falls within the realm Biomedical Engineering which is a new area for Electrical and Electronics Engineering students. Medical knowledge combined with the electronics system is essential here, giving EEE students an unique opportunity to branch out into a new interdisciplinary field.

References

1. A. Arivarasi *et al.*, "An advanced cost-efficient IoT method for stroke rehabilitation using smart gloves," *Nanotechnology and Precision Engineering*, vol. 6, no. 4, Aug. 2023, doi: 10.1063/10.0020290.
2. Z. Yue, X. Zhang, and J. Wang, "Hand rehabilitation robotics on poststroke motor recovery," *Behavioural Neurology*, vol. 2017, pp. 1–20, Jan. 2017, doi: 10.1155/2017/3908135.
3. E. L. Altschuler *et al.*, "Rehabilitation of hemiparesis after stroke with a mirror," *The Lancet*, vol. 353, no. 9169, pp. 2035–2036, Jun. 1999, doi: 10.1016/s0140-6736(99)00920-4.
4. S. L. Wolf *et al.*, "Effect of Constraint-Induced Movement therapy on upper extremity function 3 to 9 months after stroke," *JAMA*, vol. 296, no. 17, p. 2095, Nov. 2006, doi: 10.1001/jama.296.17.2095.
5. "A wearable hand rehabilitation system with soft gloves," *IEEE Journals & Magazine | IEEE Xplore*, Feb. 01, 2021. https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=9146885
6. M. B. A. Mondal, A. T. M. H. Hasan, N. Khan, and Q. D. Mohammad, "Prevalence and risk factors of stroke in Bangladesh: A nationwide population-based survey," eNeurologicalSci, vol. 28, p. 100414, Sep. 2022, doi:10.1016/j.ensci.2022.100414.
7. Venketasubramanian and M. Mannan, "Stroke burden and stroke services in Bangladesh," Cerebrovascular Diseases Extra, vol. 11, no. 2, pp. 69–71, Jul. 2021, doi: 10.1159/000517234.
8. A. Arivarasi et al., "An advanced cost-efficient IoT method for stroke rehabilitation using smart gloves," Nanotechnology and Precision Engineering, vol. 6, no. 4, Aug. 2023, doi: 10.1063/10.0020290.
9. T. Aghil, S. G. Rahul, S. B. Kumaar, Y. Vijay, S. Kumar, and B. Sidhharth, "A futuristic approach for stroke rehabilitation using smart gloves," Journal of Physics, vol. 2115, no. 1, p. 012025, Nov. 2021, doi: 10.1088/1742-6596/2115/1/012025.
10. Vo, Q. N. T., Huynh, T., & Dao, S. V. T. (2021). Applying soft actuator technology for hand rehabilitation. In *IFMBE proceedings* (pp. 123–132). https://doi.org/10.1007/978-3-030-75506-5_10
11. B. Wang, A. McDaid, M. Biglari-Abhari and K. C. Aw, "Design and development of a glove for post-stroke hand rehabilitation," 2017 IEEE International Conference on Advanced Intelligent Mechatronics (AIM), Munich, Germany, 2017, pp. 1047-1051, doi: 10.1109/AIM.2017.8014157.
12. Nussbaum EL, Houghton P, Anthony J, Rennie S, Shay BL, Hoens AM. Neuromuscular Electrical Stimulation for Treatment of Muscle Impairment: Critical Review and Recommendations for Clinical Practice. Physiother Can. 2017;69(5):1-76. doi: 10.3138/ptc.2015-88. PMID: 29162949; PMCID: PMC5683854.
13. Frothingham, S. (2019, August 7). *What's the average hand size for men, women,and children?* Healthline.
14. J. Johnson, "What to know about distal interphalangeal (DIP) joint pain," MedicalNewsToday, Jan. 09, 2023. Available: https://www.medicalnewstoday.com/articles/326823
15. E. Korzeniewska, A. Krawczyk, J. Mróz, E. Wyszyńska, and R. Zawiślak, "Applications of smart textiles in Post-Stroke rehabilitation," Sensors, vol. 20, no. 8, p. 2370, Apr. 2020, doi: 10.3390/s20082370. Available: https://doi.org/10.3390/s20082370

16. B. L. Shideler, T. C. Bulea, C. Ji, C. J. Stanley, A. Gravunder, and D. L. Damiano, "Toward a hybrid exoskeleton for crouch gait in children with cerebral palsy: neuromuscular electrical stimulation for improved knee extension," Journal of Neuroengineering and Rehabilitation, vol. 17, no. 1, Sep. 2020, doi: 10.1186/s12984-020-00738-7.
17. J. R. Young, "Output circuits for cutaneous muscle stimulators", 2010. https://conservancy.umn.edu/handle/11299/103933

18. Sanches, Marcelo & Gaino, Ruberlei & Kozan, Renan & Teixeira, Marcelo & de Carvalho, Aparecido & Covacic, Márcio & Alves, C. & Urban, Mateus & Junqueira, Marcos & Cardim, Rodrigo & Assunção, Edvaldo & Gentilho Jr, Edno. (2014). Digital controller design considering hardware constraints: Application in a paraplegic patient. Revista Brasileira de Engenharia Biomédica. 30. 232-241. 10.1590/1517-3151.0196.
19. Yin, Liuliu & Wang, Fang & Han, Sen & Li, Yuchen & Sun, Hao & Lu, Qingjie & Yang, Cheng & Wang, Quangzhao. (2016). Application of drive circuit based on L298N in direct current motor speed control system. 101530N. 10.1117/12.2246555.
20. Liu, Y., Liao, Y. G., & Lai, M. (2020). Lithium-Ion polymer battery for 12-Voltage applications: experiment, modeling, and validation. Energies, 13(3), 638. https://doi.org/10.3390/en13030638
21. Karlina, F. H., Sunarno, N., Waruwu, M. M., & Wijaya, R. (2021b). Study of several types of lithium-polymer batteries with 3S battery Management system. IOP Conference Series. Earth and Environmental Science, 927(1), 012023. https://doi.org/10.1088/1755-1315/927/1/012023
22. Su, H. (2022). A novel wearable soft glove for hand rehabilitation and assistive grasping. Sensors, 22(16), 6294. https://doi.org/10.3390/s22166294
23. Ji, X., & Xiao, X. (2023). Personalized and safe soft glove for rehabilitation training. Electronics, 12(11), 2531. https://doi.org/10.3390/electronics12112531
24. S. M. Ilyas, S. F. Jawed, C. S. Shakeel, L. H. Bawany, and R. Amin, "DESIGN AND DEVELOPMENT OF a STROKE REHABILITATION GLOVE FOR MEASURING AND MONITORING HAND MOTIONS," *Pakistan Journal of Rehabilitation*, vol. 11, no. 2, pp. 167–178, Jul. 2022, doi: 10.36283/pjr.zu.11.2/023. (Comparison)
25. A. M. Malik, Z. MD. Yusof, K. A. Kushairy, F. Z. H. Hafiza, and A. Ismail, "Development of Smart Glove system for therapy treatment," in *Proc. IEEE Conf.*, May 2015, pp. 1-6. ,doi:https://ieeexplore.ieee.org/document/7292220
26. L. E. Emokpae, R. N. Emokpae Jr., and B. Emokpae, "Flex Force Smart Glove Prototype for physical therapy rehabilitation," in *Proc. IEEE Conf.*, Oct. 2018, pp. 1-5. https://ieeexplore.ieee.org/document/8584774
27. Rehabilitation robotic hand gloves price in Bangladesh. (2024, March 22). Tista Online Shop. https://tista.com.bd/rehabilitation-robotic-hand-gloves-stroke-patients/

28. Ubuy Bangladesh. (n.d.). syrebo Hand Rehabilitation Robot Gloves, E10 Model Bangladesh | Ubuy. https://www.ubuy.com.bd/en/product/FTQIMRV2Q-syrebo-hand-rehabilitation-robot-gloves-e10-model-self-training-finger-rehabilitation-device-hand-stroke-recovery-equipment

Appendix

Arduino Nano Code to control the control Unit and Communication Unit:

```
// Sensor Pins

const int flexSensorPin1 = A6; // Sensor 1

const int flexSensorPin2 = A1; // Sensor 2

const int flexSensorPin3 = A3; // Sensor 3

const int flexSensorPin4 = A4; // Sensor 4

const int flexSensorPin5 = A5; // Sensor 5

const int FSR_PIN = A2;       // Force Sensor


// Motor Pins

const int motorPin1 = 3;  // Vacuum Pump

const int motorPin2 = 5; // Vacuum Pump

const int motorPin3 = 7;  // Air Pump

const int motorPin4 = 9;  // Air Pump


// Sensor Variables

int sensorValue1 = 0, flexAngle1 = 0;

int sensorValue2 = 0, flexAngle2 = 0;

int sensorValue3 = 0, flexAngle3 = 0;

int sensorValue4 = 0, flexAngle4 = 0;

int sensorValue5 = 0, flexAngle5 = 0;

int fsrReading = 0;  // Pressure sensor reading
```

```
// Sensor 1

int sensorStraight1 = 570, sensorHalfBent1 = 500, sensorBent1 = 370, sensorThreeQuarterBent1 = 340;


// Sensor 2

int sensorStraight2 = 590, sensorHalfBent2 = 609, sensorBent2 = 646, sensorThreeQuarterBent2 = 667;


// Calibration Values for Sensor 3, 4, 5 (You can adjust these based on actual sensor readings)

int sensorStraight3 = 570, sensorHalfBent3 = 500, sensorBent3 = 370, sensorThreeQuarterBent3 = 340;

int sensorStraight4 = 570, sensorHalfBent4 = 500, sensorBent4 = 370, sensorThreeQuarterBent4 = 340;

int sensorStraight5 = 570, sensorHalfBent5 = 500, sensorBent5 = 370, sensorThreeQuarterBent5 = 340;


// Pressure sensor thresholds

const int SAFE_FORCE_MIN = 200;

const int SAFE_FORCE_MAX = 700;


unsigned long previousMillis = 0;

unsigned long startTime = 0;        // Track when the motor started

unsigned long totalElapsedTime = 0; // Accumulate total time across sessions


const long onDuration = 5000;  // 5 seconds ON

const long offDuration = 2000; // 2 seconds OFF


bool isRunning = false;

bool motorsActive = false;

int iterationCount = 0;

bool sendSensorValues = false
```

```
char incoming_value;

void setup() {
  Serial.begin(9600);

  // Setup motor pins
  pinMode(motorPin1, OUTPUT);
  pinMode(motorPin2, OUTPUT);
  pinMode(motorPin3, OUTPUT);
  pinMode(motorPin4, OUTPUT);



  pinMode(FSR_PIN, INPUT);  // pressure sensor pin
}

void loop() {
  // Check for Bluetooth input
  if (Serial.available()) {
    incoming_value = Serial.read();
    Serial.println(incoming_value);

    if (incoming_value == 'A') {
      // Start motors and enable sensor value transmission
      isRunning = true;
      sendSensorValues = true;
      motorsActive = true;
```

```
    if (startTime == 0) startTime = millis(); // Record start time only once
    previousMillis = millis();  // Reset cycle timer
    startMotors();  // Immediately turn on motors
  }
  else if (incoming_value == 'B') {

    isRunning = false;
    sendSensorValues = false;
    stopAllMotors();

    // Calculate total elapsed time
    unsigned long currentElapsedTime = (millis() - startTime) / 1000;
    totalElapsedTime += currentElapsedTime;

    Serial.print("Total Iterations Completed: ");
    Serial.print(iterationCount);
    Serial.print(", Total Time: ");
    Serial.print(totalElapsedTime);
    Serial.println(" seconds");


    startTime = millis();
  }
}


if (sendSensorValues) {
```

```
    readFlexSensorValues();
    readPressureSensor();
  }

  if (isRunning) {
    controlPumps();
  }
}

void readFlexSensorValues() {

  sensorValue1 = analogRead(flexSensorPin1);
    flexAngle1 = mapSensorValues(sensorValue1, sensorStraight1, sensorHalfBent1, sensorBent1, sensorThreeQuarterBent1);

  sensorValue2 = analogRead(flexSensorPin2);
    flexAngle2 = mapSensorValues(sensorValue2, sensorStraight2, sensorHalfBent2, sensorBent2, sensorThreeQuarterBent2);

  sensorValue3 = analogRead(flexSensorPin3);
    flexAngle3 = mapSensorValues(sensorValue3, sensorStraight3, sensorHalfBent3, sensorBent3, sensorThreeQuarterBent3);

  sensorValue4 = analogRead(flexSensorPin4);
```

```
  flexAngle4 = mapSensorValues(sensorValue4, sensorStraight4, sensorHalfBent4, sensorBent4, sensorThreeQuarterBent4);



  sensorValue5 = analogRead(flexSensorPin5);
  flexAngle5 = mapSensorValues(sensorValue5, sensorStraight5, sensorHalfBent5, sensorBent5, sensorThreeQuarterBent5);



  printSensorValues(1, sensorValue1, flexAngle1);
  printSensorValues(2, sensorValue2, flexAngle2);
  printSensorValues(3, sensorValue3, flexAngle3);
  printSensorValues(4, sensorValue4, flexAngle4);
  printSensorValues(5, sensorValue5, flexAngle5);
}

int mapSensorValues(int sensorValue, int sensorStraight, int sensorHalfBent, int sensorBent, int sensorThreeQuarterBent) {
  int flexAngle;
  if (sensorValue >= sensorHalfBent) {
    flexAngle = map(sensorValue, sensorStraight, sensorHalfBent, 0, 45);
  } else if (sensorValue >= sensorBent) {
    flexAngle = map(sensorValue, sensorHalfBent, sensorBent, 45, 90);
  } else if (sensorValue >= sensorThreeQuarterBent) {
    flexAngle = map(sensorValue, sensorBent, sensorThreeQuarterBent, 90, 120);
  }
  return constrain(flexAngle, 0, 120);
}
```

```
void printSensorValues(int sensorNum, int sensorValue, int flexAngle) {
  Serial.print("Sensor ");
  Serial.print(sensorNum);
  Serial.print(" Value: ");
  Serial.print(sensorValue);
  Serial.print("  Bending Angle ");
  Serial.print(sensorNum);
  Serial.print(": ");
  Serial.println(flexAngle);
}

void readPressureSensor() {
  fsrReading = analogRead(FSR_PIN);

  Serial.print("Pressure Sensor Reading: ");
  Serial.println(fsrReading);

  if (fsrReading < SAFE_FORCE_MIN) {
    Serial.println("Warning! Force is Low! Check Battery!");
  } else if (fsrReading <= SAFE_FORCE_MAX) {
    Serial.println("Force is safe.");
  } else {
    Serial.println("Force too high! Stop the machine!");
  }
}
```

```
void startMotors() {
  analogWrite(motorPin1, 255);  // Vacuum Pump ON
  digitalWrite(motorPin2, LOW);
  analogWrite(motorPin3, 255);  // Air Pump ON
  digitalWrite(motorPin4, LOW);

  Serial.println("Air and Vacuum Pumps ON");
}

void controlPumps() {
  unsigned long currentMillis = millis();

  if ((currentMillis - previousMillis) < onDuration) {
    if (!motorsActive) {
      startMotors();
      motorsActive = true;
    }
  } else if ((currentMillis - previousMillis) < (onDuration + offDuration)) {
    stopAllMotors();
    motorsActive = false;
  } else {
    previousMillis = currentMillis;
    iterationCount++;  // Increment iteration count
  }
}

void stopAllMotors() {
```

```
  digitalWrite(motorPin1, LOW);
  digitalWrite(motorPin2, LOW);
  digitalWrite(motorPin3, LOW);
  digitalWrite(motorPin4, LOW);

  Serial.println("All motors stopped.");
}


}
```