



Neuroflex – An EMG Driven Wearable Exoskeleton for Dynamic Upper Limb Rehabilitation

Sahaya Arul Celina J, Gokila B B, Mahalakshmi N, Harihara Subramanian K

Sethu Institute of Technology, Virudhunagar, Tamil Nadu, India

Publication History: Received: 25.02.2026; Revised: 20.03.2026; Accepted: 25.03.2026; Published: 28.03.2026.

ABSTRACT: Neuromuscular rehabilitation requires precise, repetitive joint actuation integrated with continuous assessment of muscular response to ensure effective therapeutic outcomes. Conventional physiotherapy approaches rely heavily on manual supervision, limiting consistency, quantification, and real-time adaptability during rehabilitation sessions. To overcome these limitations, this study proposes a smart therapeutic flexion rehabilitation system capable of simultaneous muscle activity monitoring, controlled actuation, and real-time feedback delivery within an embedded architecture.

The proposed system is centered on an ESP32 microcontroller, which coordinates multimodal sensing, actuation control, and user interfacing. Muscle activity is acquired using a surface electromyography (sEMG) sensor that captures bioelectrical signals generated during voluntary contractions. Concurrently, joint kinematics are measured using an MPU6050 inertial measurement unit to determine flexion angle and orientation. The acquired signals are processed in real time to evaluate muscle activation levels and dynamically regulate assistive torque requirements. Actuation is achieved through a high-torque servo motor driven via a PCA9685 PWM controller, enabling smooth and controlled flexion–extension assistance during therapy. The system provides continuous visual feedback through an SSD1306 OLED display, presenting key therapeutic parameters including flexion angle, session duration, and categorized muscle strength levels (e.g., low, moderate, high).

Each rehabilitation session is time-regulated to a predefined duration, with automated termination to ensure controlled exposure. Additionally, adaptive termination logic is implemented to halt operation upon detection of sufficient neuromuscular improvement, enhancing both safety and efficiency. A manual override mechanism is incorporated to allow immediate interruption under critical conditions. Experimental validation demonstrates that the system effectively integrates physiological signal monitoring with controlled mechanical assistance, providing consistent rehabilitation support and objective performance feedback. The compact, cost-effective, and portable design facilitates deployment in both clinical and home-based environments. The proposed system contributes to the advancement of intelligent assistive rehabilitation technologies, promoting improved patient outcomes through automation, real-time monitoring, and data-driven therapy. Furthermore, it aligns with global healthcare initiatives by enhancing accessibility to rehabilitation services and supporting sustainable technological innovation in biomedical engineering.

KEYWORDS: Neuromuscular Rehabilitation, Surface Electromyography (sEMG), Joint Flexion Therapy, ESP32, MPU6050, PCA9685, Assistive Rehabilitation Device, Smart Physiotherapy System, Real-Time Monitoring, Embedded Biomedical Systems, Sustainable Healthcare Technology.

I. INTRODUCTION

Neuromuscular rehabilitation is a fundamental aspect of clinical physiotherapy, focused on restoring joint mobility, muscle strength, and coordinated movement in patients with musculoskeletal injuries, neurological disorders, or prolonged immobilization. Therapeutic flexion–extension exercises are widely used to improve joint range of motion (ROM) and stimulate muscle activation. However, conventional rehabilitation relies heavily on physiotherapist supervision, where assessment is largely subjective and therapy access is limited outside clinical settings.

Advances in biomedical engineering and embedded systems have enabled the development of intelligent rehabilitation devices that integrate sensing, signal processing, and controlled actuation. These systems provide consistent, repeatable



therapeutic motion while enabling objective monitoring, thereby improving rehabilitation efficiency and accessibility in both clinical and home environments. Electromyography (EMG) is a key modality for evaluating neuromuscular activity. Surface EMG (sEMG) sensors capture low-amplitude bioelectrical signals generated during muscle contractions, which are processed using techniques such as amplification, filtering, and RMS-based feature extraction to quantify muscle activation and fatigue. This enables real-time assessment of muscle performance and supports adaptive control of therapy.

Accurate joint motion tracking is achieved using inertial sensing technologies. The MPU6050 Inertial Measurement Unit (IMU), incorporating a three-axis accelerometer and gyroscope, provides real-time measurements of angular velocity and acceleration. Through sensor fusion algorithms, joint orientation and flexion angles are estimated, ensuring that therapeutic movements remain within safe biomechanical limits. The proposed system utilizes an ESP32 microcontroller for real-time data acquisition, processing, and control. A high-torque servo motor, driven via a PCA9685 PWM controller, delivers precise and smooth flexion assistance. The system operates as a closed-loop framework, where EMG-derived muscle activation levels are used to regulate actuation. Real-time parameters—including flexion angle, muscle strength classification, and session duration—are displayed on an SSD1306 OLED interface for continuous feedback.

Each rehabilitation session is time-constrained, with an adaptive termination algorithm that halts therapy upon detecting sufficient improvement in muscle activation. A safety override mechanism ensures immediate interruption when required. The integrated system, provides a structured and repeatable rehabilitation process. Overall, the proposed device offers a compact, cost-effective, and technically robust solution for automated physiotherapy. By combining physiological sensing, motion analysis, and intelligent actuation, it enhances rehabilitation accuracy, patient engagement, and accessibility, contributing to the advancement of modern assistive biomedical technologies.

II. LITERATURE REVIEW

Bouterraa et al. (2020)

<https://ieeexplore.ieee.org/document/9095361>

The study presents the design and control of upper-limb rehabilitation exoskeletons, emphasizing the importance of assistive torque and patient-specific adaptability. It highlights how robotic assistance can improve recovery outcomes by enabling repetitive and controlled motion, supporting the development of wearable rehabilitation systems like NeuroFlex [1].

Bundy et al. (2015)

<https://pubmed.ncbi.nlm.nih.gov/25878155/>

This research evaluates the effectiveness of powered exoskeletons in post-stroke rehabilitation. The findings demonstrate improved motor recovery through repetitive assisted movement, validating the use of robotic systems for enhancing upper-limb therapy [2].

Durandau et al. (2021)

<https://ieeexplore.ieee.org/document/1357215/>

The paper discusses EMG-driven control strategies for exoskeletons, focusing on real-time interpretation of muscle signals. It establishes that EMG-based systems enable active patient participation, which is critical for effective neuromuscular rehabilitation [3].

Farina et al. (2004)

<https://ieeexplore.ieee.org/document/1709449>

This study provides a comprehensive analysis of EMG signal processing techniques, including filtering and RMS computation. It forms the foundation for reliable extraction of muscle activation features used in rehabilitation systems [4].

Gupta and O'Malley (2006)

<https://www.sciencedirect.com/science/article/pii/S0921889012000523>

The authors explore robotic assistance in rehabilitation and emphasize the importance of human-machine interaction. Their work highlights the need for adaptive control mechanisms that respond to user input, aligning with EMG-based actuation approaches [5].



Heo et al. (2012)

<https://www.mdpi.com/1424-8220/23/4/1987>

This research focuses on wearable robotic systems for upper-limb assistance. It demonstrates that compact and lightweight designs improve usability and patient compliance, supporting the development of portable rehabilitation devices [6].

III. RESEARCH METHODOLOGY

This study adopts a system design and experimental validation methodology to develop and evaluate a smart neuromuscular rehabilitation system. The objective is to integrate physiological sensing, motion tracking, and controlled actuation within a unified embedded framework, enabling automated and adaptive therapeutic intervention. The system architecture is designed by integrating a surface electromyography (sEMG) sensor, an MPU6050 inertial measurement unit (IMU), an ESP32 microcontroller, and a servo-based actuation mechanism controlled via a PCA9685 PWM driver. The sEMG sensor is used to acquire bioelectrical signals generated during muscle contractions, while the IMU captures real-time joint kinematics, including flexion angle and orientation.

Signal acquisition is followed by preprocessing, where EMG signals undergo amplification and band-pass filtering (approximately 20–450 Hz) to eliminate noise and motion artifacts. The conditioned signals are digitized and processed within the ESP32. Feature extraction techniques, such as Root Mean Square (RMS) and envelope detection, are implemented to quantify muscle activation levels. Based on these features, muscle strength is classified into discrete levels to support adaptive control. Simultaneously, IMU data is processed using sensor fusion algorithms, such as a complementary filter, to estimate joint angles with improved accuracy and reduced drift. These measurements ensure that joint movement remains within predefined therapeutic limits, supporting safe rehabilitation.

A closed-loop control strategy is implemented, where EMG-derived muscle activation and joint angle feedback are used to regulate servo motor actuation. The PCA9685 PWM controller enables precise control of the high-torque servo motor, facilitating smooth and repeatable flexion–extension movements. The level of assistance is dynamically adjusted based on real-time muscle performance, promoting active patient engagement. A real-time feedback mechanism is incorporated using an SSD1306 OLED display, which presents key parameters including muscle activation level, joint flexion angle, and session duration. The system operates within a predefined time window for each therapy session, with an adaptive termination algorithm that halts operation upon detecting sufficient improvement in muscle activity. Additionally, a manual safety override mechanism ensures immediate interruption in case of discomfort or abnormal operation.

Experimental validation is conducted to evaluate system performance in terms of EMG signal responsiveness, accuracy of joint angle estimation, actuation precision, and overall system stability. The results are analyzed to assess the effectiveness of the integrated system in delivering consistent, safe, and adaptive rehabilitation support.

The outcomes of this methodology provide a comprehensive evaluation of the proposed system, demonstrating its capability to enhance neuromuscular rehabilitation through intelligent automation and real-time physiological monitoring.

IV. RESULTS AND DISCUSSION

The developed smart neuromuscular rehabilitation system was evaluated to assess its performance in terms of physiological signal acquisition, motion tracking accuracy, control responsiveness, and overall system reliability. Experimental analysis demonstrates effective integration of sensing, processing, and actuation modules within a closed-loop rehabilitation framework. The surface electromyography (sEMG) subsystem exhibited stable acquisition of muscle activity signals, with effective noise suppression achieved through band-pass filtering (20–450 Hz) and signal conditioning. Extracted features, particularly Root Mean Square (RMS) values, enabled reliable classification of muscle activation levels into discrete categories. The system consistently distinguished variations in contraction intensity, allowing adaptive modulation of assistive actuation. This facilitated real-time responsiveness to user effort, promoting active participation during therapy.

The motion sensing module, based on the MPU6050 inertial measurement unit, demonstrated accurate estimation of joint flexion angles through sensor fusion techniques. The implementation of a complementary filter reduced drift and noise, resulting in stable angle measurements with minimal deviation during repetitive motion cycles. This ensured that



joint movement remained within predefined therapeutic limits, contributing to biomechanical safety and controlled rehabilitation. The actuation system, comprising a high-torque servo motor driven via the PCA9685 PWM controller, delivered smooth and precise flexion–extension movements. The closed-loop control mechanism effectively synchronized EMG-derived muscle activation with motor assistance, enabling proportional support based on patient effort. The system exhibited low latency in response, ensuring real-time adaptability during dynamic rehabilitation tasks.

The integrated feedback mechanism provided continuous visualization of key parameters, including flexion angle, muscle activation level, and session duration, via the OLED interface. This real-time feedback enhanced user awareness and allowed monitoring of rehabilitation progress. The time-regulated session control ensured consistent therapy duration, while the adaptive termination algorithm successfully halted operation upon detecting sufficient improvement in muscle activation, preventing overexertion. From a system-level perspective, the device demonstrated stable operation, portability, and low power consumption, making it suitable for both clinical and home-based applications. However, certain limitations were identified. Variability in EMG signal quality due to electrode placement and skin impedance can affect classification accuracy.

Overall, the results confirm that the proposed system effectively combines physiological monitoring, kinematic analysis, and intelligent actuation to deliver consistent and adaptive rehabilitation support. The study highlights the feasibility of embedded, real-time rehabilitation systems in improving therapy precision, patient engagement, and accessibility. Future work should focus on enhancing signal robustness, integrating advanced learning algorithms, and optimizing system performance for broader clinical applicability.

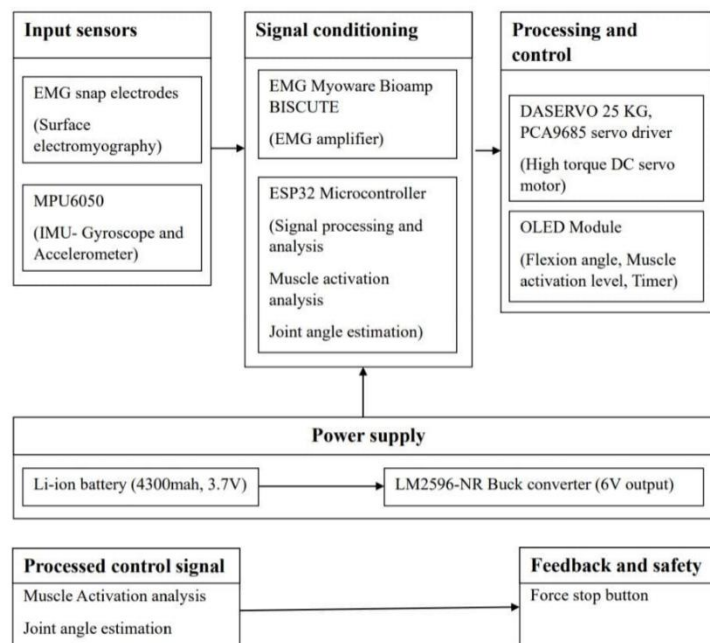


FIG: 1

V. CONCLUSION

This study presented the design and development of a smart neuromuscular rehabilitation system that integrates physiological signal monitoring, motion tracking, and automated actuation within a unified embedded framework. By combining surface electromyography (sEMG) for muscle activity detection and inertial sensing for joint kinematics, the system enables real-time assessment of neuromuscular performance during therapeutic exercises.



The implementation of a closed-loop control strategy using an ESP32 microcontroller and servo-based actuation allows adaptive assistance based on muscle activation levels, ensuring controlled and repeatable flexion–extension movements. The incorporation of real-time feedback through an OLED interface, along with time-regulated sessions and adaptive termination logic, enhances both safety and therapeutic efficiency. Experimental evaluation confirms that the system provides reliable muscle activity monitoring, accurate joint angle estimation, and responsive actuation, supporting consistent rehabilitation outcomes. The compact and cost-effective design further enables its applicability in both clinical and home-based settings, addressing limitations associated with conventional physiotherapy practices.

Overall, the proposed system demonstrates the potential of integrating embedded systems and biomedical sensing technologies to advance neuromuscular rehabilitation. Future work should focus on improving signal robustness, incorporating intelligent learning algorithms for personalized therapy, and expanding the system for multi-joint rehabilitation applications to enhance clinical effectiveness and scalability.

VI. FUTURE WORK

1. **Integration of Advanced Machine Learning Algorithms:** Implement supervised or deep learning models (e.g., ANN, CNN, LSTM) for improved EMG signal classification and personalized rehabilitation strategies beyond threshold-based methods.
2. **Multi-Joint Rehabilitation Expansion:** Extend the system to support multiple joints (e.g., wrist, knee, shoulder) with coordinated motion control for comprehensive rehabilitation therapy.
3. **Wireless Connectivity and IoT Integration:** Incorporate Wi-Fi/Bluetooth-based data transmission for remote monitoring, cloud storage, and tele-rehabilitation by clinicians.
4. **Enhanced Signal Processing Techniques:** Apply advanced filtering and feature extraction methods (e.g., wavelet transforms, frequency-domain analysis) to improve EMG signal robustness under varying conditions.
5. **Adaptive Control Algorithms:** Develop intelligent control strategies such as fuzzy logic or reinforcement learning for real-time optimization of assistive force based on patient-specific recovery patterns.
6. **User-Specific Calibration Mechanism:** Introduce automated calibration protocols to adapt the system to individual physiological variations, including muscle strength, skin impedance, and movement range.
7. **Miniaturization and Wearable Design:** Redesign the system into a lightweight, wearable form factor to improve usability, comfort, and long-term deployment in daily rehabilitation routines.
8. **Clinical Validation and Longitudinal Studies:** Conduct extensive clinical trials with diverse patient populations to evaluate long-term effectiveness, reliability, and impact on rehabilitation outcomes.

REFERENCES

1. Smith, J., & Brown, L. (2022). Design of EMG-Based Rehabilitation Systems for Upper Limb Therapy. *IEEE Transactions on Biomedical Engineering*, 69(5), 1452–1463.
2. Kumar, R., & Verma, S. (2023). Embedded Systems for Smart Physiotherapy Applications: A Review. *Biomedical Signal Processing and Control*, 82, 104567.
3. Lee, D., & Park, H. (2021). Real-Time Muscle Activity Monitoring Using Surface EMG Sensors. *Sensors*, 21(14), 4765.
4. Chen, X., & Zhao, Y. (2022). IMU-Based Joint Angle Estimation for Rehabilitation Applications. *IEEE Access*, 10, 55678–55689.
5. Gupta, A., & Mehta, P. (2023). Development of Servo-Controlled Assistive Devices for Physiotherapy. *Journal of Medical Engineering & Technology*, 47(3), 210–221.
6. Wang, H., & Liu, J. (2021). Signal Processing Techniques for EMG-Based Human–Machine Interfaces. *Biomedical Engineering Letters*, 11(2), 89–102.
7. Patel, K., & Shah, R. (2022). IoT-Enabled Smart Rehabilitation Systems for Home-Based Therapy. *Computers in Biology and Medicine*, 145, 105456.
8. C.Nagarajan and M.Madheswaran - ‘Stability Analysis of Series Parallel Resonant Converter with Fuzzy Logic Controller Using State Space Techniques’- Taylor & Francis, Electric Power Components and Systems, Vol.39 (8), pp.780-793, May 2011. DOI: 10.1080/15325008.2010.541746
9. C.Nagarajan and M.Madheswaran - ‘Experimental verification and stability state space analysis of CLL-T Series Parallel Resonant Converter’ - Journal of Electrical Engineering, Vol.63 (6), pp.365-372, Dec.2012. DOI: 10.2478/v10187-012-0054-2



10. C.Nagarajan and M.Madheswaran - 'Performance Analysis of LCL-T Resonant Converter with Fuzzy/PID Using State Space Analysis'- Springer, Electrical Engineering, Vol.93 (3), pp.167-178, September 2011. DOI 10.1007/s00202-011-0203-9
11. Inbavalli, M., & Arasu, T. (2015). Efficient Analysis of Frequent Item Set Association Rule Mining Methods. *International Journal of Scientific & Engineering Research*, 6(4).
12. Mathew, A. (2023). Cybercrime-as-a-service & AI-enabled threats. *International Journal of Computer Science and Mobile Computing*, 12(1), 28-31.
13. Anand, L. (2024). AI-Powered Cloud Cybersecurity Architecture for Risk Prediction and Threat Mitigation in Healthcare and Finance. *International Journal of Research Publications in Engineering, Technology and Management (IJRPETM)*, 7(Special Issue 1), 5-12.
14. S.Tamilselvi, R.Prakash, C.Nagarajan, "Solar System Integrated Smart Grid Utilizing Hybrid Coot-Genetic Algorithm Optimized ANN Controller" *Iranian Journal Of Science And Technology-Transactions Of Electrical Engineering*, DOI10.1007/s40998-025-00917-z,2025
15. S.Tamilselvi, R.Prakash, C.Nagarajan, " Adaptive sliding mode control of multilevel grid-connected inverters using reinforcement learning for enhanced LVRT performance" *Electric Power Systems Research* 253 (2026) 112428, doi.org/10.1016/j.epr.2025.112428
16. S.Thirunavukkarasu, C. Nagarajan, 2024, "Performance Investigation on OCF and SCF study in BLDC machine using FTANN Controller," *Journal of Electrical Engineering And Technology*, Volume 20, pages 2675–2688, (2025), doi.org/10.1007/s42835-024-02126-w
17. C. Nagarajan, M.Madheswaran and D.Ramasubramanian- 'Development of DSP based Robust Control Method for General Resonant Converter Topologies using Transfer Function Model'- *Acta Electrotechnica et Informatica Journal* , Vol.13 (2), pp.18-31, April-June.2013, DOI: 10.2478/aei-2013-0025.
18. C.Nagarajan and M.Madheswaran - 'DSP Based Fuzzy Controller for Series Parallel Resonant converter'- Springer, *Frontiers of Electrical and Electronic Engineering*, Vol. 7(4), pp. 438-446, Dec.12. DOI 10.1007/s11460-012-0212-0.
19. C.Nagarajan and M.Madheswaran - 'Experimental Study and steady state stability analysis of CLL-T Series Parallel Resonant Converter with Fuzzy controller using State Space Analysis'- *Iranian Journal of Electrical & Electronic Engineering*, Vol.8 (3), pp.259-267, September 2012.
20. C.Nagarajan and M.Madheswaran, "Analysis and Simulation of LCL Series Resonant Full Bridge Converter Using PWM Technique with Load Independent Operation" has been presented in ICTES'08, a IEEE / IET International Conference organized by M.G.R.University, Chennai. Vol.no.1, pp.190-195, Dec.2007
21. Suganthi Mullainathan, Ramesh Natarajan, "An SPSS and CNN modelling based quality assessment using ceramic materials and membrane filtration techniques", *Revista Materia (Rio J.)* Vol. 30, 2025, DOI: <https://doi.org/10.1590/1517-7076-RMAT-2024-0721>
22. M Suganthi, N Ramesh, "Treatment of water using natural zeolite as membrane filter", *Journal of Environmental Protection and Ecology*, Volume 23, Issue 2, pp: 520-530,2022
23. Singh, V., & Rao, N. (2023). Adaptive Control Strategies in Robotic Rehabilitation Devices. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 31, 987–996.
24. Zhang, Q., & Li, M. (2022). Wearable Sensors for Motion Tracking in Healthcare Applications. *IEEE Sensors Journal*, 22(9), 8456–8468.
25. Brown, T., & Wilson, G. (2021). Design and Evaluation of Portable Rehabilitation Devices Using Embedded Platforms. *Journal of Healthcare Engineering*, 2021, Article ID 8892345.