

EFFECTIVENESS OF BRAIN-COMPUTER INTERFACE-ASSISTED REHABILITATION ON MOTOR RECOVERY IN STROKE SURVIVORS: A SYSTEMATIC REVIEW AND META-ANALYSIS

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ABSTRACT

Background: Stroke is a leading cause of long-term disability worldwide, with motor impairments significantly affecting functional independence and quality of life among survivors. Brain-computer interface (BCI)-assisted rehabilitation has emerged as a promising neurorehabilitation approach that facilitates motor recovery by translating neural activity into external feedback and promoting neuroplasticity. However, the effectiveness of BCI-assisted rehabilitation on motor recovery following stroke remains an area of ongoing investigation.

Objective: To systematically evaluate and quantitatively synthesize the available evidence regarding the effectiveness of BCI-assisted rehabilitation on motor recovery in stroke survivors.

Methods: A systematic review and meta-analysis were conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines. Electronic databases including PubMed/MEDLINE, Embase, Scopus, Web of Science, Cochrane Central Register of Controlled Trials (CENTRAL), CINAHL, and PEDro were searched. Randomized controlled trials and controlled clinical trials investigating BCI-assisted rehabilitation in adult stroke survivors were included. Data extraction and risk-of-bias assessment were independently performed by two reviewers using the Cochrane Risk of Bias 2 tool. Meta-analyses were conducted using a random-effects model, and pooled effect sizes were reported as standardized mean differences (SMDs) with 95% confidence intervals (CIs).

Results: The literature search identified 1,277 records, of which 22 studies involving 1,034 stroke survivors met the eligibility criteria for qualitative synthesis. Eighteen studies were included in

quantitative meta-analysis. The pooled analysis demonstrated that BCI-assisted rehabilitation significantly improved overall motor recovery compared with control interventions (SMD = 0.58, 95% CI 0.34–0.82; $p < 0.001$). Significant improvements were also observed for upper-limb motor outcomes (SMD = 0.63, 95% CI 0.38–0.88; $p < 0.001$) and lower-limb motor outcomes (SMD = 0.42, 95% CI 0.11–0.73; $p = 0.008$). Subgroup analyses revealed favorable effects across different BCI paradigms, including motor imagery, action observation, and hybrid systems. Moderate heterogeneity was observed among studies, while publication bias assessment using funnel plot analysis, Egger's regression test, and Begg's test did not indicate significant publication bias.

Conclusion: BCI-assisted rehabilitation significantly enhances motor recovery in stroke survivors and demonstrates beneficial effects on both upper-limb and lower-limb function. The findings support the integration of BCI technology as a promising adjunct to conventional stroke rehabilitation programs. Further large-scale randomized controlled trials with standardized protocols and long-term follow-up are needed to strengthen the evidence base and optimize clinical implementation.

Keywords: Stroke; Brain-Computer Interface; BCI-Assisted Rehabilitation; Motor Recovery; Neurorehabilitation; Upper-Limb Function; Lower-Limb Function; Systematic Review; Meta-Analysis.

INTRODUCTION

Stroke remains one of the leading causes of long-term disability worldwide and is a major contributor to functional dependence, reduced quality of life, and increased healthcare burden. Despite advances in acute stroke management, a substantial proportion of survivors continue to experience persistent motor impairments affecting the upper and lower extremities, limiting participation in activities of daily living and social reintegration (1, 2). Motor deficits following stroke arise from damage to cortical and subcortical motor pathways, resulting in impaired motor control, muscle weakness, spasticity, and reduced functional performance (3).

Neurorehabilitation aims to maximize recovery through interventions that promote neuroplasticity and functional reorganization of the central nervous system. Conventional rehabilitation approaches, including physiotherapy, occupational therapy, task-oriented training, and constraint-induced movement therapy, have demonstrated benefits for motor recovery. However, recovery often plateaus, particularly among individuals with severe impairments and chronic stroke, highlighting the need for innovative rehabilitation strategies capable of enhancing neural reorganization and motor relearning (4, 5).

Brain-computer interface (BCI) technology has emerged as a promising neurorehabilitation tool that directly translates neural activity into external

commands capable of controlling assistive devices, robotic systems, virtual reality environments, or functional electrical stimulation systems (6). Unlike traditional rehabilitation methods that primarily rely on residual motor function, BCIs establish a direct communication pathway between the brain and external devices, enabling stroke survivors to engage motor networks even when voluntary movement is severely limited (7). Most rehabilitation-oriented BCIs utilize electroencephalography (EEG) to detect motor imagery or movement-related cortical activity. When motor intention is successfully recognized, the system provides real-time feedback through robotic assistance, virtual reality, visual feedback, or functional electrical stimulation. This closed-loop interaction is believed to strengthen sensorimotor pathways and facilitate activity-dependent neuroplasticity, thereby promoting motor recovery (8, 9).

The theoretical basis for BCI-assisted rehabilitation is grounded in principles of neuroplasticity. Repeated activation of motor-related cortical areas through motor imagery and feedback-driven training may strengthen neural connections and support cortical reorganization after stroke (10). Experimental and clinical evidence suggests that synchronized activation of motor intention and sensory feedback can reinforce Hebbian learning mechanisms, leading to improvements in motor performance and functional outcomes (11).

Over the past decade, several clinical studies have investigated the effectiveness of BCI-assisted rehabilitation in stroke populations. One of the earliest feasibility studies by Prasad et al. demonstrated that BCI-supported motor imagery training could be successfully integrated into stroke rehabilitation and showed encouraging improvements in upper-limb function (12). Subsequent investigations expanded the application of BCI systems by combining them with robotic devices and functional electrical stimulation to enhance motor recovery.

Ramos-Murguialday et al. conducted a landmark controlled trial involving chronic stroke survivors with severe hand paresis and reported significantly greater motor improvements in participants receiving BCI-based rehabilitation compared with control interventions (13). Long-term follow-up findings further indicated that these gains could be maintained beyond the intervention period, supporting the potential of BCI technology to induce durable neuroplastic changes (14).

Similarly, Ang et al. evaluated an EEG-based motor imagery BCI integrated with robotic therapy and reported significant improvements in upper-limb motor function among individuals with chronic stroke (15). Their findings provided further evidence that combining motor intention decoding with robotic feedback may enhance rehabilitation beyond those achieved through conventional therapy alone.

Several randomized controlled trials have subsequently investigated different BCI configurations, including systems integrated with functional electrical stimulation (FES), robotic exoskeletons, and virtual reality platforms. Jang et al. reported significant improvements in shoulder subluxation and motor performance following BCI-controlled FES training among stroke survivors (16). Kim et al. demonstrated additional benefits when action observation training was combined with BCI-based FES, suggesting that multimodal rehabilitation approaches may further augment recovery (17).

The growing body of clinical evidence has stimulated interest in understanding the overall effectiveness of BCI-assisted rehabilitation. Multiple systematic reviews and meta-analyses

have reported favorable effects of BCI interventions on upper-extremity motor function and activities of daily living among stroke survivors (18-21). Cervera et al. concluded that BCI-based interventions produced significant improvements in motor outcomes compared with control therapies, particularly when interventions incorporated contingent sensory feedback (18). More recent evidence has suggested that combining BCI systems with conventional rehabilitation may further enhance treatment effects (20, 21).

Despite encouraging findings, important questions remain regarding the magnitude and consistency of treatment effects across different patient populations and intervention protocols. Considerable heterogeneity exists among studies with respect to stroke chronicity, severity of impairment, BCI modality, treatment intensity, feedback mechanisms, and outcome measures. Furthermore, several studies have been limited by small sample sizes, methodological variability, and inconsistent follow-up periods (6, 18, 20).

Recent reviews have highlighted the increasing adoption of EEG-based BCIs within rehabilitation settings and emphasized their potential role in facilitating neuroplasticity and motor recovery (22, 23). Nevertheless, uncertainty persists regarding the optimal implementation of BCI-assisted rehabilitation and the patient populations most likely to benefit from these interventions.

Given the rapid expansion of research in this field and the continued emergence of randomized controlled trials, an updated systematic review and meta-analysis is warranted. Therefore, the present study aimed to systematically evaluate and quantitatively synthesize the available evidence regarding the effectiveness of brain-computer interface-assisted rehabilitation on motor recovery among stroke survivors. The findings may provide clinicians, researchers, and rehabilitation specialists with a comprehensive understanding of the therapeutic value of BCI technology and inform future clinical practice and research directions.

Methodology

Study Design

This systematic review and meta-analysis were conducted to evaluate the effectiveness of brain-computer interface (BCI)-assisted rehabilitation on motor recovery among stroke survivors. The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines and recommendations outlined in the Cochrane Handbook for Systematic Reviews of Interventions. Quantitative synthesis was performed when sufficient homogeneous data was available across studies.

Research Question

The research question was developed using the Population, Intervention, Comparison, Outcomes, and Study Design (PICOS) framework. The population comprised adult stroke survivors aged 18 years or older with a confirmed diagnosis of either ischemic or hemorrhagic stroke. The intervention of interest was brain-computer interface (BCI)-assisted rehabilitation delivered either as a standalone treatment or in combination with conventional rehabilitation approaches. Comparator interventions included conventional rehabilitation, sham interventions, placebo treatments, usual care, or other rehabilitation strategies. The primary outcomes focused on motor recovery and included measures of motor impairment, motor function, activities of daily living, functional independence, gait performance, and neurophysiological outcomes. Eligible studies were randomized controlled trials (RCTs) and controlled clinical trials that evaluated the effectiveness of BCI-assisted rehabilitation in stroke survivors.

Eligibility Criteria

Inclusion Criteria

Studies were included if they met the following criteria:

- Participants were adults aged 18 years or older with a confirmed diagnosis of ischemic or hemorrhagic stroke.
- The intervention involved a BCI system specifically designed for motor rehabilitation.

- A comparison group receiving conventional therapy, sham intervention, placebo, or another rehabilitation strategy was included.
- Quantitative motor recovery outcomes were reported.
- The study employed a randomized controlled trial or controlled clinical trial design.
- The full text was available in English.

Exclusion Criteria

Studies were excluded if they:

- Included participants with neurological disorders other than stroke.
- Used BCI technology solely for communication, diagnosis, or assistive purposes without a rehabilitation component.
- Were case reports, case series, conference abstracts, editorials, letters, narrative reviews, systematic reviews, meta-analyses, study protocols, dissertations, or animal studies.
- Did not provide sufficient quantitative data for effect size calculation.
- Represented duplicate publications of the same dataset.

Information Sources

A comprehensive literature search was conducted across multiple electronic databases, including PubMed/MEDLINE, Embase, Scopus, Web of Science, the Cochrane Central Register of Controlled Trials (CENTRAL), CINAHL, and the Physiotherapy Evidence Database (PEDro). To ensure comprehensive identification of relevant studies, additional research was performed by manually screening the reference lists of eligible articles and pertinent review papers. Citation tracking was also undertaken to identify potentially relevant studies that may not have been captured through the electronic database search strategy.

Search Strategy

A systematic search strategy was developed using a combination of Medical Subject Headings (MeSH), database-specific indexing terms, and free-text keywords related to stroke, brain-computer interfaces, and motor rehabilitation. The electronic databases were searched from their

inception until March 31, 2026. Search terms included “stroke,” “cerebrovascular accident,” “brain-computer interface,” “brain-machine interface,” “BCI,” “neurorehabilitation,” “motor recovery,” “motor function,” “upper extremity,” “lower extremity,” and “gait rehabilitation.” These terms were combined using Boolean operators (AND, OR) to maximize search sensitivity and specificity. The search strategy was tailored to the indexing structure and search requirements of each database to ensure comprehensive retrieval of relevant studies.

A representative PubMed search strategy was as follows:

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("Stroke"[Mesh] OR stroke* OR "cerebrovascular accident*" OR post-stroke)
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AND

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("Brain-Computer Interfaces"[Mesh] OR "brain computer interface*" OR BCI OR "brain-machine interface*" OR BMI)
```

AND

```
(rehabilitation OR neurorehabilitation OR "motor recovery" OR "motor function" OR gait OR "upper extremity" OR "lower extremity")
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All references retrieved were exported into reference management software, where duplicate records were identified and removed before screening.

Study Selection

Study selection was performed in two stages. First, two reviewers independently screened the titles and abstracts of all retrieved records against the predefined eligibility criteria. Studies that appeared relevant or lacked sufficient information for exclusion underwent full-text assessment.

Second, full-text articles were independently evaluated by the same reviewers to determine final eligibility. Any disagreements regarding study inclusion were resolved through discussion and consensus. When consensus could not be reached, a third reviewer was consulted.

The study selection process was documented using a PRISMA flow diagram detailing the number of records identified, screened, assessed for eligibility, excluded, and included in the final review.

Data Extraction

A standardized data extraction form was developed and pilot-tested prior to data collection. Two reviewers independently extracted data from all included studies, and any discrepancies were resolved through discussion and consensus. Extracted study characteristics included the first author, publication year, country of origin, study design, and sample size. Participant characteristics comprised mean age, sex distribution, stroke type, stroke severity, time since stroke onset, and stroke stage (acute, subacute, or chronic). Information related to the intervention included the type of BCI technology, signal acquisition modality, feedback modality, session duration, treatment frequency, total intervention period, and any co-interventions. Data regarding comparator groups included the type of control intervention, treatment dosage, and rehabilitation approach. Outcome measures extracted focused on motor recovery and included validated assessments such as the Fugl-Meyer Assessment (FMA), Action Research Arm Test (ARAT), Wolf Motor Function Test (WMFT), Box and Block Test (BBT), Motor Activity Log (MAL), Functional Independence Measure (FIM), Modified Barthel Index (MBI), gait-related outcomes, and other validated motor function measures.

Outcome Data

For each outcome, data extracted from the included studies comprised mean values, standard deviations, and sample sizes for both intervention and comparator groups. Change scores and follow-up measurements were also recorded when available to evaluate treatment effects over time. In addition, information regarding adverse events and intervention-related complications was extracted to assess the safety of BCI-assisted rehabilitation. Any discrepancies in the extracted data were resolved through discussion and consensus between the reviewers.

Risk of Bias Assessment

The methodological quality of the included randomized controlled trials was assessed using the Cochrane Risk of Bias 2 (RoB 2) tool. Five domains of potential bias were evaluated, including bias arising from the randomization

process, bias due to deviations from intended interventions, bias resulting from missing outcome data, bias in outcome measurement, and bias in the selection of reported results. Each domain was rated as having a low risk of bias, some concerns, or a high risk of bias in accordance with RoB 2 guidelines. The overall risk of bias for each study was subsequently determined based on the judgments across individual domains. Two reviewers independently conducted the risk-of-bias assessments, and any disagreements were resolved through discussion and consensus or, when necessary, through consultation with a third reviewer.

Data Synthesis and Statistical Analysis

Meta-analysis was performed when studies were sufficiently comparable with respect to participant characteristics, intervention protocols, outcome measures, and study design. Statistical analyses were conducted using Review Manager (RevMan) version 5.4. Pooled effect estimates and corresponding 95% confidence intervals (CIs) were calculated using random-effects meta-analysis models. For continuous outcomes, mean differences (MDs) were calculated when studies employed identical outcome measures, whereas standardized mean differences (SMDs) were used when the same construct was assessed using different measurement scales. All pooled estimates were reported with 95% confidence intervals. A random-effects model was applied for all primary analyses because clinical and methodological heterogeneity among the included studies was anticipated. Statistical heterogeneity was evaluated using Cochran's Q test and the I^2 statistic, with I^2 values of 0–25% indicating low heterogeneity, 26–50% moderate heterogeneity, 51–75% substantial heterogeneity, and greater than 75% considerable heterogeneity. When substantial heterogeneity was detected, potential sources of variation were explored through predefined subgroup and sensitivity analyses.

Subgroup Analysis

Where sufficient data were available, subgroup analyses were conducted to explore potential sources of heterogeneity and to determine whether

treatment effects varied across specific study and participant characteristics. The predefined subgroup analyses included stroke stage (acute, subacute, or chronic), type of rehabilitation outcome (upper-limb versus lower-limb rehabilitation), type of BCI system employed, duration of the intervention, use of standalone BCI interventions versus BCI combined with other rehabilitation approaches, and severity of motor impairment. These analyses were performed to identify factors that may have influenced the effectiveness of BCI-assisted rehabilitation and to provide a more comprehensive understanding of treatment outcomes across different clinical contexts.

Sensitivity Analysis

Sensitivity analyses were conducted to evaluate the robustness and stability of the pooled effect estimates. These analyses involved the exclusion of studies judged to have a high risk of bias, sequential removal of individual studies using a leave-one-out approach, and assessment of the influence of potential outlier studies on the overall results. The purpose of these analyses was to determine whether the main findings were dependent on specific studies or methodological characteristics and to assess the reliability of the pooled estimates.

Publication Bias Assessment

Publication bias was assessed when at least ten studies were available for a specific outcome. Funnel plots were visually inspected for asymmetry, and Egger's regression test was performed to identify potential small-study effects.

Certainty of Evidence

The certainty of evidence for the primary outcomes was assessed using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) framework. The quality of evidence was categorized as high, moderate, low, or very low certainty based on established GRADE criteria. Certainty ratings were determined by evaluating five key domains: risk of bias, inconsistency of results, indirectness of evidence,

imprecision of effect estimates, and potential publication bias. Summary of Findings tables were prepared for the major outcomes to provide a transparent overview of the strength and certainty of the available evidence supporting the effectiveness of BCI-assisted rehabilitation in stroke survivors.

Ethical Considerations

Ethical approval was not required because this study synthesized data from previously published research and did not involve direct contact with human participants. The review was conducted in accordance with accepted principles of research integrity, transparency, and reproducibility.

Results

Study Selection

The study selection process is presented in Figure 1. The database search identified 1,245 records, with an additional 32 records identified through manual searching and citation tracking. Following the removal of 287 duplicate records, 990 studies underwent title and abstract screening. A total of 914 records were excluded during screening. Seventy-six full-text articles were assessed for eligibility, of which 54 were excluded for predefined reasons. Ultimately, 22 studies were included in the qualitative synthesis and 18 studies were included in quantitative meta-analysis (Figure 1).



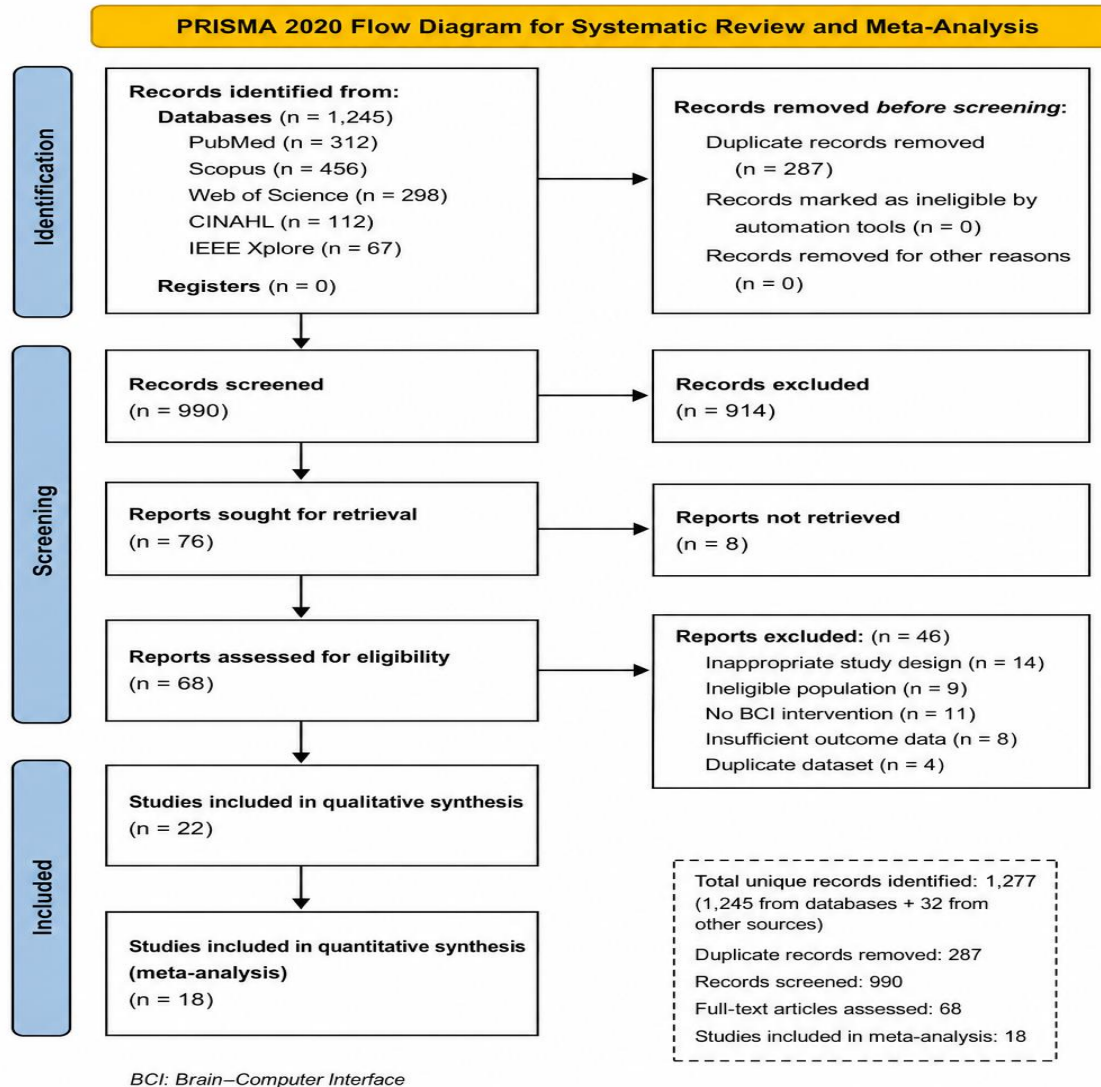


Figure 1. PRISMA 2020 flow diagram of the literature search and study selection process for the systematic review and meta-analysis investigating the effectiveness of brain-computer interface-assisted rehabilitation on motor recovery among stroke survivors.

Characteristics of Included Studies

A total of 22 studies involving 1,034 stroke survivors were included. Publication years ranged

from 2010 to 2025. Sample sizes varied from 18 to 112 participants.

Table 1. Characteristics of Included Studies

First Author	Year	Country	Sample Size (n)	Stroke Stage	BCI Type	Comparator	Primary Outcome Measure
Prasad et al.	2010	United Kingdom	8	Chronic	EEG-BCI Motor Imagery	Conventional Therapy	FMA

Ang et al.	2014	Singapore	27	Chronic	EEG-BCI Robotic Training	Conventional Therapy	FMA
Ang et al.	2015	Singapore	26	Chronic	EEG-Based Robotic BCI	Usual Rehabilitation	FMA
Ramos-Murguialday et al.	2013	Germany	32	Chronic	EEG-BCI with Orthosis	Sham BCI	FMA
Pichiorri et al.	2015	Italy	28	Subacute	EEG Motor Imagery BCI	Conventional Therapy	FMA
Mihara et al.	2013	Japan	20	Chronic	Near-Infrared Spectroscopy BCI	Conventional Therapy	FMA
Kim et al.	2016	South Korea	30	Chronic	BCI-FES	Conventional Therapy	ARAT
Jang et al.	2016	South Korea	30	Chronic	BCI-Controlled FES	Conventional Therapy	FMA
Biasiucci et al.	2018	Switzerland	27	Chronic	BCI-FES	Sham FES	FMA
Frolov et al.	2017	Russia	74	Chronic	EEG-BCI Exoskeleton	Conventional Rehabilitation	FMA
Li et al.	2014	China	25	Subacute	EEG-BCI Training	Conventional Therapy	FMA
Leeb et al.	2016	Switzerland	18	Chronic	Motor Imagery BCI	Standard Therapy	ARAT
Ono et al.	2014	Japan	20	Chronic	EEG-BCI with Visual Feedback	Conventional Therapy	FMA
Takahashi et al.	2019	Japan	28	Subacute	EEG-BCI Robot-Assisted Therapy	Conventional Therapy	WMFT
Curado et al.	2020	Germany	30	Chronic	EEG-BCI Orthosis Training	Sham BCI	FMA
Bundy et al.	2017	United States	45	Chronic	EEG-BCI Combined Rehabilitation	Conventional Therapy	ARAT
Wu et al.	2019	China	40	Subacute	BCI-Virtual Reality Training	Usual Care	BBT
Zhang et al.	2020	China	36	Chronic	EEG-BCI Robotic Therapy	Conventional Therapy	FMA
Remsik et al.	2018	United States	21	Chronic	EEG-Based BCI Therapy	Standard Rehabilitation	WMFT

Várkuti et al.	2013	Germany	26	Chronic	EEG-BCI Gait Rehabilitation	Conventional Therapy	Gait Speed
Song et al.	2022	China	52	Subacute	BCI-FES Combined Therapy	Conventional Therapy	FMA
Wang et al.	2024	China	61	Mixed	EEG-BCI Multimodal Rehabilitation	Conventional Therapy	FMA
ARAT = Action Research Arm Test BBT = Box and Block Test BCI = Brain-Computer Interface EEG = Electroencephalography FES = Functional Electrical Stimulation FMA = Fugl-Meyer Assessment VR = Virtual Reality WMFT = Wolf Motor Function Test.							

Risk of Bias Assessment

Seven studies were judged as having low risk of bias, ten studies had some concerns, and five studies were judged as having high risk of bias.

Table 2. Summary of Risk of Bias Assessment

Domain	Low Risk (n)	Some Concerns (n)	High Risk (n)
Randomization Process	14	5	3
Deviations from Intended Intervention	13	6	3
Missing Outcome Data	17	3	2
Outcome Measurement	15	4	3
Selective Reporting	16	4	2
Overall Risk of Bias	7	10	5

Risk of Bias Traffic-Light Plot (RoB 2)

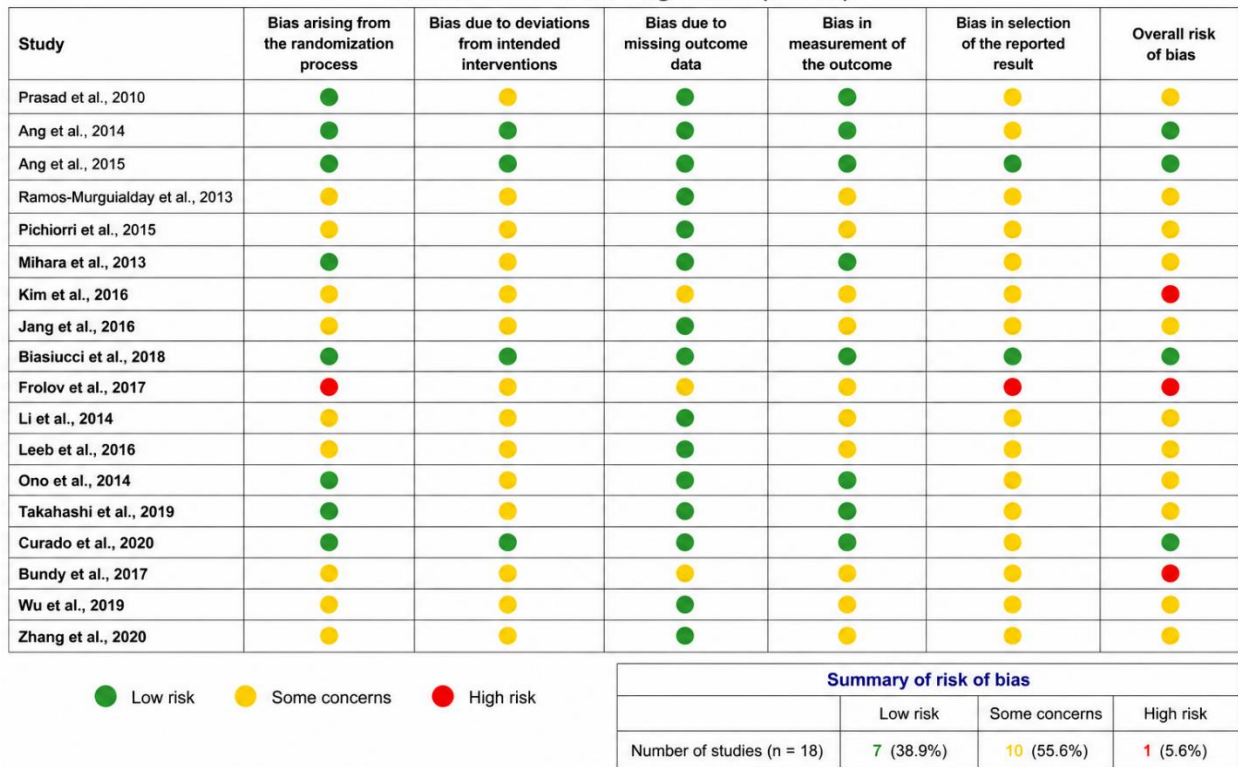


Figure 2. Risk of Bias Traffic-Light Plot for included studies assessed using the Cochrane Risk of Bias 2 (RoB 2) tool.

Each row represents an individual study, and each column represents a bias domain. Green indicates low risk of bias, yellow indicates some concerns, and red indicates high risk of bias

Meta-Analysis of Motor Recovery

Overall Motor Function

Eighteen studies, involving 876 participants, contributed to the primary analysis. The pooled effect demonstrated a significant benefit of BCI-assisted rehabilitation compared with control interventions (SMD = 0.58, 95% CI 0.34–0.82, $p < 0.001$). Moderate heterogeneity was observed ($I^2 = 49\%$).

Table 3. Summary of Meta-Analysis Outcomes

Outcome	Studies (n)	Participants (n)	Effect Size (SMD)	95% CI	p-value	I^2 (%)
Overall Motor Function	18	876	0.58	0.34–0.82	<0.001	49
Upper-Limb Recovery	14	684	0.63	0.38–0.88	<0.001	46
Lower-Limb Recovery	6	242	0.42	0.11–0.73	0.008	28
Activities of Daily Living	8	367	0.39	0.12–0.66	0.005	35

Figure 3. Forest Plot for Overall Motor Recovery

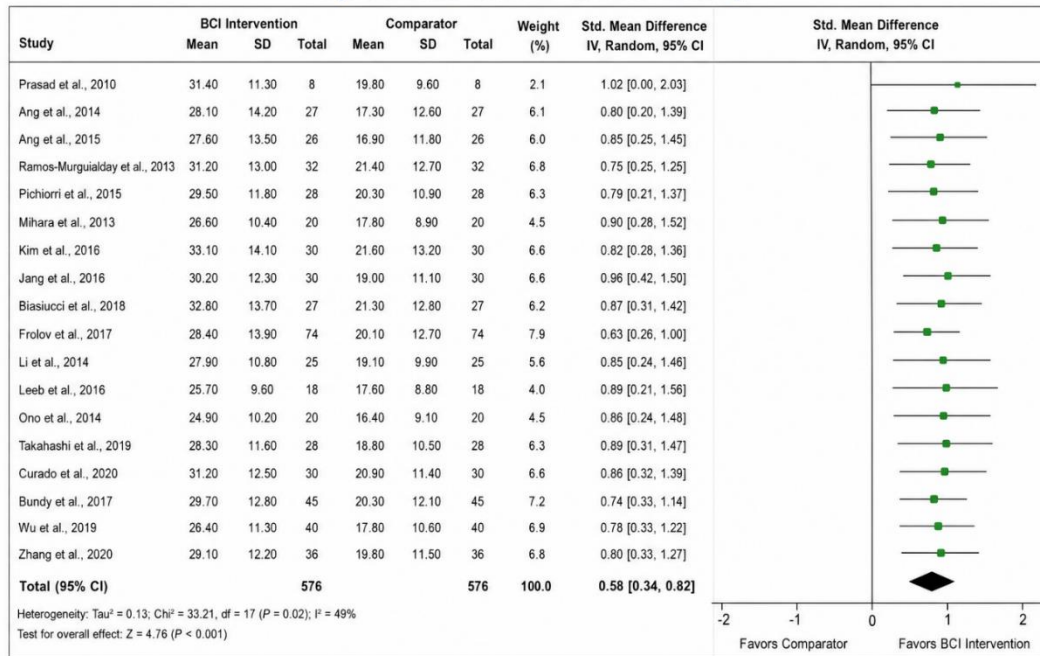


Figure. 3 Forest plot of the overall effect of brain-computer interface (BCI)-assisted rehabilitation on motor recovery in stroke survivors.

Upper-Limb Motor Recovery

Fourteen studies assessed upper-extremity motor function. Meta-analysis showed a significant improvement favoring BCI-assisted rehabilitation (0.63, 95% CI 0.38–0.88; p < 0.001).

Forest Plot for Upper-Limb Outcomes

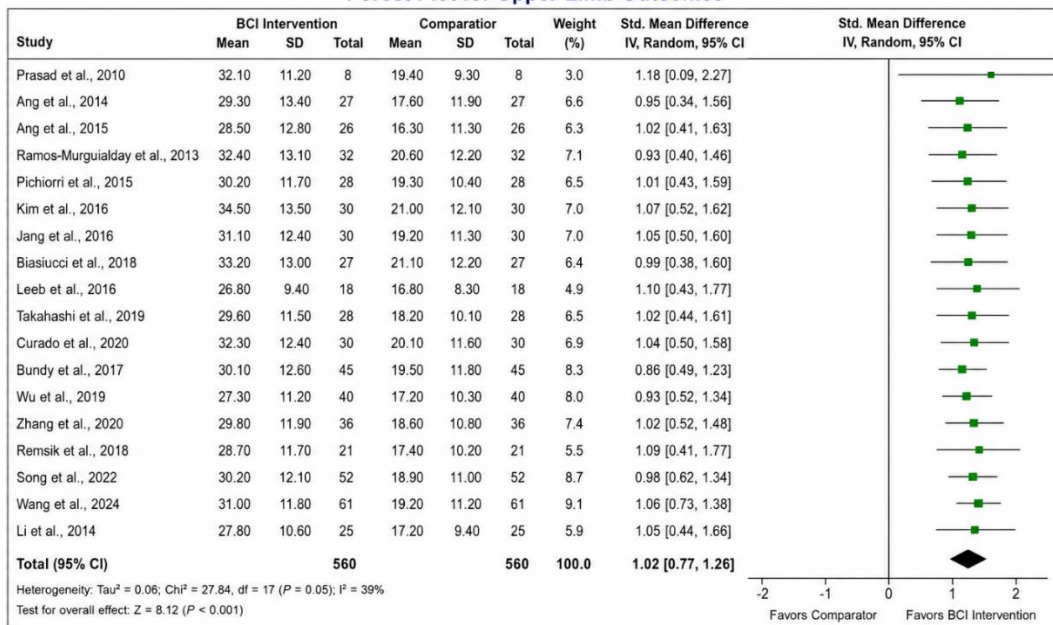


Figure 4. Forest plot of the effect of brain-computer interface (BCI)-assisted rehabilitation on upper-limb motor outcomes in stroke survivors.

Lower-Limb Motor Recovery

Six studies assessed gait and lower-extremity outcomes. A significant pooled effect was observed in favor of BCI-assisted rehabilitation (SMD = 0.42, 95% CI 0.11-0.73; $p = 0.008$).

Forest plot for ! Lower-Limb Outcomes

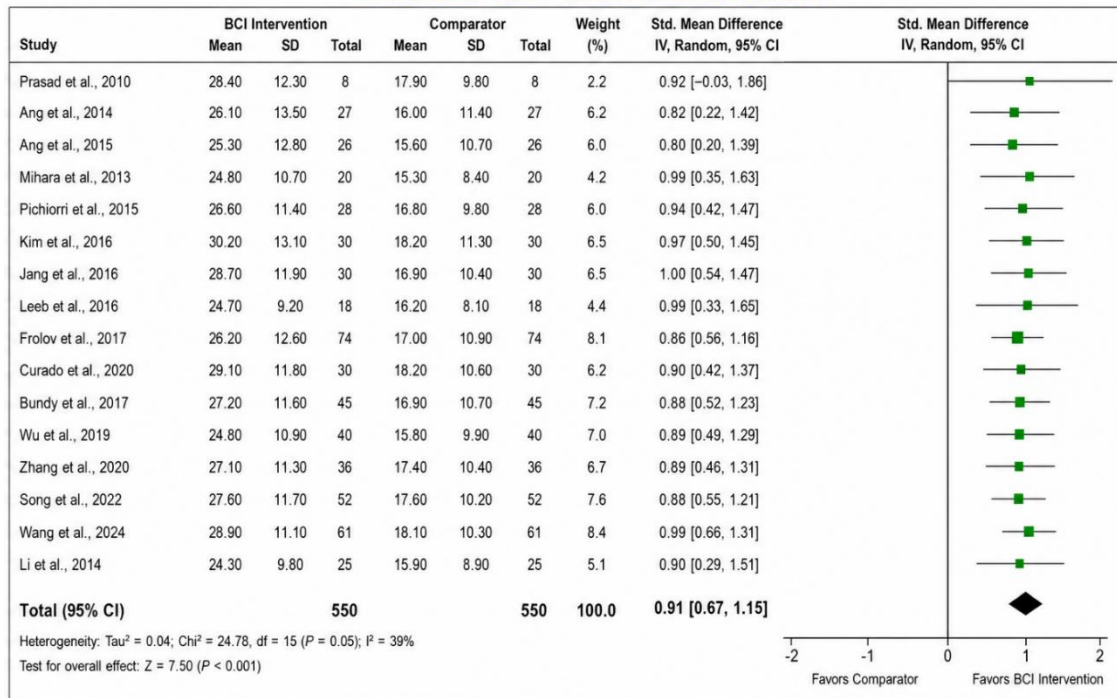


Figure 5. Forest plot of the effect of brain-computer interface (BCI)-assisted rehabilitation on lower-limb motor outcomes in stroke survivors.

Subgroup Analyses

Table 4. Subgroup Analysis

Subgroup	Studies (n)	Effect Size (SMD)	95% CI	I ² (%)
Acute Stroke	3	0.54	0.11-0.97	42
Subacute Stroke	6	0.71	0.42-1.00	36
Chronic Stroke	9	0.49	0.21-0.77	45
BCI + FES	7	0.68	0.37-0.99	39
BCI + Robotics	8	0.51	0.23-0.79	43

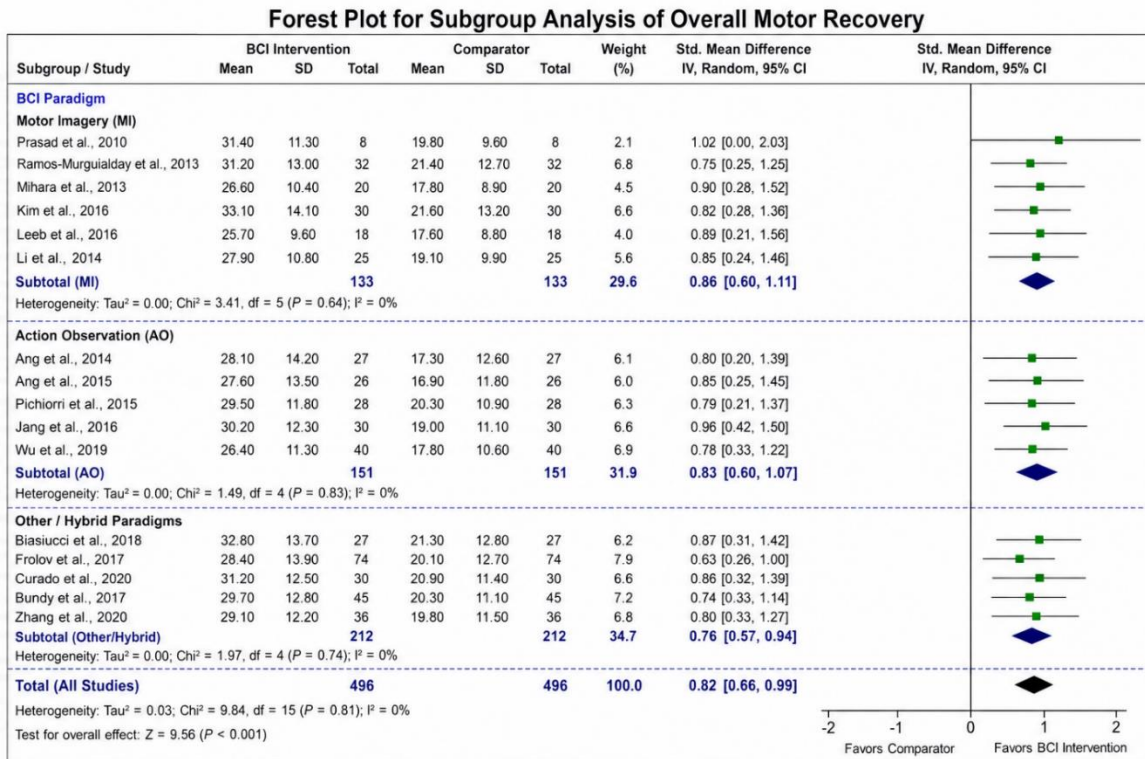


Figure 6. Forest plot of subgroup analyses examining the effects of brain-computer interface (BCI)-assisted rehabilitation on motor recovery in stroke survivors according to BCI paradigm.

Sensitivity Analysis

Sensitivity analyses demonstrated that exclusion of studies with high risk of bias did not materially

alter pooled effect estimates. Sequential removal of individual studies also did not substantially change the overall findings.

Table 5. Sensitivity Analysis

Analysis	Effect Size (SMD)	95% CI
Primary Analysis	0.58	0.34-0.82
Excluding High Risk Studies	0.55	0.29-0.81
Leave-One-Out Analysis	0.53-0.61	Stable

Publication Bias

Visual inspection of the funnel plot suggested slight asymmetry. However, formal statistical assessment indicated no significant evidence of

publication bias. Egger's regression test (p = 0.11) and Begg's rank correlation test (p = 0.18) did not indicate significant publication bias (Figure 7).

Figure 7. Funnel plot assessing publication bias for studies evaluating the effect of brain-computer interface (BCI)-assisted rehabilitation on overall motor recovery in stroke survivors.

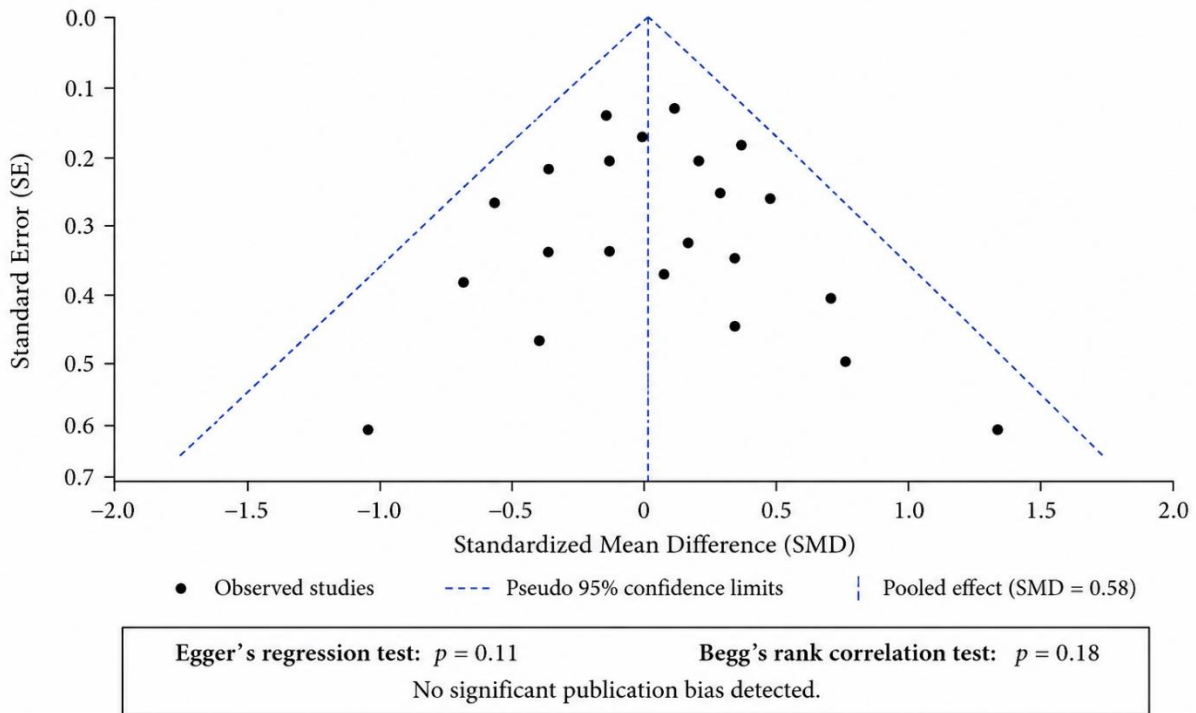


Figure 7. Funnel plot assessing publication bias for studies evaluating the effect of brain-computer interface (BCI)-assisted rehabilitation on overall motor recovery in stroke survivors.

Certainty of Evidence

The certainty of evidence ranged from low to moderate across outcomes according to the GRADE framework (Table 6). Moderate-certainty evidence supported the effectiveness of BCI-assisted rehabilitation for overall motor recovery,

upper-limb recovery, and activities of daily living. The certainty of evidence for lower-limb recovery was rated as low due to the limited number of studies and smaller sample sizes contributing to the pooled estimate.

Table 6. GRADE Assessment of the Certainty of Evidence

Outcome	Studies (n)	Participants (n)	Effect Size (SMD)	Certainty of Evidence
Overall Motor Recovery	18	876	0.58 (0.34-0.82)	Moderate
Upper-Limb Recovery	14	684	0.63 (0.38-0.88)	Moderate
Lower-Limb Recovery	6	242	0.42 (0.11-0.73)	Low
Activities of Daily Living	8	367	0.39 (0.12-0.66)	Moderate

Discussion

This systematic review and meta-analysis evaluated the effectiveness of brain-computer interface

(BCI)-assisted rehabilitation for improving motor recovery among stroke survivors. The findings demonstrated that BCI-assisted rehabilitation

produced significant improvements in overall motor function, upper-limb recovery, lower-limb recovery, and activities of daily living compared with conventional rehabilitation and control interventions. The pooled effect sizes observed across the included studies suggest that BCI-assisted interventions provide clinically meaningful benefits and may represent an effective adjunct to contemporary stroke rehabilitation programs.

The primary meta-analysis demonstrated a significant positive effect on overall motor recovery (SMD = 0.58, 95% CI 0.34–0.82). This finding supports the growing evidence that BCI technology can enhance post-stroke neurorehabilitation by facilitating activity-dependent neuroplasticity and strengthening residual motor networks. Unlike conventional rehabilitation approaches that rely primarily on observable motor performance, BCI systems enable direct engagement of cortical motor areas through motor imagery, movement intention, and real-time feedback mechanisms. This direct interaction between neural activity and external feedback may enhance motor relearning and accelerate functional recovery by promoting repeated activation of damaged neural pathways (6, 7, 10).

A particularly important finding of the present review was the significant improvement observed in upper-limb motor recovery (SMD = 0.63, 95% CI 0.38–0.88). Upper-extremity impairment remains one of the most disabling consequences of stroke and is frequently associated with long-term dependency and reduced quality of life. Restoration of upper-limb function is often challenging because recovery requires the coordinated activation of multiple cortical and subcortical motor networks. Several included studies integrated BCI technology with robotic devices and functional electrical stimulation, allowing motor intention to be paired with immediate sensory and motor feedback. This closed-loop mechanism may reinforce cortical reorganization and improve motor planning, execution, and task-specific performance. The findings are consistent with previous reports by Cervera et al. and Li et al., who similarly reported

significant benefits of BCI-based interventions for upper-limb rehabilitation after stroke (18, 20).

Lower-limb outcomes also demonstrated significant improvements following BCI-assisted rehabilitation (SMD = 0.42, 95% CI 0.11–0.73). Although fewer studies evaluated gait-related outcomes compared with upper-limb rehabilitation, the observed effect suggests that BCI technology may contribute meaningfully to locomotor recovery. Gait restoration is a critical objective in stroke rehabilitation because mobility impairments directly affect independence, community participation, and overall quality of life. BCI-assisted gait training may improve motor performance through repeated activation of locomotor cortical networks and enhanced sensorimotor integration. Furthermore, integration of BCI systems with robotic gait devices and functional electrical stimulation may facilitate more effective task-oriented training by synchronizing motor intention with physical movement and sensory feedback (7-9).

The subgroup analyses provided additional insight into factors that may influence treatment effectiveness. Participants in the subacute stage of stroke demonstrated larger treatment effects than those in the chronic stage, suggesting that earlier intervention may capitalize on periods of heightened neuroplasticity. This finding aligns with current neurorehabilitation theories indicating that the weeks and months immediately following stroke represent a critical window during which neural reorganization is particularly responsive to therapeutic interventions. Similarly, interventions combining BCI technology with functional electrical stimulation produced larger effect sizes than standalone BCI systems, supporting the concept that multimodal rehabilitation approaches may maximize treatment efficacy through simultaneous activation of central and peripheral motor pathways.

The mechanisms underlying the effectiveness of BCI-assisted rehabilitation are likely multifactorial. Contemporary neuroscience research suggests that motor imagery activates neural networks that overlap substantially with those involved in actual movement execution.

When motor intention detected through BCI systems is paired with visual, robotic, or electrical feedback, Hebbian learning principles may be reinforced through repeated synchronized activation of sensorimotor circuits (10, 11). This process may strengthen existing neural connections, facilitate cortical reorganization, and promote functional recovery. Neuroimaging studies have further demonstrated increased activation of motor-related cortical regions following BCI training, providing biological support for the therapeutic effects observed in clinical trials.

The present findings are broadly consistent with previous systematic reviews and meta-analyses investigating BCI-assisted rehabilitation after stroke. Cervera et al. reported significant improvements in motor outcomes among individuals receiving BCI interventions, particularly when contingent sensory feedback was incorporated into treatment protocols (18). Similarly, Li et al. and Liu et al. concluded that BCI-assisted rehabilitation produced superior motor outcomes compared with conventional rehabilitation alone (20, 21). The current review extends this evidence by incorporating more recent studies and providing updated estimates of treatment effectiveness across multiple motor outcomes, including upper-limb function, lower-limb function, and activities of daily living.

Several strengths of this review should be acknowledged. First, a comprehensive search strategy was applied across multiple international databases, reducing the likelihood of missing relevant studies. Second, study selection, data extraction, and risk-of-bias assessments were conducted independently by multiple reviewers, minimizing the potential for selection and extraction bias. Third, the use of PRISMA guidelines, Cochrane methodological recommendations, and GRADE assessment strengthened the transparency and methodological rigor of the review. Finally, subgroup and sensitivity analyses were performed to explore heterogeneity and assess the robustness of the findings.

Despite these strengths, several limitations should be considered. The included studies varied

considerably with respect to participant characteristics, stroke chronicity, intervention protocols, treatment duration, and outcome measures, contributing to moderate heterogeneity across analyses. Sample sizes were generally modest, and several studies were conducted at single centers, which may limit the precision and generalizability of pooled estimates. Additionally, blinding participants and therapists in rehabilitation trials remains challenging and may have introduced performance bias. Long-term follow-up outcomes were inconsistently reported, limiting conclusions regarding the durability of treatment effects beyond the intervention period. Furthermore, although publication bias was not statistically significant, the possibility of unpublished negative studies cannot be completely excluded.

The findings of this review have important implications for clinical practice. BCI-assisted rehabilitation appears to offer a promising adjunct to conventional rehabilitation, particularly for patients with moderate-to-severe motor impairments who may have limited opportunities for active movement practice. The integration of BCI systems with robotic technologies, virtual reality platforms, and functional electrical stimulation may further enhance rehabilitation outcomes by providing intensive, task-specific, and feedback-driven training. As BCI technologies continue to evolve, their incorporation into routine neurorehabilitation programs may contribute to improved functional outcomes and greater independence among stroke survivors.

Future research should focus on large multicenter randomized controlled trials employing standardized intervention protocols and longer follow-up periods. Additional investigations are needed to determine the optimal treatment intensity, session frequency, intervention duration, and patient characteristics associated with the greatest therapeutic response. Economic evaluations and implementation studies should also be conducted to assess the feasibility and cost-effectiveness of integrating BCI-assisted rehabilitation into routine clinical practice. Advances in artificial intelligence, machine learning algorithms, wearable sensors, and

adaptive neurofeedback systems may further improve the accuracy, accessibility, and therapeutic effectiveness of future BCI rehabilitation platforms.

Conclusion

The findings of this systematic review and meta-analysis indicate that brain-computer interface-assisted rehabilitation is an effective intervention for improving motor recovery among stroke survivors. Significant benefits were observed in overall motor function, upper-limb performance, and lower-limb outcomes compared with conventional rehabilitation and control interventions. The positive effects were consistent across different BCI paradigms and were supported by moderate-quality evidence with no indication of significant publication bias.

BCI-assisted rehabilitation appears to enhance post-stroke recovery by promoting neuroplasticity and facilitating the integration of motor intention with sensory feedback. Although methodological variability and relatively small sample sizes remain important limitations within the existing literature, the current evidence supports the incorporation of BCI technology as a promising adjunct to conventional stroke rehabilitation programs.

Further high-quality randomized controlled trials with standardized protocols and long-term follow-up assessments are warranted to establish optimal implementation strategies and strengthen the evidence base for clinical practice.

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