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(REVIEW ARTICLE)

Emerging brain computer interface-based approaches in stroke rehabilitation: A review of current evidence and comparison with conventional physiotherapy

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Abstract

Background: Stroke is one of the leading causes of long-term disability worldwide and is increasingly being reported among young adults, resulting in substantial physical, psychological, and socioeconomic challenges. Although conventional physiotherapy plays a central role in stroke rehabilitation, many individuals with severe motor deficits do not achieve complete functional recovery. In recent years, Brain–Computer Interface (BCI) technology has emerged as a promising adjunct to rehabilitation by directly interpreting brain activity to facilitate movement, promote neuroplasticity, and enhance motor recovery through external assistive devices.

Objective: To review the current evidences on the role of Brain-Computer Interface (BCI) approaches and comparison with conventional physiotherapy in stroke rehabilitation.

Methods: A literature review was performed by searching electronic databases, including PubMed, Google Scholar, ScienceDirect, ProQuest, and Mendeley, for studies published between 2015 and 2025. The search was carried out using keywords related to Brain–Computer Interface (BCI), EEG-based BCI, stroke rehabilitation, neuroplasticity, and neurorehabilitation. Studies were screened according to predefined inclusion and exclusion criteria, and 10 relevant articles comprising systematic reviews, meta-analyses, randomized controlled trials, review articles, and case studies were included for critical appraisal and evidence synthesis.

Results: The Reviewed studies consistently showed that non-invasive EEG-based Brain–Computer Interface (BCI), when used alongside conventional physiotherapy and other rehabilitation approaches such as functional electrical stimulation, robotic-assisted therapy, and virtual reality, was associated with improved upper-limb motor function, motor control, functional independence, and neuroplasticity in individuals with stroke. Several studies also reported that BCI enhanced communication abilities in patients with severe paralysis and locked-in syndrome. While invasive BCI systems offered greater signal accuracy, non-invasive EEG-based BCIs were considered safer, more practical, and better suited for routine clinical rehabilitation.

Conclusion: Based on the reviewed evidences, Brain–Computer Interface (BCI) shows promise as an adjunct to conventional physiotherapy for improving stroke rehabilitation outcomes. Further high-quality studies are needed to establish standardized protocols and confirm its long-term clinical effectiveness.

Keywords: Brain–Computer Interface (BCI); EEG-Based BCI; BCI In Stroke Rehabilitation; BCI and Neuroplasticity; BCI in Paralysis; Conventional Physiotherapy; Neurorehabilitation.

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1. Introduction

Stroke remains a leading cause of long-term disability worldwide and has traditionally been associated with older adults. However, the incidence of stroke among younger adults has risen substantially over recent decades, largely attributable to the increasing prevalence of modifiable cardiovascular risk factors, including hypertension, diabetes mellitus, obesity, smoking, and unhealthy lifestyle behaviors[1]. Stroke is a neurological disorder that occurs when the blood supply to the brain is interrupted due to either ischemia or hemorrhage , resulting in damage to brain cells and loss of neurological function[2].It is one of the leading causes of death and long-term disability worldwide despite major advances in medical treatment[4]. This epidemiological shift has significant socioeconomic implications, as stroke during early and middle adulthood disrupts education, employment, and family responsibilities, resulting in considerable long-term individual and societal burden[3].

Post stroke patients develop Motor impairment with a prevalence rate of 82% as significant complication followed by hemiparesis, muscle weakness, spasticity, poor balance, impaired coordination, and difficulty walking[5]. These impairments limit activities of daily living and reduce functional independence[7]. These disabilities often reduce independence and negatively affect the patient's quality of life[6].Neuroplasticity is the brain's ability to reorganize and form new neural connections after injury. This process helps restore lost functions and it is considered one of the main goals of modern stroke rehabilitation[5].

Conventional rehabilitation interventions have demonstrated efficiency in improving functional outcomes following stroke. Nevertheless, many patients, particularly those with severe motor impairments, continue to experience persistent functional deficits and fail to achieve complete recovery[7].These limitations highlight the need for innovative rehabilitation approaches that directly modulate neural activity, harness neuroplasticity, and optimize functional recovery beyond the capabilities of conventional therapies[8].

Brain Computer Interface (BCI) works by detecting motor intention or motor imagery from the brain and providing immediate feedback through external devices[9].This continuous feedback helps improve neuroplasticity, promotes cortical reorganization, and enhances motor recovery after stroke[7]. Brain–Computer Interfaces are classified into invasive and non-invasive systems. Invasive BCIs require surgical implantation of electrodes into the brain and provide highly accurate signals[10].In contrast, non-invasive BCIs use electroencephalography (EEG) electrodes placed on the scalp and are safer, and more suitable for routine stroke rehabilitation. BCI using EEG, processes these signals, and converts them into commands to control external devices such as robotic systems, functional electrical stimulation (FES), virtual reality (VR), or exoskeletons without relying on normal muscle activity[9].

Physiotherapy plays an important role in stroke rehabilitation by improving muscle strength, balance, coordination, mobility, and functional independence[7]. Conventional rehabilitation includes task-specific training, gait training, strengthening exercises, balance training, neuromuscular facilitation techniques, and constraint-induced movement therapy(CIMT)[6].

Recent advances in neuroscience and technology has led to the development of Brain–Computer Interface (BCI) technology. Several randomized controlled trials, systematic reviews, and meta-analyses have reported that BCI-assisted rehabilitation improves upper-limb motor function, functional independence, and brain reorganization more effectively than conventional rehabilitation alone. Combining BCI with functional electrical stimulation, robotic therapy, and virtual reality has shown even greater improvements in motor recovery[9].

2. Material and methods

2.1. Study design

A literature review was conducted to review the current evidences on the role of Brain-Computer Interface (BCI) approaches and comparison with conventional physiotherapy in stroke rehabilitation.

2.2. Search strategy

Databases such as PubMed, Google scholar, Research gate were searched using the following key words: Brain–Computer Interface (BCI), EEG-based BCI, BCI in stroke rehabilitation, BCI and neuroplasticity, BCI in paralysis, Conventional physiotherapy, Neurorehabilitation. Relevant articles published between 2015 and 2025 were identified and screened for eligibility.

2.3. Eligibility Criteria

2.3.1. Inclusion Criteria

- Studies involving the use of Brain–Computer Interface (BCI) in neurorehabilitation or assistive communication.
- Studies including patients with stroke, paralysis, Amyotrophic Lateral Sclerosis (ALS), or Locked-in Syndrome.
- Systematic reviews, review articles, randomized controlled trials, clinical trials, and experimental studies.
- Articles published in English between 2015 and 2024.
- Full-text articles that are available in search engines

2.3.2. Exclusion criteria

- Articles unrelated to neurorehabilitation or assistive communication.
- Duplicate publications were not considered as per CASP
- Conference abstracts or articles without complete data and full-text availability.
- Articles published before 2015 was not part of review

2.4. Study Selection

The study selection followed a systematic screening process. A total of 35 articles were identified from PubMed, Google Scholar, and ScienceDirect. After removing 7 duplicate articles, 28 articles were screened based on their titles and abstracts. Of these, 13 articles were excluded because they were not related to the study topic or did not meet the inclusion criteria. The remaining 15 full-text articles were assessed for eligibility, and 5 articles were excluded due to insufficient outcome data, irrelevant study objectives, duplicate publication, or lack of rehabilitation outcomes. Finally, 10 studies were included in this literature review.

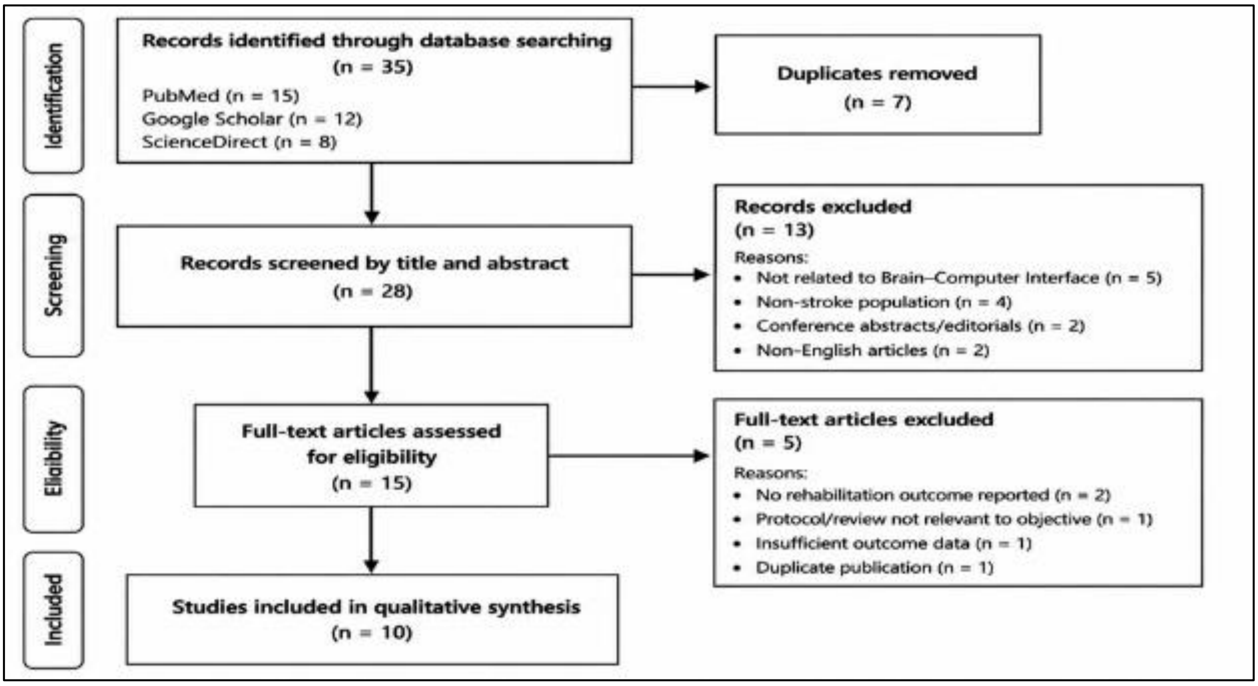

Figure 1 Flow diagram showing the study selection process for the narrative review.

2.5. Data Extraction

Data from the included studies were extracted systematically. The extracted information included the author(s), year of publication, study design, participant characteristics, outcome measure (Brain computer interface). The findings were then summarized and compared to identify common patterns and associations across the included studies.

3. Results

The articles based on evidence-based review, comprised of 3 systematic reviews, 1 meta-analysis, 1 case studies, and 5 review articles that indicate BCI as an effective adjunct to conventional stroke rehabilitation. Among the included studies, non-invasive EEG-based BCI with physiotherapy (10 studies) showed the greatest improvement in functional outcomes , followed by FES + BCI (7 studies), robot-assisted therapy (6 studies), and virtual reality (5 studies), all of which improved limb function, motor control, neuroplasticity, and functional independence.

Invasive BCIs provided higher signal accuracy but were limited by surgical risks, whereas non-invasive BCIs were safer and more practical for clinical use.

Overall, BCI shows strong potential to enhance motor recovery and functional outcomes in young adults with stroke.

Table 1 Summary of studies included in the narrative review.

SL. NO	Author(s)	Study type	Interventions	Key findings
1	Birbaumer N 2025	Narrative review	Brain–Computer Interfaces, neurofeedback, deception detection, brain stimulation	BCI and neurofeedback are effective for communication in locked-in syndrome and stroke rehabilitation while highlighting important ethical considerations
2	Mokienko OA 2024	Narrative review	Intracortical implant-based invasive Brain–Computer Interfaces	Intracortical BCIs enable patients with severe paralysis to control robotic limbs, communicate effectively, and regain functional independence
3	Bobrov PD 2023	Systematic review	Non- invasive BCI training, motor imagery, BCI-exoskeleton therapy	Strong evidence supports BCI-assisted motor imagery and exoskeleton training for improving upper-limb recovery after stroke.
4	Sun X, Li M, Li Q 2022	Narrative review	BCI applications for post-stroke cognitive rehabilitation	BCI has significant potential to improve cognition, attention, memory, and executive function after stroke.
5	Homberg V 2021	Systematic review	Long-term BCI-based rehabilitation (BCI neurofeedback, Functional Electrical Stimulation, robotic therapy, hand exoskeletons)	BCI technologies provide a promising long-term rehabilitation strategy for severe upper-limb paresis after stroke.
6	Camargo-Vargas D 2021	Systematic review	EEG-based BCI systems for upper and lower limb rehabilitation with virtual reality feedback	EEG-based BCIs combined with VR improve limb rehabilitation, patient motivation, and rehabilitation efficiency.
7	Young MJ 2021	Narrative review	Brain–Computer Interfaces for neurorecovery and neurorehabilitation	BCIs show promise in restoring neurological function, improving independence, communication, and rehabilitation outcomes.
8	Yang S, Li R, Li H 2021	Narrative review	Various BCI technologies for stroke rehabilitation (BCI + FES, VR, robotic devices, exoskeletons)	BCI technology enhances neuroplasticity and improves motor, sensory, speech, and cognitive recovery following stroke.

9	Soekadar SR 2018	Meta-analysis	BCI-based motor rehabilitation compared with conventional rehabilitation	BCI-based rehabilitation produced significantly greater improvements in upper-limb motor function than control therapy and promoted neuroplasticity.
10	Ryan DB 2015	Case study	Non-invasive P300 EEG-based Brain–Computer Interface (BCI) communication system	The participant with locked-in syndrome after brainstem stroke successfully communicated using a non-invasive BCI, demonstrating improved independence and communication.

4. Discussion

Brain–Computer Interface (BCI) is a promising technology in stroke neurorehabilitation. BCI enhances neuroplasticity, cortical reorganization, and motor relearning, leading to improved motor recovery. Combining BCI with conventional physiotherapy provides better functional outcomes than conventional rehabilitation alone. Non-invasive BCIs are safer and more practical, whereas invasive BCIs offer higher signal accuracy but involve surgical risks and higher costs. Current evidence is encouraging however, small sample sizes, lack of standardized protocols, and limited long-term follow-up restrict widespread clinical application. Further large-scale randomized controlled trials are needed to establish standardized clinical guidelines.

5. Conclusion

The evidence suggests that technology-assisted rehabilitation, particularly non-invasive EEG-based BCI combined with physiotherapy, significantly improves upper-limb function and functional outcomes. FES + BCI, robot-assisted therapy, and virtual reality further enhance motor recovery and support functional independence. Hence Brain–Computer Interface (BCI) being a promising adjunct to conventional stroke rehabilitation can increases motor recovery, neuroplasticity, functional independence, and communication in patients with neurological impairments for faster recovery.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that there is no conflict of interest.

Statement of ethical approval

Ethical approval was not required for this study because it is a literature review based exclusively on previously published literature and did not involve human participants or animals.

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Author contributions

- Dr. S Anil Kumar P.T : Conceptualization, literature search, study selection, data extraction, manuscript preparation, and final approval.
- Dr. Belle Sharvani P.T: Study supervision, critical review, and manuscript revision.
- Dr. Manjunatha H: Administrative support, manuscript review, and final approval.

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