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Acknowledgments

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Health research and education innovation mock manuscript layout

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Abstract This mock example has been prepared to assist you in preparing your manuscript for publication. It uses an example of a previously published scoping review to illustrate the layout of the manuscript, including the font, size, line spacing, text justification and alignment, headings, and arrangement of tables and figures. References must be cited and listed using AMA style. Authors should disclose funding sources before the references. The last page provides the necessary statements concerning ethics, conflicts of interest, data availability, and proper authorship, all of which must be included.

Keywords Text, Table, Figure, Manuscript Format

Introduction

Recovery of motor function is a primary objective in rehabilitation medicine, as it enables individuals to regain independence, participate in daily activities, and reduces the risk of secondary complications such as falls. A significant portion of individuals with neurological or musculoskeletal impairments continue to experience long-lasting deficits, even after receiving standard rehabilitation therapies.[1] Emerging rehabilitation technologies, such as neurofeedback systems and brain-computer interface (BCI) tools, represent new approaches for supporting recovery by capturing physiological signals and translating them into meaningful feedback. These systems may supplement, enhance, or restore motor and cognitive functions by modifying interactions between the individual and their environment in real time.[2] In addition to providing functionally relevant feedback, advanced neurorehabilitation tools can actively engage patients in therapy by leveraging mental strategies or encouraging the use of impaired extremities.[3]

The feedback facilitated by such systems may play a crucial role in supporting the neural mechanisms underlying recovery. To date, the application of neurofeedback-based interventions for upper extremity rehabilitation is well-documented, with substantial evidence from clinical trials and systematic reviews.[4] Conversely, their implementation for lower extremity or gait recovery is less extensively studied. Nonetheless, these systems possess unique benefits; for example, training can often be administered without the need for extensive weight support systems, making them accessible for a wider patient population.

The aim of this review is to systematically and critically examine the current body of evidence on neurofeedback and physiological signal-based feedback systems for rehabilitation of lower extremity function. Specifically, the review explores which non-invasive feedback systems have been tested for lower limb rehabilitation and what current research indicates regarding their effectiveness and clinical impact.

Methods

Protocol and Registration

This scoping review was developed and reported following the PRISMA Extension for Scoping Reviews (PRISMA-ScR) checklist. The review protocol was registered at XXX (XXX).

Eligibility Criteria

Studies were included if they met the following criteria: (1) original research involving adult participants (≥18 years old) with motor deficits due to neurological or musculoskeletal conditions; (2) the use of non-invasive neurofeedback or physiological signal-based feedback interventions targeting lower limb rehabilitation; (3) any comparator or lack thereof; (4) reporting of outcomes related to lower limb performance, functional improvement, or feedback system accuracy; (5) description of system design and feedback modalities; and (6) full-text articles in English with complete data. Eligible study designs were randomized controlled trials, single-group studies, quasi-experimental and crossover studies, as well as case reports. Exclusion criteria were review articles; study protocols; articles with retracted data; editorials or letters; conference abstracts; studies examining only healthy subjects; and studies focusing on purely assistive (as opposed to rehabilitative) technologies.

Study Search and Selection

A literature search was conducted between June 15-30, 2025, across PubMed, Scopus, and Web of Science databases. The PubMed search strategy employed the following query: ("Brain-Computer Interfaces"[mh] OR "brain computer interface"[tiab] OR "brain-computer interface"[tiab] OR "brain machine interface"[tiab] OR "brain-machine interface"[tiab] OR BCI[tiab] OR "Neurofeedback"[mh] OR Neurofeedback*[tiab] OR Neurobiofeedback*[tiab]) AND ("stroke" [tiab] OR "cerebrovascular accident" [tiab] OR "CVA" [tiab] OR "Stroke/rehabilitation" [mh]) AND ("Lower Extremity"[Mesh] OR "leg"[tiab] OR "legs"[tiab] OR "lower limb"[tiab] OR "lower-limb"[tiab] OR "lower extremity"[tiab] OR "ankle"[tiab] OR "foot"[tiab] OR "dorsiflexion"[tiab] OR "plantar flexion"[tiab] OR "plantarflexion"[tiab] OR "gait" [tiab] OR "walking" [tiab] OR "locomotion" [tiab] OR "ambulation" [tiab] OR "lower limb rehabilitation" [tiab] OR "Gait" [mh] OR "Walking" [mh]). Searches in Scopus and Web of Science utilized the keywords and Boolean operaitors: (brain-computer interface OR neurofeedback) AND stroke rehabilitation, AND (gait OR walking OR lower limb). A supplementary manual search of the reference lists from the selected articles was conducted to identify additional publications that were not captured through the database searches.

Data Extraction

Two reviewers independently extracted the following data from each selected source: authors and year of publication, study methodology, participant characteristics (sample size, age, relevant clinical information), intervention or system features, implementation or training protocols, and outcome measures assessed using standardized tools. All extracted information was compiled into a summary table for further analysis. Any discrepancies between the two reviewers were addressed by a third reviewer, who verified the extracted data against the original references and finalized the summary table.

Quality Appraisal

The National Institutes of Health (NIH) Study Quality Assessment Tools were used to evaluate internal validity and assess risk of bias in included studies (Supplementary 1). Two reviewers independently assessed the quality of each study using the corresponding tool. Any differences in assessment were discussed to reach agreement. Based on predefined criteria, studies were rated as "good," "fair," or "poor" quality, depending on the number of quality indicators met for each study type.

Data Synthesis

We conducted a narrative synthesis of the included studies to comprehensively map the evidence in accordance with our research objectives. Findings are presented in descriptive tables and thematically synthesized based on key review questions.

Results

General Study Characteristics

The initial screening identified 457 records, from which 22 studies were ultimately selected for inclusion in the final review (Figure 1). The studies were published between 2014 and 2025, and consisted of 7 randomized controlled trials (RCTs),[5–11] 1 non-randomized controlled trial,[12] 3 single-arm investigations,[13–15] and 11 studies utilizing quasi-experimental or pilot designs.[16–26] Among the included studies, 4 RCTs[7–10] and 2 case series[17,26] were assessed as having "good" methodological quality, while the remainder were rated as "fair" or "poor" (see Supplementary 1).

In terms of participant characteristics, 4 controlled studies and 2 single-arm investigations enrolled individuals with a condition duration of more than 6 months.[5,7,11,12,14,15] Conversely, 4 controlled studies and 1 single-arm study included participants within the early or subacute phase.[6,8–10,13]

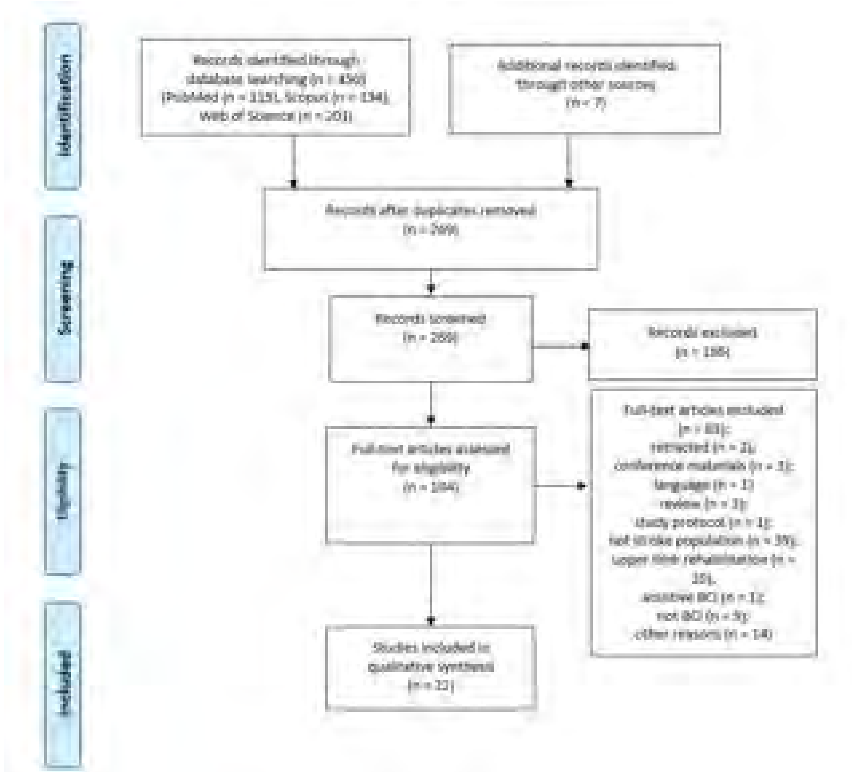

Figure 1. Flowchart of study selection.

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Table 1. Clinical studies of BMI-FES technology for lower limb after stroke.

Source	Study design	Patient sample	Protocol	Main results
McCrimmon C. et al., 2015[17]	Case series	N=9; age: 35-83 years; time since stroke: 8-102 months; FMA-LE: 18-29	12 sessions of 1 h over 4 weeks	Increase in walking speed by ≥0.06 m/s (N=5), 6MWT by ≥10% (N=5), AROM by ≥2.5° (N=3), FMA-LE by ≥10% (N=3); decoding accuracy 62-89%
Chung E. et al., 2015[5]	RCT, control – FES	N=10; age: 44 and 50 years; time since stroke: 16 months and 8 months; TUG test: 28.7±12.6 sec and 27.0±17.0 sec	5 sessions of 30 min over 5 days	Only in BCI-FES group: reduction in TUG time to 22.7±11.4 sec, improvement in cadence and step length ($p<0.05$)
Mrachacz-Kersting N. et al., 2016[12]	Non-RCT, control – sham system	N=22; age: 46±12.5 and 22±11 years; time since stroke: 15±6 and 18±4.5 months; FMA-LE: 24.9±6.5 and 26.4±5.2; 10MWT: 0.76±0.29 and 1.16±0.28 m/s	3 sessions of 15 min over 1 week	Only in BCI-FES group: improvement in FMA-LE to 25.7±6.5 ($p=0.011$) and 10MWT to 0.84±0.31 m/s ($p=0.007$)
Chung E. et al., 2020[11]	Blinded RCT, control – FES	N=25; age: 52±15 and 54±15 years; time since stroke: 11±6 and 16±7 months; gait velocity 0.29±0.1 m/s and 0.24±0.1 m/s	15 sessions of 0.5 h over 5 weeks	Increase of gait velocity in BCI-FES group to 0.42±0.12 m/s, in FES group – to 0.28±0.12 m/s ($p=0.002$ favor BCI-FES), increase of cadence and step length ($p<0.05$ favor BCI-FES)

Abbreviations: 6MWT — 6-minute walk test; 10MWT — 10-meter walk test; AROM — active range of motion; BBS — Berg Balance Scale; BCI — brain-computer interface; CSP — common spatial patterns; EEG — electroencephalography; ERSP— event-related spectral perturbation; FES — functional electrical stimulation; FMA-LE — Fugl-Meyer Assessment for lower extremity; LDA — linear discriminant analysis; PSD — power spectral density; RCT — randomized controlled trial; TUG — timed up and go.

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Discussion

The literature review found that EEG-based BCIs combined with functional electrical stimulation (EEG-BCI-FES) are the most widely studied non-invasive BCI modality for rehabilitation, showing therapeutic benefits in four controlled trials. In contrast, BCIs using mechanical devices or visual feedback alone have been less explored, with only two RCTs each; both BCI-mechanical and visual feedback BCIs had one good-quality RCT, while BCI-FES had two. BCIs linked to lower limb exoskeletons are still in early development, with only proof-of-concept studies focusing mainly on feasibility rather than clinical outcomes.

BCI-FES stands out for both research volume and physiological rationale, as it leverages muscle contractions via electrical impulses based on Hebbian plasticity principles.[5] EEG is the main brain signal acquisition method in these studies, while fNIRS is emerging as a promising alternative due to its robustness and simplicity[6], though only two clinical trials have used it in BCIs so far.

Robotic exoskeleton BCIs, though promising for future research, currently lack sufficient evidence, as high-intensity robotic gait training usually does not involve enough patient engagement for neuroplastic changes. Integrating cognitive (BCI) and physical rehabilitation may optimize outcomes.[7] Additionally, BCIs have shown potential for improving cognitive function in neurological recovery, offering an extra benefit for post-stroke patients.[8]

Results should be interpreted cautiously due to significant heterogeneity in study protocols, timing post-stroke, outcome assessments, and generally small sample sizes. Many studies are pilot or feasibility trials, and possible language/database limitations exist.

Given the diversity of BCI technologies and the limited number of controlled trials, a scoping review was chosen over a systematic review to better capture the evidence landscape. No similar review has appeared in the past five years. Future work should include meta-analyses to clarify the therapeutic value of BCIs—especially BCI-FES and BCI-mechanical systems—in lower limb rehabilitation

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