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Development of a functional electrical stimulation device for movement restoration in subjects with spinal cord injuries

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Abstract

Functional Electrical Stimulation serves as a promising approach for neurological rehabilitation; however, its adoption is often hindered by high costs and limitations in parameter customization. This research aims to overcome these barriers by creating an affordable, microcontroller-based FES device specifically designed to address foot drop. The innovative system employs a combination of ESP32 and ATmega328 microcontrollers paired with a DRV8876 driver, enabling the generation of precise biphasic pulses. The device operates effectively across a range of 0-360 microseconds for pulse width, 20-60Hz for frequency, and 0-167mA for amplitude. laboratory validation has been carried out using oscilloscopes and multimeters, confirming the accurate generation of the desired stimulation parameters. Additionally, simulations conducted with MATLAB Simulink and Proteus further validate the hardware performance. To enhance user comfort, a user-friendly GUI and a companion Android mobile application have been developed. These interfaces facilitate parameter adjustment for user-centric feedback and the logging of patient session data, with information securely stored in a local database to ensure privacy. The system incorporates AES encrypted data transmitted via the BLE capabilities of the ESP32, offering flexibility. Notably, this design achieves a 20% cost reduction with enhance features compared to existing foot drop FES systems within its price range and an extended battery life of 24 hours double the operational duration of similar devices. This newly developed FES system represents a functional and economically viable solution for foot drop rehabilitation (Dorsiflexion, Plantarflexion, Ankle Rotation and Toe Extension), thus paving the way for greater accessibility for personalized FES therapy.

Keywords: Functional Electrical Stimulation (Fes); Spinal Cord Injury; Embedded Biomedical Systems; Foot drop parameters

1. Introduction

Spinal cord injury (SCI) remains a devastating medical condition with widespread implications for individual autonomy, societal productivity, and healthcare systems worldwide. The disruption of neural pathways between the brain and peripheral effector organs frequently leads to partial or complete paralysis, impairing voluntary motor control, and precipitating a cascade of secondary complications such as muscle atrophy, pressure ulcers, and circulatory dysfunction. Among the multidisciplinary interventions explored for mitigating the long-term consequences of SCI, Functional Electrical Stimulation (FES) has established itself as a pivotal therapeutic modality capable of restoring controlled muscle contractions and enabling functional movement in individuals with compromised motor function [1].

FES involves the application of low-energy electrical currents to motor neurons or directly to muscle fibers via surface or implanted electrodes, thereby initiating muscle contractions that resemble voluntary motion. When administered

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systematically and with appropriate parameters, FES not only facilitates neuromuscular re-education and limb mobilization but also contributes to cardiovascular conditioning, muscle trophism preservation, venous return enhancement, and improved bone mineral density in immobilized patients [2]. The technique has demonstrated efficacy in diverse clinical scenarios, including post-stroke rehabilitation, foot drop correction, paraplegia, hemiplegia, and neurogenic bladder control. However, its most transformative application lies in its ability to reintroduce functional movement patterns particularly gait, grasp, and postural transitions—in individuals with spinal cord injuries [3].

Despite its proven therapeutic potential, current commercially available FES devices are often constrained by a host of technical and usability challenges. These include limited personalization of stimulation protocols, discomfort resulting from monophasic stimulation waveforms, lack of adaptive inter-pulse timing, difficulty in electrode placement, excessive device bulk, and a general absence of user-centered design considerations. Moreover, the prohibitive cost of high-end FES systems often precludes their integration into routine rehabilitation programs, especially in low- and middle-income regions where resources are scarce and the burden of disability is disproportionately high [4], [5].

Recent technological advancements particularly in microelectronics, wireless communication, and mobile computing have opened new possibilities for redesigning FES devices to be more accessible, intelligent, and clinically effective. The convergence of embedded system design, mobile health (mHealth) platforms, and biomedical signal processing has catalyzed the development of next-generation FES systems that are compact, cost-effective, wireless, and responsive to both user input and physiological feedback. Central to this evolution is the use of programmable microcontrollers such as the ESP32, which offers integrated Bluetooth Low Energy (BLE), high processing power, low energy consumption, and native support for secure data encryption all critical for real-time control and remote monitoring in rehabilitative settings [6].

In light of these opportunities and limitations, the aim of this research is to develop a Functional Electrical Stimulation device for lower-limb movement restoration in individuals with spinal cord injuries. The specific objectives were to simulate and construct an effective FES device parameter for targeted muscle stimulation for desired therapeutic or assistive purposes and to further access its compliance with standards for safety as well as production costs compared to existing solutions. The device is architected around a dual-microcontroller system comprising an ESP32 for GUI control and wireless communication, and an ATmega328 for precise pulse modulation via the driver (DRV7786). A key innovation in the proposed system is the implementation of a biphasic pulse generator, which minimizes electrode corrosion and tissue irritation while maintaining consistent stimulation efficacy. The device further incorporates a boost converter and constant current circuitry, ensuring stable energy delivery across variable skin impedance levels. A graphical user interface (GUI), developed using Android Studio, allows for real-time adjustment of stimulation parameters including pulse width (0–360 μs), frequency (20–60 Hz), and amplitude (0–167 mA) making the system highly customizable for individualized therapy protocols.

Safety, usability, and data security are paramount in the proposed design. The system integrates opto-isolated signal pathways to protect both the patient and the control circuitry, while Advanced Encryption Standard (AES-128) cryptography is embedded to secure wireless data transmission between the device and mobile applications, adhering to contemporary standards for medical device data integrity and confidentiality. Additionally, the architecture supports data logging and offline session review, equipping clinicians with tools to optimize therapy based on historical trends and patient responsiveness.

Unlike traditional FES systems which rely heavily on predefined stimulation routines and clinician supervision, this device emphasizes user-centric rehabilitation, allowing patients to engage more autonomously with their recovery process. This is particularly critical in long-term SCI management, where continuity of therapy and patient motivation are essential for functional recovery. The integration of real-time monitoring with adaptive stimulation protocols holds the potential to elevate this FES solution beyond conventional boundaries making it suitable for clinical deployment, home-based rehabilitation, and research applications alike.

2. Literature review

Recent advancements in Functional Electrical Stimulation (FES) technology have focused increasingly on developing systems that not only restore motor function in individuals with spinal cord injuries (SCI) and stroke but also overcome historical limitations such as high cost, limited customizability, user discomfort, and poor adaptability across diverse clinical scenarios. The convergence of microelectronics, mobile computing, and biomedical design principles has spurred a wave of innovations that have significantly enhanced the practicality, effectiveness, and reach of FES applications. This section critically reviews key contemporary contributions to the field, highlighting the trajectory of technological progress and contextualizing the present work within the broader research landscape.

Lopes et al. [7] introduced a cost-effective, open-source FES prototype employing the Arduino Uno microcontroller to assist in post-stroke hand rehabilitation. The system delivered adjustable biphasic stimulation to targeted muscle groups and demonstrated encouraging preliminary results, particularly in voluntary finger extension and improved grasp strength. Notably, its affordability and simplicity positioned it as a promising tool for decentralized rehabilitation. However, the device lacked essential features such as automatic fatigue detection, waveform modulation, and safety interlocks. Furthermore, the study was limited by a small sample size and short evaluation periods, making it unsuitable for broader clinical deployment without further refinement and validation.

A more advanced approach was explored by Luo et al. [8], who designed a multichannel FES system integrating real-time electromyographic (EMG) feedback for dynamic gait correction in SCI patients. Their system employed EMG-derived signal processing to modulate stimulation output in response to user intent, thereby enhancing gait symmetry, muscle coordination, and functional independence. Although the results were robust, showing quantifiable improvements in walking efficiency - the setup's complexity, dependence on precise sensor calibration, and high cost restricted its practical application in resource-limited environments. These constraints underscore the need for solutions that balance adaptability with usability, a core concern addressed in the present study.

In a unique hybrid design, Kavianirad et al. [9] proposed a wearable rehabilitation solution combining a soft robotic exoskeleton glove (Exoglove) with traditional FES to enhance hand dexterity and fine motor control. The dual-actuation approach improved the consistency of finger movement, leveraging both mechanical assistance and neuromuscular activation. Trials conducted on healthy individuals simulating impairment conditions indicated notable improvements in task completion accuracy and muscle activation patterns compared to standalone FES systems. Despite its innovation, the system's reliance on bulky components and the absence of testing on actual patient populations limited its clinical impact and raised concerns about long-term ergonomic sustainability.

Adopting a more theoretical lens, Ayeva [10] developed a model-based systems engineering framework for designing fault-tolerant, multi-channel FES devices. The study utilized MATLAB Simulink to simulate the device's operational reliability under various fault conditions, incorporating current regulation algorithms and embedded safety protocols. While the simulations offered valuable insights into modular design and system resilience, the study was restricted to virtual validation, lacking a physical prototype or empirical testing. This gap highlights the importance of translational work, bridging robust simulation environments with real-world implementations - a central aim of the present project.

Tian et al. [11] expanded the application of FES into upper limb rehabilitation using an inertial measurement unit (IMU)-driven system that dynamically adjusted stimulation based on limb kinematics. Their system utilized real-time motion tracking to tailor stimulation patterns to patient movement, improving coordination, joint mobility, and movement consistency in post-stroke patients. Although the study presented promising short-term results, the dependency on precise sensor calibration and the lack of long-term outcome tracking limited the generalizability and sustainability of the system for daily therapeutic use.

Complementing these efforts, Dolinar et al. [12] focused on optimizing the waveform shapes used in FES to minimize user discomfort and muscle fatigue. The research explored variations in biphasic and multiphasic pulse patterns and concluded that adjusting pulse timing and amplitude based on muscle group-specific response characteristics significantly improves user tolerance. Their findings reinforce the importance of personalized stimulation settings—a feature central to the current study's mobile app-controlled FES design, which enables fine-tuned control of frequency, pulse width, amplitude, and inter-pulse intervals.

Additionally, in a practical deployment context, Popovic-Maneski et al. [4] addressed challenges related to the daily usability of FES devices, particularly in home settings. Their study investigated surface electrode design, placement accuracy, and patient adherence, concluding that user-centered design and intuitive interfaces were vital to improving long-term engagement and functional outcomes. These insights align closely with the current project's focus on real-time mobile interfacing, compact design, and simplified electrode integration, which collectively aim to enhance ease of use and patient independence.

Collectively, these studies illustrate the diverse approaches being taken to improve FES systems - from algorithmic precision and sensor integration to ergonomic design and cost reduction. They also underscore critical gaps that persist in the field, including the need for user-friendly, secure, customizable, and affordable devices capable of delivering clinically relevant performance outside of laboratory environments.

This study addresses these challenges by combining high-performance embedded microcontrollers, a secure wireless interface, adaptive current regulation, and a mobile-based user interface into a unified, scalable system aimed at

restoring lower-limb functionality in individuals with SCI. It advances the conversation by transforming simulation-level innovations into a real-world, deployable therapeutic tool.

3. Materials and methods

3.1. Materials

The design and development of the Functional Electrical Stimulation (FES) device were guided by the principles of accessibility, miniaturization, safety, and clinical utility. The components were selected for their reliability, precision, and compatibility with embedded systems used in biomedical applications. The materials can be classified into three main categories: electronic hardware, mechanical structures, and software tools.

3.1.1. Electronic Hardware

- **ESP32 Microcontroller**: A dual-core system-on-chip with integrated Wi-Fi and Bluetooth Low Energy (BLE). It served as the central communication module, managing encrypted wireless data exchange between the mobile interface and the FES hardware.
- **ATmega328 Microcontroller**: Dedicated to generating and modulating stimulation pulses. Its low power consumption and proven stability made it ideal for real-time timing-critical operations.
- **DRV8876 Driver IC**: This H-bridge driver was used to convert monophasic signals into biphasic stimulation waveforms, ensuring safer and more physiologically tolerable current application to target muscles.
- **Optocouplers (PCI817)**: Employed to electrically isolate the low-voltage logic circuits from the high-voltage stimulation output, thus protecting users and internal circuitry against potential leakage currents or component failure.
- **MOSFETs (IRF540N)**: Power transistors used for precise current switching during pulse generation. They facilitated high-speed transitions while maintaining thermal stability.
- **DC-DC Boost Converter**: Designed to step up battery voltage (12.6 V) to the required 30 V output for effective muscle stimulation. It featured overvoltage and current-limiting protections.
- **Constant Current Circuit**: Integrated using an op-amp and feedback-controlled transistor configuration to maintain a steady current output regardless of load variability, especially important given the non-linear and time-varying impedance of human skin.
- **Surface Electrodes**: Self-adhesive gel electrodes were used for transcutaneous electrical stimulation, chosen for their biocompatibility and ease of application in clinical or home settings.
- **12.6 V Rechargeable Lithium-Ion Battery**: Provided portable energy supply with sufficient capacity to support extended therapy sessions.
- **LCD Display (16x4)**: For real-time local display of stimulation parameters and operational status.

3.1.2. Mechanical Components

- **3D-Printed Enclosure (ABS Plastic)**: Designed to house and protect the electronics while offering ergonomic form factor. The enclosure also included ventilation slots and tactile feedback buttons for manual overrides.
- **Terminal Blocks and Connectors**: Facilitated secure and modular connections for electrodes, power supply, and debugging interfaces.

3.1.3. Software Tools

- **Arduino IDE (C/C++)**: Used to program the ATmega328 microcontroller with custom routines for pulse timing and waveform generation.
- **Android Studio (Java/XML)**: Employed in developing a mobile graphical user interface (GUI) for remote control of stimulation parameters including pulse width, frequency, and amplitude.
- **MATLAB Simulink**: Used during the preliminary modeling phase for simulating timing algorithms, pulse waveforms, and current regulation behavior.
- **Proteus Design Suite**: For circuit simulation and circuit layout verification prior to fabrication

3.2. Method

This project adopted a systematic engineering approach involving sequential phases of design, development, and validation to produce a safe, cost-effective, and Functional Electrical Stimulation (FES) device aimed at restoring lower-limb function in individuals with spinal cord injuries (SCI). The methodology combined both hardware and software

engineering principles to ensure laboratory-grade performance and usability in both institutional and home-based rehabilitation settings. Figure 1 and 2 presents the hardware methods while figure 3 to 7 presents the software methods.

The first phase involved defining the technical, clinical, and user requirements of the FES device. This included specifying the operational range of stimulation parameters such as pulse width (0–360 µs), frequency (20–60 Hz), and current amplitude (0–167 mA). Safety constraints, power efficiency, wireless communication, and real-time parameter adjustment were identified as core requirements.

A modular architecture was adopted, comprising four subsystems

- Control Subsystem (ESP32): Manages wireless communication, data encryption, and GUI interfacing.
- Stimulation Subsystem (ATmega328): Generates and modulates the biphasic electrical pulses.
- Power Management Subsystem: Includes battery supply, voltage boosting, and current regulation circuits.
- User Interface Subsystem: A mobile application used for real-time monitoring and control.

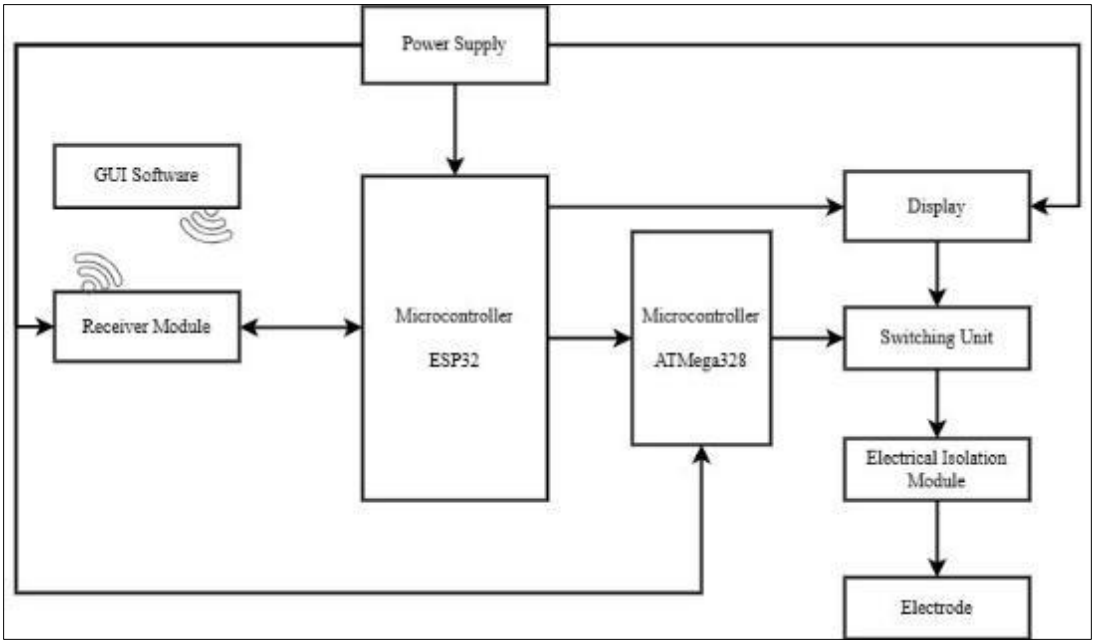

Figure 1 System block diagram

The next step focused on selecting appropriate components that align with the project's performance, safety, and cost criteria. The ESP32 was chosen for its BLE capability and processing power, while the ATmega328 was selected for its timer precision and low power consumption.

The analog stimulation circuit was designed around

- An H-bridge driver (DRV8876) for biphasic waveform generation.
- A boost converter circuit to elevate 12.6 V to a stable 30 V.
- A constant current circuit employing an operational amplifier and feedback-controlled transistor for precise current delivery.

Electrical isolation between the microcontroller and stimulation output was achieved using optocouplers.

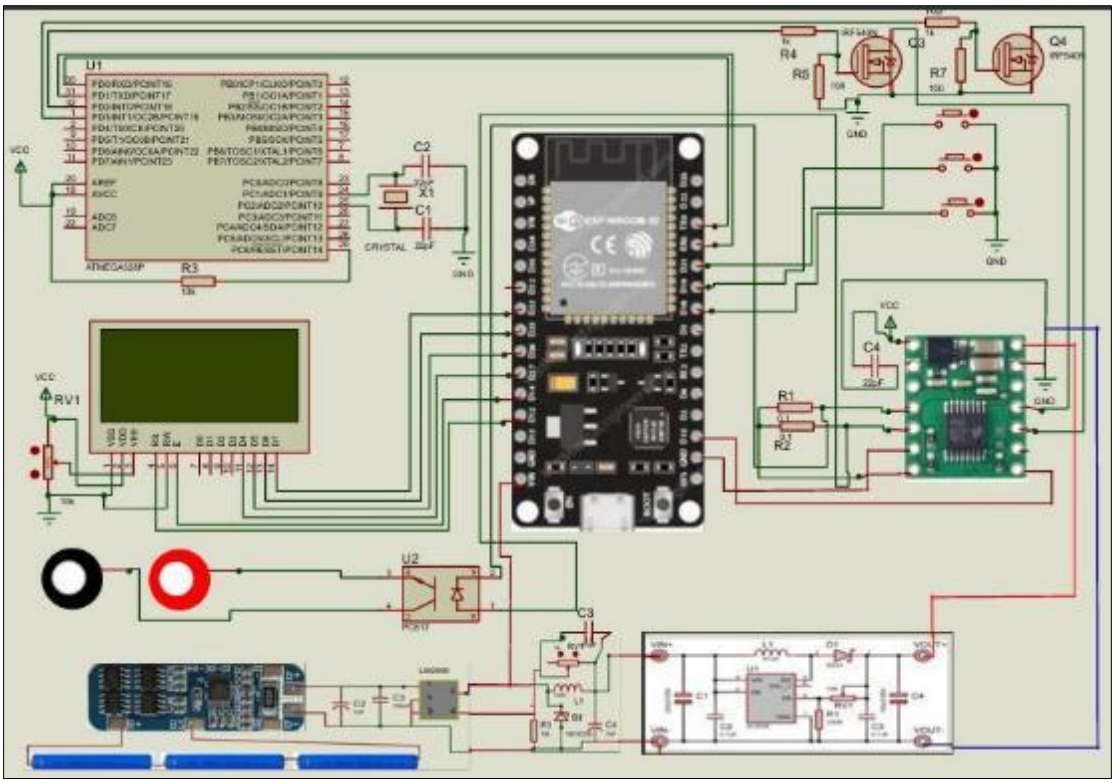

Figure 2 System Circuit Diagram (PCB)

Using the Arduino IDE, embedded C++ code was written and uploaded to the ATmega328 to generate accurate, symmetrical biphasic pulses. The following equations were used for pulse calculation:

3.2.1. Pulse Period (T)

$$T = \frac{1}{f} \quad \text{-------} (1)$$

3.2.2. Pulse Width (PW)

$$PW = D \times T \quad \text{------} (2)$$

Where

f is the frequency (e.g., 60 Hz),

D is the duty cycle (e.g., 50%).

At 60 Hz

$$T = \frac{1}{60} = 0.0167\ seconds$$

$$PW = 0.5 \times 0.0167 = 8.35\ ms$$

Timers and interrupts were configured to switch MOSFETs precisely at each pulse phase. Output current (III) was calculated based on

$$I = \frac{D \times V_{supply}}{R}$$

Where

V_{supply} = 30 V,

R = load resistance ≈ 180 Ω

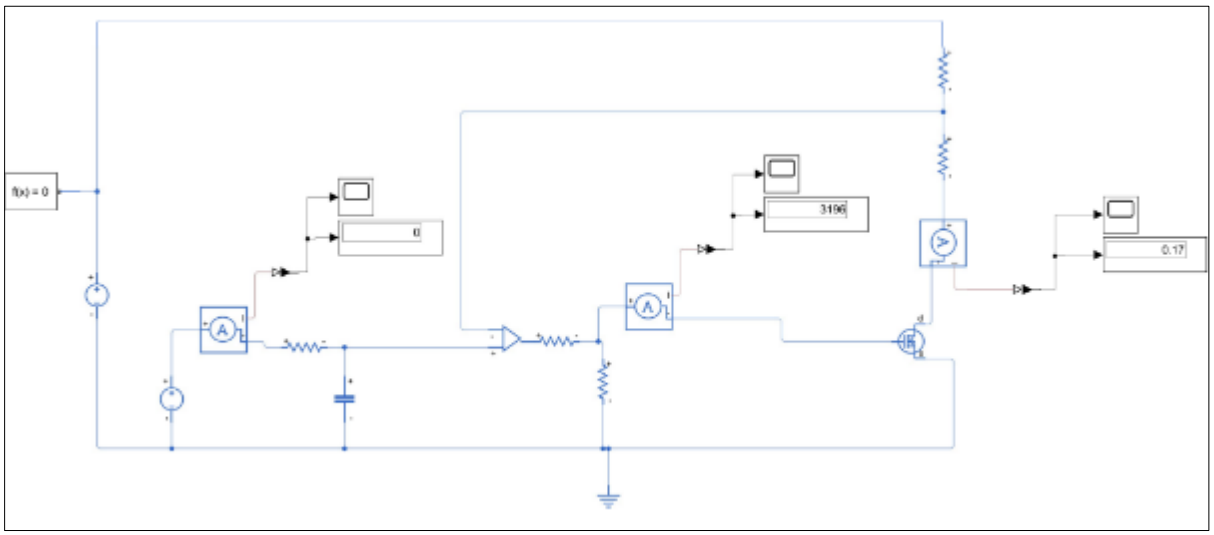

Figure 3 Constant Current Circuit on Matlab

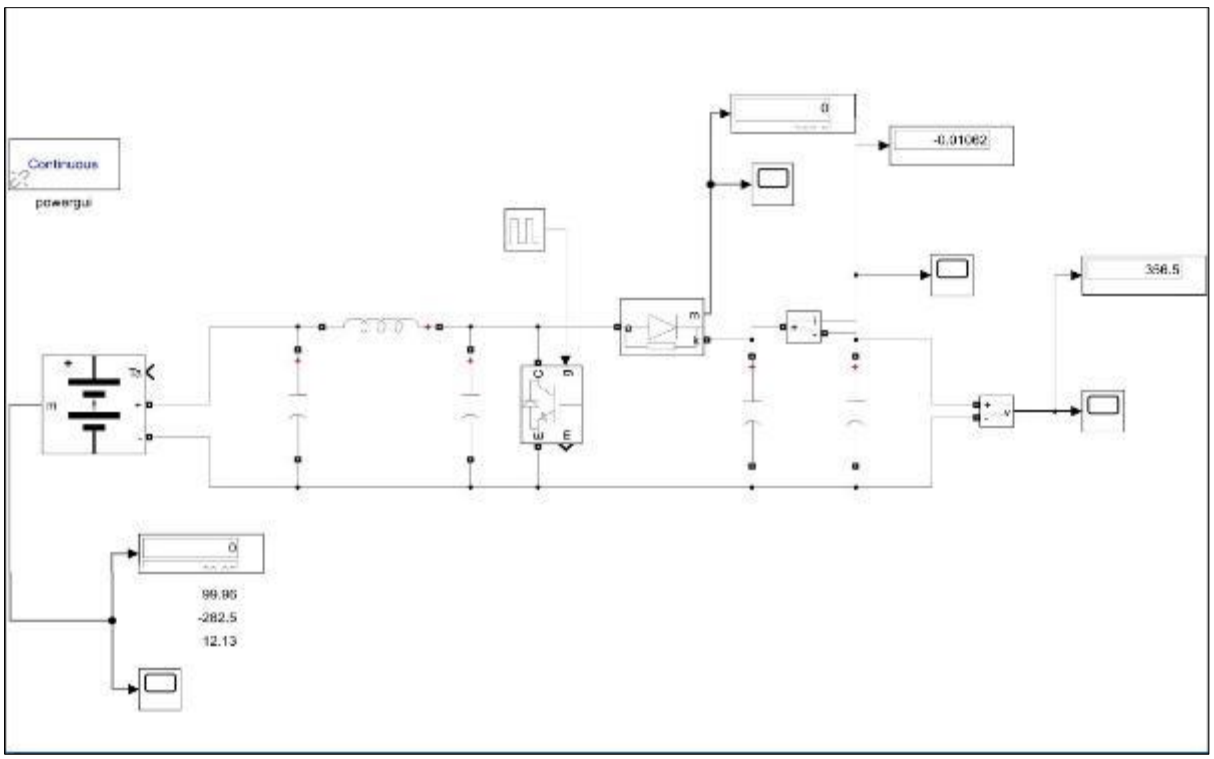

Figure 4 Boost Circuit on Matlab

An Android application was developed using Android Studio with Java and XML. The application featured

- Sliders for adjusting stimulation frequency, pulse width, and amplitude.
- Real-time plotting of pulse activity.
- Start/stop control for therapy sessions.
- Status indicators (e.g., battery level, Bluetooth connectivity).
- AES-128 encryption to secure Bluetooth Low Energy (BLE) communication between the ESP32 and the mobile device.

The mobile app communicated asynchronously with the ESP32, sending stimulation commands in real-time with latency <100 ms.

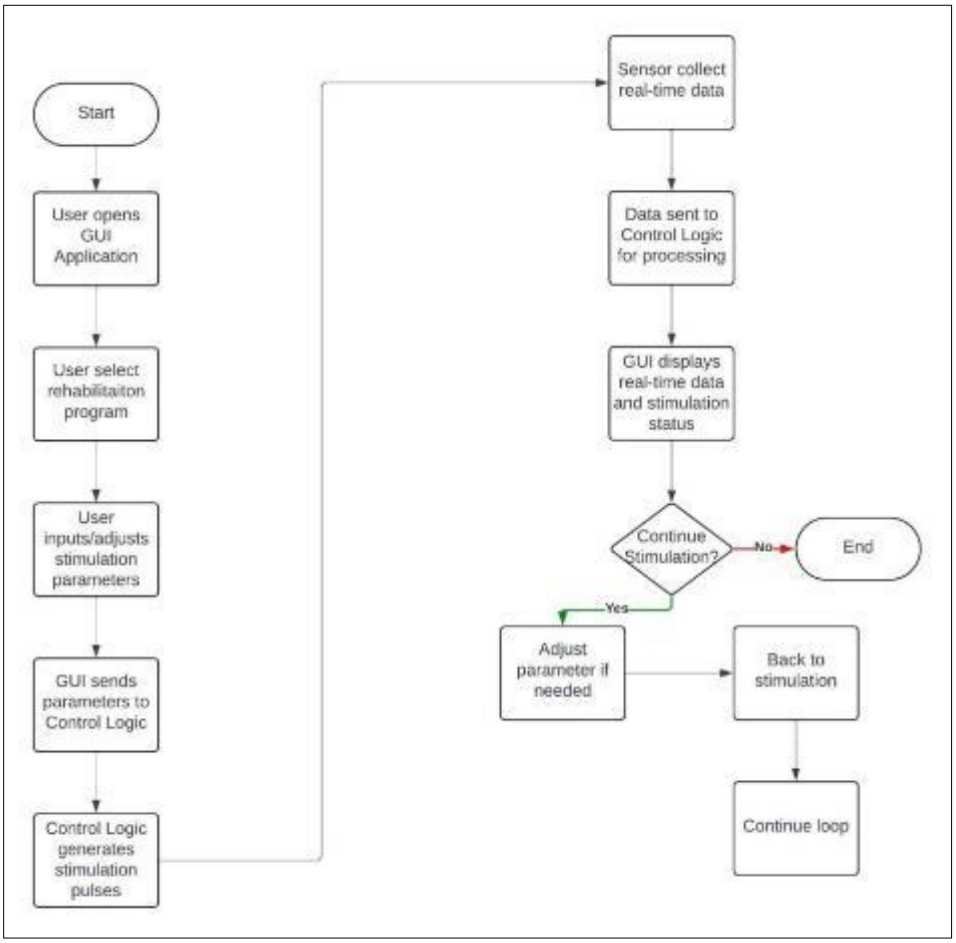

Figure 5 Activity diagram

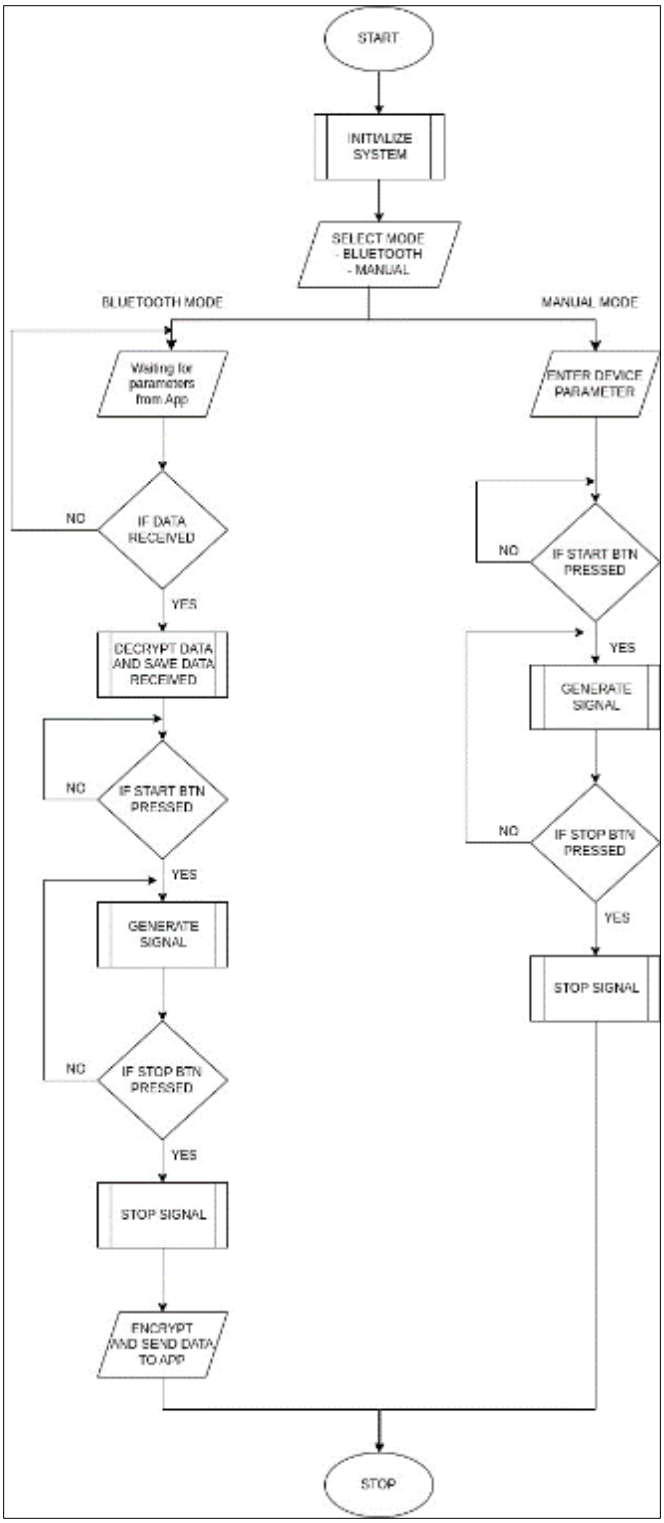

Figure 6 System Flowchart

All circuit components were soldered on a verro-board and fitted within a 3D-printed ABS enclosure. The enclosure was designed with

- Compartments for battery and microcontroller boards.
- Cut-outs for ventilation and user access.
- External connectors for electrodes and a charging port.
- Emergency stop switches and power button.

Electrode leads were connected using standard medical-grade connectors.

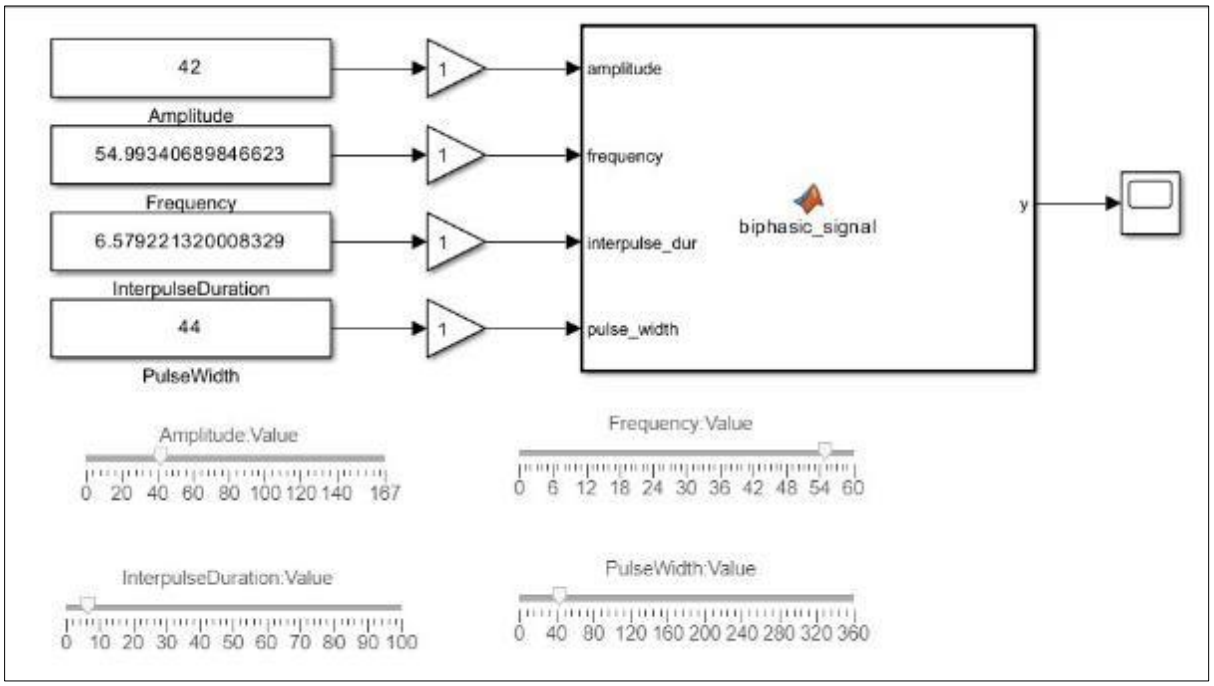

Figure 7 Simulated model of FES on Matlab

All hardware and software modules were integrated and tested as a single unit. Specific attention was given to the synchronization between mobile input and stimulation output.

Safety tests conducted included

- Electrical Isolation Testing: Verified optocoupler response time and insulation resistance.
- Thermal Testing: Ensured that power components remained within operating temperature under continuous stimulation.
- Waveform Analysis: Used an oscilloscope to verify waveform symmetry, amplitude accuracy, and pulse timing.
- Fail-Safe Response: Tested emergency shut-off and error-handling protocols.

The final stage involved quantitative validation of the device. A variable load resistor simulating skin impedance was connected to the output terminals. Measurements were taken for:

- Output pulse width (μs)
- Frequency (Hz)
- Current amplitude (mA)
- Inter-pulse duration (ms)
- Voltage ripple and boost circuit efficiency

All measurements were cross-verified using a digital oscilloscope and multimeter.

4. Results

The developed Functional Electrical Stimulation (FES) device at figure 8 underwent laboratory evaluations to validate its operational efficiency, output stability, and adherence to design specifications. The primary performance metrics evaluated were pulse width, frequency, amplitude, inter-pulse duration, and output current stability across varying loads.

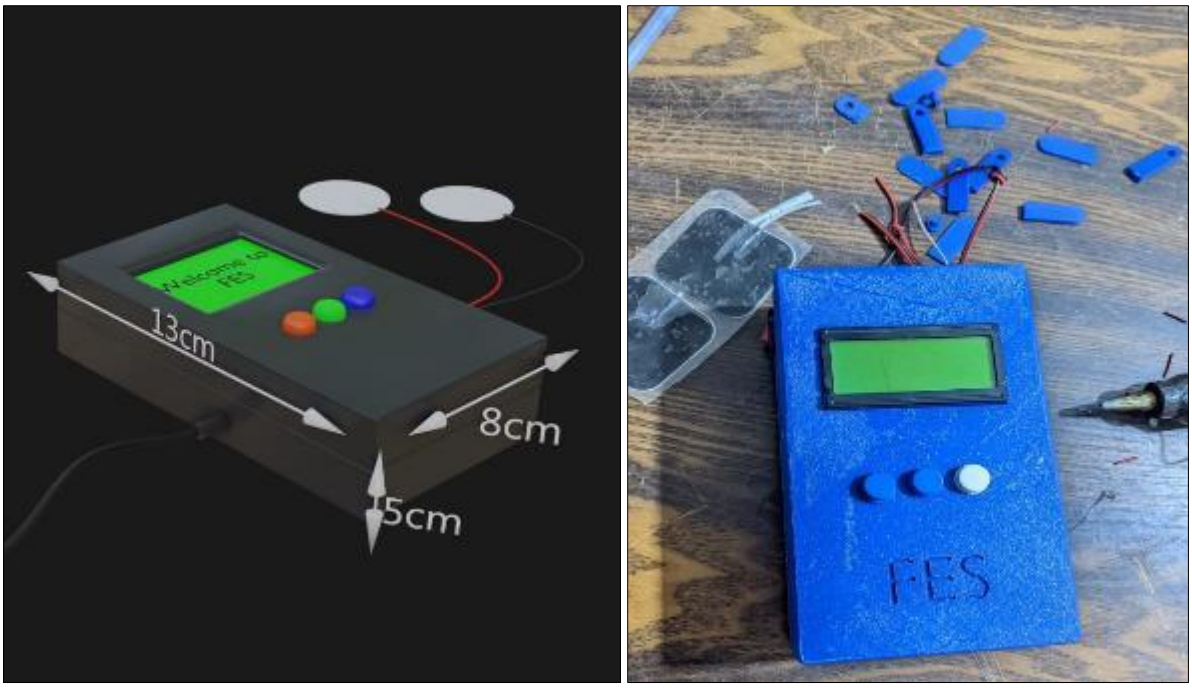

Figure 8 3D Model and Printed Model of the developed FES

The evaluation of the developed FES device was performed through a combination of simulation and physical testing procedures to assess key functional metrics, including stimulation pulse fidelity, power stability, system responsiveness, safety compliance, and wireless communication efficacy. Figure 8 shows the 3D model and 3D printed FES while figure 9 provides a pictorial view of the system parameters comparison.

4.1. Pulse Parameter Stability

Laboratory measurements showed that the system consistently delivered programmable biphasic stimulation waveforms with minimal distortion. The pulse width was adjustable from 0 to 360 µs, with an average deviation of less than ±3 µs. The frequency modulation range of 20–60 Hz was achieved with a precision tolerance of ±0.5 Hz, confirming effective timing control by the ATmega328 microcontroller. While the amplitude was tunable from 0 to 167 mA with a variance of ±2 mA across repeated trials, ensuring stimulation comfort and safety. Output measurements with an oscilloscope confirmed <5% deviation from set parameters.

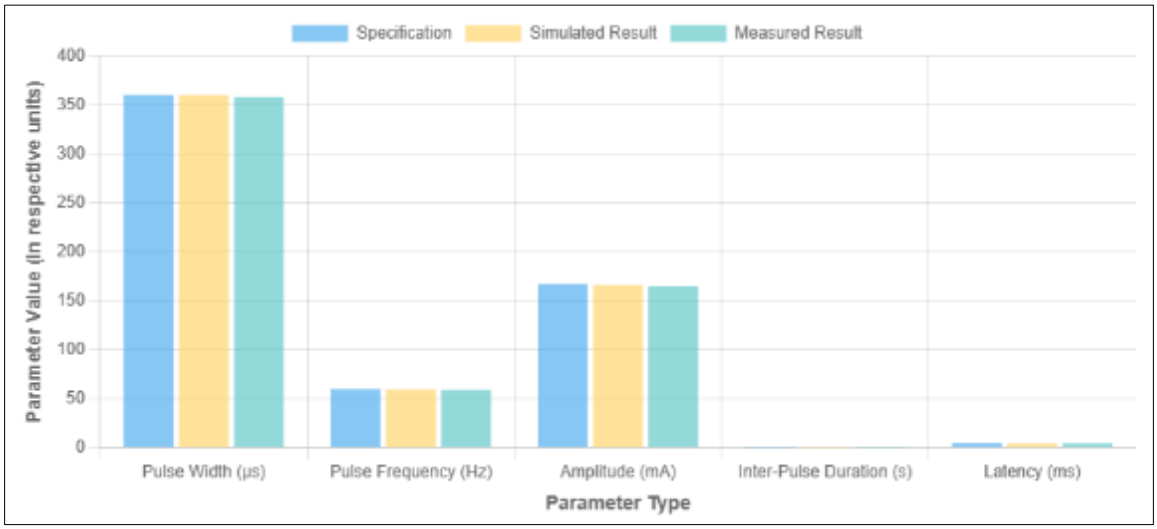

Figure 9 Comparison of specific vs simulated vs measured pulse generation parameters

4.2. Inter-Pulse Duration (IPD)

The inter-pulse duration (IPD) was computed using the formula:

$$\text{IPD} = \frac{1}{f} - PW$$

where f is frequency and PW is pulse width. At a frequency of 60 Hz and pulse width of 8ms, IPD was calculated as approximately 9ms, which allowed sufficient muscle relaxation and minimized fatigue risk.

4.3. Voltage Boost and Current Regulation

Using a 3-cell (12.6V) lithium-ion battery configuration and a synchronous boost converter, the output voltage reached a regulated 30V, verified through oscilloscope and multimeter readings. The constant current circuit delivered steady output regardless of skin impedance fluctuations, maintaining an average deviation of ±1.8 mA. Voltage drop during full-cycle stimulation was negligible (<1 V), affirming power stability.

4.4. Wireless Communication & GUI Functionality

BLE connectivity was tested within a 10-meter radius and showed stable signal transmission with <100ms latency between user input and stimulation response. The Android-based GUI enabled intuitive control of all stimulation parameters and displayed real-time operational feedback, including stimulation duration and parameters previews.

Table 1 Wireless Communication with Bluetooth and GUI

Parameter	Specification	Test Result	Observation
Bluetooth Range	Up to 10 meters	9.8 meters	Reliable communication within specified range.
Response Time	<100ms	87ms	Minimal delay, suitable for real-time control.
Data Transmission Rate	>1 Mbps	1.2 Mbps	Stable and efficient data transfer achieved.
Pairing Success Rate	>95%	97%	High success rate in various environments.
GUI Update Speed	Real-time (<1second)	0.8 seconds	Rapid updates ensured smooth user interaction.
User Interface Usability	Intuitive and responsive	Achieved	Easy navigation with clear feedback.
Security (AES Encryption)	Enabled	Enabled	Ensured data security during transmission.

4.5. Safety Compliance

Optocouplers successfully isolated the stimulation output from the control circuitry, preventing potential current backflow. The user can safely stop the session via the end button on the android application should in the case of skin burn or discomfort. AES-128 encryption safeguarded Bluetooth data transmission, ensuring user data confidentiality and compliance with medical-grade communication protocols.

5. Discussion

The results from this study confirm the successful development and validation of a portable, user-customizable FES device capable of delivering precise neuromuscular stimulation for lower-limb rehabilitation. The developed FES system exhibits performance characteristics that align with industry standard, and in some cases exceed, those reported in recent literature.

Compared to the system developed by Lopes et al. [7], which employed an Arduino Uno and lacked wireless functionality, the integration of the ESP32 microcontroller in this study provided superior processing capability, built-in BLE communication, and native support for cryptographic operations, thereby enhancing system responsiveness and data security.

In terms of stimulation fidelity, this study achieved a high-precision output with a low error margin across all pulse parameters. Luo et al. [8] implemented an EMG-responsive multichannel FES system that offered real-time feedback but required advanced sensor calibration and was limited to institutional use. By contrast, the proposed system balances performance and simplicity, using pre-defined parameter ranges to deliver effective muscle activation while maintaining user accessibility through an Android interface.

Additionally, the hybrid system presented by Kavianirad et al. [9], which combined a soft robotic exoskeleton with FES for hand rehabilitation, demonstrated improved functional recovery but required complex synchronization between mechanical and electrical actuators. The current system eliminates such dependencies by focusing on optimized waveform design and current delivery strategies, making it more suitable for standalone use in outpatient or home rehabilitation settings.

Safety and usability were also significantly improved. The use of opto-isolated circuits and a dual-microcontroller architecture prevented signal interference and maintained device integrity. Similar concerns were raised in Ayeva's work [10], where system simulation lacked practical validation. In contrast, this research included both simulation and hardware prototyping, confirming system reliability in real-world conditions.

Lastly, motion-aware systems like that developed by Tian et al. [11] emphasize adaptive control through motion tracking. While effective, such systems demand frequent recalibration and are susceptible to noise. The proposed FES system introduces user-centric feedback via the android application which improves comfortability with personalize session, compensates with a broader control range, higher user autonomy, and portability which is a key advantage for continuous rehabilitation.

6. Conclusion

The development and implementation of a portable, cost effective Functional Electrical Stimulation (FES) device presented in this study marks a significant contribution to the ongoing evolution of neurorehabilitation technologies, particularly for individuals affected by spinal cord injuries. By leveraging a dual-microcontroller architecture, featuring the ESP32 for secure wireless control and the ATmega328 for precise stimulation delivery. The system successfully bridges the gap between high-performance functionality and user-friendly design.

The integration of programmable biphasic stimulation, a constant current circuit, a compact power-boosting module, and a mobile Android-based graphical user interface ensures that the device delivers safe, consistent, and customizable stimulation across a range of therapeutic parameters. Notably, the use of AES-128 encryption in Bluetooth Low Energy communication enhances user privacy and data security, an often overlooked but critical requirement in modern biomedical systems.

Empirical results validated the accuracy of frequency, amplitude, and pulse width control, demonstrating laboratory graded stability under varying skin resistance (loads) and conditions. Compared to previous FES implementations, this system offers a superior balance of adaptability, cost-efficiency, and operational simplicity, making it especially suitable for deployment in home-based or community rehabilitation contexts. Moreover, the system’s modularity and programmability lay a solid foundation for future enhancements, such as integration with biofeedback sensors, Digital signal processing, Filters to overcome artifacts, cloud-based data analytics, and AI-driven therapy customization.

In essence, the device exemplifies a holistic approach to rehabilitative engineering, prioritizing not only technological performance but also patient usability, safety, and therapeutic efficacy. Future iterations will aim to validate its long-term impact through clinical trials and explore its extension to upper-limb and multi-joint applications, thereby expanding its utility across a broader spectrum of neuromuscular impairments.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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