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AI-Enabled IoT-Based Neuro-Muscular Rehabilitation Exosleeve with Adaptive Motion Assistance and Real-Time Biofeedback

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ABSTRACT: This project presents the development of an AI-enabled, IoT-integrated neuro-muscular rehabilitation exosleeve designed to assist patients with motor impairments. The exosleeve combines advanced sensors, adaptive motion assistance, and real-time biofeedback to facilitate personalized rehabilitation therapy. Leveraging machine learning algorithms, the system dynamically adjusts assistance levels based on the user's muscle activity and movement patterns, promoting optimal recovery while preventing muscle overexertion. Real-time biofeedback through IoT connectivity enables continuous monitoring by clinicians, allowing remote adjustments and data-driven progress tracking. This innovative integration aims to enhance rehabilitation outcomes by providing adaptive, patient-specific support that encourages active participation, accelerates motor function recovery, and improves quality of life for individuals with neuro-muscular disorders.

KEYWORDS: AI-enabled rehabilitatio, Neuro-muscular exosleeve, IoT-based healthcare, Adaptive motion assistance, Real-time biofeedback, Machine learning in rehabilitation Wearable assistive devices, Motor function recovery, Remote patient monitoring, Personalized therapy

I. INTRODUCTION

The Neuro-Muscular Rehabilitation Exosleeve is an advanced wearable assistive device designed to aid patients suffering from muscle weakness, partial paralysis, or neuromuscular disorders during rehabilitation. Unlike traditional physiotherapy tools, the exosleeve integrates embedded systems, IoT connectivity, AI-based movement analysis, and neuromuscular electrical stimulation (NMES) to provide personalized and adaptive therapy.

The system detects muscle activity via sEMG (Surface Electromyography), monitors joint movement with IMU sensors, and assists in limb movement through motor-
actuated or pneumatic artificial muscles. Real-time feedback is sent to the therapist through a secure mobile or cloud platform, enabling remote rehabilitation and progress tracking

Objectives of this Paper:

- To design a wearable neuromuscular rehabilitation exosleeve for assisting limb movement.
- To integrate AI for adaptive motion assistance based on patient condition.
- To use IoT for real-time monitoring and remote data transmission.
- To develop a biofeedback system to improve rehabilitation effectiveness and user engagement.

II LITERATURE SURVEY

Traditional rehabilitation robots do not consider the patient's real-time movement intention during active training, which reduces patient engagement and affects rehabilitation effectiveness. Using machine learning algorithms, the system decodes the user's intention to perform different hand and wrist movements, even if the actual movement is weak or absent. the system is designed to be comfortable, portable, and easy to

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use, making it suitable for home-based rehabilitation without expert supervision. Overall, this research demonstrates that high-density EMG combined with AI can provide an effective and user-friendly solution for restoring motor function and improving independence in stroke patients.

III. METHODOLOGY

A. EMG Signal Acquisition

The methodology begins with the acquisition of muscle activity using surface electromyography (EMG) sensors placed on the patient's arm. These sensors capture low-amplitude electrical signals generated during muscle contraction.

B. Signal Amplification and Filtering

The acquired EMG signals are passed through an EMG bio-amplifier, where they are amplified and filtered to remove noise and improve signal quality. **Analog-to-Digital Conversion**

The conditioned analog signals are converted into digital data using the ADS1115, a 16-bit analog-to-digital converter, ensuring high-resolution signal processing.

C. Motion Data Acquisition

Simultaneously, the MPU6050 sensor captures motion data such as acceleration and angular velocity, providing information about limb orientation and movement.

D. Data Processing Unit

Both EMG and motion data are transmitted to the ESP32 microcontroller, which acts as the central processing unit of the system.

E. Decision-Making and Control

The ESP32 processes the data in real time and determines the user's movement intention using predefined algorithms.

F. Feedback Mechanism

An OLED display provides real-time visual feedback, while a vibration motor and buzzer deliver haptic and alert-based feedback to the user.

G. User Control Interface

A push button is included for manual control and emergency operation of the system.

H. Power Management

The system is powered by a 3.7V lithium-ion battery supported by a TP4056 charging module and a boost converter for stable voltage supply.

I. Overall System Operation

The system operates in a closed-loop manner, continuously monitoring sensor data and providing adaptive motion assistance to enhance rehabilitation efficiency

CONTROL SYSTEM

HARDWARE REQUIREMENT

SENSORS

Electromyogram (EMG) Sensor

The Electromyogram (EMG) sensor is a critical component in the proposed rehabilitation exosleeve, designed to detect the electrical activity produced by skeletal muscles during contraction. Surface EMG sensors are non-invasive devices that consist of electrodes placed on the skin over target muscle groups.

These electrodes capture the bioelectric signals generated by motor unit action potentials, which reflect the intensity and timing of muscle activation.

In this project, the EMG sensor serves as the primary interface for interpreting user intent and muscle engagement. The raw EMG signals are characterized by low amplitude (typically in the range of 0–10 mV) and require amplification and filtering to eliminate noise and motion artifacts. Signal conditioning circuits perform band-pass filtering (commonly between 20 Hz and 500 Hz) to isolate relevant muscle activity frequencies.

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Fig.1. Electromyogram (EMG) Sensor

The processed EMG data is then digitized using an analog-to-digital converter (ADC) integrated within the microcontroller unit. These digitized signals feed into machine learning algorithms that classify muscle activation patterns and predict intended movements.

The real-time acquisition and analysis of EMG signals enable the exosleeve to provide adaptive motion assistance tailored to the user's neuromuscular state, enhancing rehabilitation outcomes.

Key advantages of using surface EMG sensors include their non-invasive nature, ease of integration into wearable devices, and capability to provide direct insights into muscle function, which is essential for personalized neuro-muscular rehabilitation.

EMG Bio-Amplifier

The EMG bio-amplifier plays a crucial role in biomedical signal acquisition by amplifying weak electrical signals generated by muscle activity. Surface electromyography (sEMG) signals are typically in the range of microvolts and are highly susceptible to noise and interference. Therefore, a bio-amplifier is required to condition these signals for further processing. The EMG bio-amplifier consists of high-gain differential amplification, filtering, and noise reduction stages to improve signal quality. It effectively removes common-mode noise, such as power line interference, using techniques like common-mode rejection ratio (CMRR). In this project, the EMG bio-amplifier (such as MyoWare) is used to capture and amplify muscle signals from the user's arm. The amplified signals are then passed to an analog-to-digital converter (ADC) for digitization and further analysis by the microcontroller. The system ensures accurate detection of muscle activity, enabling real-time control of assistive devices. Additionally, proper signal conditioning enhances reliability and minimizes errors caused by motion artifacts and environmental noise. Overall, the EMG bio-amplifier is essential for converting low-amplitude biological signals into usable electrical signals for intelligent rehabilitation systems.

Fig.2. EMG Bio-Amplifier

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ADS1115 ADC

The ADS1115 is a high-precision, 16-bit analog-to-digital converter (ADC) widely used in biomedical and embedded applications for accurate signal acquisition. It is designed to convert low-level analog signals into digital data with high

resolution and reliability. The ADS1115 features an internal programmable gain amplifier (PGA), which allows it to amplify small input signals, making it suitable for applications such as EMG signal processing. It supports multiple input channels and communicates with microcontrollers using the I2C protocol, ensuring easy interfacing and low power consumption. In this project, the ADS1115 is used to convert the amplified EMG signals into digital form for processing by the ESP32 microcontroller. The high resolution of the ADC ensures precise measurement of muscle activity, improving the overall accuracy of the system. Additionally, the device offers a fast-sampling rate and built-in noise reduction features, which enhance signal quality. Its compact size and efficiency make it ideal for wearable and portable rehabilitation devices. Overall, the ADS1115 ADC plays a vital role in ensuring accurate data acquisition and reliable system performance in real-time biomedical applications

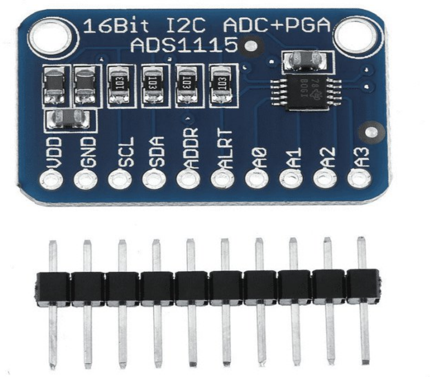

Fig.3. ADS1115 ADC

MPU6050

The MPU6050 is a widely used motion tracking sensor that integrates a 3-axis accelerometer and a 3-axis gyroscope into a single chip, enabling the measurement of linear acceleration and angular velocity. It is based on Micro-Electro-Mechanical Systems (MEMS) technology and provides accurate motion sensing capabilities for embedded and biomedical applications. The sensor includes a Digital Motion Processor (DMP), which helps in processing complex motion data and reduces the computational load on the microcontroller. It communicates with external devices using the I2C protocol, ensuring efficient and low-power data transmission. In this project, the MPU6050 is used to monitor the movement, orientation, and joint angles of the patient's limb during rehabilitation. The real-time motion data obtained from the sensor is processed by the ESP32 microcontroller to analyse movement patterns and assist in controlling the servo motor. The combination of accelerometer and gyroscope data improves accuracy and stability in motion tracking. Additionally, the sensor is compact, low-cost, and suitable for wearable applications. Overall, the MPU6050 plays a vital role in providing reliable motion sensing for real-time rehabilitation monitoring and control systems**.**

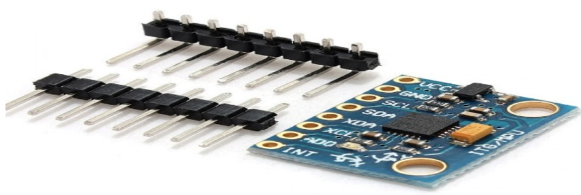

Fig.4. Microcontroller or Embedded System

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Microcontroller – ESP32

The ESP32 microcontroller serves as the central processing unit in the proposed neuro-muscular rehabilitation exosleeve system, responsible for real-time data acquisition, signal processing, actuator control, and wireless communication. The ESP32 is a powerful, low-cost, and energy-efficient system-on-chip (SoC) featuring a dual-core Tensilica Xtensa LX6 processor, operating at up to 240 MHz, which provides sufficient computational capability to handle simultaneous sensor data streams and execute machine learning iThe MPU6050 is a widely used motion tracking sensor that integrates a 3-axis accelerometer and a 3-axis gyroscope into a single chip, enabling the measurement of linear acceleration and angular velocity. It is based on Micro-Electro-Mechanical Systems (MEMS) technology and provides accurate motion sensing capabilities for embedded and biomedical applications.

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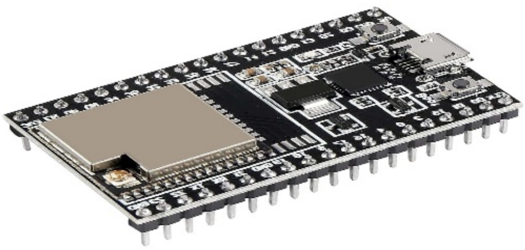

Fig. 5. Microcontroller – ESP32

The microcontroller integrates multiple analog-to-digital converters (ADCs) for digitizing analog signals from electromyogram (EMG) sensors and inertial measurement units (IMUs), enabling precise and timely muscle activity and motion data capture. Its versatile GPIO pins facilitate the control of actuators and interfacing with other peripheral components of the exosleeve.

Moreover, the ESP32 supports built-in Wi-Fi (802.11 b/g/n) and Bluetooth Low Energy (BLE) connectivity, which enables seamless IoT integration by transmitting real-time biofeedback and sensor data to cloud platforms or mobile applications for remote monitoring and adaptive rehabilitation control. This wireless capability also supports over-the-air (OTA) firmware updates, ensuring system scalability and maintainability.

The ESP32's compact form factor and low power consumption make it well-suited for wearable applications, where portability and extended battery life are critical. Overall, the ESP32 microcontroller enables a robust, real-time, and connected platform essential for implementing adaptive motion assistance and biofeedback in neuro-muscular rehabilitation.

ACTUATION SYSTEM

SERVO MOTOR

The servo motor is a precision electromechanical actuator widely used in control systems for accurate position, speed, and torque control. It operates based on a closed-loop feedback mechanism, where the actual position is continuously compared with the desired position to ensure precise movement. Servo motors are typically controlled using Pulse

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Width Modulation (PWM) signals, where the pulse width determines the angle of rotation. In rehabilitation and assistive devices, servo motors play a crucial role in providing controlled and smooth motion.

In this project, the servo motor is used to assist the movement of the patient's limb based on the detected EMG signals and motion data. The ESP32 microcontroller generates PWM signals to control the servo motor, enabling adaptive motion assistance according to the user's intention. The system ensures real-time response and accurate positioning, which is essential for effective rehabilitation. Additionally, servo motors are compact, energy-efficient, and easy to interface with microcontrollers, making them suitable for wearable applications. However, they require a stable power supply and are limited in rotation range. Overall, the servo motor is an essential component for implementing controlled actuation in intelligent rehabilitation systems.

Fig. Servo Motor

Connectivity (IoT Layer)

- **Wi-Fi/Bluetooth Module** – For wireless data transfer (ESP32 has inbuilt Wi-Fi + BLE).
- **Cloud Integration** – Supports remote monitoring and analytics.

The connectivity layer forms the backbone of the proposed exosleeve system by enabling seamless data transmission, remote monitoring, and real-time interaction between the rehabilitation device and healthcare providers. The IoT framework integrates wireless communication protocols such as Wi-Fi and Bluetooth Low Energy (BLE) to transfer motion, muscle activity, and biofeedback data from the wearable sensors to a central processing unit or cloud server.

The use of **ESP32-based modules** provides dual connectivity support with inbuilt Wi-Fi and BLE, ensuring low-power operation and robust data exchange. Wi-Fi connectivity facilitates high-bandwidth communication for continuous data logging and cloud-based machine learning analytics, while BLE enables direct mobile application support for patient–therapist interaction in resource-constrained environments

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Through this IoT-enabled architecture, rehabilitation data can be stored, visualized, and analyzed remotely, allowing clinicians to customize therapy protocols and track patient progress in real time.
Additionally, secure cloud integration ensures scalability, interoperability, and adherence to healthcare data standards. This connectivity layer thus transforms the exosleeve into a **smart, networked rehabilitation system** capable of supporting personalized, adaptive, and tele-rehabilitation solutions.

BIOFEEDBACK SYSTEM

LED Indicators / OLED Display

Visual feedback plays a critical role in enhancing user engagement and providing intuitive guidance during rehabilitation exercises. In the proposed exosleeve system, LED indicators and OLED displays are employed as real-time visual biofeedback components.Visual feedback plays a critical role in enhancing user engagement and providing

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intuitive guidance during rehabilitation exercises. In the proposed exosleeve system, **LED indicators** and **OLED displays** are employed as real-time visual biofeedback components. On the other hand, OLED displays are incorporated to present detailed rehabilitation metrics, including joint angle data, exercise repetitions, muscle activity levels, and system alerts. Due to their high contrast, wide viewing angles, and low power consumption, OLED displays are particularly effective in wearable healthcare devices. The integration of graphical visualization enables patients to monitor their progress directly, while therapists can use the data for fine-tuned adjustments to therapy protocols.

Fig. OLED Display

POWER SUPPLY

Rechargeable Li-ion Battery Pack

The proposed exosleeve system is designed as a portable and wearable rehabilitation device, necessitating a reliable and lightweight power source. A rechargeable lithium-ion (Li-ion) battery pack is employed to meet the energy demands of embedded sensors, actuators, microcontrollers, wireless. The proposed exosleeve system is designed as a portable and wearable rehabilitation device, necessitating a reliable and lightweight power source. A rechargeable lithium-ion (Li-ion) battery pack is employed to meet the energy demands of embedded sensors, actuators, microcontrollers, wireless communication modules, and display units. Li-ion batteries are preferred due to their high energy density, low self-discharge rate, compact size, and long cycle life, making them ideal for continuous wearable operation. The battery pack is integrated with a **Battery Management System (BMS)** to ensure safe operation by preventing overcharging, over-discharging, and thermal runaway. Voltage regulation circuits and DC-DC converters are incorporated to provide stable power supply levels to various system components, ensuring uninterrupted functioning of AI-driven processing and IoT connectivity.

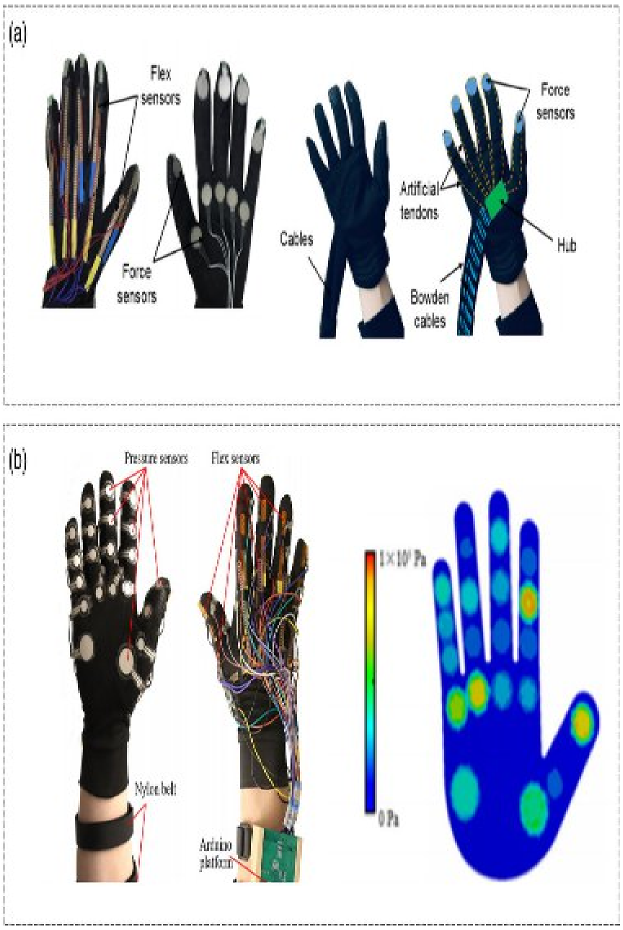
Fig. OLED Display

EXOSLEEVE STRUCTURE

The exosleeve structure is a wearable assistive framework designed to support and enhance the movement of the human limb during rehabilitation. It is typically made using lightweight, flexible, and durable materials to ensure comfort and ease of use for the patient. The structure is designed to fit around the arm and align with the natural joints to provide effective motion assistance. In this project, the exosleeve integrates sensors such as EMG electrodes and motion sensors to capture muscle activity and limb movement in real time. The structure also accommodates actuators like servo motors, which provide controlled assistance based on the processed signals. Proper ergonomic design is essential to ensure that the exosleeve does not restrict natural movement or cause discomfort during prolonged use. Additionally, the design focuses on portability and ease of wear, allowing the device to be used in both clinical and home environments. The exosleeve acts as a physical interface between the human body and the electronic system, enabling efficient transfer of assistive force. Overall, the exosleeve structure plays a vital role in ensuring effective rehabilitation by combining comfort, flexibility, and functional support.

The exosleeve structure is a wearable assistive device designed to support upper limb rehabilitation by providing mechanical assistance and real-time interaction with the user. It is fabricated using lightweight, flexible, and breathable materials such as fabric, elastic polymers, or soft composites to ensure comfort during prolonged usage. The design follows ergonomic principles to align with the natural anatomy of the arm, including joints such as the elbow and wrist, thereby enabling smooth and natural movement without restriction. In this project, the exosleeve serves as a platform for integrating various sensors and actuators, including EMG electrodes for muscle signal acquisition, MPU6050 for motion tracking, and servo motors for actuation. The structure ensures proper placement of these components to maintain signal accuracy and effective force transmission.

Furthermore, the exosleeve is designed to distribute pressure evenly across the limb to avoid discomfort or injury during operation. Adjustable straps or fastening mechanisms are incorporated to fit different arm sizes and ensure stability during movement. The system supports modular integration, allowing easy maintenance and component replacement. The exosleeve also enhances safety by limiting excessive movement and providing controlled assistance based on real-time feedback from sensors. Additionally, its compact and portable design makes it suitable for both clinical rehabilitation and home-based therapy. The integration of soft robotics concepts further improves flexibility and adaptability of the device. Overall, the exosleeve structure acts as a crucial interface between the human body and the electronic control system, ensuring efficient rehabilitation, improved patient comfort, and enhanced recovery outcomes.



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IV. EXPECTED RESULT

The proposed AI-enabled IoT-based neuro-muscular rehabilitation exosleeve is expected to provide accurate detection of muscle activity and effective assistance for upper limb movement. The EMG sensor, along with the bio-amplifier and ADC, is expected to capture and process muscle signals with high precision and minimal noise. The integration of the MPU6050 sensor is expected to enhance motion tracking accuracy by providing real-time information about limb orientation and movement. The system is expected to respond quickly to the user's muscle intention, enabling real-time control of the servo motor for smooth and adaptive movement assistance. The closed-loop feedback mechanism is expected to improve movement accuracy and ensure safe operation. Additionally, the OLED display and vibration motor are expected to provide clear visual and haptic feedback, improving user interaction and engagement during rehabilitation exercises. The overall system is expected to be portable, cost-effective, and suitable for both clinical and home-based rehabilitation. It is anticipated to enhance patient participation, improve motor function recovery, and reduce dependency on manual therapy. Furthermore, the integration of IoT capabilities is expected to enable remote monitoring and data analysis for better treatment evaluation. Overall, the system aims to deliver an efficient, user-friendly, and intelligent rehabilitation solution with improved performance compared to existing methods.

The image shows an OLED display integrated into the wearable exosleeve system. It provides real-time visual feedback of EMG signal strength. The display indicates muscle activity levels (e.g., HIGH, MEDIUM, LOW). A graphical bar is used to represent the intensity of the EMG signal. It also shows movement-related parameters such as velocity and displacement. The OLED is connected to the microcontroller, which processes sensor data. It updates instantly based on the user's muscle activity. The compact design makes it suitable for wearable applications.

V. CONCLUSION

The proposed system provides an effective solution for rehabilitation by integrating EMG and motion sensors to detect muscle activity and deliver real-time assisted movement using a servo motor. It is designed to be cost-effective, portable, and user-friendly, making it suitable for practical use. The system improves patient engagement and supports better recovery outcomes. Overall, it enhances rehabilitation efficiency and promotes patient independence.

VI. FUTURE SCOPE

Future improvements can include the use of advanced AI algorithms for better accuracy and motion prediction. The system can be enhanced with IoT-based remote monitoring and mobile application support. Further developments may focus on improving battery life and wearable design for better comfort. The system can also be extended to support multi-joint movement and full arm rehabilitation. Additionally, real-time clinical testing can be conducted for better validation and performance analysis.

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