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Upper-Limb Rehabilitation After Stroke Using tDCS Combined with Motor Imagery BCI: A Review of Post-2020 Randomized Controlled Trials

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Abstract. The persistence of upper-limb motor impairments after stroke is often compounded by the limitations of conventional rehabilitation, which is hindered by insufficient training intensity, poor task relevance, and low adherence. Motor-imagery brain-computer interfaces (MI-BCIs) can promote neuroplasticity via a closed-loop process involving decoding, external feedback, and reinforcement learning. In parallel, transcranial direct current stimulation (tDCS) can modulate cortical excitability and network connectivity, and is therefore used either as pre-training priming or concurrently with training to enhance learning. In recent years, randomized controlled trials (RCTs) combining tDCS with MI-BCI have produced inconsistent findings: some studies report benefits in specific subgroups or parameter combinations, but overall incremental benefits are unstable. Focusing on RCTs published since 2020, this narrative synthesis summarizes clinical efficacy, moderators, safety, and mechanistic evidence, with emphasis on comparisons across stroke stage/severity, motor-evoked potential (MEP) status, tDCS timing and montage, dose, and the allocation of effective closed-loop BCI training time. The evidence indicates that MI-BCI leads to consistent short-term improvements in upper-limb function, whereas the added benefits of tDCS depend on patient stratification, parameter optimization, and may be limited by insufficient synergy or mutual cancellation. Future work should adopt preregistered, stratified randomization within multicenter, adequately powered trials; directly compare priming versus concurrent strategies; and jointly analyze mechanistic markers (EEG/TMS/fMRI) and clinical outcomes using prespecified primary-secondary endpoint linkages to move the combined protocol from feasible to reproducible and scalable.

Keywords: Stroke, Transcranial Direct Current Stimulation (tDCS), Motor Imagery, Brain-Computer Interface (BCI), Randomized Controlled Trial (RCT)

1. Introduction

Stroke is a leading cause of long-term disability in adults. Upper-limb motor impairment, in particular, significantly impairs activities of daily living and restricts social participation. Although conventional occupational therapy and intensive training can be effective, insufficient training dose,

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limited feedback quality, and difficulties sustaining motivation continue to restrict outcomes for some patients. Motor-imagery brain-computer interfaces (MI-BCIs) decode motor intention from EEG and trigger robotic devices, exoskeletons, functional electrical stimulation, or virtual-reality feedback, forming an intention-feedback closed loop. This paradigm delivers task-relevant sensorimotor input even when voluntary movement is limited, thereby creating conditions for plastic reorganization. Transcranial direct current stimulation (tDCS) uses weak direct currents to modulate cortical excitability and network state, and is commonly applied either as pre-training priming or concurrently with training to lower learning thresholds and facilitate training-related plasticity. However, the marginal benefit of combining these interventions is inconsistent. To interpret these inconsistencies, a unified framework is needed to compare stroke stage and severity, MEP status, stimulation timing and dose, and the allocation of effective closed-loop BCI training time within a fixed total session duration. Accordingly, using RCTs published since 2020 as core evidence, this paper explores whether the combined approach outperforms MI-BCI alone or sham-controlled conditions, and analyzes factors influencing efficacy. It also assesses safety and feasibility, and discusses whether mechanistic evidence supports synergy and its relation to clinical outcomes. Based on these considerations, a parameterized framework for clinical translation is proposed, and key directions for future study design are outlined.

2. Clinical trials screening and characteristics

2.1. Literature screening and inclusion criteria

Using a narrative synthesis combined with evidence mapping, randomized controlled trials published since 2020 on tDCS combined with MI-BCI for post-stroke upper-limb rehabilitation were summarized. The search covered PubMed, Embase, Web of Science, and Cochrane CENTRAL, supplemented by backward reference tracking to identify additional relevant studies. The screening process followed the PRISMA 2020 guideline; details are shown in Figure 1 [1].

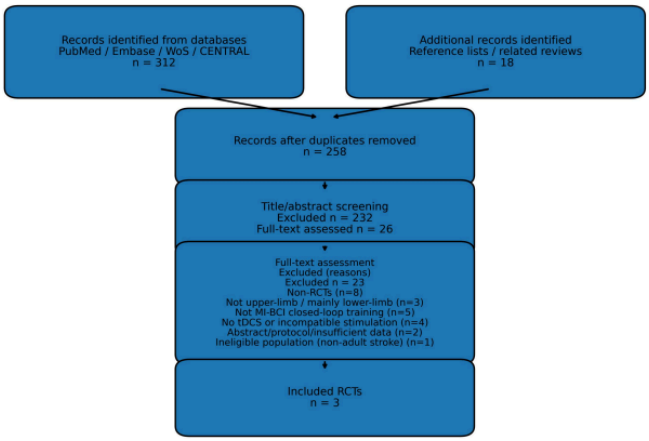

Figure 1. PRISMA 2020 flow diagram for study selection

Inclusion criteria were: adults with stroke; a randomized controlled design; an intervention including closed-loop MI-BCI training combined with active tDCS (either priming or concurrent); and a control condition of sham tDCS + MI-BCI, MI-BCI alone, or usual rehabilitation. All included studies reported at least one upper-limb function or activity outcome. Since 2020, the number of RCTs on tDCS + MI-BCI has increased, but study designs are highly heterogeneous. Key differences include tDCS timing (priming vs concurrent/split), electrode montage and dose, and the

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allocation of effective closed-loop BCI training time under a fixed total session duration. As presented in Figure 2, such design differences may influence learning curves and the training dose delivered, potentially reducing the comparability of clinical outcomes across trials. In addition, detailed design features, such as study characteristics and the parameter matrix, are summarized in Table 1.

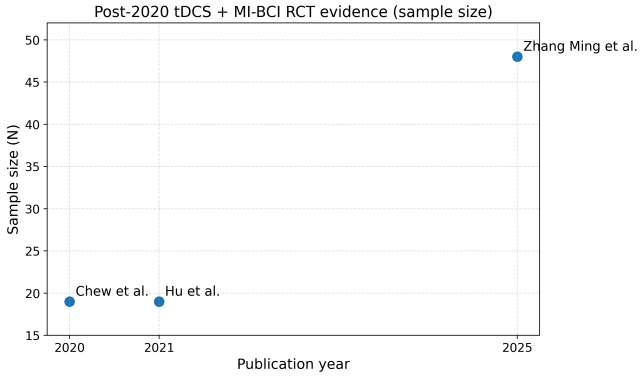

Figure 2. Evidence map of post-2020 RCTs: year vs. sample size

Table 1. Study features and parameter matrix of included trials

Study	Stage	N	tDCS	BCI	Key Outcome(s)
Chew et al., 2020	Chronic	19	1 mA, 20 min, bilateral M1 (ipsilesional anode/contralesional cathode), priming	MI-BCI 60 min/session × 10; robotic feedback	FMA-UE
Hu et al., 2021	Chronic (subcortical)	19	20 min, priming (pilot; similar montage)	MI-BCI 60 min/session × 10; robotic feedback	FMA + rs-fMRI
Ming et al., 2025	Subacute (14–180 d)	48	30 min/session (combined: 15 min); 5/wk × 4 wks (20 sessions)	KI-BCI 30 min/session (combined: 15 min); robotic assistance	FMA-UE / ARAT / MBI / MSS + qEEG

2.2. Data extraction and quality assessment

During data extraction, key intervention factors and outcome measures were collected. Intervention factors included sample size and participant characteristics (e.g., stroke stage, severity, lesion side, and MEP status), which are crucial for assessing the variability in treatment effects. Besides, core tDCS parameters such as target site, polarity, intensity, duration, and timing may influence neuroplasticity and thus upper-limb recovery. BCI training elements (task type, signal features, feedback modality, training frequency, and total dose) were also extracted. For outcomes, primary and secondary endpoints, follow-up time points, and adverse events were recorded. Risk of bias was assessed using the RoB 2 framework, which evaluates five key domains: randomization, intervention deviations, missing data, outcome measurement, and selective reporting. This structured assessment helps identify sources of bias and interpret uncertainty in the evidence [2]. For primary outcomes, the Fugl-Meyer Assessment-Upper Extremity (FMA-UE) scale is commonly used [3]. In addition, the conceptual framework (Figure 3) illustrates how tDCS modulates plasticity thresholds and network states, thereby influencing the translation pathway from MI-BCI closed-loop learning to clinical outcomes.

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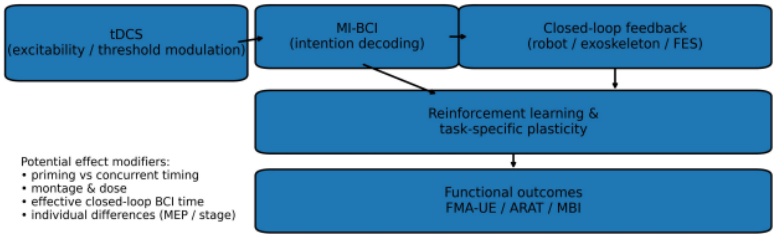

Figure 3. Conceptual model of tDCS-enhanced MI-BCI rehabilitation mechanisms

3. The clinical efficacy and implementation considerations of tDCS combined with MI-BCI

3.1. The clinical efficacy and variability in response

As shown in Figure 4, the included RCTs span a range of sample sizes. Overall, the results suggest that MI-BCI training can produce short-term improvements in upper-limb function, whereas incremental benefits from adding tDCS are inconsistent. This instability may reflect multiple factors, including population heterogeneity (e.g., stroke stage, severity, and pathway integrity), differences in stimulation and training parameters (e.g., timing, target, and dose), and compression of the effective BCI training dose. Under a fixed total session duration, differences in how time is allocated may lead to insufficient training dose, thereby undermining the stability of clinical benefits.

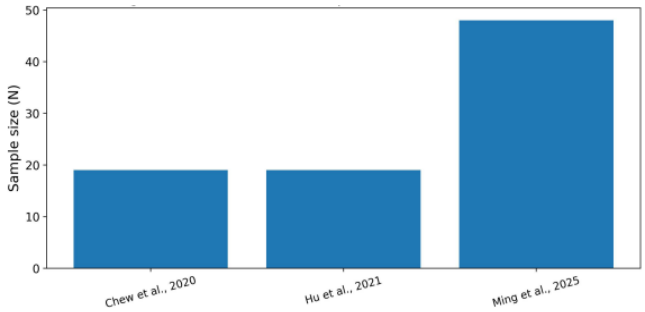

Figure 4. Distribution of sample sizes in included RCTs

For example, Chew et al. reported in a double-blind RCT that both active tDCS priming + MI-BCI and sham priming + MI-BCI improved FMA-UE, but the between-group difference was not significant. Nevertheless, the MEP-negative subgroup showed a clearer trend toward improvement, suggesting that patients with reduced corticospinal excitability may benefit more from exogenous modulation by tDCS [4]. In addition, though Hu et al.'s pilot study did not reveal any additional advantage of the combined intervention on clinical scales, neuroimaging analysis highlighted significant reorganization of the sensorimotor and default-mode networks in the MI-BCI-only group, which was not replicated in the combined group. This discrepancy may indicate that, under certain parameter combinations, tDCS could alter the trajectory of network reorganization and impede synergy [5]. In the three-arm RCT by Ming et al., the kinesthetic imagery BCI (KI-BCI) group outperformed tDCS alone overall; the combined group performed better than tDCS on the MSS outcome but did not exceed KI-BCI. Because the combined group split each session equally into 15 minutes of tDCS and 15 minutes of KI-BCI, the effective closed-loop BCI training dose may have been insufficient, diluting potential synergy [6].

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3.2. Comparative efficacy of tDCS combined with MI-BCI

Existing systematic reviews and meta-analyses generally conclude that combining tDCS with MI-BCI is feasible for post-stroke upper-limb rehabilitation, but the magnitude of benefit depends on treatment parameters and inter-individual differences, and small sample sizes limit the generalizability of conclusions [7]. The combined strategy can improve upper-limb function, but results vary widely. Some studies report significant improvements in clinical scales such as FMA-UE and observe favorable imaging changes (e.g., renormalization of sensorimotor networks) [8,9]. Other find no additional efficacy compared with single interventions [10,11]. Such discrepancies likely arise from several factors. tDCS settings (montage, timing, dose, and stimulation schedule) can lead to different neuromodulatory effects. MI-BCI task design (task difficulty, feedback modality, and training frequency) may also contribute to variability in outcomes [12]. Moreover, individual patient characteristics-particularly stroke stage, severity, and integrity of neural pathways-have a pronounced influence on response. For example, among MEP-negative patients, tDCS may improve function by engaging residual pathways, but effects can vary substantially across individuals.

3.3. Safety, feasibility, and risk management

tDCS combined with MI-BCI has shown favorable safety and feasibility across existing studies. Most trials report no serious adverse events. Common transient and tolerable symptoms include scalp tingling, mild burning or erythema, fatigue, and increased attentional load [13]. Nevertheless, although overall risk is low, safety monitoring remains important. Within guideline-concordant dosing, risks are generally minimal; however, as clinical use expands, adverse event reporting and standardized stopping criteria should be strengthened. This is especially crutial in heterogeneous patient populations, where flexible protocol adjustments may be necessary to ensure participant safety. From an implementation perspective, combined-protocol parameters (e.g., stimulation intensity, duration, and frequency) are key determinants of efficacy and feasibility, while patient acceptance and adherence are also crucial.

4. Mechanistic evidence and evidence quality

4.1. Associations between mechanistic markers and clinical outcomes

When evaluating the impact of combined stimulation on post-stroke upper-limb rehabilitation, the relationship between mechanistic markers and clinical outcomes determines how treatment effects should be interpreted. EEG, TMS, and fMRI are commonly used to assess training-related network reorganization. Evidence suggests that network renormalization induced by closed-loop learning may be associated with functional improvements. However, under combined stimulation, mechanistic pathways may shift, leading to unstable incremental clinical benefits. Therefore, evaluation of the combined strategy should consider the full chain of mechanism, process, and outcome.

Specifically, studies should examine mechanistic changes (e.g., EEG/TMS/fMRI markers) together with process measures such as effective closed-loop training time and learning curves, rather than inferring synergy solely from stimulation parameters. Integrating these components can better explain outcome variability across trials. Moreover, concordant directions of mechanistic change do not necessarily imply larger clinical gains. For instance, EEG markers may reflect

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improved modulation of motor intention, yet improvements on clinical scales also depend on the transferability of training tasks, the accuracy and latency of feedback, and the stability of learning across sessions. If process measures (e.g., effective closed-loop time or successful-trial ratio) are insufficient, physiological modulation may still fail to translate into measurable functional advantages on clinical scales.

4.2. Risk of bias and recommendations for improving study quality

Risk of bias arises from multiple sources, as summarized schematically in Figure 5. One significant challenge is the blinding of therapists, which is difficult due to the device operation and stimulation sensations, potentially compromising objectivity. Besides, many studies rely on small, single-center designs, which can result in imbalances in the randomization process, increasing the risk of bias. In addition, insufficient allocation concealment and the lack of preregistered outcome reporting may introduce selective reporting bias.



Figure 5. Overview of RoB 2 (schematic)

To mitigate these risks, future studies should strengthen bias control. Trial designs should ensure rigorous randomization and implement effective blinding between intervention providers and outcome assessors. To enhance transparency, protocols should be preregistered and made publicly available before study initiation. Trials should report process measures such as effective closed-loop training time and learning curves to quantify training quality, rather than relying solely on endpoint scales. Key process variables (e.g., MEP status and stroke stage) should be specified a priori and clearly reported to facilitate interpretation of heterogeneous results. In addition, harmonizing core outcomes and follow-up time points can boost cross-study comparability. By transparently reporting randomization, allocation concealment, blinding procedures, and missing-data handling, interpretation bias due to design differences can be minimized, ultimately improving the reliability and comparability of the findings.

5. Conclusion

This review synthesized randomized controlled trials since 2020 on tDCS combined with motor-imagery brain-computer interface (MI-BCI) for post-stroke upper-limb rehabilitation. By integrating the screening workflow, evidence mapping, a parameter matrix, and risk-of-bias visualization, we compared design differences across trials. The evidence indicates that MI-BCI provides consistent short-term benefits for upper-limb function, whereas additional gains from adding tDCS are unstable and dependent on population characteristics, stimulation parameters, and allocation of training dose. Limitations include the small number of eligible RCTs, small sample sizes, and substantial heterogeneity; moreover, some studies require improvements in blinding and reporting transparency, which affects confidence in conclusions. Future research should expand sample sizes through

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preregistration and standardized reporting, adopt stratified randomization designs, and harmonize core outcomes and process measures (e.g., effective closed-loop training time) to improve comparability and reproducibility across studies.

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