Medicinska istraživanja 2026 | DOI: 10.5937/medi0-62154

OPEN ACCESS

Medical Research | Published by Faculty of Medicine University of Belgrade

ORIGINAL ARTICLE

The use of hybrid systems in neurorehabilitation: A narrative review

Olivera Djordjevic[1,2], Ana Radic[1], Aleksandra Vidakovic[1,2], Sindi Mitrovic[1,2], Suzana Dedijer Dujovic[1,2], Tijana Dimkic Tomic[1,2], Ljubica Konstantinovic[1,2]

[1] Rehabilitation Clinic "Dr Miroslav Zotovic", Neurorehabilitation Department, Belgrade, Serbia

[2] University of Belgrade, Faculty of Medicine, Belgrade, Serbia

Submitted: 14 October 2025

Revised: 04 March 2026

Accepted: 06 March 2026

Online First: 11 March 2026

Check for updates

Correspondence to:
Olivera Djordjevic

Rehabilitation Clinic "Dr Miroslav Zotovic", Neurorehabilitation Department

13 Sokobanjska Street, Belgrade, Serbia

Email: olivera.djordjevic@med.bg.ac.rs

Summary

The use of hybrid systems in neurorehabilitation represents a significant advancement in the field, integrating multiple technological and therapeutic approaches to enhance recovery outcomes for patients with neurological impairments. Recent technological advancements have given rise to hybrid neurorehabilitation systems – integrative platforms that combine biological signals with artificial intelligence to deliver more effective, personalized rehabilitation. This multifaceted approach addresses the complex nature of neural damage and plasticity, offering personalized and adaptive rehabilitation protocols. Hybrid systems in neurorehabilitation commonly integrate modalities such as brain-computer interfaces, robotics, functional electrical stimulation and virtual reality. These systems leverage multimodal sensory feedback and advanced control algorithms to promote neuroplasticity, functional reorganization, and motor relearning by actively involving the patient's neural and muscular activity in real-time therapeutic interventions. Clinical studies have demonstrated that hybrid systems can improve motor functions in stroke survivors, spinal cord injury patients, and individuals with neurodegenerative diseases more effectively than conventional rehabilitation alone. These systems offer quantifiable performance metrics, allowing clinicians to tailor interventions and monitor progress objectively.

Furthermore, the technology enables intensive, repetitive, and task-specific practice, which are critical factors in neural recovery. Overall, hybrid systems in neurorehabilitation exemplify the convergence of neuroscience, engineering, and clinical therapy, resulting in innovative solutions that maximize functional recovery. Future developments will likely focus on increasing system accessibility, optimizing user interfaces, and integrating machine learning algorithms to refine adaptive rehabilitation strategies further.

Keywords: hybrid systems, brain-computer interface, functional electrical stimulation, robotics, virtual reality

Cite this article as: Djordjevic O , Radic A, Vidakovic A, Mitrovic S, Dedijer Dujovic S, Dimkic Tomic T et al. The use of hybrid systems in neurorehabilitation: A narrative review; Medicinska istraživanja 2026; DOI: 10.5937/medi0-62154

INTRODUCTION

Neurorehabilitation is a rapidly evolving field aiming to restore and enhance motor and functional abilities in individuals affected by neurological conditions such as stroke, spinal cord injury, and other motor impairments. Traditional rehabilitation approaches, while effective to some extent, often face limitations in terms of patient engagement, intensity, and adaptability to individual needs. Recently, hybrid systems that integrate multiple advanced technologies have emerged as a promising frontier in neurorehabilitation. Hybrid systems refer to integrated technological frameworks that synergistically combine at least two modalities, such as brain-computer interface (BCI), robotics, functional electrical stimulation (FES), and virtual reality (VR), or advanced BCIs employing multiple EEG-based biosignals. Hybrid neurorehabilitation systems leverage the complementary strengths of different technologies to maximize patient outcomes. For example, the integration of brain-computer interfaces further enhances these systems by allowing patients to actively initiate and control rehabilitation exercises even with impaired voluntary motor control (1). The combination of robotic exoskeletons or end-effector devices with FES enables active muscle engagement and functional movement restoration, which surpasses passive movement guidance (2). This multimodal approach supports neuroplasticity and motor (re)learning, which are critical for meaningful recovery (3-5).

The clinical goal of hybrid systems is to provide personalized, adaptive therapy that evolves according to the patient's residual motor function and progress throughout rehabilitation. Such systems aim to improve not only the speed but also the quality and durability of recovery. Hybrid systems have been applied in upper and lower limb rehabilitation, particularly after stroke and spinal cord injury, showing promising improvements in motor function and patient outcomes (1-4). As research and technology continue to advance, hybrid neurorehabilitation devices offer new hope for restoring independence and quality of life in patients with neurological impairments.

This narrative review aims to present a comprehensive overview of the current state of hybrid neurorehabilitation systems, discussing their components, mechanisms, therapeutic targets, and clinical efficacy. Additionally, it highlights ongoing challenges and future directions in the development and implementation of these innovative neurorehabilitation solutions. It also sets the context for understanding how hybrid systems are transforming neurorehabilitation by combining biological and artificial elements to overcome the limitations of conventional therapies.

METHODS

A systematic literature search was conducted across multiple electronic databases: PubMed Central (PMC), PubMed, and Google Scholar to identify relevant peer-reviewed articles and reviews published from January 2014 to October 2025. The search strategy employed combinations of key terms including "neurorehabilitation," "hybrid systems," "brain-computer interface," "functional electrical stimulation," "robotics," "virtual reality," "closed-loop," "telerehabilitation," and "motor recovery."

Inclusion criteria encompassed English-language studies and reviews focusing on hybrid neurorehabilitation interventions integrating two or more assistive modalities aimed at neurological function restoration in humans or relevant animal models. Studies addressing single-mode therapies or non-hybrid systems were excluded. Screening based on titles, abstracts, and full texts enabled the identification of pertinent works. Data were synthesized qualitatively into thematic sections concerning different hybrid modalities, mechanisms, clinical outcomes, and implementation challenges.

HYBRID BRAIN-COMPUTER INTERFACE (BCI) SYSTEMS IN NEUROREHABILITATION

Brain-Computer Interfaces (BCIs) are systems that enable direct communication between the brain and external devices, bypassing impaired neural circuits. They decode brain signals obtained via electroencephalography (EEG) or invasive recording techniques, such as electrocorticography (ECoG), to control neuroprosthetics, robotics, or functional electrical stimulation (FES) systems. Though BCIs have evolved greatly since their inception in the 1960s, single-modality BCIs, especially EEG-based, face significant challenges including low signal-to-noise ratio, susceptibility to artifacts, and limited degrees of freedom.

Rationale for Hybrid BCIs

To overcome these limitations, hybrid BCIs (hBCIs) synergize multiple biosignals and input modalities, such as combining EEG and electromyography (EMG), or pairing motor imagery (MI) with steady-state visually evoked potentials (SSVEPs). This multimodal approach enhances classification accuracy, signal reliability, and operational bandwidth, enabling more precise and versatile neuro-controlled devices (6-9). For example, McGeady et al. (6) implemented a hybrid MI-SSVEP BCI. They reported classification accuracies of 77.3 ± 8.2% for three right upper limb movements (palmar grasp, pinch grip, and elbow flexion), 94.4 ± 3.5% for SSVEP, and 80.9 ± 8.1% for MI. The hybrid system reports distinct SSVEP and MI accuracies because it evaluates each component separately, with overall success (77.3%) only when both align correctly. The system processed MI using common spatial patterns and linear discriminant analysis, while SSVEP used canonical correlation analysis for frequency detection from flickering stimuli. Classification Accuracies Obtained Accuracies, SSVEP at 94.4±3.5% and MI at 80.9±8.1%, stemmed from online closed-loop trials where participants executed hybrid tasks. SSVEP detection targeted specific stimulus frequencies, while MI focused on motor execution patterns in mu/beta rhythms; leave-one-trial-out cross-validation on per-trial EEG data yielded these independent modality rates.

Clinical Applications and Efficacy

Recent research underscores the efficacy of hBCI-based neurorehabilitation for motor function recovery after stroke, spinal cord injury, and other neurological diseases (10). Clinical trials demonstrate that hBCI systems integrated with FES or robotic assistance facilitate voluntary motor activation, improve range of motion, hand dexterity, and reduce spasticity (11,12).

A meta-analysis of randomized controlled trials involving 258 stroke patients found that BCI-assisted rehabilitation resulted in significant functional improvements in upper-limb motor scores compared with conventional therapy (13). Similarly, for spinal cord injury, BCIs have been applied to restore hand grasp and walking functions, often augmented by hybrid systems combining BCIs with FES (14,15).

Integrating BCIs with VR environments further enriches therapy by providing immersive feedback, enhancing patient motivation, and cognitive engagement. Hybrid approaches combining MI, action observation, and SSVEP have been shown to improve motor imagery vividness and promote sensorimotor cortex activation beyond single-modality BCIs (16).

Technological Developments

Artificial intelligence (AI) algorithms are increasingly employed in hBCI systems to optimize the translation of brain signals into control commands. For instance, Xavier Fidêncio et al. (17) introduced an adaptive error-related potential-based hBCI system using reinforcement learning to adjust BCI decoding parameters and enhance signal robustness dynamically. AI techniques enable hBCIs to compensate for neural signal variability, reduce recalibration needs, and adapt to individual EEG patterns in real-time interactive tasks. Portable and wearable hBCI platforms are under development for home-based and telerehabilitation applications, increasing therapy frequency and accessibility. However, deploying these systems remotely poses challenges in safety monitoring, user compliance, and data security, necessitating robust solutions before mainstream adoption (18).

Challenges and Limitations

Despite significant progress, hBCIs face notable obstacles restricting widespread clinical use. These include:

- Signal acquisition and processing complexity: Noise, artifacts, and inter-subject variability challenge the reliability of signal detection.
- User training and fatigue: BCI operation requires patient concentration and learning, which can lead to fatigue.
- Device usability: Wearable sensors and interface components must balance signal quality with patient comfort and convenience.
- Standardization: Lack of unified protocols complicates comparison and clinical translation.
- Cost and infrastructure: High costs and needs for specialized personnel limit availability.

Addressing these challenges will be crucial for advancing hBCI systems beyond specialized research settings.

Future Directions

Future work in hBCIs should focus on:

- Multimodal signal integration: Leveraging additional biosignals (e.g., those obtained by photoplethysmography, by eye tracking) to increase reliability.
- AI-driven adaptation: Enhancing continuous, automatic model updating and fatigue detection.
- Hybrid interfaces: Combining BCIs with emerging feedback modalities such as augmented reality (AR) and haptics.
- Clinical validation: Conducting large multi-center randomized controlled trials to establish efficacy and cost-effectiveness.
- User-centric design: Developing intuitive, minimally invasive, and portable systems suitable for daily-life use.

Such advances will progressively realize the goal of practical, home-based hBCI neurorehabilitation solutions with broad clinical impact.

Summary

Hybrid BCIs represent a paradigm shift in neurorehabilitation by integrating multimodal neural and physiological signals with adaptive AI-based processing to enable patient-driven, closed-loop control of assistive devices. They offer significant potential to enhance motor recovery and quality of life in neurological populations but require ongoing innovation to address technical, usability, and clinical integration challenges.

HYBRID ROBOTIC SYSTEMS IN NEUROREHABILITATION

Overview and Rationale

Robotic-assisted rehabilitation has transformed the landscape of neurorehabilitation by providing precise, repetitive, and task-specific motor training essential for promoting neuroplasticity and functional recovery. However, traditional robotic systems typically operate in an open-loop manner, providing fixed assistance patterns without dynamically adapting to the patient's voluntary efforts or current motor state.

Hybrid robotic systems address this limitation by integrating robotics with physiological signal inputs such as electromyography and brain-computer interfaces. This integrative approach enables closed-loop control, modulating robotic assistance in real time based on the user's motor intent, effort level, and fatigue, thereby facilitating active participation and personalized training intensity.

System Architectures and Modalities

Hybrid robotic systems commonly use exoskeletons or end-effector devices for upper- or lower-limb rehabilitation, paired with biosignal acquisition modules. EMG-controlled exoskeletons detect muscle activation signals to tailor assistance, encouraging volitional effort while supporting movement execution. BCIs integrated into robotic systems utilize decoded brain signals to command robotic actuators directly, closing the loop between cortical intent and limb movement.

An example is an AI-driven dual-arm robotic platform combined with EMG-guided neuromuscular electrical stimulation, which adaptively assists upper-limb movements while stimulating weakened muscles. This synergy has been demonstrated to improve joint range of motion, muscle torque, and reduce spasticity in chronic stroke patients (19).

For lower limb recovery, robotic gait trainers combined with functional electrical stimulation and EMG feedback have shown promise in enhancing walking speed, gait symmetry, and endurance in stroke and spinal cord injury populations). The EMG/sensory feedback is directed toward the robotic device for closed-loop control. Closed-loop control allows adaptive modulation of robotic forces and stimulation timing based on patient effort and sensory feedback, leading to better neuroplastic outcomes compared to passive gait training (1). EMG feedback and sensory feedback serve as inputs that enable the robot to adaptively modulate its forces and stimulation timing based on the patient's effort levels.

Clinical Evidence

Multiple randomized controlled trials suggest that hybrid robotic-assisted neurorehabilitation can offer advantages over conventional therapies on selected outcomes. For instance, a meta-analysis by Höhler et al. (3) reported significant gains in upper-limb motor scores when robotics was combined with EMG or BCI feedback compared with conventional physical therapy alone. Patients also demonstrated better capacity for independent functional tasks and reduced muscle spasticity.

A recent multicenter study found that hybrid BCI-robotic systems improved motor recovery and cortical reorganization in patients with hemiparetic stroke, attributing this success to enhanced sensorimotor coupling and repetitive volitional engagement (20). Additionally, hybrid neuroprosthesis systems combining robotics with FES have been clinically effective in restoring hand grasp and gait patterns, especially when closed-loop control algorithms adapt stimulation intensity based on user feedback (3,4).

Technological Challenges and Innovations

Despite efficacy, several technical and practical challenges must be addressed for wider clinical acceptance:

- Device Portability and Comfort: Many hybrid robotic devices remain bulky, hindering naturalistic movement and limiting use outside specialized centers.
- Signal Acquisition Reliability: Surface EMG and non-invasive BCI signals can be noisy, requiring advanced filtering and calibration.
- User Training Burden: Initial system setup and user training require substantial time and expert supervision.
- Cost and Accessibility: High procurement and maintenance costs restrict availability, especially in low-resource settings.

Emerging solutions emphasize AI-driven adaptive assistance that continuously learns and predicts patient needs. Integration with wearable biosensors, wireless data transmission, and lightweight exoskeleton materials are priorities to enhance usability and the feasibility of home-based training.

Furthermore, user-centered design approaches that incorporate input from patients and clinicians accelerate translation and enhance technology acceptance.

Summary

Hybrid robotic neurorehabilitation systems represent a critical evolution in motor recovery paradigms by integrating biosignal-driven, closed-loop control of robotic devices. Clinical evidence supports their superiority in promoting neuroplasticity, enhancing motor function, and improving patient engagement compared to traditional therapies. Addressing current limitations through technological innovation and accessibility initiatives is essential to realize their therapeutic promise fully.

HYBRID FUNCTIONAL ELECTRICAL STIMULATION SYSTEMS IN NEUROREHABILITATION

Functional electrical stimulation involves the application of electrical currents to activate muscles artificially, facilitating movements in paralyzed or weakened limbs. This technology has been effectively used to restore gait, grasp, and postural control in patients recovering from stroke, spinal cord injuries, and other neurological disorders (21). Traditional FES systems are often open-loop and manually controlled, limiting their ability to adapt to patient-specific neural activity and engagement.

Concept and Design of Hybrid FES Systems

Hybrid FES systems operate within a closed-loop framework by integrating additional biosignals, such as electroencephalography (via BCI), electromyography, and/or robotic assistance, facilitating real-time adaptation to the patient's intention and physiological state. Such integration maximizes therapeutic efficiency by coupling cortical motor commands with peripheral muscle stimulation and biomechanical support.

Khan et al. (22) provided a comprehensive systematic review highlighting advances in FES-based rehabilitation, classifying systems as either open-loop (manual) or closed-loop controlled by BCIs or EMG signals. Closed-loop BCI-FES systems interpret motor imagery-related EEG signals, triggering and adjusting stimulation patterns to facilitate targeted movement execution and enhance motor cortex engagement. The incorporation of virtual reality (VR) environments further supports cortical activation and motivation by guiding patients through interactive, visually enriched therapy sessions (Figure 3 in their review).

Clinical Efficacy

Clinical evidence confirms the positive impact of hybrid BCI-FES systems on motor function recovery post-stroke. Meta-analyses report significant improvements in Fugl-Meyer Assessment scores and Action Research Arm Test outcomes compared to conventional therapy or FES alone. (22-24). These systems promote Hebbian plasticity by synchronizing cortical activity with voluntary muscle contraction (Hebb's principle: "cells that fire together wire together"), fostering stronger corticospinal connections and more functional motor patterns.

Recent randomized controlled trials demonstrate improvements in hand function, gait parameters, and spasticity following BCI-FES. Hybrid FES systems facilitate prolonged and repetitive training by intelligently modulating stimulation parameters based on continuous biosignal feedback, as shown by Dalla Gasperina et al. (25), who developed a cooperative control system that distributed torque between robotics and FES to optimize muscle fatigue resistance and motor performance.

Technological Advances

Hybrid FES systems employ sophisticated control algorithms, including iterative learning control, adaptive feedback controllers, and AI-based classifiers to fine-tune stimulation intensity and timing (19). These controls help maintain optimal muscle activation, prevent fatigue, and enhance functional movement patterns. The integration with robotic devices enables synergistic support: robotics provides structural assistance, and FES activates musculature, enabling naturalistic and effective rehabilitative movements.

Innovations also focus on user-friendly electrode arrays, wireless stimulation devices, and wearable multi-channel stimulators to increase comfort and expand out-of-clinic therapy options. Coupling FES with BCIs and VR environments further enriches the sensory and cognitive aspects of rehabilitation, driving motivation and engagement.

Challenges and Future Directions

Although hybrid FES systems markedly improve neurorehabilitation outcomes, challenges include:

- Calibration complexity and variability in electrode placement.
- Managing discomfort or involuntary contractions.
- Integration hurdles for robust, portable, and affordable home-use systems.
- Need for long-term clinical trials to quantify the durability of improvements.

Future research aims to enhance closed-loop controller precision, develop adaptive AI techniques for real-time fatigue detection, and expand telerehabilitation applications. Combining multimodally acquired signals from different phases of movement initiation or execution with sensor fusion and personalized therapy protocols remains crucial.

Summary

Hybrid FES systems integrating real-time neural intentions, robotic support, and closed-loop adaptive controllers provide significant therapeutic benefits in neurorehabilitation. They enhance volitional control, foster neural plasticity, and improve sustained motor function recovery in neurological disorders.

HYBRID VIRTUAL REALITY SYSTEMS IN NEUROREHABILITATION

Overview and Rationale

Virtual reality (VR) technology has transformed from a speculative tool into a clinically validated modality for neurorehabilitation. VR offers immersive, interactive, and task-oriented environments that simulate real-world activities, providing multisensory feedback to patients and enhancing their motivation and engagement. When integrated into hybrid neurorehabilitation systems, VR complements other assistive technologies, such as BCIs, robotics, and FES, creating enriched therapeutic interventions that engage neural circuits more effectively and promote neuroplasticity.

VR facilitates intensive, repetitive motor practice within a safe and controlled virtual environment. Its potential to deliver task-specific training tailored to the patient's level of function and to adapt dynamically responder profiles has attracted broad research and clinical interest.

Components of Hybrid VR Systems

Hybrid neurorehabilitation involving VR typically couples immersive VR environments with biosignal-driven control from BCIs, EMG, or robotic interfaces. These systems enable patients to perform virtual tasks guided by motor intention or assistance, facilitating sensorimotor integration, error-based learning, and cognitive engagement.

For instance, the HYPER project (5) developed an integrated hybrid platform combining robotics, motor neuroprostheses, and virtual reality to promote motor function restoration in stroke and spinal cord injury patients. This system uses multimodal sensors (EEG, EMG, tactile feedback). It integrates a brain-neural-machine interface with VR to provide enhanced cognitive and physical interaction, aiming at personalized and progressive therapy. Multimodal sensors, including tactile feedback alongside EEG and EMG, capture patient data to drive the brain-neural-machine interface. This enables real-time monitoring of patient motor intent and physical responses during therapy. The system uses this sensory input to deliver enhanced sensory cues back to the patient via neuroprosthetics and VR, fostering cognitive-physical interaction and motor restoration. Robot control adapts to patient signals, but tactile elements primarily reinforce patient proprioception and plasticity.

VR-based mirror therapy is another application leveraging the mirror neuron system: reflecting movements of an unimpaired limb in VR "tricks" the brain into activating motor pathways on the affected side. Visual feedback in VR drives cortical reorganization, promoting recovery, especially after stroke (26).

Clinical Evidence

Recent clinical studies and systematic reviews have demonstrated significant functional improvements using hybrid VR neurorehabilitation systems. Meta-analyses show that VR-hybrid interventions enhance upper and lower limb motor skills post-stroke, multiple sclerosis, and other neurological conditions, with measurable changes in Fugl-Meyer Assessment scores, balance metrics, gait kinematics, and daily-living activities.

A 2025 meta-analysis of 27 randomized controlled trials (1156 participants) found that hybrid VR combined with conventional therapy significantly improves motor function and manual dexterity after stroke, with sustained benefits over time, supporting motor skill improvements in the upper limbs (27).

In addition to motor recovery, VR-based hybrids improve cognitive function, attention, and psychological well-being by providing engaging, motivating environments that encourage active participation and reduce therapy dropout rates. (28,29).

Randomised control trials integrating VR with BCI and robotics report superior outcomes, driven by the closed-loop feedback loop, which enhances motor learning and cortical plasticity. In closed-loop systems combining VR, BCI, and robotics for rehabilitation, the feedback is directed to both patients and technology. Patient-directed feedback includes sensory cues (e.g., tactile, visual via VR, neuroprosthetic stimulation) that reinforce motor intent, enhance proprioception, and promote cortical plasticity/motor learning. Technology-directed feedback uses patient signals (EEG, EMG) to adapt robot control and VR scenarios in real-time, creating the adaptive loop.

VR's adaptability for remote and home-based rehabilitation also supports telerehabilitation efforts, broadening therapeutic reach and frequency.

Technological Advances and Innovations

Advancements focus on creating more immersive, multisensory VR environments using head-mounted displays, haptic feedback devices, and real-time integration of biomechanical and neural data for more naturalistic interaction. AI-driven personalization algorithms tailor task difficulty and feedback based on patient progress and fatigue.

Hybrid VR systems increasingly feature tri-manual interaction capabilities and combined BCI-VR platforms that enhance real-time feedback, improving rehabilitation quality and engagement (30).

Challenges and Future Perspectives

Despite robust potential, challenges impede seamless integration of VR into hybrid systems, including:

- High costs of advanced VR hardware and integration components.

- User discomfort issues, such as cybersickness and fatigue, occur during prolonged VR exposure.
- Necessity of intuitive interfaces that cater to patients with cognitive and sensory impairments.
- Requirement for standardized protocols and outcome measures to evaluate efficacy.
- Ensuring accessibility and equity in remote or resource-limited settings.

Future research should emphasize cost-effective system development, improved user ergonomics, and large-scale longitudinal studies of the durability of VR hybrid therapy. Integration with AI will refine adaptive algorithms, enhancing therapy personalization.

Summary

Hybrid virtual reality neurorehabilitation systems combine immersive, engaging environments with biosignal and robotic control to enrich motor and cognitive therapy. Evidence supports their benefits in enhancing neuroplasticity, functional recovery, and patient motivation, making them an indispensable component of modern neurorehabilitation.

CONCLUSION

The field of neurorehabilitation is rapidly evolving as hybrid systems integrate robotics, functional electrical stimulation, brain-computer interfaces, and virtual reality. Such multimodal systems offer the potential to deliver precisely targeted, engaging, and effective therapy by combining neural decoding, muscle activation, mechanical assistance, and sensory feedback into a unified rehabilitation platform.

Although promising clinical evidence supports the benefits of hybrid technologies in motor recovery, their translation into widespread clinical practice faces technical, cost, and usability challenges. Future directions include developing more compact, user-friendly systems with adaptive control, enhanced sensor fusion, and real-time neurofeedback. Integration of artificial intelligence to personalize therapy and long-term monitoring through wearable solutions may further enhance effectiveness.

In summary, hybrid systems represent an innovative frontier in neurorehabilitation, offering new opportunities to restore function and independence in patients with neurological disabilities. Continued interdisciplinary collaboration between clinicians, engineers, neuroscientists, and patients will be essential to realize their full potential in improving rehabilitation outcomes.

Acknowledgment: N/A

Funding Information: The authors declare that the study received no funding

Conflicts of interest: The authors have no conflicts of interest to report

Author Contributions: All the authors made a substantial contribution to the conception and design of the work, drafting the work or reviewing it critically for important intellectual content, made final approval of the version to be published, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. **Specific authors' contribution:** Conceptualization, ODj, AR, AV, SM, SDD, TDT, LJK; Methodology, ODj, AR, AV, SM, SDD, TDT, LJ.; Writing: ODj,; Review & Editing, ODj, AR, AV, SM, SDD, TDT Supervision, LjK

Ethical approval: N/A

Informed consent: N/A

References

1. Leerskov KS, Spaich EG, Jochumsen MR, Andreasen Struijk LNS. Design and Demonstration of a Hybrid FES-BCI-Based Robotic Neurorehabilitation System for Lower Limbs. Sensors (Basel). 2025;25(15):4571. doi: 10.3390/s25154571
2. Leerskov K. Hybrid FES-Robotic Rehabilitation System for Lower Limb Neurorehabilitation: Design and evaluation. Aalborg University Open Publishing, 2024. doi: 10.54337/aau768141147
3. Höhler C, Trigili E, Astarita D, Hermsdörfer J, Jahn K, Krewer C. The efficacy of hybrid neuroprostheses in the rehabilitation of upper limb impairment after stroke, a narrative and systematic review with a meta-analysis. Artif Organs. 2024 ;48(3):232-253. doi: 10.1111/aor.14618.
4. Dell'Eva F, Guanziroli E, Camerini V, Gandolla M, Brignole L, Maludrottu S, et al. A multifaceted hybrid ES-robotic device for gait training in individuals with neurological disorders. Nat Commun. 2025 ;16(1):8510. doi: 10.1038/s41467-025-63474-3.
5. De Mauro A, Carrasco E, Oyarzun D, Ardanza A, Frizera-Neto A, Torricelli D, et al. Advanced hybrid technology for neurorehabilitation: The HYPER Project. In: Gulrez T, Hassanien A, editors. *Advances in Robotics and Virtual Reality.* Intelligent Systems Reference Library, vol 26. Berlin/Heidelberg: Springer; 2012. p. 89–108. doi:10.1007/978-3-642-23363-0_4
6. McGeady C, Vuckovic A, Puthusserypady S. A hybrid MI–SSVEP based brain–computer interface for potential upper limb neurorehabilitation: a pilot study. In: 2019 7th International Winter Conference on Brain–Computer Interface (BCI). Piscataway (NJ): IEEE; 2019. p. 1–6. doi:10.1109/IWW-BCI.2019.8737333
7. Novičić M, Djordjević O, Miler-Jerković V, Konstantinović L, Savić AM. Improving the Performance of Electrotactile Brain–Computer Interface Using Machine Learning Methods on Multi-Channel Features of Somatosensory Event-Related Potentials. Sensors. 2024; 24(24):8048.
8. Savic, A, Novicic, M, Miler-Jerkovic V, Djordjevic O, Konstantinovic, L. Electrotactile BCI for Top-Down Somatosensory Training: Clinical Feasibility Trial of Online BCI Control in Subacute Stroke Patients. Biosensors 2024, 14, 368.
9. Savić AM, Novičić M, Đorđević O, Konstantinović L, Miler-Jerković V. Novel electrotactile brain-computer interface with somatosensory event-related potential based control. Front Hum Neurosci. 2023; 23(17):1096814
10. Knežević S. Brain-Computer Interfaces In Neurorehabilitation For Central Nervous System Diseases: Applications in Stroke, Multiple Sclerosis And Parkinson's Disease. Sanamed. 2025 Feb 16;20(1).

11. Kumari R, Janković M, Costa A, Savić A, Konstantinović L, Djordjević O.et al. Short term priming effect of brain-actuated muscle stimulation using bimanual movements in stroke. Clin Neurophysiol. 2022; 138:108-121
12. Tonin A, Semprini M, Kiper P, Mantini D. Brain-Computer Interfaces for Stroke Motor Rehabilitation. Bioengineering (Basel). 2025 Jul 30;12(8):820. doi: 10.3390/bioengineering12080820
13. Yang W, Zhang X, Li Z, Zhang Q, Xue C, Huai Y. The Effect of Brain-Computer Interface Training on Rehabilitation of Upper Limb Dysfunction After Stroke: A Meta-Analysis of Randomized Controlled Trials. Front Neurosci. 2022 Feb 7;15:766879. doi: 10.3389/fnins.2021.766879.
14. Cajigas I, Davis KC, Meschede-Krasa B, Prins NW, Gallo S, Naeem JA. Et al. Implantable brain-computer interface for neuroprosthetic-enabled volitional hand grasp restoration in spinal cord injury. Brain Commun. 2021 Oct 21;3(4):fcab248. doi: 10.1093/braincomms/fcab248. Erratum in: Brain Commun. 2022 Jun 23;4(3):fcac143. doi: 10.1093/braincomms/fcac143.
15. Lorach H, Galvez A, Spagnolo V, Martel F, Karakas S, Intering N. et al. Walking naturally after spinal cord injury using a brain-spine interface. Nature. 2023;618(7963):126-133. doi: 10.1038/s41586-023-06094-5.
16. Li Z, Li M, Cui H, Chen X. Enhancing Motor Rehabilitation Using a Hybrid BCI Paradigm: Integrating High-Frequency SSVEP with Action Observation and Motor ImageryJ Neurorestoratol. 2025;13(6):100238.:100238. doi10.1016/j.jnrt.2025.100238
17. Xavier Fidêncio A, Grün F, Klaes C, Iossifidis I. Hybrid brain-computer interface using error-related potential and reinforcement learning. Frontiers in Human Neuroscience. 2025 ;19:1569411
18. Swarnakar R. Brain-Computer Interfaces in Rehabilitation: Implementation Models and Future Perspectives. Cureus. 2025 Jul 28;17(7):e88873. doi: 10.7759/cureus.88873
19. Ben Abdallah I, Bouteraa Y, Alotaibi A. AI-driven hybrid rehabilitation: synergizing robotics and electrical stimulation for upper-limb recovery after stroke. Frontiers in Bioengineering and Biotechnology. 2025 ;13:1619247.
20. Cantillo-Negrete J, Rodríguez-García ME, Carrillo-Mora P, Arias-Carrión O, Ortega-Robles E, Galicia-Alvarado MA.et al. The ReHand-BCI trial: a randomized controlled trial of a brain-computer interface for upper extremity stroke neurorehabilitation. Front Neurosci. 2025;19:1579988. doi: 10.3389/fnins.2025.1579988.
21. Malesevic J, Kostic M, Kojic V, Djordjevic O**,** Konstantinovic Lj, Keller T, et al. BEAGLE-A Kinematic Sensory System for Objective Hand Function Assessment in Technology-Mediated Rehabilitation. IEEE Transactions on Neural Systems and Rehabilitation Engineering. 2021; 29:1817-26. doi: 10.1109/TNSRE.2021.3108848
22. Khan MA, Fares H, Ghayvat H, Brunner IC, Puthusserypady S, Razavi B, et al. A systematic review on functional electrical stimulation based rehabilitation systems for upper limb post-stroke recovery. Front Neurol. 2023.8;14:1272992. doi: 10.3389/fneur.2023.1272992.
23. Remsik AB, van Kan PLE, Gloe S, Gjini K, Williams L Jr, Nair V.et al. BCI-FES With Multimodal Feedback for Motor Recovery Post-stroke. Front Hum Neurosci. 2022; 16 :725715. doi: 10.3389/fnhum.2022.725715..
24. Biasiucci A, Leeb R, Iturrate I, Perdikis S, Al-Khodairy A, Corbet T, et al. Brain-actuated functional electrical stimulation elicits lasting arm motor recovery after stroke. Nat Commun 9, 2421 (2018). doi:10.1038/s41467-018-04673-z
25. Dalla Gasperina S, Ferrari F, Gandolla M, Pedrocchi A, Ambrosini E. Hybrid Cooperative Control of Functional Electrical Stimulation and Robot Assistance for Upper Extremity Rehabilitation. IEEE Trans Biomed Eng. 2024 Sep;71(9):2642-2650. doi: 10.1109/TBME.2024.3384939.
26. Wei D, Hua XY, Zheng MX, Wu JJ, Xu JG. Effectiveness of robot-assisted virtual reality mirror therapy for upper limb motor dysfunction after stroke: study protocol for a single-center randomized controlled clinical trial. BMC Neurol. 2022;22(1):307. doi: 10.1186/s12883-022-02836-6.
27. Enríquez-Canto Y, Pizarro-Mena R, Ludueña-Hernández K, Alexandre-Vergara K, Riveros-Basoalto G, Dresdner-Figueroa A. Use of Virtual Reality in Upper Extremity Rehabilitation of Adults After Stroke and Its Effect on Functionality: Systematic Review and Meta-Analysis. Phys Ther. 2025;105(9):pzaf103. doi: 10.1093/ptj/pzaf103.
28. Acuña Luna KP, Hernandez-Rios ER, Valencia V, Trenado C, Peñaloza C. Deep Learning-Enhanced Motor Training: A Hybrid VR and Exoskeleton System for Cognitive-Motor Rehabilitation. Bioengineering (Basel). 2025 ;12(4):331. doi: 10.3390/bioengineering12040331.
29. Cardile D, Arena C, Corallo F, Giuffrida GM, Giustiniani A, Maggio MG.et al. A systematic review on the use of virtual reality in post-stroke patients: exploring when modalities make the difference in executive and motor recovery. Frontiers in Virtual Reality.;6:1653968.
30. Teng J, Cho S, Lee SM. Tri-manual interaction in hybrid BCI-VR systems: integrating gaze, EEG control for enhanced 3D object manipulation. Front Neurorobot. 2025 Aug 14;19:1628968. doi: 10.3389/fnbot.2025.1628968.

PRIMENA HIBRIDIH SISTEMA U NEUROREHABILITACIJI

Olivera Đorđević[1,2], Ana Radić[1], Aleksandra Vidaković[1,2], Sindi Mitrović[1,2], Suzana Dedijer Dujović[1,2], Tijana Dimkić Tomić[1,2], Ljubica Konstantinović[1,2]

Sažetak

Primena hibridnih sistema u neurorehabilitaciji predstavlja važan napredak na ovom polju, objedinjujući terapeutski i tehnološki pristup čiji je cilj poboljšanje funkcionalnog ishoda kod pacijenata sa neurološkim deficitom. Preduslov za razvoj hibridnih sistema su tehnološka rešenja koja omogućavaju kombinovanje bioloških signala i inovativne tehnologije u sprovođenju rehabilitacije. Strategija usmerena na više mehanizama kontrole izvođenja funkcionalnog zadatka uzima u obzir složenu prirodu neurološkog oštećenja i plasticiteta i omogućava raznovrsniji rehabilitacioni pristup. Hibridni sistemi u neurorehabilitaciji su u mogućnosti da integrišu sledeće modalitete: mozak – računar interfejs, robotičku asistenciju, funkcionalnu električnu stimulaciju i virtulenu realnost. Cilj primene ovih sistema je stimulisanje motornog učenja, obezbeđivanje multimodalnog senzornog *feedbacka* i korišćenje naprednijih kontrolnih algoritama upravljanja kroz aktivno učešće pacijenta u terapeutskim procedurama u realnom vremenu. Kliničke studije su pokazale da hibridni sistemi mogu da unaprede motorne funkcije kod ispitanika nakon moždanog udara, lezija kičmene moždine, kod pacijenata sa neurodegenerativnim bolestima. One su pokazale merljive promene relevantnih ishodnih varijabli funkcionalnosti kod ovih pacijenata. Pored toga, nove tehnologije omogućavaju dozirane, individualizovane, repetitivne i ciljane rehabilitacione postupke, koji su veoma važni u neurološkom oporavku.

Hibridnim sistemi u neurorehabilitaciji su primer integrisanja neuronauka, inženjerskog i kliničkog pristupa, čiji je cilj maksimiziranje funkcionalnog oporavka pacijenata sa neurološkim deficitom kod kojih je konvencionalni rehabilitacioni pristup dao suboptimalne rezultate. Fokus budućeg razvoja novih tehnologija u neurorehabilitaciji treba da bude usmeren na njihovu širu dostupnost, poboljšanje ergonomike i korisničkog interfejsa i integrisanje sa algoritmima mašinskog učenja u cilju dalje individualizacije i obezbeđivanja adaptabilnih strategija rehabilitacije ovih pacijenata.

Ključne reči: hibridni sistemi, mozak-računar interfejs, funkcionalna električna stimulacija, virtuelna realnost

Primljen: 14. 10. 2025. I **Revidiran**: 04. 03. 2026. I **Prihvać**en: 06. 03. 2026. I **Online First:** 11. 03. 2026.

Medicinska istraživanja 2026