IOT BASED SYSTEM FOR PARALYZED HAND CONTROL

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ABSTRACT

Paralysis of the hand severely impacts the quality of life of millions of individuals worldwide. Traditional rehabilitation therapy consists of regular observation by health experts and is subject to irregular therapeutic movements, geographic barriers, and significant economic constraints. This dissertation presents the design and implementation of an IoT-based smart glove system for paralyzed hand rehabilitation that provides personalized therapeutic exercises through an intelligent wearable device. The system consists of a reference functional hand tracking glove, a paralyzed hand therapy smart glove, and a smartphone application interface. The smartphone records motion patterns from the functional hand glove and transmits exercise patterns to the therapeutic smart glove, which subsequently guides the paralyzed hand through prescribed rehabilitation exercises. The system employs an ESP32 microcontroller for sensor data acquisition, actuator control, and wireless communication. Flex sensors integrated into the glove monitor finger movement angles and grip force in real time. A vacuum pump actuation mechanism assists finger movements during therapeutic exercises. Cloud infrastructure provides centralized data storage, processing, and synchronization services between users and devices. Finger-wise individual exercise control and pattern-based exercise delivery mechanisms were implemented to enable precise, personalized rehabilitation. The system aims to provide real-time personalized rehabilitation therapy with remote monitoring by healthcare professionals, enabling patients to exercise multiple times daily without direct supervision. The expected outcomes include improved hand function, reduced dependence on supervised treatment, increased patient compliance with rehabilitation procedures, and broader accessibility to quality rehabilitation for patients regardless of geographic location or economic status.

Keywords: IoT, Paralyzed hand rehabilitation, Smart glove, Finger-wise exercise control, Pattern-based therapy, ESP32, Flex sensors, Mobile health, Assistive technology, Neuroplasticity

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LIST OF ABBREVIATIONS

API	Application Programming Interface
BLE	Bluetooth Low Energy
EMG	Electromyography
ESP32	Espressif Systems 32-bit Microcontroller
HIPAA	Health Insurance Portability and Accountability Act
HTTP	Hypertext Transfer Protocol
IoT	Internet of Things
MCU	Microcontroller Unit
MQTT	Message Queuing Telemetry Transport
PWM	Pulse Width Modulation
ROM	Range of Motion
SDK	Software Development Kit
SLIIT	Sri Lanka Institute of Information Technology
SPI	Serial Peripheral Interface
UI	User Interface
UX	User Experience
Wi-Fi	Wireless Fidelity
WBS	Work Breakdown Structure

1. INTRODUCTION

Paralysis of the hand is one of the most debilitating conditions that reduces human autonomy and quality of life. When an individual is rendered incapable of using their hands following stroke, spinal cord injury, traumatic brain injury, or other neurological impairments, they face significant challenges in carrying out simple day-to-day activities such as eating, writing, or even basic gestures of communication. Rehabilitation is a rigorous, consistent, and intensive process that traditional healthcare systems are ill-suited to provide efficiently.

The motivation to conduct this research stems from observing the harsh reality that millions of individuals worldwide are trapped in a cycle of insufficient rehabilitation due to a scarcity of opportunities. Current physiotherapy practices, while effective, are hindered by resource limitations, geographical separation, and the fact that patients can obtain professional treatment for only a few hours per week. Meanwhile, research consistently demonstrates that recovery rates improve substantially when exercise frequency and consistency increase.

With the development of Internet of Things (IoT) technologies, combined with advancements in wearable sensors and mobile computing, there is an unprecedented potential to revolutionize rehabilitation therapy. By designing a smart, autonomous system capable of delivering prescribed exercises to patients at home, we can potentially transform rehabilitation practice and offer hope to millions who need to recover hand function. The vision for this project is to create a system in which patients receive high-quality, tailored rehabilitation therapy multiple times daily, guided by the judgment of their physiotherapist but delivered through intelligent technology that eliminates geography, cost, and timing as barriers to recovery.

1.1 Background and Literature Survey

Paralysis of the upper limb results in disability in millions of individuals worldwide due to stroke, spinal cord injury, traumatic brain injury, and neurodegenerative diseases. The World Health Organization estimated that almost 15 million individuals suffer from stroke annually, and a large number of them develop persistent motor disability [6]. Hand recovery after paralysis may be slow, but its pace can be significantly accelerated by increasing the frequency and consistency of exercises and rehabilitation interventions.

Traditional rehabilitation practices are carried out by physiotherapists through direct contact with patients. While this approach can be effective, it carries several inherent limitations. Resource intensiveness characterizes traditional physiotherapy, as it requires dedicated healthcare professionals, specialized facilities, and expensive equipment that creates significant demand on healthcare systems. Patients are typically in contact with physiotherapists for short periods during a day, commonly 30–60 minutes per session, which limits the potential for accelerated intensive rehabilitation.

Geographic and economic conditions make traditional physiotherapy very costly for patients who live far from rehabilitation clinics. High costs and transportation challenges cause many patients to miss therapy sessions, significantly compromising their rehabilitation outcomes. Patients from rural or underprivileged areas often lack access to specialized rehabilitation services. Additionally, traditional methods fail to provide patients with the means to continue therapeutic exercises independently between sessions, leaving significant gaps in daily rehabilitation compliance.

Recent advancements in IoT-enabled rehabilitation systems have reported promising results. Chen et al. demonstrated that robotic glove systems can provide efficient stroke rehabilitation with improved clinical outcomes [1]. Kumar and Patel designed an IoT-based personalized rehabilitation system using machine learning algorithms that showed significant upper limb recovery improvement [2]. Rodriguez et al. combined mirror therapy with wearable technology for paralyzed hand rehabilitation, proving the success of technology integration in therapy sessions [3].

Thompson and Williams examined smart glove prototypes with gamification features to improve user compliance in hand rehabilitation [4]. Their research indicated that interactive features significantly improve patient adherence to prescribed exercises. Lee et al. presented comprehensive IoT ecosystems in rehabilitation settings, demonstrating the feasibility of creating integrated therapeutic environments [5]. Nakamura et al. contributed sensor fusion algorithms specifically designed for wearable rehabilitation devices, providing key technical insights for accurate finger movement detection [7].

Ahmed et al. investigated safety considerations in automated rehabilitation robotics, establishing essential safety protocols for systems that physically interact with patients [8]. Garcia et al. explored cloud-based analytics for personalized physical therapy, demonstrating how data-driven platforms can enhance exercise prescription and outcome prediction [9]. Wilson et al. addressed HIPAA compliance in IoT-enabled healthcare applications, providing a regulatory framework applicable to the development of this system [10].

Table 1.1: Comparison of Existing Rehabilitation Systems

System	Technology Used	Key Feature	Limitation
Chen et al. (2023)	Robotic Glove	Stroke rehabilitation	Requires clinical setting
Kumar & Patel (2024)	IoT + ML	Personalized therapy	Complex setup
Rodriguez et al. (2023)	Wearable + Mirror therapy	Motor recovery	Limited autonomy
Thompson & Williams (2024)	Smart Glove + Gamification	User engagement	No remote monitoring
Proposed System	**IoT Smart Glove + Mobile App**	**Finger-wise + Pattern exercise**	**Prototype stage**

1.2 Research Gap

Despite enormous improvements in rehabilitation technology, several key gaps persist in existing IoT-based paralyzed hand rehabilitation systems. The most significant gap is inadequate exercise frequency and duration. Existing systems fail to account for the critical constraint that recovery speed is a direct function of exercise frequency. The majority of existing solutions remain therapist-dependent, preventing patients from performing exercises multiple times daily as required for optimal recovery.

Geographic and economic constraints persist as existing IoT-based rehabilitation devices have not significantly addressed the problem of missed therapy sessions caused by expense and distance to physiotherapy centers. These systems still require constant professional attention or center-based application, limiting their utility for remote populations.

There is no integrated independent exercise prescription system among available solutions. None of the current systems provide a complete environment where exercises can be prescribed for specific durations and patients can perform them autonomously using smart device technology. Furthermore, most available solutions emphasize guided sessions rather than assisting patients in performing prescribed routines daily according to physiotherapist recommendations in the absence of professional presence.

A critical technical gap identified in existing systems is the absence of finger-wise individual exercise control. Current rehabilitation glove systems tend to actuate the entire hand simultaneously, lacking the precision to target individual fingers independently. This is a significant limitation because rehabilitation protocols frequently require isolated finger movements to address specific motor deficits.

Pattern-based exercise delivery, where a healthy hand's movement is captured and replicated on the paralyzed hand, is another area insufficiently addressed in existing literature. While mirror therapy principles are established, their technical implementation in autonomous, patient-operated IoT systems remains limited. Poor long-term monitoring characterizes dominant solutions, which focus on short-term exercise delivery without long-term progress monitoring and outcome prediction capabilities.

1.3 Research Problem

The primary research question this project addresses is: What would be the design and implementation of an IoT-based intelligent glove system that enables autonomous, repetitive, and personalized hand rehabilitation exercises for paralyzed patients with finger-wise control, pattern-based exercise delivery, adequate clinical supervision, and safety protocols?

Specific Research Questions

1. Accessibility Challenge: How can paralyzed hand rehabilitation be made available to patients regardless of geographic location or economic status, overcoming barriers that discourage consistent therapy attendance?
2. Exercise Frequency Optimization: How can the system enable patients to perform prescribed rehabilitation exercises multiple times per day without direct therapist supervision, increasing exercise frequency to accelerate recovery rates?

3. Finger-Wise Control: How can the system achieve individual finger actuation to enable targeted rehabilitation exercises for specific fingers, rather than whole-hand generalized movements?
4. Pattern-Based Therapy: How can healthy hand movement patterns be captured and transmitted in real time to guide the paralyzed hand through precise replication exercises?
5. Personalization and Prescription: How can physiotherapists remotely prescribe customized exercise routines through an online system that translates these prescriptions into specific physical movements delivered by the smart glove?
6. Safety and Autonomy Balance: How can the system balance patient safety during autonomous exercises with sufficient autonomy to allow unsupervised normal rehabilitation activity?
7. Clinical Integration: How can the IoT system be integrated with existing healthcare workflows to enable real-time monitoring, progress tracking, and treatment plan adjustment by healthcare professionals?
8. Effectiveness Measurement: How can the system effectively measure and report on rehabilitation progress to enable data-driven treatment planning and outcome prediction?

1.4 Research Objectives

1.4.1 Primary Objective

To design and implement an IoT-based smart glove system for rehabilitation of paralyzed hands using pre-programmed automatic exercise sessions with finger-wise individual control and pattern-based exercise delivery mechanisms, where exercises are prescribed by physiotherapists via a mobile application and patients can perform therapeutic sessions autonomously without physiotherapist intervention, thereby increasing exercise frequency and recovery rates while reducing cost and geographical limitations.

1.4.2 Specific Objectives

9. Design and develop a smart rehabilitation glove incorporating flex sensors, vacuum pump actuators, and an ESP32 microcontroller capable of executing precise, individual finger movement assistance for all five fingers independently.
10. Implement a finger-wise exercise control module that enables targeted actuation of individual fingers based on rehabilitation requirements, rather than whole-hand simultaneous movement.
11. Develop a pattern-based exercise delivery mechanism that captures movement patterns from a functional hand glove and replicates them on the paralyzed hand in real time or through pre-stored exercise sequences.

12. Develop a mobile application as the central command interface for healthcare professionals and patients to perform exercise prescription, real-time monitoring, progress tracking, and communication.
13. Integrate cloud infrastructure for secure data storage, processing, and synchronization between the smart glove hardware and the mobile application.
14. Implement comprehensive safety mechanisms including movement validation algorithms, emergency stop functionality, and force-limiting controls to ensure patient safety during autonomous use.
15. Design and conduct systematic testing and validation protocols including hardware integration testing, software functionality testing, communication protocol verification, and performance benchmarking.

2. METHODOLOGY

2.1 Overall System Description

The proposed system for rehabilitating a paralyzed hand leverages IoT technology centered on the integration of an end-to-end smart glove ecosystem. The system design consists of multiple interdependent components that work synergistically to facilitate effective, autonomous rehabilitation therapy that can be performed multiple times daily by the patient without direct professional supervision.

The system begins with a smart rehabilitation glove that incorporates advanced actuators to control the patient's individual fingers safely and precisely. The glove includes flex sensors at each finger joint to monitor movement angles, grip force measurements, and compliance with prescribed exercise patterns in real time. A vacuum pump mechanism provides the mechanical force necessary to assist finger flexion and extension movements during therapeutic exercises.

The glove is wirelessly linked to a mobile application that serves as the core patient and clinician interface portal. The mobile application provides complete functionality including exercise prescription management, real-time monitoring, progress visualization, and communications between patients and their clinicians. A voluntary functional glove component is employed to record healthy hand movement patterns, which the smart rehabilitation glove subsequently replicates to provide accurate rehabilitation exercises to the paralyzed hand.

2.2 System Architecture

The system architecture follows a distributed IoT design with cloud processing and storage. The smart glove device serves as the primary data collection and actuation endpoint, equipped with an ESP32 microcontroller that handles sensor data acquisition, actuator control, and wireless communication protocols via Wi-Fi and Bluetooth Low Energy (BLE).

Cloud infrastructure provides centralized data storage, processing capacity, and synchronization services between users and devices. The cloud platform ensures secure data transmission using HTTPS and MQTT protocols, maintains patient privacy protection policies, and provides scalable processing capacity to accommodate multiple concurrent users and high-volume data analytics requirements.

The mobile application layer provides the user interface for both patients and healthcare professionals. Built using cross-platform development technologies to ensure compatibility across Android and iOS devices, the application communicates bidirectionally with both the cloud backend and the smart glove hardware. The application enables physiotherapists to prescribe exercises remotely, monitor patient compliance, and adjust treatment protocols based on progress data.

[Figure 2.1: System Architecture Diagram – See Appendix for detailed schematic]

2.3 Finger-Wise Exercise Control Module

One of the key innovations of this system is the finger-wise individual exercise control module. Unlike existing rehabilitation gloves that actuate all fingers simultaneously, this system implements independent control channels for each of the five fingers. This capability is critical because many rehabilitation protocols require isolated finger movements to address specific motor deficits following stroke or nerve damage.

The ESP32 microcontroller manages five independent PWM (Pulse Width Modulation) output channels, each controlling a micro-valve that regulates the vacuum pressure supplied to the corresponding finger actuator in the therapeutic glove. A dedicated software layer interprets exercise prescriptions and translates them into timed actuation sequences for individual fingers.

Flex sensors mounted at the proximal interphalangeal (PIP) and metacarpophalangeal (MCP) joints of each finger in the functional hand glove capture real-time angular displacement data. This data is processed by the ESP32 to determine the precise degree of flexion and extension for each finger, which is then mapped to corresponding actuation signals for the paralyzed hand glove. The system achieves a measurement resolution of approximately 1 degree of angular displacement, enabling precise movement replication.

Safety limits are embedded at the firmware level for each finger channel independently. Maximum pressure thresholds prevent over-extension or over-flexion of the paralyzed hand's joints. If a sensor reading indicates that a prescribed movement would exceed safe joint angles, the corresponding actuator is automatically halted and an alert is sent to the mobile application.

2.4 Pattern-Based Exercise Delivery

The pattern-based exercise delivery mechanism enables physiotherapists or patients to record specific movement sequences using the functional hand glove and replay them on the paralyzed hand. This approach is grounded in established mirror therapy principles and neuroplasticity research, which demonstrate that observing and replicating contralateral limb movements promotes motor cortex reorganization and accelerates recovery.

The pattern recording process operates as follows: the patient or clinician wears the functional hand glove and performs the desired exercise movement. The ESP32 samples flex sensor data at 50 Hz across all five channels, capturing a time-series representation of the complete hand movement pattern. This pattern data is compressed and stored both locally on the device and in the cloud database.

During exercise playback, the stored pattern is retrieved and decoded by the ESP32. The actuation sequence is executed to replicate the original movement on the paralyzed hand, with configurable parameters including playback speed (50%–150% of recorded speed), number of repetitions, rest intervals between repetitions, and the specific set of fingers to include in the exercise. The mobile application provides a library of saved patterns, enabling physiotherapists to build personalized exercise programs that patients can execute independently.

Real-time pattern transmission mode allows the functional hand glove and the paralyzed hand glove to operate synchronously. In this mode, the functional hand glove streams sensor data to the ESP32 central unit via BLE with a latency below 50 milliseconds, and the paralyzed hand glove replicates the movements in near real time. This mode is particularly useful for supervised therapy sessions conducted remotely via video consultation.

2.5 Implementation Approach

The implementation methodology follows an iterative development model with systematic testing and validation at each phase. The development is organized into five phases: hardware design and procurement, firmware development, mobile application development, cloud integration, and system integration testing.

2.5.1 Hardware Development

The hardware development phase focuses on the physical construction of both the functional hand glove and the therapeutic smart glove. The functional hand glove integrates five flex sensors (one per finger) connected to the analog-to-digital conversion (ADC) channels of the ESP32. A 3.7V LiPo battery provides portable power, regulated to 3.3V for the microcontroller and sensors.

The therapeutic smart glove employs a pneumatic actuation mechanism powered by a small vacuum pump. Five micro solenoid valves, individually controlled by the ESP32 through a motor controller board, regulate air pressure to soft pneumatic actuators positioned along each finger. The actuators are constructed from flexible silicone tubing that, when pressurized, creates a bending force to assist finger flexion.

The ESP32 central unit serves as the processing hub connecting both gloves. It handles all sensor data acquisition, actuator control, Wi-Fi connectivity for cloud communication, and BLE connectivity for mobile application interaction. The central unit is housed in a compact enclosure that can be worn on the wrist or placed on a table during therapy sessions.

2.5.2 Software Development

Firmware development for the ESP32 was conducted using the Arduino framework with the ESP-IDF SDK. The firmware implements multi-tasking using FreeRTOS, with separate tasks handling sensor acquisition, actuator control, BLE communication, Wi-Fi data synchronization, and safety monitoring. The sensor acquisition task runs at 50 Hz, while the safety monitoring task runs at 100 Hz to ensure rapid response to any unsafe conditions.

The mobile application was developed using Flutter, a cross-platform framework enabling deployment on both Android and iOS from a single codebase. The application communicates with the ESP32 via BLE for real-time control and with the cloud backend via HTTPS REST API for data management. Key application screens include the exercise prescription interface for clinicians, the exercise execution interface for patients, the progress monitoring dashboard, and the pattern recording and management library.

The cloud backend was implemented using Firebase, providing real-time database functionality, user authentication, and cloud storage. Firebase's real-time database enables sub-second synchronization of exercise data and patient progress metrics between the mobile application and authorized healthcare professionals' devices.

Table 2.1: Time Frame and Project Schedule

Task	Duration	Start Week	End Week
Literature Review & Research	4 Weeks	1	4
Hardware Selection & Procurement	4 Weeks	5	8
Hardware Design & Development	14 Weeks	9	22
Cloud Database Integration	2 Weeks	23	24
Software & App Development	6 Weeks	25	30
System Integration & Testing	11 Weeks	31	41
Data Collection & Analysis	2 Weeks	42	43
Evaluation & Documentation	2 Weeks	44	45

2.6 Commercialization Aspects of the Product

The IoT-based smart glove system presents significant commercialization potential across several market segments. The primary target market is rehabilitation clinics and hospitals seeking cost-effective, scalable rehabilitation solutions. A subscription-based software-as-a-service (SaaS) model for the mobile application and cloud platform could provide recurring revenue, while the hardware glove sets could be sold or leased as medical devices.

A secondary market opportunity exists in the home rehabilitation segment, where patients who have completed formal clinical rehabilitation require ongoing maintenance therapy. A simplified consumer version of the system, with guided exercise programs prescribed by clinicians and executed at home, would address this underserved market. Pricing analysis suggests a per-unit hardware cost of approximately LKR 33,500 for the prototype, with economies of scale reducing manufacturing costs by an estimated 60–70% in production volumes.

Partnership opportunities with physiotherapy professional associations, health insurance providers, and national rehabilitation programs could accelerate adoption. Regulatory approval pathways for medical devices in Sri Lanka (National Medicines Regulatory Authority) and international markets (FDA, CE marking) would be necessary for commercial deployment. Intellectual property protection through patents for the finger-wise actuation mechanism and pattern-based delivery algorithm should be pursued prior to commercial launch.

2.7 Testing and Implementation

2.7.1 Functional Requirements

The system's functional requirements encompass the complete operational capabilities necessary for effective rehabilitation delivery. Exercise prescription functionality shall allow healthcare professionals to create rehabilitation plans with specific movement patterns, time parameters, intensity levels, and scheduling information. The system shall support individual finger exercise prescription as well as full-hand pattern-based exercise programs.

Exercise execution capability shall allow the smart glove to replicate prescribed movements accurately with appropriate force delivery and safety checks throughout therapeutic sessions. The system shall support both pre-programmed pattern playback mode and real-time mirroring mode. Communication capabilities must include secure messaging between patients and clinicians, automated progress reporting, safety incident alerts, and integration with existing healthcare information systems.

Table 2.3: Functional Requirements Summary

Requirement ID	Description	Priority
FR-01	Physiotherapist can prescribe exercise per individual finger	High
FR-02	System records movement	High

	pattern from functional hand glove	
FR-03	Smart glove replicates prescribed pattern on paralyzed hand	High
FR-04	Mobile app displays real-time sensor data and exercise status	High
FR-05	System triggers emergency stop on safety limit breach	Critical
FR-06	Patient progress data is synchronized to cloud database	Medium

2.7.2 Non-Functional Requirements

Reliability specifications demand a minimum of 99.5% system availability during planned operating times and automatic recovery from common failure modes. The system must include robust error handling and graceful degradation capabilities in cases of partial system failures, such as cloud connectivity loss, ensuring that locally stored exercises can still be executed autonomously.

Performance requirements specify that the BLE communication latency between the functional hand glove and the central unit shall not exceed 50 milliseconds. The cloud data synchronization shall complete within 2 seconds under normal network conditions. The mobile application shall respond to user interactions within 100 milliseconds. The system shall support a minimum of 4 hours of continuous operation on a single battery charge.

Security requirements mandate encrypted data transmission using TLS 1.3 for all cloud communications and AES-128 encryption for BLE data transfer. User authentication shall be implemented using multi-factor authentication for healthcare professional accounts. All patient data shall be stored in compliance with applicable healthcare data protection regulations.

2.7.3 Test Cases

Functional testing encompasses exercise execution accuracy verification, communication protocol validation, data collection and storage validation, user interface functionality testing, and system component integration testing. Each test case includes distinct acceptance criteria and validation activities.

Table 2.5: Test Case Summary

Test ID	Test Description	Expected Result	Status
TC-01	Individual finger actuation test	Correct finger moves independently	Pass
TC-02	Pattern recording and playback	Recorded motion replicated accurately	Pass
TC-03	BLE communication latency	Latency < 50ms	Pass
TC-04	Safety limit emergency stop	Actuator stops on threshold breach	Pass
TC-05	Cloud data sync verification	Data synced within 2 seconds	Pass
TC-06	Battery life under continuous use	Minimum 4 hours operation	Pass

3. RESULTS AND DISCUSSION

3.1 Results

The implementation of the IoT-based smart glove system yielded comprehensive results across hardware performance, software functionality, and system integration. The developed prototype successfully demonstrated all core functionalities including individual finger-wise exercise control, pattern-based exercise delivery, real-time BLE communication, and cloud data synchronization.

3.1.1 Hardware Performance Results

The flex sensor array integrated into the functional hand glove demonstrated high measurement accuracy across all five fingers. Calibration testing confirmed a linear response characteristic for each flex sensor within the 0–90 degree angular displacement range. The mean absolute error (MAE) of angle measurement across all five sensors was 2.3 degrees, which is within the acceptable tolerance for rehabilitation exercise guidance.

The vacuum pump actuation mechanism successfully demonstrated individual finger control capability. Each of the five solenoid valve channels operated independently without cross-interference. The pneumatic actuators achieved full finger flexion (approximately 80 degrees at MCP joint) within 1.2 seconds of actuation signal, and returned to the extended position within 0.9 seconds upon pressure release. These response times are well within the acceptable range for therapeutic exercise delivery.

Table 3.1: Finger Movement Accuracy Results

Finger	Target Angle (°)	Achieved Angle (°)	MAE (°)
Thumb	60	57.8	2.2
Index	70	68.1	1.9
Middle	75	72.4	2.6
Ring	70	67.2	2.8
Little	65	62.9	2.1
Average	**68**	**65.7**	**2.3**

3.1.2 Pattern-Based Exercise Delivery Results

The pattern recording and playback functionality was tested across ten distinct hand movement patterns, including grip, pinch, extension, lateral pinch, and composite multi-finger sequences. Pattern recording accuracy was evaluated by comparing the sensor time-series data from the original recording to the playback execution data. The mean temporal correlation coefficient across all tested patterns was 0.94, indicating high fidelity in movement pattern replication.

Real-time pattern transmission mode was tested with BLE communication between the functional hand glove and the central unit. Measured communication latency ranged from 28 to 47 milliseconds across 100 test trials, with a mean latency of 38 milliseconds. This performance satisfies the system requirement of sub-50 millisecond latency and is adequate for smooth real-time movement replication without perceptible delay.

3.1.3 System Performance Metrics

Table 3.2: System Performance Metrics

Metric	Target	Achieved
BLE Communication Latency	< 50 ms	38 ms (mean)
Flex Sensor MAE	< 5°	2.3°
Pattern Replication Accuracy	> 0.85 correlation	0.94 correlation
Battery Life (continuous use)	> 4 hours	4.7 hours
Cloud Sync Time	< 2 seconds	1.3 seconds (mean)
Emergency Stop Response Time	< 200 ms	87 ms (mean)

3.2 Research Findings

The research yielded several significant findings that contribute to the body of knowledge in IoT-based rehabilitation technology. The most important finding is the demonstrated feasibility of individual finger-wise actuation using low-cost pneumatic mechanisms controlled by a commodity microcontroller. The ESP32's processing capability was sufficient to manage five independent actuation channels simultaneously while maintaining all communication and safety monitoring functions.

The pattern-based exercise delivery approach proved highly effective in achieving natural movement replication. The 0.94 temporal correlation coefficient achieved in pattern playback represents a significant improvement over simpler, fixed-sequence actuation approaches reported in comparable literature. This finding supports the hypothesis that capturing and replaying natural hand movements produces more physiologically appropriate rehabilitation exercises compared to predefined, mechanically fixed movement sequences.

The finger-wise control capability revealed important insights about rehabilitation exercise requirements. During informal evaluation sessions, it was observed that exercises targeting isolated index finger extension were significantly more complex to replicate accurately than whole-hand grip patterns due to the smaller range of motion involved. This finding suggests that sensor resolution and actuator precision requirements scale non-linearly with the specificity of the targeted exercise.

The cloud integration testing revealed that network connectivity reliability is a critical dependency for the remote monitoring features of the system. In environments with unstable internet connectivity, which is common in rural areas that represent a primary target population for this system, the system must rely on locally stored exercise programs. The offline exercise execution capability was confirmed to function correctly, though real-time progress reporting to clinicians was naturally not possible during offline operation.

3.3 Discussion

The results demonstrate that the proposed IoT-based smart glove system successfully addresses the primary research objectives. The system achieved all performance targets specified in the non-functional requirements and demonstrated functional correctness across all primary use cases. The finger-wise exercise control and pattern-based delivery mechanisms represent genuine innovations over existing rehabilitation glove systems described in the literature review.

Comparison with existing systems highlights the advantages of the proposed approach. Unlike the robotic glove system of Chen et al. [1], which requires a clinical setting, the proposed system is designed for home use. The system's cost, estimated at LKR 33,500 per prototype unit, is significantly lower than comparable commercial rehabilitation robotics systems, which typically cost USD 5,000–15,000. This cost advantage is a critical factor for accessibility in the Sri Lankan and broader South Asian market context.

The pattern-based exercise delivery mechanism provides a significant advantage over the fixed-prescription approaches described in existing literature. By allowing physiotherapists to record and prescribe actual hand movement patterns, the system enables a level of exercise personalization that closely mirrors the movements performed in a traditional physiotherapy session. This approach has strong theoretical grounding in mirror neuron theory and bilateral transfer motor learning principles, which suggest that movement observation and execution activate overlapping neural pathways relevant to motor recovery.

Several limitations of the current prototype were identified during testing. The pneumatic actuation mechanism, while effective, limits the portability of the system due to the vacuum pump's size and noise. Future iterations should explore soft robotic actuators or motor-driven mechanisms that can achieve the required finger forces in a more compact and quiet form factor. The flex sensor calibration drift over extended use was also identified as a potential issue, suggesting that periodic recalibration or more stable sensing technologies such as inertial measurement units (IMUs) should be explored.

The mobile application interface received positive informal feedback from potential users during informal evaluation. The exercise prescription workflow for clinicians was intuitive, and the exercise execution interface for patients was simple enough for users with limited technical literacy to operate. Future formal usability testing with target patient populations and physiotherapy professionals will be essential before clinical deployment.

3.4 Summary of Student Contribution

This dissertation represents the individual research contribution of Vihanga Kaveesha Liyanage (IT22884992). The complete scope of work encompassed all phases of the project lifecycle, from initial literature review and system conceptualization through hardware implementation, software development, system integration, and evaluation.

The key contributions of this work include: (1) the conceptualization and design of the finger-wise individual exercise control architecture for low-cost pneumatic rehabilitation gloves; (2) the development and implementation of the pattern-based exercise delivery mechanism using flex sensor arrays and ESP32 microcontrollers; (3) the development of the Flutter-based mobile application with exercise prescription and monitoring capabilities; (4) the design and implementation of the cloud integration architecture using Firebase; and (5) the systematic testing and performance evaluation of the integrated system.

Hardware procurement, assembly, firmware programming, and testing were conducted independently. The mobile application was coded from scratch, and the cloud backend was architected and configured by the student. Literature review, gap identification, methodology design, data analysis, and documentation were completed under the guidance of the dissertation supervisor, Ms. Narmada Gamage, and co-supervisor, Mr. Uditha Dharmakeerthi.

4. CONCLUSION

This dissertation presented the design, implementation, and evaluation of an IoT-based smart glove system for paralyzed hand rehabilitation. The system successfully demonstrated the feasibility of delivering autonomous, personalized, finger-wise controlled rehabilitation exercises to patients without requiring direct physiotherapist presence. All primary research objectives were achieved, and all system performance targets were met or exceeded in prototype testing.

The two key innovations of this work — finger-wise individual exercise control and pattern-based exercise delivery — represent meaningful advances over existing rehabilitation glove technology. The finger-wise control capability enables targeted rehabilitation of specific fingers according to clinical assessment, rather than generalized whole-hand exercises. The pattern-based delivery mechanism captures the naturalness and specificity of physiotherapist-guided exercises and makes them available for patient self-administration at any time.

The system addresses the fundamental problem of exercise frequency limitation in traditional rehabilitation. By enabling patients to perform prescribed rehabilitation exercises multiple times daily at home, the system has the potential to significantly accelerate recovery rates compared to conventional outpatient physiotherapy. The remote monitoring capabilities allow healthcare professionals to supervise patient compliance and progress without requiring physical presence, addressing geographic and resource barriers to quality rehabilitation.

The prototype cost of approximately LKR 33,500 demonstrates the economic viability of the approach for the Sri Lankan market and comparable emerging market contexts. With production-scale manufacturing, unit costs are expected to decrease substantially, further improving accessibility. The commercialization pathway through a SaaS subscription model for the digital platform and leased hardware could provide a sustainable business model for wider deployment.

Future work should focus on several priority areas. Formal clinical validation studies with stroke or spinal cord injury patients, conducted in partnership with rehabilitation hospitals, are the most critical next step to establish clinical effectiveness. Hardware miniaturization, particularly of the pneumatic actuation system, should be explored to improve the system's portability and wearability. Machine learning integration for adaptive exercise optimization based on patient progress data represents a promising direction for enhancing the personalization capabilities of the system.

Regulatory approval processes for medical device classification in Sri Lanka and target export markets should be initiated in parallel with clinical validation. Additionally, longitudinal studies examining patient compliance and long-term rehabilitation outcomes with the system will be essential to build the evidence base necessary for healthcare system adoption and insurance coverage.

In summary, this research makes a meaningful contribution to the field of digital rehabilitation technology and assistive devices. The developed system demonstrates that affordable, effective, autonomous hand rehabilitation is achievable using accessible IoT technologies, and has significant potential to democratize access to quality rehabilitation therapy for paralyzed hand patients globally.

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APPENDICES

Appendix A: Budget Details

Table 3.3: Detailed Budget

Item	Cost (LKR)
ESP32 Microcontroller	6,000.00
Flex Sensors (×10, 2 sets)	7,000.00
Vacuum Pump	2,500.00
Wires and Connectors	2,000.00
Motor Controller Board	2,000.00
Solenoid Valves (×5)	3,000.00
Glove Materials and Enclosure	3,000.00
Travelling Cost	4,000.00
Miscellaneous / Other	4,000.00

Total Estimated Budget: LKR 33,500.00

Appendix B: System Architecture Diagrams

Figure B.1 presents the complete system architecture including the functional hand glove, central ESP32 unit, paralyzed hand glove, mobile application, and cloud database components with their interconnections and communication protocols.

Figure B.2 presents the Work Breakdown Structure (WBS) illustrating the hierarchical decomposition of all project tasks across five work packages: Requirement Analysis, Hardware Development, Software Development, System Integration and Testing, and Deployment and Optimization.

[Architecture diagrams are included as separate attachments per SLIIT submission guidelines]

Appendix C: ESP32 Firmware – Core Task Structure

The firmware implements five FreeRTOS tasks: (1) SensorAcqTask – samples all five flex sensors at 50 Hz and buffers data; (2) ActuatorControlTask – reads exercise parameters and drives solenoid valve PWM signals; (3) SafetyMonitorTask – runs at 100 Hz, checks sensor readings against safety thresholds and triggers emergency stop if violated; (4) BLECommTask – manages BLE GATT server for mobile application connectivity and real-time data streaming; (5) CloudSyncTask – manages Wi-Fi connectivity and uploads exercise completion records and progress metrics to Firebase.

Appendix D: Mobile Application Screen Descriptions

Login Screen: Multi-factor authentication for both patient and clinician roles with role-based navigation.

Exercise Prescription (Clinician): Interface for selecting individual fingers, setting repetitions, duration, speed, and recording or selecting exercise patterns.

Exercise Execution (Patient): Simple start/stop interface with real-time visual feedback of glove sensor data and exercise progress timer.

Progress Dashboard: Charts showing session history, range of motion trends, and compliance percentage over time.

Pattern Library: List of saved exercise patterns with playback controls, editing options, and assignment to patient schedules.