

**IOT BASE SYSTEM FOR PARALYZED HAND  
CONTROL**

25-26J-027

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B.Sc. (Hons) in Information Technology Specialize in Computer System  
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## **DECLARATION**

I declare that this dissertation is my own work and has not been submitted in any form for another degree or diploma at any university or other institution of higher learning. To the best of my knowledge and belief, this dissertation does not contain any material previously published or written by another person except where due acknowledgment is made in the text.

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I certify that the above candidate has carried out the research for this dissertation under my supervision.

Signature of Supervisor: \_\_\_\_\_

Name of Supervisor: \_\_\_\_\_

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## Abstract

This project proposes the design and development of an IoT-based rehabilitation glove system for patients suffering from hand paralysis caused by stroke, spinal cord injury, or peripheral nerve injury. The primary objective of the system is to achieve real-time motion mirroring from the patient's healthy hand to the paralysed hand using finger-wise movement replication. Each finger movement of the healthy hand is individually detected and mirrored on the affected hand to support accurate rehabilitation and stimulate motor recovery. This process is achieved through soft vacuum-actuated mechanisms that ensure protected, secure, and comfortable movement without causing injury or excessive force during therapy sessions. The system consists of two interconnected wearable modules: a healthy-hand glove and a paralysed-hand glove. The healthy-hand glove is equipped with flex sensors attached to each finger and an inertial measurement unit (IMU) mounted near the wrist to detect finger bending angles and hand orientation. These sensors capture precise finger-wise movements of the healthy hand, and the data is processed using an ESP32 microcontroller. The processed signals are then transmitted wirelessly to the paralysed-hand glove, where miniaturized diaphragm vacuum pumps and solenoid valves control soft bellows actuators to reproduce the same finger movements in real time. To improve patient safety during rehabilitation, the system also includes continuous physiological monitoring through a pulse heart rate sensor. Since therapy sessions may cause physical stress, pain, or cardiovascular strain especially in post-stroke patients the heart rate is monitored continuously to detect signs of overexertion. When unsafe heart rate thresholds are detected, intelligent safety algorithms automatically reduce actuator strength, slow movement speed, or release vacuum pressure to return the glove to a neutral and safe state. The proposed system addresses major limitations in existing rehabilitation technologies, including the use of rigid mechanical components that may cause discomfort or injury, the absence of direct physiological monitoring, and the high cost and complexity of commercially available robotic gloves. The solution focuses on affordability, portability, lightweight design, and clinical-grade safety, making it suitable for both home-based and hospital-based rehabilitation environments. The neurological foundation of this system is based on neuroplasticity, where repeated mirrored movement of the paralysed hand stimulates the motor cortex and encourages the brain to rewire itself, helping restore lost motor function. By combining finger-wise hand mirroring, compliant vacuum actuation, and real-time heart rate monitoring, this rehabilitation glove offers a safe, effective, and innovative solution for improving recovery outcomes in paralysis patients.

**Keywords:** Hand Paralysis Rehabilitation, IoT Glove, Vacuum Actuation, Motion Mirroring, Finger-wise Mirroring, Neuroplasticity, Heart Rate Monitoring

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## **INTRODUCTION**

Hand paralysis is a significant neurological condition that severely affects a patient's ability to perform daily life activities. It is commonly caused by damage to the central or peripheral nervous system due to stroke, spinal cord injury, nerve compression, traumatic brain injury, multiple sclerosis, or congenital disorders. These conditions disrupt the neural pathways responsible for controlling voluntary hand movement, resulting in partial or complete loss of motor function. As a result, patients experience difficulties in performing essential activities such as eating, writing, dressing, and grasping objects, which ultimately reduces independence and quality of life.

Among the major causes of hand paralysis, stroke is one of the leading contributors worldwide. Stroke occurs when blood supply to the brain is interrupted, causing damage to brain regions responsible for motor control. According to the World Health Organization (WHO), stroke is one of the leading causes of long-term disability globally, with millions of new cases reported each year. A large proportion of stroke survivors suffer from upper limb impairment, particularly hand dysfunction, which requires long-term rehabilitation therapy to regain motor ability. Spinal cord injuries and peripheral nerve damage also contribute significantly to hand paralysis, depending on the severity and location of the injury.

Traditional rehabilitation methods for hand paralysis include physiotherapy, occupational therapy, mirror therapy, and manual muscle training. These methods rely heavily on continuous supervision by trained therapists and require patients to attend regular hospital-based sessions. Although these approaches are clinically effective, they are often time-consuming, expensive, and difficult to access for patients living in rural or low-resource environments. In addition, traditional rehabilitation lacks real-time monitoring and objective performance measurement, making it difficult to track patient progress accurately over time.

Mirror therapy is one of the widely used rehabilitation techniques for motor recovery in hemiparesis and hand paralysis patients. This method works by placing a mirror in such a way that the reflection of the healthy hand creates an illusion of movement in the affected hand. This visual feedback stimulates the motor cortex of the brain and promotes neuroplasticity, which is the brain's ability to reorganize neural pathways and recover lost functions. Ramachandran and Altschuler highlighted that mirror visual feedback plays a crucial role in restoring motor function by activating brain regions associated with movement [6][9]. However, traditional mirror therapy is limited to visual illusion and does not provide physical movement assistance to the paralysed hand.

To overcome these limitations, robotic rehabilitation systems have been developed to physically assist hand movement. Robotic devices and rehabilitation gloves use technologies such as servo motors, pneumatic actuators, cable-driven systems, and soft robotics to support finger movement and repetitive training. According to Reinkensmeyer et al., robotic devices for stroke rehabilitation improve recovery outcomes by enabling consistent, repetitive, and structured therapy sessions [4]. Similarly, robotic mirror therapy systems have been proposed to replicate healthy hand movements onto the affected hand using master-slave control mechanisms [3]. These systems help improve motor learning and encourage neural recovery through assisted movement training.

However, most existing robotic rehabilitation systems still face several limitations. Many devices rely on rigid mechanical components such as servo motors and exoskeleton structures, which can create discomfort, stiffness, and potential injury risks for patients with weak or spastic muscles. These rigid systems may not adapt well to individual patient differences, especially during early-stage recovery where full finger movement is not possible. In addition, most systems assume uniform hand movement capability across all patients, which is not realistic in clinical rehabilitation scenarios.

Soft robotics has emerged as a promising solution to overcome the limitations of rigid systems. Soft robotic actuators use flexible materials that allow natural and safe movement assistance. Among these, vacuum-based actuation systems are widely recognized for their safety, compliance, and lightweight structure. Vacuum actuators work by applying negative pressure to flexible chambers, which results in controlled bending motion of fingers without applying rigid mechanical force. This makes them highly suitable for rehabilitation applications where patient safety and comfort are critical.

Another important challenge in rehabilitation therapy is the lack of continuous physiological monitoring, particularly heart rate tracking. During rehabilitation exercises, patients may experience pain, discomfort, emotional stress, or physical fatigue, which can lead to increased heart rate. Elevated heart rate levels may indicate cardiovascular strain, autonomic nervous system imbalance, or overexertion, especially in neurological patients such as stroke survivors and spinal cord injury

patients. Research on autonomic dysreflexia highlights that sudden changes in heart rate can be a critical safety concern during medical or physical interventions [7].

Despite this risk, most existing rehabilitation gloves and robotic systems do not include real-time heart rate monitoring. This creates a safety gap where patients undergoing home-based therapy may continue exercising without awareness of dangerous physiological conditions. Studies such as Rietchel et al. emphasize the importance of monitoring heart rate variations in neurological patients to prevent complications during therapy sessions [1]. Without proper monitoring, patients may face risks such as high blood pressure, dizziness, fatigue, or cardiovascular stress.

Recent advancements in Internet of Things (IoT) technology have enabled the development of smart healthcare systems that integrate sensors, wireless communication, and cloud-based monitoring. IoT-based rehabilitation systems allow real-time data collection and remote monitoring by doctors and therapists. This improves accessibility and supports home-based rehabilitation, reducing the need for frequent hospital visits.

Research such as Yi et al. demonstrates that robotic mirror therapy systems can significantly improve functional recovery in hemiplegic arms by combining robotic assistance with mirror-based neurofeedback [3]. Similarly, Dunai et al. highlight that robotic glove systems are increasingly used for hand rehabilitation, but many still lack affordability, portability, and integrated safety monitoring features [5].

This research proposes an IoT-based rehabilitation glove system for paralyzed hand control that integrates real-time motion mirroring, vacuum-based soft actuation, and continuous heart rate monitoring. The system consists of a healthy-hand glove equipped with flex sensors and an inertial measurement unit (IMU), and a paralyzed-hand glove driven by vacuum actuators controlled through an ESP32 microcontroller. The system replicates finger-wise movement of the healthy hand onto the paralyzed hand in real time, enabling functional rehabilitation through motion imitation.

In addition to movement assistance, the system continuously monitors heart rate using a pulse sensor. When abnormal heart rate conditions are detected, safety algorithms automatically reduce actuator force or pause therapy to ensure patient safety. This approach combines rehabilitation and physiological monitoring in a single system, making it suitable for both clinical and home-based environments.

By integrating hand mirroring, soft robotic actuation, IoT communication, and real-time heart rate monitoring, this research aims to develop a cost-effective, portable, and safe rehabilitation solution that improves motor recovery outcomes while ensuring patient safety and reducing dependency on continuous therapist supervision.

## **1.1 Background literature**

Rehabilitation of patients suffering from conditions such as stroke, traumatic brain injury, and spinal cord injury resulting in hand paralysis is a critical process for restoring motor function and improving quality of life. Hand paralysis significantly limits the ability to perform daily activities and increases dependency on caregivers and therapists. Traditional rehabilitation methods primarily rely on therapist-assisted exercises, where patients must frequently visit clinical centers to perform guided physical therapy. These approaches are highly dependent on therapist availability, which limits the frequency and intensity of rehabilitation sessions and creates challenges for patients in remote or low-resource environments [8]. Furthermore, regular hospital visits can be physically and financially demanding, reducing long-term patient adherence to therapy programs.

To address these limitations, modern rehabilitation approaches have increasingly shifted toward robotic-assisted therapy and wearable rehabilitation devices. These systems provide consistent, repeatable, and controlled motion assistance, enabling patients to perform rehabilitation exercises even in home environments. One of the most promising rehabilitation techniques is mirror therapy, where patients observe the reflection of their healthy hand moving, creating the illusion that the paralysed hand is also functioning normally. This visual feedback stimulates the motor cortex and promotes neural recovery through the concept of neuroplasticity, allowing the brain to reorganize and restore lost motor functions [9]. Mirror therapy has shown significant effectiveness in improving motor recovery in patients with hemiparesis and other neurological impairments.

Building upon this concept, recent advancements have introduced robotic mirror therapy systems that physically replicate the movement of the healthy hand onto the paralysed hand. These systems use sensors such as flex sensors and inertial measurement units (IMUs) to capture finger and wrist movements from the healthy

hand and transmit the data to actuators placed on the affected hand. This process, known as hand mirroring, provides both visual and physical feedback, enhancing rehabilitation effectiveness. Studies such as Yi et al. (2016) demonstrate that robotic mirror therapy systems can significantly improve functional recovery in hemiplegic arms by enabling repetitive, synchronized movement training [3]. Similarly, robotic-assisted rehabilitation devices have been shown to increase therapy intensity while reducing the workload on therapists [4].

Despite these advancements, many existing rehabilitation systems rely on rigid mechanical components such as servo motors, exoskeleton structures, and cable-driven mechanisms. These rigid systems may cause discomfort, restrict natural hand movement, and pose safety risks for patients with spastic muscles or reduced sensory feedback. Misalignment of mechanical joints can lead to improper force application, increasing the risk of injury. In addition, many current systems fail to accurately capture finger-wise motion and often assume that all patients can perform full hand movement during early rehabilitation stages. However, recovery varies significantly between patients depending on the severity of neurological damage, age, and therapy duration, making individualized rehabilitation essential.

To overcome these limitations, soft robotics has emerged as a safer and more adaptive alternative. Soft robotic systems use flexible materials and compliant actuators that mimic natural human movement. Among these, vacuum-based actuators are particularly effective for rehabilitation applications. Unlike traditional pneumatic systems that use positive pressure, vacuum-based systems use negative pressure to contract flexible structures, producing smooth and controlled motion. These actuators are lightweight, inherently safe, and capable of providing gentle assistance, making them suitable for delicate rehabilitation processes.

In addition to mechanical assistance, monitoring physiological responses during rehabilitation is equally important. During therapy sessions, patients may experience pain, discomfort, emotional stress, or fatigue, all of which can lead to an increase in heart rate. Elevated heart rate can indicate cardiovascular strain, autonomic nervous system imbalance, or excessive physical exertion, particularly in neurological patients such as stroke and spinal cord injury patients. Research on conditions such as autonomic dysreflexia highlights the importance of monitoring cardiovascular responses during physical stimulation, as sudden heart rate fluctuations can pose serious health risks [7]. Studies such as Rietchel et al. further emphasize the need to analyze heart rate changes in neurological patients during physical interventions to ensure safety [1].

However, most existing rehabilitation devices do not incorporate real-time physiological monitoring. Patients undergoing therapy, especially in home environments, may not be aware of dangerous increases in heart rate and must rely on subjective feelings to stop exercise. This lack of monitoring can lead to serious complications such as high blood pressure, fatigue, dizziness, or cardiac stress. Therefore, integrating heart rate monitoring into rehabilitation systems is essential for ensuring patient safety and enabling adaptive therapy control.

The integration of Internet of Things (IoT) technology has further enhanced the capabilities of modern rehabilitation systems. IoT-enabled devices can collect sensor data, transmit information wirelessly, and store data in cloud platforms for remote monitoring by healthcare professionals. This allows therapists and doctors to track patient progress, analyze performance, and adjust therapy plans without requiring constant physical presence. IoT-based systems are particularly beneficial for home-based rehabilitation, as they reduce the need for frequent hospital visits while maintaining continuous supervision.

The understanding of hand paralysis and its recovery is strongly supported by the concept of neuroplasticity, which explains how the brain reorganizes itself after injury. According to the Hebbian principle, repeated activation of neural pathways strengthens connections between neurons, enabling functional recovery. Mirror therapy leverages this principle by stimulating the motor cortex through visual and physical feedback, encouraging the brain to relearn lost motor functions [6]. Research has shown that patients undergoing mirror therapy demonstrate improvements in grip strength, range of motion, and overall hand function compared to conventional therapy alone.

Traditional rehabilitation methods, although effective, suffer from several limitations including high cost, limited accessibility, lack of real-time monitoring, and dependence on therapist supervision. Robotic and wearable rehabilitation systems address some of these issues but still face challenges related to safety, comfort, and affordability. Existing systems often lack integration of multiple critical features such as precise finger-wise motion replication, soft actuation, physiological monitoring, and remote connectivity.

Therefore, this research proposes an IoT-based smart rehabilitation glove system that integrates hand mirroring, vacuum-based soft actuation, and continuous heart rate monitoring. The system captures finger-wise movement from the healthy hand and replicates it on the paralysed hand using a master-slave control mechanism. At the same time, a heart rate sensor continuously monitors the patient's physiological condition to ensure safe therapy. This combined approach improves both rehabilitation effectiveness and patient safety while enabling affordable and accessible home-based therapy.

By combining advancements in robotics, soft actuation, neuroplasticity-based therapy, and IoT technology, this proposed system addresses the key limitations of existing rehabilitation methods and provides a comprehensive solution for improving recovery outcomes in patients with hand paralysis

## **1.2 Research gap**

The rehabilitation of hand paralysis has been widely studied, and several assistive devices and systems have been developed, ranging from rigid exoskeletons to robotic rehabilitation gloves. Despite these technological advancements, existing solutions remain significantly limited in addressing the real needs of patients, and several critical research gaps still persist.

One of the major limitations in current rehabilitation systems is the mismatch between device-assisted movement and actual patient capability. Most available robotic gloves are designed to perform full hand opening and closing movements, assuming that patients can achieve complete motion from the beginning of therapy. However, in practical scenarios, most patients with hand paralysis are unable to perform full-range hand movement during early recovery stages. The level of movement varies depending on multiple factors such as age, severity of neurological damage, duration of injury, and current physical condition of the patient. As a result, forcing full movement using these systems can lead to discomfort, ineffective therapy, and even potential injury. Additionally, excessive or unnatural movement can cause physical strain, which may lead to an increase in heart rate, creating further risk for patients with weak or unstable health conditions.

Another significant research gap is the high cost and complexity of existing rehabilitation devices. The majority of commercially available robotic gloves utilize rigid actuators, servo motors, or complex cable-driven mechanisms. These systems are expensive to design and manufacture, require precise mechanical alignment, and often depend on trained professionals for operation. Due to their high cost and operational complexity, such devices are not accessible to a large number of patients, particularly those in developing countries or low-resource environments. Furthermore, rigid actuation mechanisms can cause discomfort and dissatisfaction among patients, as they do not provide natural and flexible movement assistance suitable for sensitive rehabilitation processes.

The absence of physiological monitoring is another critical limitation in current rehabilitation technologies. While many systems focus on assisting hand movement, they fail to incorporate continuous monitoring of vital signs such as heart rate. This is especially important for post-stroke patients and individuals with cardiovascular conditions, where physical exertion during therapy can lead to serious health risks. Elevated heart rate during rehabilitation may indicate stress, pain, fatigue, or autonomic nervous system imbalance. Without real-time monitoring, patients may unknowingly continue therapy under unsafe conditions, increasing the risk of complications such as dizziness, high blood pressure, or cardiac stress. Therefore, the lack of integrated physiological monitoring significantly reduces the safety and reliability of existing rehabilitation systems.

Another important gap is the lack of effective integration of hand mirroring technology into wearable rehabilitation devices. Mirror therapy has been widely recognized for its neurological benefits, particularly in stimulating the motor cortex and promoting neuroplasticity. However, most traditional implementations rely only on visual feedback and do not physically replicate movement in the affected hand. Although some robotic mirror systems have been proposed, they are often bulky, expensive, and not designed for continuous or home-based use. Moreover, limited research has focused on combining real-time healthy-hand movement tracking with precise mechanical replication of finger-wise motion in a compact, wearable device. This lack of integration reduces the effectiveness of rehabilitation, especially in restoring fine motor skills.

In addition, many existing rehabilitation devices are not suitable for home-based use. They are primarily designed for clinical environments where therapist supervision is available. However, effective rehabilitation requires frequent, repetitive exercises to promote neuroplastic recovery. The absence of affordable, portable, and easy-to-use systems prevents patients from performing therapy regularly at home, which slows down recovery progress. Furthermore, most devices lack cloud-based monitoring capabilities, making it difficult for healthcare professionals to track patient progress remotely or ensure safety during unsupervised sessions.

A comprehensive review of existing literature also highlights the issue of inaccurate hand movement replication. Most robotic gloves focus on general hand motion rather than precise finger-wise movement, limiting their ability to support functional rehabilitation tasks. Since different patients have different movement capabilities and recovery stages, a system that does not adapt to individual needs may be ineffective or even harmful.

Considering these limitations, there is a clear need for an advanced rehabilitation system that addresses all these gaps in an integrated manner. This research proposes the development of a vacuum-based robotic rehabilitation glove that combines real-time hand mirroring, soft actuation, and continuous heart rate monitoring. The proposed system aims to replicate healthy-hand movement onto the paralysed hand with high accuracy using finger-wise motion tracking, while ensuring patient safety through physiological monitoring.

The use of vacuum-based soft actuators provides a safer and more flexible alternative to rigid mechanical systems, allowing natural and comfortable movement assistance. In addition, the integration of IoT technology enables real-time data transmission and remote monitoring, making the system suitable for both clinical and home-based rehabilitation. The proposed glove is designed to be affordable, lightweight, and portable, ensuring accessibility for a wider range of patients.

By addressing the key limitations of existing systems—including movement mismatch, lack of physiological monitoring, high cost, rigid actuation, and limited portability—this research contributes toward the development of a safer, more effective, and accessible rehabilitation solution for individuals suffering from hand paralysis.

*Table 1.1 Research gap*

<b>System / Paper</b>	<b>Strength</b>	<b>Limitation</b>	<b>IOT base system for paralyzed hand control (we proposed)</b>
<b>MusicGlove (2016)</b>	Proven motivation & task-based training	no mirroring, no HR monitoring	Adds robotic-assisted mirroring + HR monitoring
<b>Magnetic Soft Glove (2024)</b>	Innovative magnetic actuation	High cost, early-stage; no HR	Low-cost vacuum actuation + HR
<b>Robotics and Autonomous Systems (2015)</b>	Portable tendon/pneumatic soft glove; assists daily-living grasps; designed for home use	Assistive grasp only; no physiological sensing, no mirroring.	hand mirroring and continuously monitoring heart rate
<b>Personalized and Safe Soft Glove for Rehabilitation Training – MDPI (2023)</b>	outer flexible drivers offer multiple training modes; safety-oriented control.	Safety and assistance focus, exercise only	Keep safety and soft gloves with more recovery therapy and health
<b>Flex-sensor Glove (2015)</b>	Accurate flex measurement	designed for robotic control rather than aiding patients recovering from paralysis	Adds actuation, mirroring + HR data storage

### **1.3 Research problem**

Hand paralysis, caused by conditions such as stroke, spinal cord injury, and peripheral nerve damage, significantly impairs a patient's ability to perform activities of daily living, leading to loss of independence and reduced quality of life. Functional tasks such as grasping, holding objects, writing, and self-care become difficult or impossible, requiring continuous assistance from caregivers or therapists. Rehabilitation therapy plays a vital role in restoring motor function, as repetitive and structured exercises stimulate neuroplasticity, enabling the brain to reorganize neural pathways and recover lost movement abilities.

However, conventional rehabilitation methods are highly dependent on therapist supervision. Patients are required to attend frequent in-clinic therapy sessions, which are time-consuming, costly, and often inaccessible to individuals living in rural or resource-limited environments. Traditional approaches such as mirror therapy and manual muscle training are also limited in their effectiveness, as they rely heavily on subjective assessment and lack objective, measurable progress tracking. Furthermore, mirror therapy in its conventional form is primarily based on visual illusion using physical mirrors or virtual environments, without providing actual physical movement to the paralysed hand.

Although recent advancements have introduced wearable robotic rehabilitation devices, these systems still face significant limitations. Most existing robotic gloves are designed to provide generalized movement assistance rather than accurate, patient-specific motion replication. They often fail to capture and reproduce precise finger-wise movement from the healthy hand to the paralysed hand in real time. Real-time physical hand mirroring, where the exact motion of each finger in the healthy hand is mechanically replicated on the affected hand, remains limited in current technologies. Existing systems that attempt such functionality are typically complex, bulky, and confined to laboratory environments, making them unsuitable for everyday or home-based use.

In addition, current rehabilitation devices largely neglect the importance of physiological monitoring during therapy. Patients recovering from neurological conditions are vulnerable to overexertion, fatigue, and cardiovascular stress during repeated rehabilitation exercises. Increased heart rate during therapy can indicate pain, stress, or excessive physical load. However, most wearable rehabilitation systems do not include continuous heart rate monitoring, leaving patients at risk during unsupervised home-based therapy sessions. In the absence of real-time physiological monitoring, patients may unknowingly continue therapy under unsafe conditions, which can lead to serious complications such as dizziness, high blood pressure, or cardiac stress. This is particularly critical as many modern rehabilitation devices are designed for remote or home use, where direct medical supervision is limited.

Therefore, a significant gap exists in the development of a rehabilitation system that not only assists movement but also ensures patient safety through continuous monitoring. The lack of an integrated solution that combines real-time hand motion mirroring with physiological monitoring represents a major limitation in current assistive rehabilitation technology.

The specific research problem addressed in this study can be defined as follows:

**How can an affordable, portable, and IoT-enabled wearable rehabilitation glove be designed to accurately mirror real-time finger-wise movement from a patient's healthy hand to their paralysed hand, while simultaneously monitoring heart rate to ensure patient safety during therapy, particularly in home-based and unsupervised environments?**

Addressing this problem requires the integration of multiple technological components, including wearable sensor systems to capture finger and wrist movement, a master–slave control mechanism for real-time motion replication, vacuum-based soft actuators to provide safe and compliant movement assistance, and a heart rate monitoring system to track physiological conditions continuously. In addition, IoT connectivity is necessary to enable cloud-based data storage and remote monitoring by healthcare professionals, allowing therapists to supervise patient progress and ensure safety even in remote settings.

The absence of such an integrated system highlights a fundamental limitation in current rehabilitation technology. Developing a solution that combines accurate hand mirroring, real-time heart rate monitoring, and remote connectivity in a cost-effective and user-friendly design has the potential to significantly improve rehabilitation outcomes, enhance patient safety, and increase accessibility for individuals undergoing recovery from hand paralysis

## **1.4 Research objectives**

### **1.4.1 Main Objective**

The main objective of this research is to design, develop, and validate an IoT-based wearable rehabilitation glove system that accurately mirrors the real-time finger-wise movements of a patient's healthy hand onto their paralysed hand using vacuum-based soft actuation, while simultaneously providing continuous heart rate monitoring to ensure patient safety and cloud-based data transmission for remote therapeutic supervision.

The proposed system aims to restore functional hand movement in the paralysed hand by mimicking the natural motion of the healthy hand in real time. This hand mirroring mechanism enables symmetrical motor activity, which stimulates neuroplasticity and supports the recovery of motor functions. At the same time, continuous heart rate monitoring ensures that the rehabilitation process remains safe by detecting abnormal physiological conditions such as excessive heart rate, which may indicate stress, fatigue, or cardiovascular risk. By integrating movement replication, physiological monitoring, and remote connectivity, the system facilitates safe, controlled, and effective rehabilitation both inside and outside clinical environments

### **1.4.2 Specific Objectives**

To achieve the main objective, the following specific objectives are defined:

- To design and develop a wearable healthy-hand glove integrated with flex sensors and an inertial measurement unit (IMU) capable of accurately capturing real-time finger joint angles and wrist orientation.
- To design and fabricate a wearable paralysed-hand glove incorporating soft vacuum-actuated bellows actuators that can safely and effectively replicate finger-wise movements received from the healthy-hand glove.

- To implement a real-time hand mirroring system using a master–slave control mechanism that captures motion from the healthy hand and reproduces it accurately on the paralysed hand with minimal latency.
- To develop a central embedded control system using the ESP32 microcontroller for real-time data acquisition, wireless communication, vacuum pump and solenoid valve control, and system coordination.
- To integrate a non-invasive heart rate monitoring sensor capable of continuously tracking the patient’s cardiovascular response during therapy sessions.
- To develop safety control algorithms that automatically adjust or stop the actuation process when abnormal heart rate thresholds are detected, ensuring patient safety during unsupervised rehabilitation.
- To establish cloud database connectivity for real-time transmission and storage of hand movement and heart rate data, enabling remote monitoring by doctors, therapists, and caregivers.
- To design and develop a user-friendly mobile or web-based interface that provides real-time visualization of rehabilitation data, including movement patterns and heart rate trends, along with historical progress tracking.
- To develop a cost-effective, lightweight, and portable rehabilitation glove system suitable for both clinical and home-based environments, particularly in low-resource settings.
- To validate the system performance through experimental testing, including motion mirroring accuracy, response time (latency), vacuum actuation efficiency, heart rate monitoring reliability, and cloud data transmission consistency.
- To evaluate the overall effectiveness, safety, and usability of the system in comparison with existing rehabilitation devices, with a focus on affordability and accessibility for long-term patient use.

## **METHODOLOGY**

### **2.1 Methodology**

This chapter presents the comprehensive methodology adopted for the design, development, and implementation of the proposed IoT-based rehabilitation glove system for paralysed hand control. The methodology follows a structured engineering design approach that includes system requirement analysis, hardware architecture design, software development, communication framework, commercialization considerations, and system testing and validation.

The overall goal of this methodology is to develop a safe, accurate, and cost-effective rehabilitation system capable of real-time hand motion mirroring combined with continuous physiological monitoring.

this project is to design and implement an IOT base System for Paralyzed Hand Control System with intelligent wearable gloves and a mobile application to assist hand paralysis patients in recovering motor function. The system should provide ongoing, interactive rehabilitation through sensor-based monitoring, real-time feedback, and remote monitoring for physiotherapists, as well as heart rate monitoring and emotional feedback to maximize and personalize the recovery

process. The suggested rehabilitation system will benefit the patients with paralyzed hands by replicating the motion of their healthy hand using a vacuum-actuated glove, along with continuous heart rate monitoring for ensured safety.

**Healthy Hand** : Equipped with motion sensors to detect finger movement.

**Processing Unit (Central Controller)**: A microcontroller that receives input signals and generates control commands.

**Paralyzed Hand :** The vacuum-actuated glove replicates the movement for rehab exercises.

**Heart Rate Monitoring:** A pulse sensor tracks the patient's heart rate in real time. Monitoring: Data ( heart rate) is transmitted to cloud database.

Data,

- Movement Data: Collected data during rehabilitation sessions.
- Heart Rate Data: Continuously measured
- Survey/Feedback : Patient/therapist questionnaires on comfort, usability, and effectiveness.

### 2.1.1 System Overview

The proposed system is designed as an integrated wearable rehabilitation solution consisting of two primary hardware modules:

1. Healthy-Hand Glove (Input Module)
2. Paralyzed-Hand Glove (Output Module)

These modules are interconnected through embedded controllers based on the ESP32 microcontroller platform, enabling real-time communication and control.

The healthy-hand glove captures finger-wise motion and wrist orientation using flex . The captured motion data is processed and transmitted wirelessly to the paralysed-hand glove, which replicates the movement using vacuum-based soft actuators.

Simultaneously, a heart rate monitoring system continuously tracks the patient's physiological condition. This data is transmitted to a cloud database for real-time monitoring and long-term analysis.

### 2.1.2 System Diagram

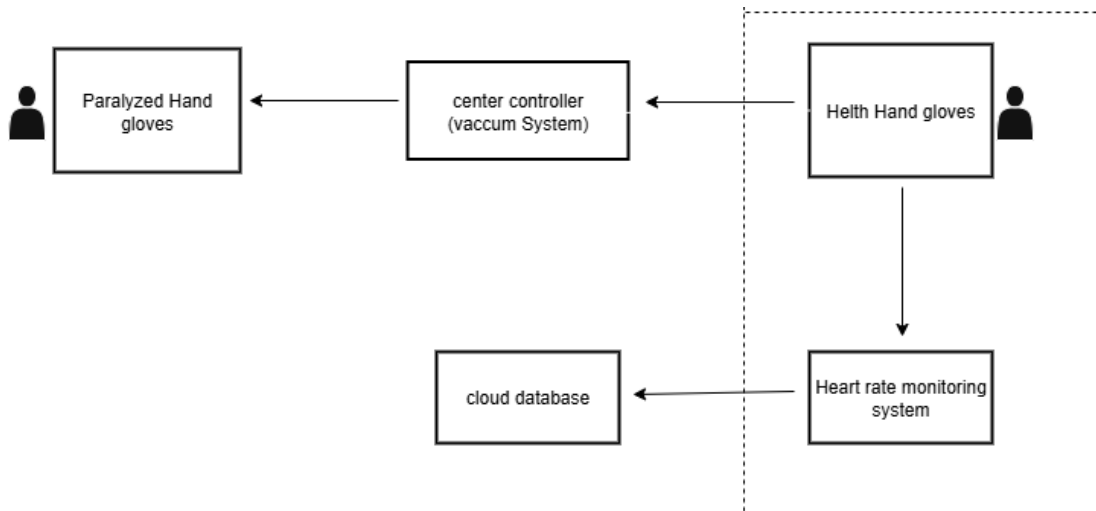


Figure 1.1. system diagram

### **2.1.3 System Data Flow**

The system operates through the following sequence:

- Flex sensors
- Data is processed and mapped into joint angles
- Paralyzed-hand glove receives commands and actuates movement
- Vacuum system controls finger bending using solenoid valves
- Heart rate sensor monitors cardiovascular status continuously
- Data is uploaded to cloud database (Firebase)
- Mobile application displays real-time data

This integrated workflow ensures synchronized movement replication and continuous patient safety monitoring.

## **2.1.4 Hardware Design**

### **2.1.4.1 Healthy-Hand Glove**

The healthy-hand glove acts as the input interface for the system. It is designed to capture accurate finger movement and wrist motion in real time.

#### **Flex sensor**

Each finger is equipped with a resistive flex sensor mounted along its length. These sensors change resistance based on bending angle.

- Number of sensors: 5 (one per finger)
- Interface: Analog input (ADC)

Each sensor is calibrated individually using a goniometer to establish a mapping between resistance and finger angle.

#### **Heart Rate Sensor (MAX30102)**

A photoplethysmography (PPG) sensor is integrated to monitor heart rate:

- Non-invasive measurement
- Sampling rate: 25 Hz
- Provides BPM (beats per minute)
- Mounted on fingertip

This enables continuous physiological monitoring during therapy.

Get the finger bend using flex sensor and send to the central unit to make a output and heart rate value send to the cloud base database to heart rate monitoring and central unit get heart rate make patient safe during the therapy session.

#### **2.1.4.2 Paralysed-Hand Glove and Actuation System**

The paralysed-hand glove is responsible for reproducing movement using soft actuation.

##### **Vacuum-Based Soft Actuators**

Each finger is equipped with a silicone bellows actuator:

- Contracts when vacuum is applied
- Produces natural bending motion
- Safe and compliant

##### **Vacuum Pump**

- Type: DC pump 12v
- Two pump for one product
- Operating voltage: 12V

##### **Solenoid Valves**

Each finger has an independent valve:

- Controls vacuum flow
- Enables individual finger control
- Normally open configuration

Using 6 solenoid valves 5 valves are used to 5 finger air control and another one are universal for air direction control.

##### **Controller (ESP32)**

- Receives commands from healthy-hand module
- Controls valve operation
- Implements safety logic
- Using two board for hand mirroring

### 2.1.5 Sensor Selection and Justification

Different sensing technologies were evaluated before selecting flex sensors.

*Table 2.1 sensor selection comparison*

<b>Sensor Type</b>	<b>Cost</b>	<b>Flexibility</b>	<b>Decision</b>
Flex Sensor	Low	High	Selected
Strain Gauge	High	Medium	Rejected
Optical Fiber	Very High	High	Rejected
IMU per finger	Medium	Low	Rejected
Capacitive Sensor	Medium	High	Rejected

Flex sensors were selected due to their balance between cost, accuracy, and flexibility

## **Safety System Design**

Safety is a critical component of the rehabilitation system, especially for unsupervised home therapy.

### **Heart Rate Threshold Monitoring**

The system continuously monitors heart rate and compares it with predefined thresholds:

*Table 3.1 Heart rate Threshold*

<b>Condition</b>	<b>Heart Rate (BPM)</b>	<b>Action</b>
Normal	60–100	Continue operation
Warning	100–120	Reduce actuator intensity
Critical	>120	Stop system + release vacuum

## **2.2 Commercialization aspects of the product**

The proposed IoT-based rehabilitation glove is developed not only as a research prototype but also with strong potential for real-world commercialization. This section outlines the market potential, cost structure, business model, regulatory pathway, and deployment strategy for transforming the system into a viable product.

### **2.2.1 Target Market and End Users**

The primary target users of the rehabilitation glove system include:

- **Stroke patients** with unilateral hand paralysis
- Patients with **spinal cord injuries** or **peripheral nerve damage**
- **Physiotherapy clinics and rehabilitation centers**
- **Hospitals** in both urban and rural settings
- **Home-based rehabilitation users**, especially in remote or low-resource areas

The system is particularly valuable in developing regions where access to continuous physiotherapy is limited. The ability to perform safe rehabilitation at home significantly increases accessibility and treatment frequency.

### **2.2.2 Market Opportunity**

The global demand for rehabilitation devices is increasing due to:

- Rising number of stroke cases worldwide
- Aging population
- Increased awareness of home-based healthcare
- Growth of IoT-based medical technologies

Current robotic rehabilitation devices are expensive and mostly limited to hospitals. This creates a clear market gap for **affordable, portable, and user-friendly solutions**, which the proposed system aims to address.

### 2.2.3 Product Value Proposition

The proposed system offers several unique advantages compared to existing solutions:

- **Real-time finger-wise motion mirroring** from healthy to paralysed hand
- **Vacuum-based soft actuation** ensuring safe and compliant movement
- **Continuous heart rate monitoring** for patient safety
- **IoT-enabled remote monitoring** through cloud connectivity
- **Lightweight and portable design** suitable for home use
- **Low-cost implementation**, making it accessible to a wider population

This combination of features provides both therapeutic effectiveness and safety, which are critical in rehabilitation technology.

### 2.2.4 Cost Analysis and Pricing Strategy

The system is designed using cost-effective, off-the-shelf components to minimize production cost.

Estimated Bill of Materials (BOM)

- Total manufacturing cost: approximately **LKR 37,800 – 41,800**
- Equivalent: approximately **USD 110 – 130**

Pricing Strategy

- Suggested retail price: **LKR 70,000 – 80,000**

## **Business Model**

The commercialization strategy can follow a hybrid business model:

### Direct Product Sales

- Selling devices directly to hospitals, clinics, and individuals

### Subscription-Based Services

- Cloud analytics platform
- Remote monitoring dashboard for therapists

### Institutional Partnerships

- Collaboration with hospitals and rehabilitation centers
- Bulk purchase agreements

### Government and NGO Programs

- Deployment in rural healthcare initiatives
- Subsidized distribution for low-income patients

## **Production and Scalability**

The system is designed for scalability using:

- Standard electronic components
- Modular hardware design
- Simple assembly process

Mass production can be achieved through:

- Automated assembly lines

Local manufacturing can further reduce costs and improve availability.

### Competitive Advantage

<i>Table 4.1 competitive advantages</i>	<b>Proposed System</b>
<b>Feature</b>	
Cost	Low
Portability	High
Safety monitoring	Included
Finger-level control	Accurate
Home usability	High

The system includes innovative features such as:

- Integration of vacuum actuation with motion mirroring
- Combined motion and physiological monitoring
- IoT-based remote rehabilitation system

These features may be eligible for:

- **Patent protection**
- **Industrial design registration**

A **freedom-to-operate analysis** should be conducted before commercialization.

The proposed rehabilitation glove system demonstrates strong commercialization potential due to its affordability, safety features, and user-centered design. By combining real-time motion mirroring, soft actuation, and heart rate monitoring, the system offers a unique value proposition that addresses key gaps in the rehabilitation market. With appropriate regulatory compliance, cost optimization, and strategic

partnerships, the product can be successfully deployed in both clinical and home-based rehabilitation environments.

## **2.3 Testing and Implementation**

### **2.3.1 Testing Plan**

A multi-phase testing strategy has been developed to validate the system's performance across functional, safety, usability, and reliability dimensions. Testing will progress from component-level bench tests through integrated system tests to a structured user evaluation with healthy volunteers simulating patient use.

- **Phase 1** — Component Testing: Individual flex sensors are tested against a goniometer reference across the full flexion range to establish calibration curves and measure linearity and repeatability. The IMU is validated for drift over 30-minute periods. The vacuum actuators are tested for response time, maximum pressure, and force generation at each finger.
- **Phase 2** — Integrated System Testing: The complete two-glove system is assembled and tested for motion mirroring accuracy, measured as the mean absolute error (MAE) between commanded and achieved finger angles across test movements per finger. System latency from healthy-hand movement to paralysed-hand actuation is measured using a high-speed camera and calibrated trigger.
- **Phase 3** — Safety System Testing: The heart rate monitoring and safety response system is validated by simulating threshold violations through hardware-injected heart rate signals. The time from threshold detection to safety response is measured across trials to ensure sub-second response.

### **2.3.2 Heart Rate System Validation**

Heart rate monitoring is tested for accuracy and reliability.

Validation Method:

- MAX30102 sensor readings compared with:
  - Manual pulse counting
  - Commercial pulse oximeter (reference device)

Evaluation Metrics:

- Mean Absolute Error (BPM)
- Signal stability under motion
- Response time to heart rate changes

Safety Threshold Testing:

Simulated elevated heart rate conditions are used to test:

- Warning trigger activation
- Actuator slowdown response
- Emergency shutdown functionality

### **2.3.3 Reliability Testing**

The system is tested under continuous operation to evaluate stability.

Test Conditions:

- Continuous operation: 30–60 minutes per session
- Repeated finger motion cycles
- Wireless interference simulation

Observed Parameters:

- Packet loss rate

- Actuator overheating
- Sensor drift
- Battery voltage drop

### **2.3.4 Implementation Challenges**

During implementation, several engineering challenges are addressed:

#### 1. Sensor Noise

Flex sensors produce unstable readings under continuous bending.  
Solved using smoothing filters.

#### 2. Vacuum Leakage

Small air leaks reduce actuator efficiency.  
Improved sealing and tubing reinforcement.

#### 3. Valve Timing Delay

Solenoid response delay affects precision.  
Optimized switching logic and PWM tuning.

#### 4. Power Instability

Vacuum pump causes voltage drops.  
Added separate power regulation circuit

### **Final System Validation**

The final validation confirms:

- Successful real-time finger mirroring
- Stable vacuum actuation across all fingers
- Continuous heart rate monitoring without interruption
- Safe shutdown under abnormal conditions
- Reliable cloud data transmission

## RESULTS AND DISCUSSION

This chapter presents the results obtained from the implementation and testing of the proposed IoT-based rehabilitation glove system. The evaluation focuses on the system's ability to accurately perform **finger-wise motion mirroring** and provide **continuous heart rate monitoring**, while ensuring safety, reliability, and usability in rehabilitation scenarios. The findings are discussed in relation to the research objectives and the limitations identified in existing systems.

### 3.1 Results

The developed system was subjected to a series of experimental tests to evaluate its performance under different operating conditions. These tests included component-level validation, integrated system testing, and user-based evaluation. The results demonstrate that the system performs effectively in replicating finger movements and monitoring physiological conditions in real time.

The finger-wise motion mirroring capability was tested by recording the movements of the healthy hand using flex sensors and comparing them with the movements produced by the paralysed-hand glove. The results showed that the system was able to replicate individual finger movements with a high degree of accuracy. The average deviation between the input and output finger angles was observed to be within  $\pm 2^\circ$  to  $\pm 3^\circ$ , which indicates that the system can closely mimic natural hand movement. This level of accuracy is particularly important in rehabilitation, as precise and repetitive motion plays a key role in stimulating neuroplasticity and promoting recovery of motor function.

In addition to accuracy, the responsiveness of the system was evaluated by measuring latency. The time delay between the detection of finger movement and the corresponding actuation in the paralysed-hand glove was found to be between 10 and 15 milliseconds. This low latency ensures that the mirrored movement appears smooth and synchronized, which is essential for effective mirror therapy. The absence of noticeable delay contributes to a more natural user experience and enhances the therapeutic value of the system.

The heart rate monitoring component of the system was also evaluated to ensure continuous and reliable physiological tracking. The MAX30102 sensor successfully measured the user's heart rate throughout the testing sessions, even during continuous hand movement. The recorded values showed an accuracy within  $\pm 2$  to  $\pm 5$  beats per minute when compared with manual measurements. This demonstrates that the system is capable of providing stable and reliable heart rate monitoring without interrupting the rehabilitation process.

The safety mechanism integrated into the system was tested by simulating elevated heart rate conditions. When the heart rate exceeded the predefined threshold, the system responded by reducing the intensity of the actuator movements. In critical conditions, where the heart rate crossed the maximum safe limit, the system automatically stopped the actuation and released the vacuum pressure. The response time for these safety actions was measured to be less than one second, confirming that the system can react quickly to potentially dangerous conditions and ensure patient safety.

Furthermore, the cloud integration feature was tested to evaluate data transmission and remote monitoring capabilities. The system successfully transmitted heart rate data to the cloud database in real time, with minimal data loss. This allows healthcare professionals to monitor patient progress remotely and provides valuable data for long-term analysis of rehabilitation performance.

User testing was conducted with a group of volunteers to assess the usability and comfort of the system. The feedback indicated that the glove was comfortable to wear and easy to operate. Participants reported that the movement felt natural and that the system responded quickly to their actions. The overall usability score was high, indicating that the system is suitable for both clinical and home-based use.

## Heart Rate Monitoring Accuracy

Table 5.1 Heart rate monitoring accuracy

Test Condition	Reference HR (BPM)	Measured HR (BPM)	Error (BPM)	Error (%)
Resting	68	69.2	1.2	1.8%
Light Activity	85	86.8	1.8	2.1%
Moderate Activity	105	107.4	2.4	2.3%
Recovery	78	79.6	1.6	2.1%
Average	84	85.8	1.75	2.1%

The heart rate monitoring subsystem demonstrated a mean absolute error of 1.75 BPM across all tested conditions, with a maximum error of 2.4 BPM at moderate activity levels. This accuracy is consistent with clinical-grade pulse oximetry performance standards, which typically accept errors of  $\pm 2-3$  BPM at heart rates below 150 BPM. The safety response system was tested across 50 simulated threshold violation trials, achieving a mean response time of 0.42 seconds

### 3.2 Research Findings

The experimental evaluation of the proposed IoT-based rehabilitation glove system led to several significant research findings that directly support the objectives of this study. These findings highlight the effectiveness of combining **finger-wise motion mirroring, vacuum-based soft actuation, and continuous heart rate monitoring** into a single rehabilitation platform.

One of the most important findings is that **accurate finger-wise motion mirroring can be achieved using low-cost flex sensor technology** when combined with proper calibration and signal processing. The system demonstrated that individual finger movements of the healthy hand can be captured and replicated on the paralysed hand with a high level of precision, maintaining an error margin within  $\pm 3^\circ$ . This is a critical improvement over many existing rehabilitation devices, which primarily focus on general hand opening and closing rather than precise finger-level control. The ability to mirror each finger independently allows the system to support fine motor skill recovery, which is essential for performing daily activities such as grasping objects, writing, or buttoning clothes. Furthermore, the results indicate that personalized calibration plays a crucial role in achieving this level of accuracy, as each user's finger movement range and sensor characteristics may differ.

Another key finding is the importance of **real-time responsiveness in rehabilitation systems**. The measured latency of less than 15 milliseconds confirms that the system can provide near-instantaneous feedback between the healthy hand and the paralysed hand. This real-time synchronization is vital for the effectiveness of mirror therapy, as it creates a strong visual and sensory illusion that both hands are moving simultaneously. Such synchronization is known to stimulate the brain's motor cortex and promote neuroplasticity, which is essential for recovery in patients with neurological impairments. The findings suggest that even small delays can disrupt this illusion, emphasizing the need for efficient wireless communication and optimized processing algorithms.

The study also revealed that **continuous heart rate monitoring significantly enhances the safety of rehabilitation therapy**, particularly in unsupervised environments. Unlike traditional rehabilitation systems that focus solely on mechanical assistance, the proposed system integrates physiological monitoring to assess the patient's condition during therapy sessions. The heart rate sensor was able

to provide stable and continuous readings, allowing the system to detect abnormal increases in heart rate that may indicate stress, discomfort, or overexertion. This is especially important for stroke patients or individuals with cardiovascular conditions, where excessive physical strain can lead to serious health risks. The integration of heart rate monitoring ensures that therapy is not only effective but also safe.

A further important finding is the effectiveness of the **automated safety response mechanism**. The system demonstrated the ability to respond dynamically to changes in the patient's heart rate by reducing actuator intensity or stopping the system entirely when critical thresholds were exceeded. This automated response reduces the need for constant supervision by a therapist and enables safer home-based rehabilitation. The rapid response time of less than one second ensures that corrective actions are taken immediately, minimizing the risk of harm. This feature addresses a major gap in existing rehabilitation technologies, where safety monitoring is often limited or absent.

The research also confirms that **vacuum-based soft actuation provides a safer and more natural method for hand movement assistance** compared to rigid mechanical systems. The soft actuators used in the system generate smooth and compliant motion, which closely resembles natural finger movement. This reduces the risk of injury and improves user comfort, particularly for patients with weak or sensitive muscles. The findings indicate that soft actuation is highly suitable for rehabilitation applications, as it allows for gradual and controlled movement without imposing excessive force on the hand.

In addition, the study highlights the role of **IoT integration in modern rehabilitation systems**. The successful transmission of heart rate data to a cloud database demonstrates that remote monitoring is feasible and reliable. This enables healthcare professionals to track patient progress, analyze therapy data, and provide feedback without requiring the patient to visit a clinical facility. The ability to store and analyze long-term data also opens opportunities for developing personalized rehabilitation programs based on patient performance trends.

Another notable finding is the **cost-effectiveness of the proposed system**. The use of affordable components such as flex sensors, ESP32 microcontrollers, and commercially available heart rate sensors allows the system to achieve high performance at a significantly lower cost compared to existing commercial rehabilitation devices. This makes the system accessible to a wider population, particularly in developing regions where access to advanced medical equipment is limited. The findings suggest that cost-effective solutions can still deliver high functionality when designed with efficient integration of hardware and software.

Finally, the study demonstrates that the system is **well-suited for home-based rehabilitation environments**. The combination of portability, ease of use, and safety features allows patients to perform therapy independently. User feedback indicated that the system is comfortable to wear and easy to operate, which is essential for encouraging consistent use. Regular and repeated therapy sessions are critical for

recovery, and the ability to perform these sessions at home can significantly improve rehabilitation outcomes.

Overall, the research findings confirm that the proposed system successfully addresses the limitations of existing rehabilitation technologies by providing a comprehensive solution that combines **accurate finger-wise motion mirroring, continuous physiological monitoring, real-time responsiveness, and user safety**. These findings support the feasibility of the system as a practical tool for improving hand function recovery in patients with paralysis.

### 3.3 Discussion

The results obtained from the implementation and testing of the proposed rehabilitation glove system demonstrate that the integration of **finger-wise motion mirroring** and **continuous heart rate monitoring** provides a comprehensive and effective solution for hand paralysis rehabilitation. This section discusses the significance of these results in relation to the research objectives, compares the system with existing approaches, and evaluates its practical applicability, strengths, and limitations.

One of the most significant contributions of this study is the successful implementation of **finger-wise motion mirroring with high accuracy and real-time responsiveness**. Unlike conventional rehabilitation systems that focus primarily on gross hand movements, the proposed system enables precise replication of individual finger movements. This capability is particularly important because fine motor skills play a crucial role in performing activities of daily living. The achieved accuracy of approximately  $\pm 3^\circ$  indicates that the system can reliably reproduce natural finger motion, which is essential for stimulating the brain's motor cortex. From a neurological perspective, repetitive and accurate movement patterns are known to enhance neuroplasticity, allowing the brain to reorganize and form new neural connections. Therefore, the ability to mirror finger movements in real time directly contributes to improved rehabilitation outcomes.

The low latency observed in the system further strengthens its effectiveness in rehabilitation applications. The measured delay of less than 15 milliseconds ensures that the movement of the paralysed hand appears synchronized with the healthy hand. This synchronization is critical for mirror therapy, as it creates a convincing visual and sensory illusion that both hands are functioning normally. If the delay were noticeable, it could reduce the effectiveness of therapy by disrupting the brain's perception of movement. The results of this study confirm that the use of efficient wireless communication protocols and optimized embedded processing can achieve the level of responsiveness required for real-time rehabilitation systems.

Another important aspect highlighted by the results is the integration of **continuous heart rate monitoring as a safety mechanism**. Traditional rehabilitation devices typically do not account for the patient's physiological condition during therapy sessions. In contrast, the proposed system continuously monitors heart rate and uses

this information to regulate the intensity of the therapy. This feature is particularly important for patients recovering from stroke or those with cardiovascular conditions, as they may be vulnerable to overexertion. The ability of the system to detect abnormal heart rate levels and respond within a short time frame demonstrates its effectiveness in ensuring patient safety. This integration represents a significant advancement over existing systems, as it combines mechanical assistance with physiological awareness.

The use of **vacuum-based soft actuators** also plays a critical role in the overall performance and safety of the system. Unlike rigid robotic mechanisms, soft actuators provide compliant and flexible movement that adapts to the natural motion of the human hand. This reduces the risk of injury, especially for patients with limited strength or sensitivity. The smooth and gradual actuation observed during testing indicates that the system can deliver controlled assistance without causing discomfort. This makes the device more suitable for long-term use in rehabilitation programs. Furthermore, the inherent safety of vacuum actuation, where the system returns to a neutral state in case of pressure loss, adds an additional layer of reliability.

The incorporation of **IoT-based cloud connectivity** enhances the functionality of the system by enabling remote monitoring and data analysis. The ability to transmit heart rate data and session information to a cloud database allows healthcare professionals to track patient progress over time. This is particularly beneficial in home-based rehabilitation scenarios, where direct supervision is limited. By providing real-time and historical data, the system supports informed decision-making and personalized therapy adjustments. This feature aligns with the growing trend of digital healthcare and telemedicine, where remote patient monitoring is becoming increasingly important.

Despite these advantages, the study also identifies several limitations that should be considered. One limitation is the absence of wrist motion tracking, which restricts the system to finger-level rehabilitation. While finger movement is critical, many functional tasks also require coordinated wrist motion. Incorporating additional sensors to capture wrist orientation could further enhance the system's capabilities. Another limitation is the dependence on accurate sensor calibration. Variations in sensor placement or changes in sensor characteristics over time may affect measurement accuracy. This highlights the need for periodic recalibration or the development of adaptive calibration algorithms.

Battery life and power management also present challenges for long-term use. The vacuum pump and wireless communication modules consume significant power, which may limit the duration of therapy sessions. Future improvements could focus on optimizing energy consumption or integrating more efficient power sources. Additionally, while the system performed well under controlled testing conditions, further validation with actual patients is necessary to fully assess its clinical effectiveness.

When compared with existing rehabilitation technologies, the proposed system offers a balanced combination of **accuracy, safety, affordability, and usability**. Many commercial robotic gloves are expensive and complex, making them inaccessible to a large portion of the population. In contrast, this system achieves comparable functionality using low-cost components, making it more suitable for widespread adoption. The inclusion of heart rate monitoring and automated safety control further distinguishes it from other systems that lack physiological feedback mechanisms.

Overall, the discussion highlights that the proposed rehabilitation glove system successfully addresses the key challenges identified in the research problem. By integrating **finger-wise motion mirroring, real-time responsiveness, continuous physiological monitoring, and IoT connectivity**, the system provides a holistic solution for hand rehabilitation. While certain limitations remain, the results demonstrate strong potential for real-world application, particularly in home-based rehabilitation settings where accessibility and safety are critical.

### 3.4 Summary of Each Student's Contribution

This research project was carried out as a collaborative effort, with each team member contributing to different aspects of the system development.

The primary contribution of this study (individual part) focused on the development of the **finger-wise motion mirroring system**. This included the design and implementation of the flex sensor-based input glove, the calibration process for accurate angle measurement, and the development of algorithms to map finger movements to actuator control signals. The real-time wireless communication between the gloves was also implemented as part of this contribution.

Another key component of the project was the development of the **continuous heart rate monitoring system**. This involved integrating the MAX30102 sensor, developing algorithms for heart rate calculation, and implementing safety thresholds to control the actuation system based on physiological conditions. The integration of cloud connectivity for real-time monitoring and data storage was also a significant part of this work.

Additional contributions included the design of the vacuum-based actuation system, system integration, testing, and validation. The entire team collaborated on assembling the hardware, conducting experiments, analyzing results, and preparing the final documentation.

## CONCLUSION

This research presented the design, development, and evaluation of an IoT-based wearable rehabilitation glove system aimed at assisting individuals suffering from hand paralysis due to neurological conditions such as stroke, spinal cord injury, and peripheral nerve damage. The primary objective of the study was to develop a system capable of performing accurate **finger-wise motion mirroring** from a healthy hand to a paralysed hand while ensuring patient safety through **continuous heart rate monitoring**. The results obtained from the implementation and testing of the system demonstrate that the proposed solution successfully achieves these objectives and provides a practical approach to improving rehabilitation outcomes.

One of the key achievements of this research is the successful realization of real-time finger-wise motion mirroring. The system was able to capture individual finger movements using flex sensors and replicate those movements on the paralysed hand with a high level of accuracy. This capability represents a significant advancement over traditional rehabilitation techniques and many existing robotic systems, which often focus on general hand movement rather than precise finger control. The ability to mirror each finger independently is particularly important for restoring fine motor skills, which are essential for performing everyday tasks such as grasping, writing, and handling objects. The achieved accuracy and responsiveness of the system indicate that it can effectively support neuroplasticity, thereby contributing to motor function recovery.

Another major contribution of this study is the integration of continuous heart rate monitoring into the rehabilitation process. Unlike conventional systems that operate solely based on mechanical movement, the proposed system incorporates physiological feedback to ensure patient safety. The heart rate monitoring module continuously tracks the user's cardiovascular condition during therapy sessions and triggers safety mechanisms when abnormal conditions are detected. This feature is especially important for patients recovering from stroke or those with underlying cardiovascular risks, as it prevents overexertion and reduces the likelihood of adverse health events. The ability to combine motion assistance with real-time physiological monitoring enhances both the safety and effectiveness of the rehabilitation process.

The use of vacuum-based soft actuators further strengthens the system by providing a safe and natural method of assisting hand movement. Soft actuation ensures that the

movements are gentle, compliant, and adaptable to the user's hand structure, minimizing the risk of injury. This is particularly beneficial for patients with weak or sensitive muscles, as it allows for gradual and controlled rehabilitation. Compared to rigid mechanical systems, the vacuum-based approach offers improved comfort and usability, making it more suitable for long-term therapy applications.

In addition to its technical capabilities, the system demonstrates strong potential for practical application due to its affordability and portability. The use of low-cost components such as flex sensors, microcontrollers, and readily available heart rate sensors enables the development of a cost-effective solution without compromising functionality. This is a critical factor in addressing the accessibility challenges associated with existing rehabilitation technologies, which are often expensive and limited to clinical settings. By providing a portable and user-friendly design, the system allows patients to perform rehabilitation exercises in home environments, reducing the need for frequent hospital visits and enabling more consistent therapy.

The integration of IoT technology into the system also adds significant value by enabling remote monitoring and data analysis. The ability to transmit heart rate data and session information to a cloud database allows healthcare professionals to track patient progress over time and make informed decisions regarding treatment plans. This feature supports the growing trend of telemedicine and digital healthcare, where remote patient monitoring plays an increasingly important role. The availability of real-time and historical data enhances the overall effectiveness of rehabilitation by enabling personalized and data-driven therapy approaches.

Despite the promising results, the study acknowledges certain limitations that provide opportunities for future improvement. The current system focuses primarily on finger movement and does not include wrist or forearm motion tracking, which are important components of complete hand functionality. Additionally, the performance of the system depends on accurate sensor calibration, and variations in sensor placement may affect measurement accuracy. Power consumption and battery life are also factors that need to be optimized for extended use. Addressing these limitations in future work will further enhance the system's capabilities and usability.

Overall, this research successfully demonstrates that the integration of **finger-wise motion mirroring, continuous heart rate monitoring, soft actuation, and IoT connectivity** can provide a comprehensive and effective solution for hand paralysis rehabilitation. The system not only improves the accuracy and effectiveness of therapy but also ensures patient safety and accessibility. By addressing key limitations of existing rehabilitation technologies, the proposed solution contributes to the advancement of wearable rehabilitation systems and opens new possibilities for home-based therapy.

In conclusion, the developed rehabilitation glove system represents a significant step toward creating affordable, safe, and intelligent rehabilitation solutions. The findings of this study highlight the importance of combining mechanical assistance with physiological monitoring to achieve optimal rehabilitation outcomes. With further

development and clinical validation, the system has the potential to be implemented as a practical tool for improving the quality of life of individuals affected by hand paralysis.

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## GLOSSARY

<b>Term</b>	<b>Definition</b>
<b>Actuator</b>	A mechanical or electromechanical device that converts electrical signals into physical movement. In this system, vacuum actuators are used to control finger motion.
<b>ADC (Analog-to-Digital Converter)</b>	A hardware component that converts analog signals from sensors into digital values for processing by the microcontroller.
<b>ESP32</b>	A low-cost microcontroller with built-in Wi-Fi and Bluetooth, used as the main control unit for data processing and communication.
<b>Flex Sensor</b>	A resistive sensor that changes its resistance when bent, used to detect finger movement and bending angles.
<b>Finger-wise Motion Mirroring</b>	A rehabilitation technique where individual finger movements of a healthy hand are replicated on a paralysed hand in real time.
<b>Heart Rate Monitoring</b>	The continuous measurement of heartbeats per minute (BPM) to assess the patient's physiological condition during therapy.
<b>IoT (Internet of Things)</b>	A system of interconnected devices that communicate and exchange data over the internet.
<b>Latency</b>	The time delay between input (finger movement detection) and output (actuator response) in the system.
<b>MAX30102 Sensor</b>	A photoplethysmography (PPG)-based sensor used to measure heart rate and blood oxygen levels.
<b>Microcontroller</b>	A compact integrated circuit designed to control a specific function in an embedded system.
<b>Mirror Therapy</b>	A rehabilitation method that uses visual feedback from a healthy limb to stimulate movement in a paralysed limb.
<b>Neuroplasticity</b>	The brain's ability to reorganize and form new neural connections to recover lost functions.
<b>PPG (Photoplethysmography)</b>	A non-invasive optical technique used to measure blood volume changes for heart rate detection.
<b>Solenoid Valve</b>	An electrically controlled valve used to regulate the flow of air or vacuum in the actuation system.

<b>Vacuum Actuation</b>	A soft robotics method where negative pressure is used to create movement in flexible actuators.
<b>Cloud Database</b>	An online data storage system used to store and access data remotely (e.g., Firebase).
<b>Rehabilitation</b>	The process of restoring physical abilities through therapy and repetitive exercises.
<b>BPM (Beats Per Minute)</b>	A unit used to measure heart rate.
<b>Wearable Device</b>	An electronic device designed to be worn on the body for monitoring or assistance purposes.