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Therapeutic Engagement Glove for Vision-Based Hand Rehabilitation

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KEYWORDS

Hand Rehabilitation, Robotic Glove, Computer Vision, MediaPipe, Servo Motors, Wireless Communication, Physi-otherapy Automation.

ABSTRACT

Hand rehabilitation therapy is essential for patients suffering from stroke, paralysis, nerve injuries, or post-surgical stiffness. Traditional physiotherapy requires continuous supervision by therapists, which can be time-consuming, expensive, and inaccessible in rural areas. This paper presents a low-cost and intelligent re-habilitation system named the Therapeutic Engagement Glove, which enables wireless replication of therapist hand movements onto a robotic glove worn by the patient.The proposed system uses computer vision techniques with OpenCV and MediaPipe to detect real-time hand landmarks from a trainer's hand via a webcam. The detected finger joint positions are processed and transmitted wirelessly to a microcontroller-based robotic glove equipped with servo motors. The robotic glove mimics the trainer's hand movements, assisting the patient in performing guided rehabilitation exercises. The system also tracks movement repetitions, calculates joint angles, and records patient progress. Experimental results demonstrate accurate movement replication with minimal latency, making the system suitable for home-based rehabilitation. This approach reduces dependency on manual therapy ses-sions and provides an affordable assistive solution for motor recovery.

INTRODUCTION

Hand motor impairment is a major consequence of neurological disorders such as stroke, spinal cord injury, cerebral palsy, and traumatic brain injury. Among these conditions, stroke remains one of the leading causes of long-term disability worldwide. A significant percentage of stroke survivors experience upper limb dysfunction, particularly affecting fine motor control of the fingers and hand. Since the human hand is essential for performing daily activities such as grasping, writing, eating, typing, and self-care, any limitation in hand movement drastically reduces independence and quality of life.

Rehabilitation therapy plays a crucial role in restoring motor function after neurological damage. Recovery is primarily achieved through repetitive, task-oriented exercises that stimulate neuroplasticity, enabling the brain to reorganize neural pathways. Continuous and guided movement training improves muscle strength, coordination, and range of motion. However, traditional rehabilitation methods rely heavily on therapist-supervised sessions conducted in hospitals or specialized centers. These sessions are often time-consuming, expensive, and limited in duration. Many patients, especially those in rural or resource-constrained areas, face difficulty accessing regular therapy due to travel constraints and financial burden.

To overcome these limitations, robotic-assisted rehabilitation systems have been introduced. Robotic devices provide consistent, repeatable, and controlled motion assistance without therapist fatigue. They also allow objective monitoring of patient progress through measurable parameters such as joint angles, repetition count, and movement duration. Despite their advantages, many commercially available rehabilitation robots are bulky, expensive, and require complex sensor integration, limiting their accessibility for home-based use.

Recent advancements in computer vision and machine learning have enabled accurate real-time hand tracking using deep learning frameworks. MediaPipe provides efficient detection of 21 hand landmarks, allowing precise estimation of finger joint positions without requiring wearable sensors. Vision-based tracking eliminates calibration complexity and improves user comfort. By combining computer vision with embedded motor control, it is possible to design an intelligent rehabilitation system that replicates therapist hand movements in real time.

This work proposes a Therapeutic Engagement Glove, a vision-based wireless robotic hand rehabilitation system. The system captures therapist hand movements using a webcam and processes them through OpenCV and MediaPipe to extract finger joint landmarks. Finger bending angles are calculated using vector-based mathematical modeling and transmitted wirelessly to a Raspberry Pi Pico microcontroller. The microcontroller generates PWM signals to control servo motors mounted on a robotic glove worn by the patient. The glove replicates the therapist's finger movements in real time, enabling guided and synchronized rehabilitation exercises.

The proposed system is designed to be low-cost, portable, and suitable for home-based therapy. In addition to movement replication, the system provides real-time monitoring through graphical visualization of finger angles and repetition tracking. Safety mechanisms are incorporated to prevent excessive motion and ensure patient comfort. By integrating vision-based tracking with wireless robotic control, the Therapeutic Engagement Glove aims to enhance accessibility, affordability, and effectiveness of hand rehabilitation therapy.

Related Work

Robotic-assisted rehabilitation systems have gained significant attention in recent years for improving motor recovery in patients with neurological impairments. Several research efforts have focused on developing sensor-based, exoskeleton-based, and vision-based hand rehabilitation systems to enhance therapy effectiveness and reduce therapist dependency.

Early rehabilitation gloves primarily relied on flex sensors and inertial measurement units (IMUs) to measure finger bending. These systems capture finger motion through embedded wearable sensors and transmit the data to a controller for analysis. Although such approaches provide reasonable accuracy, they often require frequent calibration and increase hardware complexity. Sensor drift, wiring constraints, and discomfort during prolonged usage are additional challenges associated with wearable sensor-based systems.

Robotic exoskeleton devices have also been developed to assist hand movement. These systems typically use DC motors, servo motors, pneumatic actuators, or cable-driven mechanisms to provide assisted finger flexion and extension. Exoskeleton-based rehabilitation systems offer controlled and repeatable motion; however, they are often bulky, expensive, and mechanically complex. Many commercial solutions are designed for clinical environments and are not easily adaptable for home-based therapy.

In recent years, computer vision–based approaches have emerged as an alternative to sensor-based motion capture. Deep learning frameworks enable real-time detection and tracking of hand landmarks without requiring wearable devices. MediaPipe, a machine learning–based framework, provides efficient and accurate detection of 21 hand landmarks, enabling estimation of finger joint angles with low latency. Vision-based systems reduce hardware dependency and improve patient comfort.

Several studies have explored combining computer vision with robotic control for rehabilitation applications. These systems capture hand gestures using cameras and map them to actuator movements. However, many existing approaches either lack real-time wireless communication, do not incorporate safety mechanisms, or focus primarily on gesture recognition rather than therapeutic motion replication.

Moreover, some rehabilitation platforms include data visualization and monitoring features to track patient progress. Real-time angle plotting and repetition tracking help therapists evaluate improvement over time. However, integrated systems that combine vision-based tracking, wireless robotic glove control, and performance monitoring in a low-cost portable framework remain limited.

In contrast to existing methods, the proposed Therapeutic Engagement Glove integrates real-time hand landmark detection using MediaPipe with wireless servo motor control through a Raspberry Pi Pico microcontroller. The system emphasizes affordability, portability, real-time replication accuracy, and home-based usability. By eliminating wearable sensors and incorporating embedded safety mechanisms, the proposed solution aims to address the limitations of conventional rehabilitation systems while maintaining effective therapeutic assistance.

PROPOSED SYSTEM

The proposed system presents a vision-based wireless robotic hand rehabilitation framework designed to replicate therapist finger movements in real time. The Therapeutic Engagement Glove integrates computer vision, wireless communication, and embedded motor control to provide guided rehabilitation assistance for patients with hand motor impairments. The system is structured to ensure portability, affordability, safety, and ease of use for both clinical and home-based environments.

The overall architecture consists of two primary modules: the Vision Processing Unit (trainer side) and the Robotic Glove Unit (patient side). These modules communicate wirelessly to ensure synchronized motion replication.

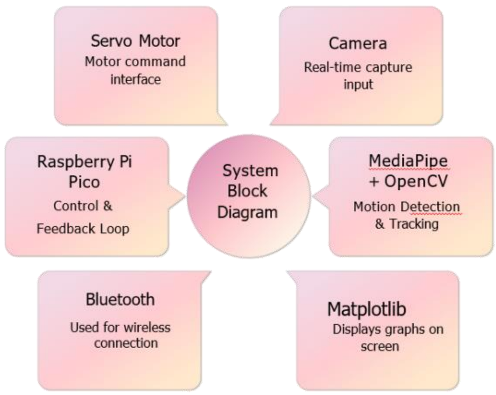
- Overall Architecture

The system architecture is organized into sequential processing stages to ensure smooth and accurate movement transfer. The major stages include image acquisition, hand landmark detection, angle computation, wireless data transmission, embedded motor control, and motion execution.

At the trainer side, a webcam captures real-time hand movements. The captured frames are processed using OpenCV for frame handling and MediaPipe for extracting 21 hand landmarks. These landmarks correspond to finger joints and palm positions. Using vector-based mathematical computation, the bending angle of each finger is calculated.

The calculated angle values are formatted into structured serial data packets and transmitted to the Raspberry Pi Pico microcontroller through USB or Bluetooth communication. On the patient side, the microcontroller receives the angle values and converts them into PWM signals that control servo motors attached to the robotic glove. Each servo motor is assigned to a specific finger and replicates the corresponding bending motion.

This modular architecture ensures low latency, stable communication, and synchronized motion between trainer and patient.



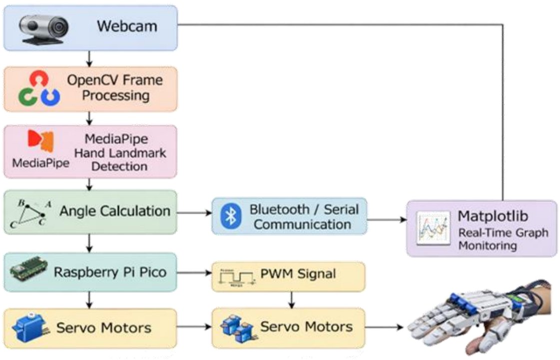


Figure 1 Block Diagram Of The Proposed Therapeutic Engagement Glove System.

The overall block diagram of the proposed Therapeutic Engagement Glove system illustrates the sequential flow of data from motion capture to robotic actuation. The system begins with real-time image acquisition using a webcam positioned in front of the therapist's hand. The webcam continuously captures video frames and forwards them to the processing unit.

The captured frames are handled by the OpenCV library, which performs frame acquisition and necessary preprocessing operations such as color space conversion. These processed frames are then passed to the MediaPipe hand tracking model, which detects 21 hand landmarks corresponding to the wrist, finger joints, and fingertips.

Based on the extracted landmark coordinates, finger bending angles are computed using vector-based mathematical calculations. The calculated angles represent the degree of flexion and extension of each finger.

These angle values are structured into serial data packets and transmitted via USB or Bluetooth communication to the Raspberry Pi Pico microcontroller. The microcontroller receives the incoming data and interprets individual angle values for each finger.

Using PWM (Pulse Width Modulation), the Raspberry Pi Pico generates control signals corresponding to the received angle values. These PWM signals drive the servo motors mounted on the robotic glove. Each servo motor is mechanically connected to a specific finger through a tendon-based mechanism, enabling accurate replication of the therapist's hand movement.

In parallel, the computed finger angle data is also sent to the Matplotlib module for real-time graphical visualization. This allows monitoring of therapy sessions and analysis of movement patterns.

The block diagram therefore represents a complete pipeline consisting of image acquisition, motion detection, angle computation, wireless transmission, embedded control, and robotic motion execution.

METHODOLOGY

The methodology of the proposed Therapeutic Engagement Glove describes the step-by-step operational workflow of the system, starting from hand motion capture to robotic motion execution. The complete process is divided into systematic stages to ensure clarity, reproducibility, and technical understanding.

The methodology is organized into the following phases:

1. Image Acquisition
2. Image Processing and Landmark Detection
3. Finger Angle Computation
4. Data Transmission
5. Embedded Control and PWM Generation
6. Robotic Motion Execution
7. Real-Time Monitoring and Visualization

- **1. Image Acquisition**

The first stage of the system involves capturing real-time video of the therapist's hand using a standard webcam. The webcam is positioned at an optimal distance to clearly detect finger movements without background interference.

The camera continuously captures frames at a fixed frame rate. Each frame is sent to the processing unit for further analysis. Proper lighting conditions are maintained to improve detection accuracy and reduce noise.

This stage ensures continuous real-time input to the system.

- **2. Image Processing and Landmark Detection**

The captured frames are processed using the OpenCV library. Initially, the image is converted from BGR color space to RGB format to ensure compatibility with the MediaPipe hand tracking framework.

MediaPipe detects 21 hand landmarks for each detected hand. These landmarks include:

- Wrist point
- Base joints (MCP)
- Middle joints (PIP)

- Distal joints (DIP)
- Fingertips

The detected landmark coordinates are represented in normalized 3D space (x, y, z). These coordinates provide spatial information required for finger angle calculation.

This stage forms the core motion tracking mechanism of the system.

- **3. Finger Angle Computation**

After extracting landmark coordinates, finger bending angles are computed using vector mathematics.

For each finger, three key landmark points are selected:

- Base joint
- Middle joint
- Fingertip

Using these points, two vectors are formed. The angle between these vectors is calculated using the cosine formula:

$\theta = \cos^{-1}((BA \cdot BC) / (|BA||BC|))$

Where:

- BA and BC represent vectors between selected joints
- θ represents the finger bending angle

The calculated angle is mapped within a safe operating range (0°–180°). This ensures smooth and controlled finger replication.

- **4. Data Transmission**

The computed angle values for all five fingers are formatted into structured serial data packets. These packets are transmitted from the processing unit to the Raspberry Pi Pico microcontroller.

Communication is established through USB serial communication or Bluetooth module. The data transmission is continuous to ensure real-time synchronization between trainer and patient modules.

- **5. Embedded Control and PWM Generation**

Upon receiving the angle data, the Raspberry Pi Pico processes the values and generates PWM signals corresponding to each finger.

Pulse Width Modulation controls the angular position of servo motors. The duty cycle of the PWM signal determines the rotation angle of the servo shaft.

Each servo motor is assigned to a specific finger of the robotic glove.

- **6. Robotic Motion Execution**

The servo motors are mechanically connected to the robotic glove using tendon-like threads. When the servo rotates, it pulls the thread, causing the corresponding finger of the glove to bend.

When the angle decreases, the servo rotates back, allowing the finger to return to its original position.

This mechanism enables accurate replication of therapist finger movements on the patient's hand.

- **7. Real-Time Monitoring and Visualization**

In addition to motion replication, the calculated finger angles are plotted using Matplotlib.

The graphical representation displays:

- Finger bending angle variation
- Repetition count
- Movement trends

This helps in monitoring therapy performance and evaluating patient improvement over time.

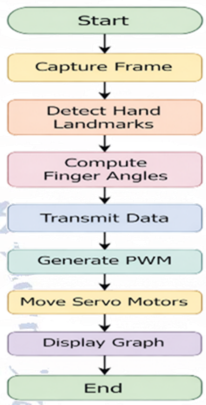


Figure 2 Flowchart Of The Proposed Rehabilitation Process.

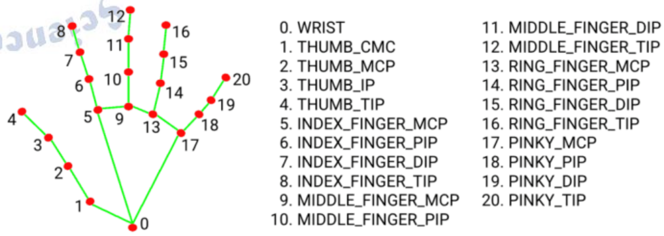


Figure 3 Hand Landmark Detection Using Mediapipe.

The detected hand landmarks are visually represented as 21 key points connected by skeletal lines, enabling precise identification of finger joint positions. Figure 3 illustrates the real-time hand landmark detection output obtained using the MediaPipe framework.

RESULTS AND DISCUSSIONS

The Results and Discussions section presents the experimental validation, system performance evaluation, and practical observations of the proposed Therapeutic Engagement Glove system. The objective of this section is to demonstrate the effectiveness, accuracy, and real-time capability of the developed rehabilitation framework.

- **Experimental Setup**

The system was tested in a controlled indoor environment with adequate lighting conditions to ensure accurate hand landmark detection. A standard webcam was used to capture therapist hand movements. The processing unit executed the Python-based vision module using OpenCV and MediaPipe libraries.

The computed finger angle values were transmitted to the Raspberry Pi Pico microcontroller through serial/Bluetooth communication. Five servo motors were connected to the robotic glove, each corresponding to one finger. The glove was worn on the patient's hand to replicate therapist movements.

The experimental setup consisted of:

- Webcam for real-time video capture
- Laptop/PC running Python environment
- MediaPipe and OpenCV libraries
- Raspberry Pi Pico microcontroller
- Servo motors (one per finger)
- Robotic glove mechanism
- Bluetooth/USB communication interface

- **Real-Time Hand Tracking Performance**

The MediaPipe framework successfully detected 21 hand landmarks in real time with high accuracy. The system maintained smooth landmark tracking even during moderate hand movements.

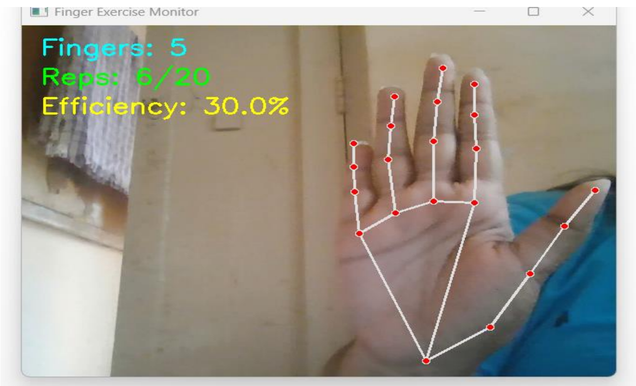


Figure 4 Real-Time Landmark Tracking Output.

The average processing speed achieved was sufficient for real-time rehabilitation applications, ensuring minimal latency between therapist movement and robotic glove response.

- **Finger Angle Computation Accuracy**

The vector-based mathematical model accurately calculated finger bending angles using detected joint coordinates. The computed angles varied proportionally with finger flexion and extension movements.

The angle values ranged approximately between:

- 0° – Fully extended finger
- 90° – Partially bent finger
- 160°–180° – Fully bent finger

The mapping between computed angles and servo motor rotation was consistent and stable throughout multiple trials.

- **Servo Motor Response Analysis**

The Raspberry Pi Pico successfully received angle data and generated PWM signals corresponding to each finger. The servo motors responded proportionally to the transmitted angle values.

The observed system characteristics include:

- Smooth motion replication
- Minimal delay between detection and actuation
- Stable wireless communication
- Consistent PWM signal generation

The average response delay between therapist movement and robotic glove motion was minimal and suitable for therapeutic applications.

- **Hardware Implementation**

The complete hardware prototype of the proposed Therapeutic Engagement Glove system was developed and experimentally validated. The robotic glove consists of servo motors mounted on a support structure and mechanically connected to individual fingers using tendon-based thread mechanisms.

The Raspberry Pi Pico microcontroller controls five servo motors, each corresponding to a specific finger. The servo motors are securely fixed to ensure stable motion transmission. The glove is designed to comfortably fit the patient's hand while allowing smooth finger movement during therapy sessions.

The hardware setup was tested for multiple motion cycles to evaluate mechanical stability and synchronization accuracy. The system successfully demonstrated real-time replication of therapist hand movements on the patient's hand.

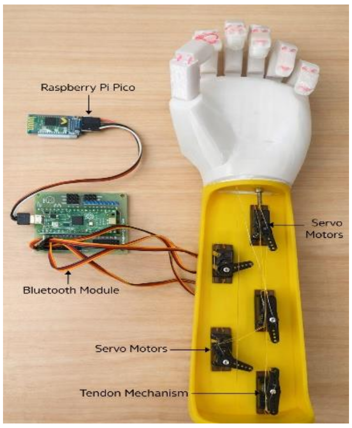


Figure 5 Hardware Prototype Of The Robotic Glove.

The proposed Therapeutic Engagement Glove successfully replicated therapist finger movements on the robotic glove in real time. The vision-based approach eliminated the need for wearable sensors on the therapist's hand, improving comfort and reducing hardware complexity.

Compared to conventional sensor-based rehabilitation systems, the proposed model offers:

• Reduced hardware cost
• Improved portability
• Wireless operation
• Real-time performance monitoring

However, the system performance may slightly depend on lighting conditions and camera positioning. Future improvements may include enhanced filtering techniques and improved mechanical design for smoother actuation.

- **System Performance Evaluation**

The overall system performance was evaluated based on:

• Tracking accuracy
• Motion synchronization
• Communication stability
• Servo response consistency

The system demonstrated reliable performance across multiple testing sessions. The wireless communication remained stable without data packet loss under normal operating conditions.

The integrated approach of vision-based tracking and embedded motor control proved effective for rehabilitation assistance.

- **Graphical Monitoring and Data Visualization**

The system plotted real-time finger angle variations using Matplotlib. The graphical output displayed continuous angle fluctuations corresponding to finger bending patterns.

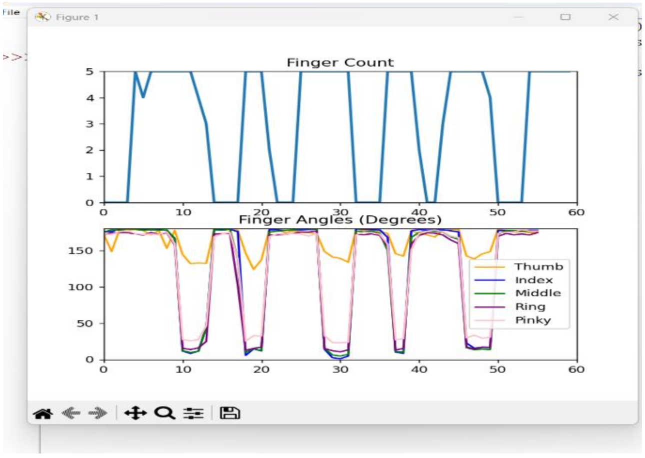


Figure 6 Finger Angle Variation Graph Output.

The graphs provided clear visualization of:

• Angle variation over time
• Repetition count
• Movement consistency

- **Therapy Session Report Generation**

In addition to real-time motion replication and graphical monitoring, the proposed system generates an automated therapy session report in CSV format. The report contains recorded finger angle values, repetition count, and timestamp information for each exercise session.

The generated report enables quantitative evaluation of rehabilitation progress. Each session is saved with a unique timestamp-based filename to ensure proper record management and future reference.

Timesta-mp	Thumb (°)	Index (°)	Middle (°)	Ring (°)	Little (°)	Repetitions
10:54:20	42	65	71	58	39	12
10:54:25	48	70	75	60	44	14
10:54:30	50	72	78	63	46	15

Table 1 Sample Output Report Generated During Therapy Session

The report file includes:

• Timestamp of exercise session
• Individual finger angle values
• Total repetition count
• Duration of exercise
• Performance statistics

	A	B	C
1	Exercise Report		
2	Date & Time	2025-12-22_10-54-20	
3	Finger Count (last)	0	
4	Total Repetitions	18	
5	Max Repetitions	20	
6	Efficiency (%)	90	
7			
8	Finger	Average Angle	
9	Thumb	155.83	
10	Index	134.26	
11	Middle	49.38	
12	Ring	48.73	
13	Pinky	52.07	

Figure 7 sample therapy session report generated by the system.

CONCLUSION

The proposed Therapeutic Engagement Glove presents a vision-based wireless robotic rehabilitation system designed to replicate therapist finger movements in real time. The system successfully integrates computer vision, mathematical angle computation, wireless communication, and embedded motor control to assist patients with hand mobility impairments.

The implementation of MediaPipe for hand landmark detection enabled accurate tracking of 21 key hand points without the need for wearable sensors. Using vector-based angle computation, the system effectively calculated finger bending angles and transmitted them to the Raspberry Pi Pico microcontroller. The microcontroller generated appropriate PWM signals to control servo motors attached to the robotic glove, enabling synchronized motion replication.

Experimental results demonstrated smooth hand tracking, minimal latency, stable communication, and consistent servo motor response. The integration of real-time graphical monitoring using Matplotlib further enhanced the system by providing visual feedback for therapy evaluation and performance analysis.

The proposed system offers several advantages including low cost, portability, wireless operation, and ease of use. By eliminating complex sensor-based gloves on the therapist side, the design improves comfort and reduces hardware complexity. The system is suitable for both clinical rehabilitation centers and home-based therapy applications.

Although the system performed effectively under controlled lighting conditions, future enhancements may include improved robustness under varying environmental conditions, advanced motion smoothing algorithms, and refined mechanical design for enhanced durability and comfort.

Overall, the Therapeutic Engagement Glove demonstrates a practical and efficient approach to vision-based robotic rehabilitation and has strong potential for further development in assistive healthcare technology.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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