PowerGrip (NeuroGrasp): A Smart Robotic Exoskeleton for Hand Rehabilitation

S M Hasibur Rahman*, Md. Mahamud Hasan*, Arif Ashab Akib*,
Mir Adnan*, MD Sami Chowdhury*
* Department of Computer Science and Engineering
United International University
Email: {0112330109, 0112330197, 0112330178, 0112330191, 0112330913}@student.uiu.edu.bd

Abstract—**The rehabilitation of hand function following a stroke or traumatic injury is a critical yet challenging aspect of physical therapy, often requiring expensive equipment and constant medical supervision. This project proposes PowerGrip (NeuroGrasp), a cost-effective, smart robotic exoskeleton designed to assist patients in regaining hand mobility and grip strength. The system operates on a bio-mimetic control architecture, utilizing Surface Electromyography (sEMG) to detect the user's neural intent and actuation via high-torque servo motors with a passive extension mechanism.**

Beyond simple assistance, the device integrates advanced neuro-rehabilitation techniques, including a "Mirror Therapy" mode where the exoskeleton synchronizes with the user's healthy hand to stimulate neuroplasticity. Safety is paramount; an adaptive variable compliance system monitors grip pressure in real-time using Force Sensitive Resistors (FSR), preventing injury or damage to fragile objects. Furthermore, the system addresses the need for remote medical oversight through an IoT-enabled telemetry feature, logging muscle strength and repetition data to a cloud dashboard for doctor review. This prototype demonstrates a comprehensive, accessible solution for autonomous daily assistance and long-term therapeutic recovery.

Index Terms—**Exoskeleton, Rehabilitation, sEMG, Mirror Therapy, IoT, ESP32, Neuroplasticity.**

I. Project Overview

The loss of hand function due to stroke, spinal cord injuries, or neuromuscular diseases significantly impacts an individual's quality of life, leading to dependency in performing Activities of Daily Living (ADLs). Traditional physical therapy is effective but is often labor-intensive, costly, and limited to clinical settings. Patients typically require thousands of repetitive movements to regain neural pathways, a process that is difficult to sustain without continuous supervision.

PowerGrip (NeuroGrasp) is designed to bridge this gap by providing an affordable, wearable robotic exoskeleton. Unlike passive orthotics, this system is an active assistive device that restores functionality through sensor-based actuation.

The core philosophy of the project is "Assist-as-Needed." The device does not simply force the hand open and closed; it detects the user's residual muscle activity or intentional movements from a healthy limb and amplifies them. This ensures active engagement from the patient, which is crucial for neuro-rehabilitation. The system integrates mechanics, electronics, and cloud computing to create a holistic rehabilitation tool. It features a robust safety mechanism to handle delicate objects, a mirror therapy mode for cognitive retraining, and an IoT-enabled logging system to quantify recovery progress. By automating the repetitive aspects of therapy and enabling home-based practice, PowerGrip aims to democratize access to high-quality rehabilitation.

Scalability and Future Application: A key innovation of the PowerGrip architecture is its modularity. While this prototype focuses on the hand, the underlying control logic—comprising EMG signal processing, master-slave synchronization, and adaptive force feedback—is joint-agnostic. The system functions as a scalable bio-robotic platform; by simply upgrading the actuation units (e.g., replacing servo motors with linear actuators) and power systems, the same ESP32-based control framework can be adapted to rehabilitate larger joints such as the elbow or knee. This versatility positions the project not just as a single device, but as a foundational blueprint for a complete full-body exoskeleton suit.

II. Hardware Components (Original Design)

The development of the PowerGrip prototype relies on the following key hardware components. Note that this section describes the *initial* design configuration before optimization.

A. ESP32 Microcontroller

The ESP32 is a powerful microcontroller developed by Espressif Systems. In the PowerGrip system, the ESP32 functions as the central control unit. It utilizes its **Dual-Core Processor** to handle real-time signal processing from the sensors on one core while managing Wi-Fi telemetry on the other. Its ADC interfaces are critical for reading faint signals, while its PWM capabilities drive the high-torque servos.

Supervised by: Taki Yashir, Lecturer, Dept. of CSE, UIU. Date: 05/01/2026.

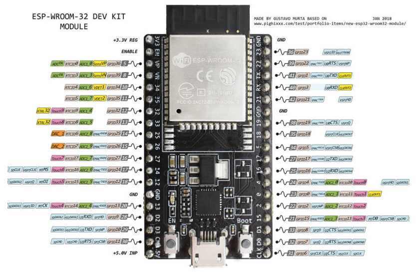

Fig. 1. Pin diagram of ESP32.

B. Bio-Signal Acquisition (Initial ECG Config)

The AD8232 is an integrated signal conditioning block for biopotential measurement. **Initially, we utilized this module in its standard ECG (Electrocardiogram) configuration** to attempt to capture bio-electrical signals from the forearm. The module features a specialized instrumentation amplifier that amplifies microvolt-level signals while rejecting common-mode noise.

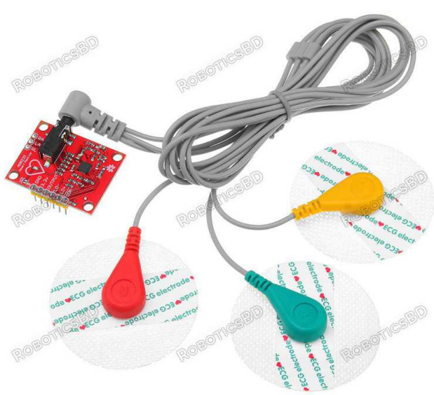

Fig. 2. AD8232 Sensor Module.

C. Force Sensitive Resistor (Initial FSR)

A standard, generic Force Sensitive Resistor was initially selected to act as the "Sensory Nervous System." It allows electronics to "feel" pressure by exhibiting a decrease in resistance with an increase in force applied to the active surface. This was intended to provide real-time feedback on grip force.

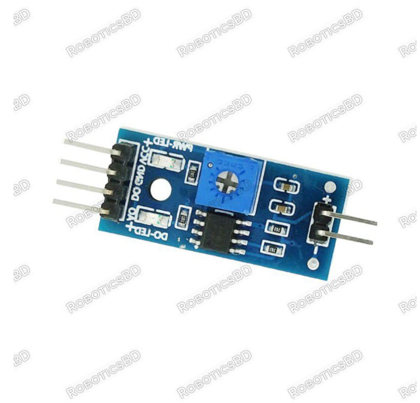

Fig. 3. FSR402 Sensor.

D. Rotary Potentiometer (10kΩ)

A potentiometer is a three-terminal resistor that functions as a position sensor. Connecting the outer terminals to power and Ground, the middle wiper pin outputs an analog voltage proportional to the shaft's angle. It is the core input device for the **Mirror Therapy** feature, measuring the bending of the healthy finger to command the exoskeleton.

Fig. 4. Rotary Potentiometer.

E. MG996R High-Torque Metal Gear Servo

The MG996R is a high-performance digital servo motor acting as the **"Muscle"** of the PowerGrip system. Unlike plastic gear servos, it features an all-metal gear train and delivers high torque (up to 11 kg-cm). When triggered, it rotates to pull the nylon tendons, actively curling the user's fingers.

Fig. 5. MG996R Servo Motor.

F. Power System (Initial)

The system is powered by a 7.4V Li-Po battery. An LM2596 DC-DC Buck Converter is used to step down this voltage to a stable 6V to drive the servos safely.

Fig. 6. LM2596 Buck Converter Module.

III. Key Features

PowerGrip (NeuroGrasp) distinguishes itself through five core functionalities that combine mechanical assistance with intelligent control.

A. Feature 1: Bio-Mimetic Muscle Control

Description: This feature serves as the core actuation logic. It mimics the biological process of muscle contraction. The system detects the user's "Neural Drive" (intention to move) even if the physical muscle is too weak to generate force.

B. Feature 2: Mirror Therapy Synchronization

Description: A neuro-rehabilitation mode based on the "Master-Slave" robotic principle designed to stimulate neuroplasticity. By visually seeing the paralyzed hand mimic the healthy hand's movements, the brain is "tricked" into reconnecting dormant neural pathways.

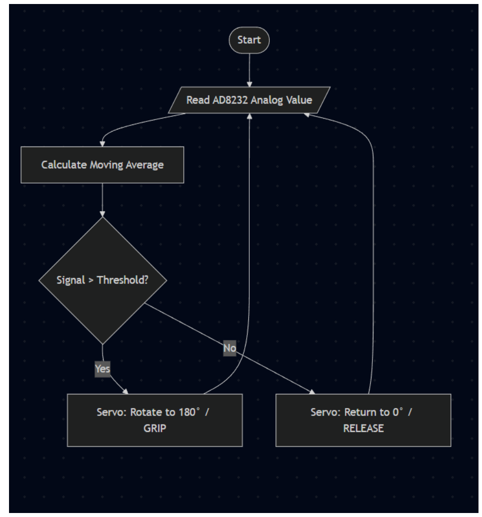

Fig. 7. Flowchart of Bio-Mimetic Control.

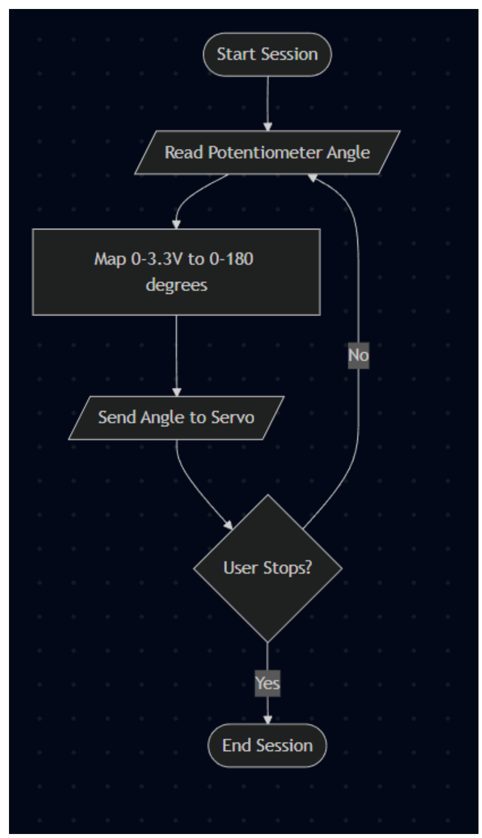

Fig. 8. Flowchart of Mirror Therapy Logic.

C. Feature 3: Adaptive Variable Compliance

Description: A closed-loop feedback system acting as an ”Artificial Reflex.” It prevents the exoskeleton from crushing fragile objects or injuring the user by monitoring grip pressure.

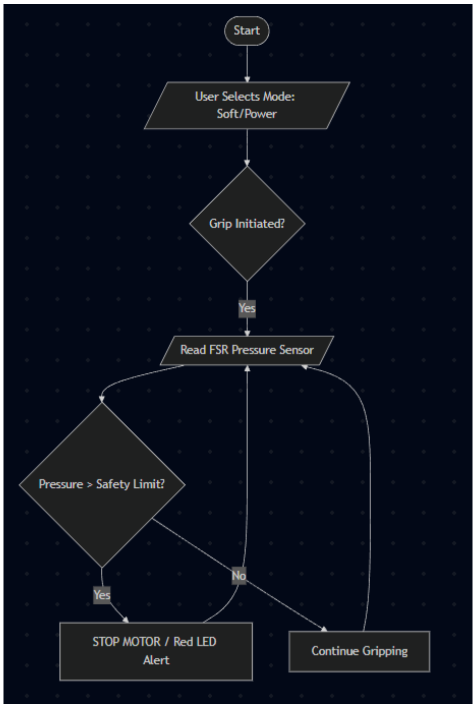

Fig. 9. Flowchart of Adaptive Safety Logic.

D. Feature 4: Remote Rehabilitation Monitoring (IoT)

Description: Transforms the exoskeleton into a connected medical device. It logs data about therapy sessions (Max Neural Drive, Repetition Count) to the ThingSpeak API, allowing clinicians to view progress graphs remotely.

E. Feature 5: Dual-Trigger Redundancy System

Description: A fail-safe hierarchy providing a manual input method that overrides sophisticated EMG algorithms, ensuring user autonomy via a manual button press.

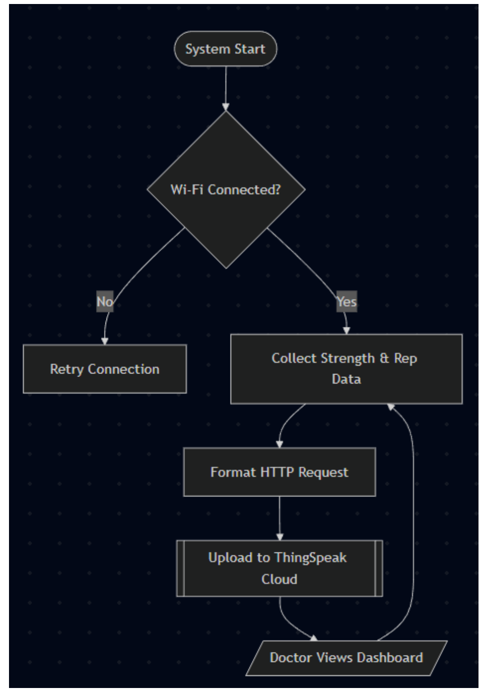

Fig. 10. Flowchart of IoT Telemetry.

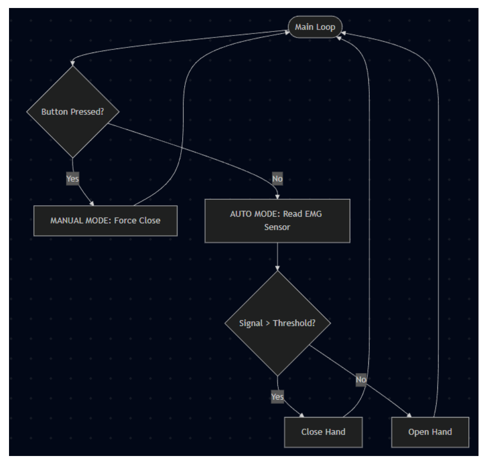

Fig. 11. Flowchart of Dual-Trigger Logic.

IV. Design Modifications and Implementation

During the construction and testing phases of the PowerGrip prototype, several modifications were made to the original design to improve system stability, safety, and reliability. This section documents the transition from the ”As-Planned” design to the ”As-Built” prototype.

A. Sensor Modification: ECG to EMG Transition

Issue: Initially, we used the AD8232 module in its standard ECG configuration. It turned out that the ECG settings (optimized for low-frequency cardiac signals) were not suitable for reading high-frequency skeletal muscle signals. The system struggled to distinguish voluntary finger flexion from noise.

Modification: We reconfigured the sensor placement and gain settings to function as an **EMG (Electromyography)** sensor. This change successfully allowed us to monitor the specific muscle readings required for ”neural drive” detection.

B. Power System Upgrade: 9V Battery Addition

Issue: In the initial single-battery setup, the high-torque servos drew significant current, causing voltage dips that affected the sensitive EMG sensors. The current setup did not have enough stable voltage headroom.

Modification: We added a separate **9V Battery** specifically to power the EMG sensor module. This isolated the noisy motor power rail (7.4V Li-Po) from the sensitive signal acquisition circuit, ensuring clean data readings.

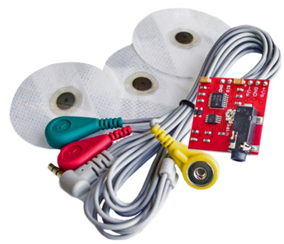

Fig. 12. EMG Sensor.

C. FSR Upgrade: Generic to FSR-402

Issue: The existing generic FSR lacked the sensitivity and reliability required for the project. It often acted as a simple switch rather than providing a pressure gradient.

Modification: We changed the existing FSR to an **Interlink Electronics FSR-402**. This specific type was needed for accurate pressure sensing when grabbing objects, as it provides a linear and repeatable response curve essential for the Adaptive Compliance algorithm.

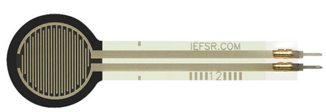

Fig. 13. Upgraded FSR-402 Sensor.

TABLE I
SUMMARY OF HARDWARE EVOLUTION

Component	**Initial Design**	**Final Modification**
Bio-Sensor	AD8232 (ECG Mode)	AD8232 (**EMG Mode**)
Sensor Power	Shared 7.4V	**Dedicated 9V Battery**

V. PROJECT DEMONSTRATION AND SOURCE CODE

To facilitate reproducibility and demonstrate the functional prototype, the complete firmware source code and a video demonstration of the PowerGrip system are available online.

- **Video Demonstration (YouTube):** https://youtu.be/yqEZVKJyuBk?si=DK5NQRlD-wjG-JK2
- **Source Code (GitHub):** https://github.com/the-hasib/PowerGrip-NeuroGrasp-.git

VI. CONCLUSION

PowerGrip (NeuroGrasp) demonstrates a scalable bio-robotic platform. By integrating bio-mimetic control, IoT telemetry, and active safety mechanisms, the system provides a comprehensive solution for autonomous daily assistance. Future iterations could adapt this framework for larger joints like the elbow or knee.