International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 03 Issue: 12 December 2025
Page No: 4563-4569
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2025.0671

Neuro-Adaptive Feedback Control in Wearable Robotics for Stroke Rehabilitation: Integrating EEG Signals with Cable-Driven Exoskeletons

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Abstract

Neuro-adaptive control systems and wearable robots have brought a revolution to stroke rehabilitation. The use of cable-driven exoskeletons based on electroencephalography (EEG) signals is one of the most significant innovations in the personalization of therapy and the improvement of motor recovery among stroke patients. This paper concentrates on the interaction between EEG-based brain-computer interfaces and adaptive control strategies of wearable robotics, and the ways they are used to address post-stroke motor rehabilitation. It discusses velocity-free neuro-adaptive control, neural optimization through observers, and leader-follower models of cooperation, which contribute to adaptive and customized robotic assistance. This paper further addresses the advantages and limitations of cable-based systems with lightweight and compliant actuation, suggesting their applicability to clinical and home-based therapy settings. The review demonstrates the promise of neuro-adaptive, EEG-controlled exoskeletons to rehabilitate motor performance and quality of life in stroke survivors by assessing current trends and providing future directions for the technology.

Keywords: *Neuro-adaptive control, EEG integration, Stroke rehabilitation, Cable-driven exoskeletons.*

1. Introduction

Stroke has been among the leading causes of irreversible disability globally, and in most cases, it leads to motor disability that requires long and intensive care. Exoskeletons and other wearable robots have become innovative technologies in neurorehabilitation, in which repetitive, task-specific movement training (a significant component of neuroplasticity and functional recovery) can be offered. These systems can be further improved by incorporating brain-computer interfaces (BCIs) and, specifically, electroencephalography (EEG)-based adaptive robot controllers to make rehabilitation more effective and personalized. One of the most revolutionary innovations in this field is the neuro-adaptive feedback control systems that can dynamically control robotic assistance based on user intention and performance using real-time brain signals. This review paper covers recent developments in neuro-adaptive control, EEG-based feedback control, and cable-based exoskeletons, and how they can be combined to enhance stroke recovery.

2. Neuro-Adaptive Control Systems: Foundations and Progress

Neuro-adaptive control systems use artificial neural networks to discover system dynamics and uncertainties in real time to generate control strategies that can adapt to the changing needs of the user and the environment. They can be applied particularly to rehabilitation robotics, where movement patterns and levels of effort vary greatly in patients. Velocity-free cooperative controllers have introduced a new approach to neuro-adaptive control to improve the precision and stability of dual-arm robots. These methods are not based on a speed parameter and therefore can be used in wearable devices, where sensor constraints are also a consideration, since they work by dynamically adjusting performance constraints [1]. Dynamic performance constraints can be added to adjust and monitor human intent more effectively during the rehabilitation process. Another issue addressed by these controllers is the problem of nonlinear dynamics and inter-limb coordination, which is a challenging problem in dual-arm and wearable robots. The clinical implications of stroke rehabilitation procedures are far-reaching, as the performance of remaining motor functions and the time required for patient recovery may be linked to frequent changes in control strategies. This flexibility improves patient engagement and motor learning. Neural optimization methods have also been further developed to produce neuro-adaptive controllers that reduce the impact of noisy data, which is a shortcoming of real-life biomedical signals such as EEG. These optimized controllers and observer-based architectures are highly effective in enhancing tracking accuracy and meeting preset performance requirements [2]. These observer-based systems are robust to variation and thus enable a more seamless and secure robotic assistance process when dealing with stroke patients whose motor cues are irregular or unpredictable. The control strategies should also fit mechanical actuator capabilities and biological limits of human joints. This has been addressed through the introduction of neuro-adaptive command-filtered backstepping control, which is suggested for systems where inputs are saturated and joints are flexible, as in exoskeleton design [3]. In this strategy, joint stability is maintained even when compliance and saturation occur by filtering command signals with neural networks and real-time adaptation to guarantee user safety and system responsiveness.

3. EEG Signal Integration for Intelligent Control

Its application to wearable robotic systems through EEG signals represents a paradigm shift in neurorehabilitation, with the potential for direct brain–machine interfacing. EEG is a non-invasive method for studying user intention in motor behavior, as well as cognitive states, and it contributes significantly to adaptive control systems. A decision-making system using hybrid EEG/EMG has been implemented in hand exoskeletons and has demonstrated increased accuracy in executing movements by decoding user intent in real time [4]. This multimodality enables more accurate decoding of user commands, especially when muscular cues are insufficient due to paresis or fatigue. Real-time signal processing is critical in such systems. EEG signals must be decoded in the shortest time possible and translated into control signals that can be interpreted as useful commands for exoskeleton control. To this end, effective algorithms have been developed to extract features from EEG signals and map them to robotic actuation with minimal latency. Such decision-making models allow the exoskeleton to respond not only to voluntary movement efforts but also to attempted movements, and they can be applied in earlier rehabilitation stages where the exoskeleton may not have explicit motor control. Immersive environments and neurofeedback have also been found to enhance the effectiveness of BCI-based rehabilitation. Environmental stimuli can be manipulated using virtual reality (VR) systems to offer real-time feedback on the mental state of the user, thereby enabling engagement and performance [5]. Such environments are helpful in adaptive therapy due to the correlation between neurofeedback and robotic control, which is responsive to the neuro-cognitive reactions of the patient. This advanced VR-, EEG-, and robotics-based feedback loop improves brain–muscle relationships that are essential for recovery. The adaptive control laws of EEG-integrated systems must be developed in a practical manner, meaning they must regulate output limits while remaining resilient to uncertainties related to the user and the environment. Adaptive tracking controllers capable of addressing such uncertainties have been applied in unmanned aerial vehicles and are now being explored for wearable robotics [6]. Stroke rehabilitation requires safe human–robot interaction, which is determined by the system's ability to constrain outputs within physiological and mechanical limits.

4. Leader-Follower Architectures and Cooperative Neuro-Adaptive Models

More recent neuro-adaptive models are increasingly based on leader–follower structures, with the robotic system (follower) replicating or assisting the movement intentions of the human operator (leader). This has been enabled by non-parametric neuro-adaptive models that do not require prior specification of dynamic models [7]. Under such strategies, the exoskeleton can learn from user actions and dynamically adapt support on a model-free basis. The benefit of this approach is scalability, as it does not require substantial pre-training, which is advantageous in clinical use where patient conditions are highly diverse. These models have been shown to be useful in formation control problems among multi-agent systems and are now being extended to human–robot dyads. Subtle support can be facilitated using the leader–follower paradigm, in which the robot selectively corrects deviations without removing user autonomy. This balance is particularly important in stroke rehabilitation, where volitional control plays a key role in neuroplasticity. This framework has been further enhanced by the inclusion of asymptotic neuro-adaptive consensus control models, in which all agents (robotic limbs) tend toward the behavior of the leader over time, even when system topology varies [8]. These models are especially useful in scenarios involving multi-joint or full-body exoskeletons, where coordination across multiple degrees of freedom is required. In such systems, synchronized limb actions ensure biomechanical efficiency and therapeutic effectiveness.

5. Role of Wearable Robotics in Neurological Rehabilitation

Robotic actuation and the neuromuscular system are closely connected in wearable exoskeletons, which represent a link between biological motion and robotic assistance. Lightweight materials, soft actuation, and smart control systems have played a significant role in the advancement of neurological rehabilitation. These robots enable repetitive and accurate movement, which is extremely important for motor recovery following stroke. Additionally, they facilitate continuity of care by enabling treatment in non-traditional healthcare settings. The integration of artificial intelligence with haptic feedback to improve user interaction and engagement should be noted as one of the most important characteristics of wearable systems, as recent research suggests [9]. AI-controlled exoskeletons can learn user-specific gait patterns, modify levels of assistance, and detect fatigue or distraction. These systems are capable of integrating sensory information with adaptive algorithms to produce a customized rehabilitation experience. Haptic feedback completes the sensorimotor loop by providing immediate tactile feedback, which is essential for relearning motor skills. The structural design of an exoskeleton strongly influences its therapeutic effectiveness. Cable-driven systems have emerged as a promising alternative to rigid-link designs due to their compliance, light weight, and reduced risk of harmful contact with the user. Cable-driven ankle exoskeletons have shown promising results in pediatric rehabilitation and can be extended to stroke rehabilitation systems [10]. These systems apply actuation forces from remotely located motors using Bowden cables to minimize on-body weight and maximize comfort.

Table 1 Comparison of Exoskeleton Control Approaches in Rehabilitation Contexts

Control Approach	Signal Input Type	Adaptability	Suitability for Stroke Rehabilitation	Key Advantages
Velocity-Free Neuro-Adaptive Control	Internal States	High	High	Eliminates need for velocity sensors
Neural Optimization with Observers	EEG/Noisy Data	High	High	Robust to noise and modeling errors
Command-Filtered Backstepping	EEG/EMG	Medium	Medium	Handles input saturation

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Leader-Follower Adaptive Control	EEG	High	High	Mimics user intention accurately
Consensus-Based Neuro-Adaptive Control	EEG/EMG	Very High	High	Ensures synchronization across joints/limbs

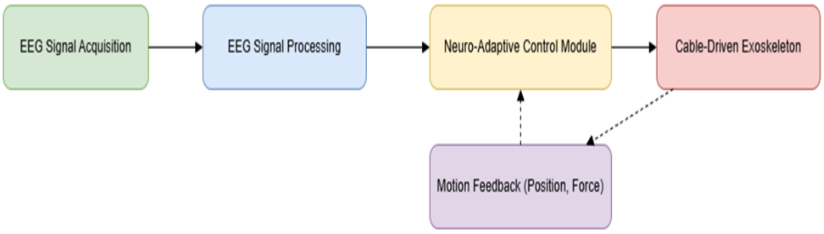

Figure 1 Schematic Diagram of EEG-Controlled Cable-Driven Exoskeleton System

This diagram illustrates the integration of EEG signal acquisition, processing, and real-time control of a cable-driven exoskeleton used in stroke rehabilitation. It demonstrates the loop from brain signal detection to robotic actuation.

6. Performance Evaluation and Adaptation in Neuro-Adaptive Systems

A multi-layered analysis that accounts for physiological parameters, biomechanical measures, and system responsiveness is essential for evaluating the performance of neuro-adaptive exoskeleton systems. Common measures of control strategy effectiveness include joint trajectory tracking error, user cognitive load, and movement smoothness. Neuro-based controllers are dynamic, allowing the system to adjust these parameters in real time, which is critical when rehabilitation requirements vary among stroke patients. Neuro-adaptive architecture-based control systems, particularly those involving EEG feedback, must remain stable under non-stationary and often unpredictable conditions. These challenges are amplified in wearable robotics, as muscle tone, involuntary movements, and fatigue vary across users, especially during extended rehabilitation sessions. These issues can be effectively addressed through real-time observer-based control, which enables estimation of unknown states and mitigation of errors introduced by noisy inputs [2]. System flexibility is central to controller effectiveness. Adaptive controllers must be recalibrated without complete retraining cycles to ensure that rehabilitation protocols evolve as the patient progresses. This adaptability allows the therapeutic focus to shift toward fine motor practice during later recovery stages. A neuro-adaptive exoskeleton is therapeutically effective because it can self-regulate its control parameters. The integration of cable-driven systems further enhances robotic flexibility. Rather than relying on rigid structures, these systems distribute forces through elastic cables, enabling more natural and smooth motion assistance. In addition, system safety is improved by reducing the risk of injury from overextension or misalignment. Such systems incorporate feedback control mechanisms that continuously monitor cable tension, which is regulated by intention signals derived from EEG data [10]. Latency is another critical performance factor. The delay between detected user intention (via EEG) and exoskeleton movement should be as short as possible to ensure effective human–machine interaction. Delays exceeding several hundred milliseconds may interfere with motor learning and become disruptive to users. Improvements in signal processing algorithms, such as adaptive filtering and real-time artifact removal, have enabled response times below 100 ms, which is clinically acceptable for rehabilitation systems [4]. Longitudinal data

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collection and analysis are necessary to evaluate system performance over time. User engagement can be assessed by tracking motor improvement, system adaptation, and real-time performance indices. These data can be used to individualize training programs and adjust difficulty levels, thereby enhancing patient motivation. Intelligent rehabilitation robotics can be realized through systems that learn from past performance trends and predict future rehabilitation needs.

7. Comparative Insights and Limitations

When comparing different neuro-adaptive control strategies, several important differences can be identified. Velocity-free control systems are particularly useful when direct velocity measurements are required but are either noisy or impossible to obtain. Slow or spasmodic motion in low-mobility stroke patients renders velocity readings unreliable. Consequently, velocity-independent control mechanisms offer a more stable alternative to conventional control systems [1]. Observer-based and command-filtered models are effective when dealing with signal saturation and noise but may be less responsive in rapidly changing environments unless continuously supplied with real-time feedback. This represents a trade-off between robustness and responsiveness that must be considered in relation to the rehabilitation phase. Observer-based models are especially effective in early-stage therapy, when patient output is minimal and highly non-deterministic. In contrast, model-free adaptive techniques may be more suitable during later stages, when dynamic interaction and rapid adaptation are required. Similarly, leader–follower and consensus-based architectures can be scaled to multi-joint coordination, but this often comes at a substantial computational cost. While these techniques are highly effective, they can present challenges in the design of lightweight wearable systems. System development must therefore balance computational complexity, power consumption, and mechanical simplicity [7][8]. Despite their advantages, EEG-based systems also have limitations. One major challenge is the quality and consistency of EEG signals, which are vulnerable to muscle activity (EMG), eye movements, and external electromagnetic interference. Additionally, EEG interpretation varies among individuals due to differences in brain morphology and electrode placement. These challenges require personalized calibration and adaptive algorithms to counter signal degradation [4]. Another concern is user fatigue and cognitive load. BCI-controlled exoskeleton systems can be mentally demanding, particularly when motor imagery-based control is used. Sustained mental effort may lead to cognitive fatigue, reducing performance and learning effectiveness over time. Therefore, such systems should monitor cognitive states and provide appropriate rest periods when needed [5].

8. Future Directions and Research Gaps

Multimodal sensing, artificial intelligence, and personalized therapy programs are expected to be further integrated into neuro-adaptive wearable robotics in the future. EEG can be used in conjunction with other biosignals, such as electromyography (EMG), galvanic skin response (GSR), and heart rate variability (HRV), to provide a more comprehensive picture of the user's physiological and emotional state. These multimodal systems are likely to improve interaction efficiency and enhance user engagement, which is critical for the success of long-term rehabilitation programs. Artificial intelligence has the potential to enhance control strategies through reinforcement learning and deep neural networks. These algorithms may enable systems to identify optimal control policies based on accumulated experience rather than predefined rules. Such systems could automatically determine appropriate assistance strategies, therapy dosage, and feedback timing, even in real-world clinical environments. In addition, exoskeletons may serve as diagnostic tools by detecting neuromuscular impairments through deviations from expected performance patterns. Another potential future direction involves the development of fully soft exosuits using textile-based actuators and sensors. These systems may offer improved comfort and flexibility, which are particularly important for prolonged use. Soft systems may allow more natural movement while maintaining effective EEG

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regulation, especially for distal joints such as the ankle and wrist, which are critical for mobility and dexterity. These technologies have not yet been clinically validated through large-scale randomized controlled trials. Most existing studies are limited to pilot investigations or laboratory-based evaluations. Future research should involve larger and more heterogeneous patient populations, accounting for variations in stroke severity and comorbid conditions. Additionally, standardized outcome measures and long-term follow-up studies are required to assess the sustained effectiveness of these systems.

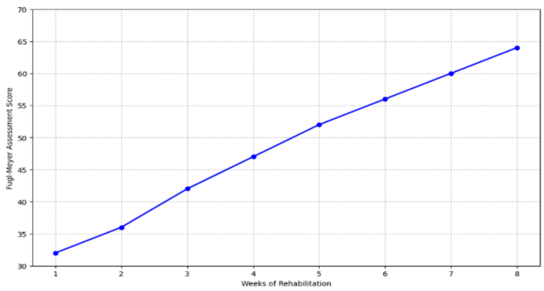

Figure 2 Graph – Improvement in Motor Function Over Time Using EEG-Controlled Exoskeleton

The graph shows the enhancement of patient motor functioning (using Fugl-Meyer Assessment scores) under 8 weeks of rehabilitation using a neuro-adaptive EEG-controlled cable-driven exoskeleton.

Conclusion

Neuro-adaptive feedback control represents a significant advancement in stroke recovery through wearable robotics. Exoskeletons are now capable of interpreting user intention and dynamically adjusting assistance levels by incorporating EEG signals alongside intelligent control systems. This personalized approach not only improves motor recovery but also enhances user engagement and independence. Leader–follower models, cable-driven actuation, and observer-based adaptation provide feasible, responsive, and scalable solutions to the challenge of restoring function after stroke. Although challenges related to signal reliability, computational load, and clinical validation remain, the convergence of neuroscience, robotics, and artificial intelligence suggests a future in which adaptive rehabilitation technologies become more accessible, effective, and patient-centered.

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