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Brain-Computer Interface In Stroke Rehabilitation: A Systematic Review Of Current Evidence And Clinical Applications

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Abstract

Brain-computer interface (BCI) technology offers a promising innovation in post-stroke rehabilitation by providing real-time neural feedback and motor imagery training to enhance neuroplasticity and motor recovery. This narrative review synthesizes evidence from randomized controlled trials evaluating BCI-based interventions for stroke survivors at acute, subacute, and chronic phases. Key findings reveal that BCI interventions, especially when combined with conventional therapy modalities such as functional electrical stimulation and visual feedback, result in significantly greater improvements in upper and lower limb motor function versus standard care. BCI approaches also show additional benefits in enhancing attention, cognitive performance, and daily activity independence. Mechanistically, BCI systems strengthen neural connectivity and modulate cortical activation through closed-loop feedback, supporting both local and network-level brain reorganization. Despite promising results, further research is required to standardize protocols, identify ideal patient profiles, and assess long-term outcomes. Overall, BCI is an effective adjunct for neurorehabilitation, particularly for patients with severe motor deficits or limited voluntary movement, with potential to transform stroke recovery paradigms

Keywords: ANT: Attention Network Test; ARAT: Action Research Arm Test; BBS: Berg Balance Scale; BCI: Brain-Computer Interface; cFMA: combined Fugl-Meyer Assessment; EMG: Electromyography; FES: Functional Electrical Stimulation; FMA-LE: Fugl-Meyer Assessment Lower Extremity; FMA-UE: Fugl-Meyer Assessment Upper Extremity; fMRI: functional Magnetic Resonance Imaging; GAS: Goal Attainment Scale; HAM-D: Hamilton Depression Scale; LC: Laterality Coefficient; LI: Laterality Index; MAAS: Mindful Attention Awareness Scale; MAL: Motor Activity Log; MAS: Modified Ashworth Scale; MBI: Modified Barthel Index; MEP: Motor Evoked Potential; MI: Motor Imagery/Motricity Index; MMSE: Mini-Mental State Examination; MRC: Medical Research Council; PSQI: Pittsburgh Sleep Quality Index; rFA: ratio of Fractional Anisotropy; RCT: Randomized Controlled Trial; SDMT: Symbol Digit Modalities Test; SGT: Schulte Grid Test; SMR: Sensorimotor Rhythm; TCT: Trunk Control Test; TMS: Transcranial Magnetic Stimulation; TUGT: Timed Up and Go Test; VR: Virtual Reality; WHOQOL-BREF: World Health Organization Quality of Life Brief; WMFT: Wolf Motor Function Test

Introduction

Stroke remains one of the leading causes of disability worldwide, with approximately 101 million stroke patients alive globally and an estimated global incidence of 11.71 million cases per year. The condition frequently results in severe motor impairments, particularly affecting the upper extremities, with up to 85% of stroke survivors experiencing upper limb dysfunction. Despite advances in acute stroke care and conventional rehabilitation approaches, approximately 30% of stroke survivors continue to experience severe motor deficits that significantly impact their ability to perform activities of daily living.

Traditional rehabilitation approaches, while beneficial, often have limited effectiveness for patients with severe motor impairments who lack residual voluntary movement. This limitation has led to the development and investigation of innovative neurological rehabilitation technologies, particularly brain-computer interface (BCI) systems. BCI technology represents a paradigm shift in neurorehabilitation by enabling direct communication between the brain and external devices, bypassing damaged neural pathways.

The theoretical foundation of BCI rehabilitation lies in the principles of neuroplasticity and motor learning. During BCI training, patients engage in motor imagery (MI) or motor attempt (MA) tasks while their brain activity is recorded via electroencephalography (EEG). The system decodes motor intentions from neural signals and provides real-time feedback through various modalities, including visual displays, functional electrical stimulation (FES), or robotic devices. This closed-loop feedback mechanism is hypothesized to promote neuroplastic changes by strengthening the association between motor intention and sensory feedback.

Recent advances in BCI technology have incorporated additional therapeutic modalities such as virtual reality (VR), mindfulness therapy, and robotic assistance, creating multimodal rehabilitation platforms. These systems aim to enhance patient engagement, motivation, and therapeutic outcomes by providing immersive and interactive rehabilitation experiences.

The growing body of evidence from randomized controlled trials suggests that BCI-based interventions may offer superior outcomes compared to conventional rehabilitation alone. However, the mechanisms underlying BCI-mediated recovery and the optimal implementation strategies remain subjects of ongoing investigation. This systematic review aims to synthesize the current evidence regarding the efficacy of BCI interventions in stroke rehabilitation and examine the clinical outcomes, safety profiles, and neuroplastic mechanisms associated with these innovative approaches.

Methods

Inclusion and Exclusion Criteria

Inclusion Criteria:

- Randomized controlled trials (RCTs) investigating BCI interventions for stroke rehabilitation
- Studies involving adult participants (≥18 years) with diagnosed stroke (ischemic or haemorrhagic)
- Interventions utilizing EEG-based BCI systems for motor rehabilitation
- Studies reporting standardized motor function outcome measures (e.g., Fugl-Meyer Assessment, Action Research Arm Test)
- Articles published in English with full-text availability
- Studies with clear methodology and outcome reporting

Exclusion Criteria:

- Non-randomized studies, case reports, and review articles
- Studies involving invasive BCI systems
- Paediatric populations (<18 years)
- Studies lacking appropriate control groups

- Interventions not specifically targeting motor function recovery
- Studies with insufficient outcome data or methodology description

Search Strategy and Study Selection

A comprehensive search was conducted to identify relevant randomized controlled trials examining BCI interventions in stroke rehabilitation. The search focused on studies published between 2013 and 2025, encompassing the most recent advances in BCI technology and clinical applications. Studies were selected based on their methodological quality, sample size, and relevance to motor function recovery in stroke patients.

Results of Literature (ROL) Table

Author and Year	**Design and Characteristics of Participants**	**Objective**	**Material and Methods**	**Outcome Measures**	**Results**
Wang et al., 2024	RCT; N=296 (150 BCI, 146 control); Ischemic stroke patients within 1 month; NIHSS 1-3	Investigate efficacy and safety of BCI rehabilitation training on upper limb motor function	MI-based BCI with VR feedback; 30 min/day, 5 days/week for 1 month; Control: traditional rehabilitation	FMA-UE (primary); ARAT, WMFT, MAS, IDAL (secondary)	BCI group: FMA-UE improvement 13.17 vs control 9.83 (p=0.0045); Difference: 3.35 points; Adverse events similar between groups
Cantillo-Negrete et al., 2025	RCT; N=30 (15 BCI, 15 sham); Stroke patients 3-24 months post-stroke; Right-handed	Assess efficacy and neuroplastic effects of BCI intervention	ReHand-BCI system with robotic hand orthosis; 30 sessions over 6 weeks; EEG, fMRI, DTI, TMS assessments	FMA-UE, ARAT (primary); LC, LI, rFA, MEPs (secondary)	Both groups improved FMA-UE significantly; BCI group showed trends of more pronounced ipsilesional cortical activity
He et al., 2025	RCT; N=48 (25 BCI, 23 control);	Evaluate effectiveness of BCI system	8-electrode EEG system with VR and robotic training; 20 min	FMA-UE, FMA-LE, EMG, fNIRS	BCI group: significantly greater FMA-UE improvement

Author and Year	**Design and Characteristics of Participants**	**Objective**	**Material and Methods**	**Outcome Measures**	**Results**
	Ischemic stroke patients	integrating MI and MA	sessions for 2 weeks		(4.0 vs 2.0, p=0.046); Enhanced motor and cognitive network activity
Wang et al., 2023	RCT; N=60 (30 BCI, 30 control); Stroke patients with hemiplegia	Compare effects of BCI combined with mindfulness therapy	BCI training + mindfulness therapy; 20 min/day, 5 days/week for 8 weeks	FMA-UE, FMA-LE, MAAS, PSQI, WHOQOL-BREF	Significant improvements in all measures for BCI group; Better motor function, attention, and quality of life
Wan et al., 2025	RCT; N=30 (14 BCI, 16 control); Stroke patients	Effects of dual-task BCI on balance and attention	MI-VR dual-task BCI pedaling system; 20 min/day, 5 days/week for 4 weeks	BBS (primary); TUGT, FMA-LE, SDMT (secondary)	BCI group showed significant improvements in BBS, TUGT, and SDMT (p<0.05); Balance and attention enhanced
Mizuno et al., 2024	RCT; N=40 (20 BCI, 20 control); Chronic severe hemiplegia patients	Hand motor recovery with BCI-based neurofeedback	EEG-SMR desynchronization with visual feedback and FES; 40 min/day for 10 days	FMA-UE (primary); EMG, fMRI (secondary)	Significant time×group interaction (p=0.037); Greater functional gain in BCI group with enhanced cortical activation

Author and Year	**Design and Characteristics of Participants**	**Objective**	**Material and Methods**	**Outcome Measures**	**Results**
Luo, 2024	RCT; N=64 (32 BCI, 32 control); Acute ischemic stroke patients	Effects of MI-based BCI on lower limb function	BCI-controlled electrical stimulation; 1 hour/day for 2 weeks	FMA-LE (primary); FAC, MBI (secondary)	BCI group showed significantly better improvements: FMA-LE ($p<0.001$), FAC ($p=0.031$), MBI ($p<0.001$)
Liu et al., 2023	RCT; N=56 (28 BCI, 28 control); Stroke patients with upper limb impairment	Effects of MI-BCI on upper limb function and attention	BCI-FES system; 20 min sessions, 5 times/week for 3 weeks	FMA-UE, ANT (primary); WMFT, MBI, SGT, SDMT (secondary)	BCI group: FMA-UE increased by 8.0 points vs control; Significant improvements in attention networks and motor function
Li et al., 2024	RCT; N=98 (BCI=33, MI=33, Control=32); Convalescent stroke patients	Compare BCI training with conventional approaches	L-B300 EEG system with VR feedback; 6 times/week for 2 weeks	MMSE, HAM-D, FMA, 6MWD, MBI, TMS	BCI group showed largest improvements in all measures; Superior cognitive, psychological, and motor recovery
Kim et al., 2024	Protocol; N=40 planned (20 per group); Subacute stroke patients	Compare real vs sham BCI on motor function and brain activity	RecoveriX PRO system with wrist extension training; 60 min/day, 5	MRC scale (primary); FMA-UE, MAS, ANT, TMS	Study protocol for double-blinded RCT; Primary outcome:

Author and Year	**Design and Characteristics of Participants**	**Objective**	**Material and Methods**	**Outcome Measures**	**Results**
			times/week for 4 weeks	(secondary)	wrist extensor strength
Lee et al., 2022	RCT; N=26 (13 AOT+BCI-FES, 13 control); Stroke patients	Effects of action observation training plus BCI-FES	EEG-based BCI with FES and action observation; 30 min sessions for 4 weeks	FMA-UE, WMFT, MAL, MBI, EEG parameters	Significant differences between groups in all motor measures and EEG parameters; Enhanced cortical activation
Ramos-Murguialday et al., 2019	Follow-up of RCT; N=28 (16 experimental, 12 sham); Chronic stroke patients	Long-term effects of BMI-based rehabilitation	SMR desynchronization with robotic orthoses; Daily training for 4 weeks with 6-month follow-up	cFMA (primary); GAS, MAL, Ashworth, EMG, fMRI	Experimental group maintained significant improvements at 6 months (13.44±1.96 vs baseline 11.16±1.73, p=0.015)
Peláez-Vélez et al., 2023	RCT; N=24 (12 VR, 12 control); Stroke patients within 6 months	Effects of VR and videogames in physiotherapy treatment	Immersive VR with Oculus Quest 2; 3 sessions/week for 6 weeks	Daniels Scale, MAS, MI, TCT, TBS, BBS, CFMHS	Significant improvements in VR group: MI (p=0.005), TCT (p=0.008), TBS (p=0.004), BBS (p=0.007)

Author and Year	**Design and Characteristics of Participants**	**Objective**	**Material and Methods**	**Outcome Measures**	**Results**
Anwar et al., 2021	RCT; N=68 (34 VR, 34 control); Stroke patients aged 40-60 years	Compare VR training vs conventional PT on balance and lower extremity function	Nintendo Wii gaming system; 60 min sessions, 4 times/week for 6 weeks	BBS, FMA-LE domains	Significant differences in BBS scores and all FMA-LE domains favoring VR group (all $p<0.001$)
Ramos-Murguialday et al., 2013	RCT; N=30 (16 experimental, 14 control); Chronic stroke with severe hand weakness	BMI efficacy in stroke neurorehabilitation	SMR desynchronization with hand/arm orthoses; Daily training for 4 weeks	cFMA (primary); Ashworth, MAL, GAS, EMG, fMRI	Significant group×time interaction ($p=0.018$); cFMA improvement 3.41±0.563 points; Enhanced fMRI laterality

Discussion

Mechanisms of Action

BCI-based rehabilitation systems engage sensorimotor circuits through closed-loop neural feedback, which is rooted in Hebbian plasticity theory—where simultaneous activation of pre- and post-synaptic elements strengthens neural pathways and supports neuroplasticity. With BCI, the patient's motor intent is decoded via EEG during motor imagery or attempted movements, and this intention triggers real or simulated limb actions through robotics or functional electrical stimulation, providing synchronous sensory feedback. This approach leverages neurofeedback training, giving patients real-time visualization of their neural activity. Such feedback enables them to regulate cognitive and motor activity, further reinforced by operant conditioning—performance-contingent rewards that encourage efficient brain–muscle communication. Multimodal integration, including visual, proprioceptive, and tactile feedback, enhances learning and motor recovery. Neuroimaging studies confirm BCI-driven interventions increase cortical activation and functional connectivity across prefrontal, supplementary motor, and primary motor cortices. For example, fNIRS and EEG findings show greater inter- and intra-hemispheric reorganization in BCI groups versus controls, indicating reestablished and strengthened sensorimotor networks necessary for motor relearning. EMG markers also confirm more targeted and compensatory recruitment of muscle groups after BCI-based training—another indicator of efficient neuroplastic change. Clinical

Effectiveness Across Stroke Phases

Acute Phase: Neuroplasticity is most robust within the first weeks after stroke. Studies show BCI combined with conventional therapy produces significant improvements in lower limb motor function, walking, and daily living, evidenced by gains in Fugl-Meyer and Barthel indices (e.g., FMA-LE improved from 7.9±1.2 to 13.5±1.4 in BCI vs 10.9±1.6 in controls, $p<0.001$).

Sub acute Phase: In patients 1 week to 6 months post-stroke, BCI interventions led to superior improvements in balance (Berg Balance Scale increase: 5.5 vs 3.4 points) and attention, with dual-task paradigms improving both executive control and response speed.

Chronic Phase: For chronic stroke (>6 months), BCI-based approaches still yield significant gains in upper limb function (FMA-UE improvements: 4–11 points over controls) and increase brain activation and connectivity—demonstrating continuing plasticity potential even long after injury.

Upper vs. Lower Extremity Recovery BCI systems are effective for both upper and lower extremities. For the upper limb, studies show 4–11 point improvements on Fugl-Meyer scales; for lower limb, walking distance and independence scores (e.g., Barthel Index, FAC) significantly increase following BCI-enhanced interventions. Combining cognitive tasks with limb training is particularly effective for improving both motor and balance outcomes.

Cognitive and Attention Benefits Beyond motor improvement, BCIs provide measurable enhancements in attention (Symbol Digit Modalities Test, Attention Network Test) and processing speed, likely due to the high attentional and cognitive demands of real-time neurofeedback. These cognitive-motor benefits are robust and correlated, suggesting that BCI platforms support broad neurological recovery in stroke.

Technology Considerations Feedback Modalities: Multimodal (visual, auditory, proprioceptive) and real-time feedback outperform single-mode or delayed systems. Training must be contingent on actual motor imagery performance to optimize neural adaptation. Training Parameters: Optimal protocols are 20-minute sessions, 5 days/week, for 2–4 weeks; minimum 60% motor imagery task accuracy required for effective BCI action.

Limitations and Future Directions Current limitations include heterogeneity in BCI systems and feedback, small samples, short follow-ups, and variable patient selection criteria. Future work should harmonize protocols and outcomes, identify candidate biomarkers (e.g., imagery ability, cognitive function), expand home-based use, and explore synergies with other neuromodulation strategies. Clinical Implications BCI technology merits integration within multidisciplinary stroke rehabilitation, especially benefiting those with severe motor impairment and limited active movement. Evidence supports use as an adjunct—rather than a replacement—for standard therapy, with tailored patient selection for best effect. For chronic stroke, where fewer therapies are effective, BCI offers a hopeful avenue for continued neuro-recovery even years post-injury.

Conclusion

Brain-computer interface (BCI) technology is transforming stroke rehabilitation by harnessing neuroplasticity for motor recovery. Evidence from randomized controlled trials demonstrates that BCI interventions, especially when combined with conventional therapies, bring about substantial improvements in both upper and lower limb function. These gains extend to enhanced attention, cognitive abilities, and independence in daily activities. The mechanism involves the synchronous activation of central motor intentions and feedback from muscles or robotic devices, leading to strengthened neural connections and improved motor learning. BCI protocols typically utilize motor imagery and multimodal feedback to accelerate recovery. However, current research is challenged by heterogeneous protocols, limited sample sizes, and short follow-ups. To maximize the benefits, future studies should standardize methods, explore long-term effects, and refine patient selection criteria based on motor imagery ability and cognitive capacity. Ultimately, BCI systems promise to be an effective adjunct in stroke rehabilitation, offering new hope for patients with severe impairments at all stages of recovery.

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