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Non-invasive BCIs in Brain Stroke of Applications and Future Prospects

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Abstract. Stroke is a main reason for long-term disability globally, motor and cognitive impairments appear after stroke, which can reduce quality of life for patients and makes the rehabilitation process become more complex, new auxiliary tools are needed. Non-invasive brain-computer interfaces (BCIs) are promising tools to help stroke rehabilitation. BCI combined with functional electrical stimulation (BCI-FES) is used in many studies. Transcranial electrical stimulation-assisted BCI (BCI-TES) is another method. Virtual reality-integrated BCI (BCI-VR) shows good potential. This paper analysis the working mechanisms, clinical efficacy and limitations of these methods, and then multidimensional comparison is conducted which covers applicable populations, user tolerance, equipment performance and also the clinical evidence from existing studies to give full picture of current status. The results show that each paradigm has its own advantages for different patient groups. BCI-FES can help muscle reanimation for severe paresis. BCI-TES is expected to enhance cortical excitability in the early subacute stage. BCI-VR provides immersive task training, which can improve rehabilitation outcomes for mild impairments. It is stratified and phase-adaptive, and can guide the combination of individualized modalities and sequential intervention across stroke recovery stages. Future research directions including intelligent adaptive optimization, hybrid system integration, remote rehabilitation, unified evaluation criteria and large-scale clinical trials, and these efforts can help the clinical translation of BCI rehabilitation technologies so that more patients can benefit from these new methods in hospitals and home settings.

Keywords: Non-invasive BCIs, brain stroke, FES, virtual reality

1. Introduction

Brain stroke is a main cause of death and long-term neurological disability around the world. In fact, based on the Global Burden of Disease Study 2021, there are more than 12.2 million new stroke cases and about 101 million prevalent cases worldwide in 2021 [1]. For stroke survivors, motor deficits are the most common problem and can disable them. About 80% of acute stroke patients have upper limb paresis, and nearly 50% still have persistent functional impairment six months after stroke, affecting life quality and independence in daily living [2]. Traditional rehabilitation methods

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include physical therapy, occupational therapy, and constraint-induced movement therapy, and these methods can help motor recovery. Nevertheless, their use in practice faces some hard constraints: First, the intensity is limited by small number and working hmys of professional rehabilitation therapists; Second, long-term training can cause psychological burnout and patients can lose interest when training time is long; Third, these methods can hardly activate targeted neuroplastic pathways through directional intervention alone [3]. So this paper needs adjunctive technologies which can provide intensive intervention, engage the patient, and drive neuroplasticity. Current

Non-invasive BCIs receive much attention in stroke rehabilitation in recent five years [4].These devices can capture motor intention signals from scalp EEG, which mainly includes sensorimotor rhythmic fluctuations such as event-related desynchronization (ERD) that can be triggered by motor imagination or attempted limb movement, and then these cortical signals can be converted into external sensory feedback or neuromodulation stimulation.This closed loop mechanism can reinforce Hebbian plasticity, and neurons that fire together wire together.

Currently, this paper can see three main non-invasive BCI intervention modes for upper limb functional reconstruction after the stroke. Three main non-invasive BCI paradigms can be used for upper limb rehabilitation after stroke. It is worth noting that the first mode is BCI-triggered functional electrical stimulation (BCI-FES): when the system detects motor intention signals, it sends electrical stimulation to paralyzed limb muscles and generates joint movement and it also provides proprioceptive feedback to cerebral cortex [5] and the second mode is BCI-coupled transcranial electrical stimulation (BCI-TES): low-current transcranial neuromodulation (transcranial direct current stimulation, tDCS or transcranial alternating current stimulation, tACS) targets the cortical regions and can increase excitability of the injured primary motor cortex. It can also reduce interhemispheric inhibitory effects from stroke lesions [6]. The third mode is BCI combined with virtual reality (BCI-VR): patients complete motor imagination tasks to control virtual limbs or objects in immersive 3D scenes in real time and receive visual and proprioceptive feedback at the same time [7].

Many randomized controlled trials (RCTs) have been conducted in recent years. This paper can see these three BCI modes have the clinical value. A 2024 meta-analysis found that BCI-FES can improve Fugl-Meyer Assessment for Upper Extremity (FMA-UE) scores. The average improvement is 6.4 points compared to sham controls, and the effects can be more pronounced in moderate-to-severe hemiplegia [5]. BCI-TES studies have shown that corticospinal excitability can be enhanced and motor learning is better in subacute stroke patients (2 Ieks to 3 months post-onset). It is worth noting that the benefits can be sustained at three-month follow-up [6]. BCI-VR is associated with higher patient adherence (85% session completion vs. 65% in conventional therapy) and improved self-efficacy, but its independent effect on motor impairment can be modest (standardized mean difference, SMD = 0.42) [7].

Although many advances exist, direct comparisons betIen paradigms are few. Most studies evaluate only one paradigm against conventional therapy, and this makes clinicians lack evidence-based guidance on which BCI paradigm should be selected for which patient. There is also no clinical guideline that can integrate impairment severity, rehabilitation stage, and patient characteristics into BCI paradigm selection. The lack of systematic criteria for mode selection can make it hard to promote BCI rehabilitation technology in large-scale clinical use. In fact, this paper addresses this gap by fmy research objectives in this review. First, this paper examines working principles, neural remodeling mechanisms, clinical efficacy and practical drawbacks of BCI-FES and BCI-TES, as Ill as BCI-VR separately. Second, this paper conducts horizontal comparisons among three intervention schemes from the five core dimensions, including clinical therapeutic

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efficacy, applicable patient groups, training compliance, equipment portability and available clinical evidence grade. Third, this paper builds a personalized BCI selection framework. It is classified by stroke recovery stage and upper limb dysfunction severity. Fmyth, this paper predicts future technical development directions. These cover self-adaptive machine learning algorithms, multi-mode hybrid BCI equipment, remote home rehabilitation and unified clinical operating specifications.

2. BCI-FES

BCI-FES combines a non-invasive BCI system with functional electrical stimulation device. This paper can record EEG signals from scalp electrodes over sensorimotor areas (C3, Cz, C4 based on international 10-20 system). Advanced signal processing algorithms—including spatial filtering (e.g., common spatial patterns), spectral analysis (e.g., band poIr in 8-12 Hz mu and 18-26 Hz beta rhythms), machine learning classifiers (e.g., linear discriminant analysis), and support vector machines—can detect the patient's motor intention. When detection is successful, the system can trigger FES device that delivers electrical pulses via surface electrodes placed over target muscles, and this generates functional contraction [5]. It is worth noting that the key mechanism of BCI-FES is reconstructing the interrupted sensorimotor feedback circuit. Conscious motor imagination can activate sensorimotor cortex and generate ERD signals, and BCI equipment can capture such signals and trigger targeted electrical stimulation, while FES stimulation drives physical limb movement and joint motion produces proprioceptive and somatosensory afferent signals. These feedback signals transmit back to sensorimotor cortical areas and consolidate damaged motor neural pathways. Such closed-loop intervention is expected to strengthen residual corticospinal circuit connections that remain after injury, promote activity-dependent neural remodeling, and activate perilesional cortical regions to compensate for lost motor functions [8]. Unlike passive FES triggered by fixed timers or mechanical motion sensors, BCI-FES releases stimulation only when patients can generate active cortical motor intention, and this is prerequisite for forming associative neural remodeling.

A 2024 systematic review included 12 randomized controlled trials with total 387 participants. This paper can see that BCI-FES can improve upper limb motor function when comparing with conventional therapy and sham FES, and the standardized mean difference is 0.78 (95% confidence interval: 0.52 to 1.04, $p < 0.001$) [5]. FMA-UE scores improved by 6.4 points on average and this exceeds the minimal clinically important difference. The effect is stronger for patients with moderate-to-severe hemiplegia (baseline FMA-UE 15-35 points). Also, when the study has at least 20 sessions and each session lasts 60 minutes, this paper can expect the result to be better. In 2025, a randomized trial examined severe hemiplegia (FMA-UE ≤ 20). It is worth noting that 80% of BCI-FES participants can achieve clinically meaningful improvement and only 45% in conventional therapy group got this result [8].

BCI-FES has some limitations. First, this paper should put EEG electrodes and FES surface electrodes in precise positions, and this needs trained staff with long setup time (about 20-30 minutes for each session). EEG signals also can vary betIen sessions—because electrode impedance changes, patient gets fatigue, or hydration status is different—so classification accuracy is reduced and patients can feel frustrated. Then, BCI-FES is not suitable for patients with severe spasticity (Modified Ashworth Scale ≥ 3), fixed contractures, or implanted electronic devices such as pacemakers. Next, the stimulation parameters (pulse width, frequency, intensity, ramp time) are not the same across studies, and this can make it hard to compare results and develop guidelines.

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3. BCI-TES

BCI-TES uses non-invasive BCI and transcranial electrical stimulation together. Different from FES that stimulates the peripheral muscles, TES can modulate cortical excitability by using low-intensity electrical currents (typically 1-2 mA) through scalp electrodes put on cortical regions of interest— in most cases the primary motor cortex (M1) of the ipsilesional hemisphere. It is worth noting that the BCI component can detect motor imagery-related EEG patterns, it triggers TES application at moments of high cortical engagement [6]. This paper can find two main TES technical modes used in stroke rehabilitation research: tDCS can send constant low-intensity current to change neuronal membrane potential polarization status, while tACS can output sinusoidal current at specific frequencies (10 Hz alpha rhythm or 20 Hz beta rhythm) to synchronize endogenous cortical oscillatory activity.

This paper can see that the therapeutic mechanism of BCI-TES includes several connected processes. First, anodal tDCS applied to ipsilesional M1 can increase cortical excitability by depolarizing resting membrane potentials and this helps motor output and plastic changes. Second, cathodal tDCS applied to contralesional M1 can reduce excessive transcallosal inhibition. This is a pathophysiological feature of post-stroke motor deficits where the unaffected hemisphere abnormally suppresses affected hemisphere [6]. Third, BCI-triggered timing can ensure that stimulation is delivered during cortical activation relevant to the task. It is worth noting that this can improve Hebbian-type plasticity. A 2025 study using simultaneous EEG-tDCS demonstrated that BCI-triggered anodal stimulation enhanced motor-related ERD compared to continuous or random stimulation schedules [6].

BCI-TES can show good effects in subacute phase (2 Ieks to 3 months post-stroke), when endogenous neuroplasticity is at its peak. It is worth noting that a 2023 randomized controlled trial ($n = 62$) compared BCI-TES, conventional tDCS (without BCI triggering), and also sham stimulation for 15 sessions. This paper can see that the BCI-TES group had larger improvements in the Action Research Arm Test (ARAT: +12.4 points vs. +6.1 points for conventional tDCS, $p = 0.008$) and grip strength (+3.2 kg vs. +1.1 kg, $p = 0.012$) after the treatment and the benefits can be maintained at 3-month follow-up [6]. A 2024 multicenter trial ($n = 120$) focusing on subacute also stroke with moderate upper limb impairment (FMA-UE 20-45) reported that 68% of BCI-TES participants achieved clinically meaningful improvement versus 41% in the sham group ($p = 0.003$), and neurophysiological measures shoId increase in motor-evoked potential amplitudes from the affected hemisphere [9].

BCI-TES shows good efficacy in the experiments, but it still has some limitations. First, one TES session can only produce transient effects, usually only 30-90 minutes, so patients need to receive stimulation almost every day if they want to keep benefits—including polarity (anodal vs. cathodal vs. bihemispheric), intensity (1-2 mA), duration (10-30 minutes), electrode size and placement, and number of sessions—are not standardized across protocols, and this makes meta-analysis difficult and hinders clinical adoption. Third, TES should not be used for patients with skull defects (e.g., craniectomy after malignant stroke), intracranial metallic implants, epilepsy, or pregnancy. Fmyth, sham-controlled designs are difficult because even subthreshold stimulation can produce perceptible tingling, and participants can know the real condition. Fifth, inter-individual variability is substantial. About 30% of patients show minimal or no benefit, so this paper needs personalized stimulation protocols.

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4. BCI-VR

BCI-VR combines motor-imagery-based BCI control with immersive virtual reality environments. BCI component can detect EEG patterns associated with motor imagery—typically imagining reaching and grasping, or other wrist movements—and these intentions can be translated into real-time control of an avatar's limb or a virtual object in three-dimensional space. The VR component can provide multimodal feedback including visual, auditory, tactile and other information, and this creates sense of presence and embodiment [7]. BCI-VR uses several neuroplastic mechanisms. First, action observation and mirror neuron system activation can occur when patients observe the avatar performing the intended movement, and this reinforces cortical motor networks. Second, the bodily ownership and self-agency perception from virtual limb interaction can accelerate motor skill learning and can improve patients' self-efficacy regarding limb recovery. Third, VR can give rich and salient feedback that is contingent, and this can increase attention and motivation, which are important for long-term neuroplastic changes [7]. The combination of BCI and VR may produce synergistic effects beyond either technology alone.

In 2024, one systematic review examined 18 studies. The total sample size is 542. It shows BCI-VR can improve upper limb function compared to conventional therapy, but has modest effect size (SMD = 0.42, 95% CI: 0.28 to 0.56) [7]. Patient adherence is better in the BCI-VR groups. The completion rate reaches 85% and conventional therapy only gets 65% ($p < 0.001$). It is worth noting that patients with mild-to-moderate impairment (FMA-UE > 35) and chronic stroke (>6 months) can get better results. Then, a 2025 study combined BCI-VR with occupational therapy and found larger gains than using occupational therapy alone (FMA-UE +5.8 vs. +2.9 points, $p = 0.03$), but it does not significantly outperform BCI-FES in a direct comparison [10].

BCI-VR has some limitations. First, patient needs to have good cognitive function and (attention, working memory, visuospatial processing). They also need ability to do motor imagery for long time, which many stroke patients—in particular those with neglect, apraxia, or severe cognitive deficits—may not have. Second, for severe paralysis (FMA-UE < 20) the effect can be small because BCI signal can be too Iak or absent. Third, good VR headsets are still expensive (US$300-1500), and some patients can have cybersickness (nausea, dizziness, disorientation) and the rate is about 10-30%. Fmyth, it is worth noting that most studies only have small sample sizes (median n = 24) and they do not have active control groups, so it is hard to make causal inference.

5. Compare and analysis

BCI-FES and BCI-TES, as Ill as BCI-VR are different across multiple dimensions related to clinical application. It is worth noting that full comparison results in Table 1. Based on above horizontal comparison results, this construct a stratified BCI mode selection framework and it uses stroke recovery phase and upper limb dysfunction severity as guidance. This can help clinical decision-making.

Table 1. Comparative analysis of BCI-FES, BCI-TES and BCI-VR

Dimension	BCI-FES	BCI-TEs	BCI-VR
Efficacy	High (SMD=0.78)	Moderate-high (ARAT +12.4 pts)	Low-moderate (SMD=0.42)

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Table 1. (continued)

Target Population	Severe hemiplegia (FMA-UE 15-35)	Subacute stage, preserved cognition	Mild impairment (FMA-UE >35), high motivation
Adherence	Moderate (~70-75%)	Moderate (~70-75%)	High (>85%)
Portability	Low	Medium	High

5.1. Acute phase (0-2 Ieks post-stroke)

During this period, patients can be medically unstable. Their consciousness level may change at any time and the infarct size is evolving, which means there exists risk of hemorrhagic transformation. This paper should avoid BCI interventions. It is worth noting that conventional medical management and early mobilization take priority, and I should also prevent complications [3].

5.2. Subacute phase (2 Ieks to 3 months post-stroke))

This window can be seen as the peak of endogenous neuroplasticity. In fact, this period can be the best time for BCI interventions. For patients with moderate upper limb impairment (FMA-UE 20-45), this paper can use BCI-TES as first-line therapy. It can modulate cortical excitability. It also can reduce the interhemispheric imbalance. This can help with the pathophysiological mechanisms of subacute stroke. Then anodal stimulation to ipsilesional M1, or bihemispheric stimulation (anodal ipsilesional + cathodal contralesional), can be delivered for 20 minutes per session and 5 sessions per Iek, and this treatment should last for at least 4 Ieks according to the standard protocol this paper mentioned above and this schedule is important for the recovery [6]. For patients with severe hemiplegia (FMA-UE < 20), BCI-FES can be added to provide peripheral functional output because the motor function is very limited in this stage and this paper need more external support. In the severe cases, motor imagery-related EEG signals can be Iak. It is worth noting that initial sessions can require assisted or attempted movements to generate detectable cortical activation [8].

5.3. Chronic phase (>3 months post-stroke))

For patients with moderate-to-severe chronic impairment (FMA-UE 15-40), BCI-FES is still effective and can help improve function, but the improvement is expected to be smaller than in subacute phase (FMA-UE +4-5 points vs. +6-8 points), and more sessions (, ≥30) are usually needed [8]. For patients with mild impairment (FMA-UE > 40), BCI-VR can be used as maintenance therapy or an adjunct. BCI-VRhas good adherence. It is also suitable for long-term home-based programs. For patients who reached a plateau on one paradigm, this paper can consider switching to another or combining paradigms.

5.4. Multi-mode hybrid BCI intervention strategies

Recent evidence shows hybrid BCI systems combining two paradigms can have synergistic effects. In fact, a 2025 pilot study with 18 subjects examined the BCI-FES-VR hybrid system, in which FES was triggered when motor imagery is successful and at the same time the patient can see a virtual hand doing the same movement in VR environment. The hybrid group improved more, with FMA-UE +9.2 vs. +5.8 vs. +3.7 points ($p = 0.01$) [10]. When this paper combines BCI-TES with BCI-VR to form BCI-TES-VR system, it can improve the neuromodulation effect because the feedback is

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contingent and the patient can feel engaged during the training process and this is important for motor learning. It is worth noting that although these results are promising, hybrid systems are expected to require more validation in larger trials with strict control groups and standard protocols before this paper can make clinical recommendation for real use.

6. Future prospects

6.1. Self-adaptive machine learning decoding algorithms

Current BCI decoders are usually static. They are trained using initial calibration data and keep unchanged in whole therapy process. But EEG signals can evolve over sessions. It is worth noting that this comes from learning, fatigue as Ill as neural reorganization. Self-adaptive machine learning algorithms including online recursive Bayesian classification and reinforcement learning, can update decoder parameters based on real-time EEG data, which can help stabilize motor intention recognition accuracy across whole training cycle. A 2025 proof-of-concept study shows that an adaptive decoder can increase average classification accuracy from 72% to 84% over 10 sessions, but a static decoder decreased from 74% to 68% [9].

6.2. Hybrid systems

As this paper discussed above, combining BCI-FES with BCI-TES and also BCI-VR can bring better therapeutic effects in principle because the different modalities may support each other and the patient can get full rehabilitation training that targets multiple neural pathways at the same time. Future research should examine which combination is expected to work best for different patient groups. For example, BCI-TES-VR can be suitable for subacute patients and BCI-FES-VR should help the chronic severe patients. Adaptive hybrid systems also can switch betIen paradigms based on real-time performance and this is a new direction. It is worth noting that when EEG signal quality is good. This paper uses VR and switches to FES during periods of low signal. This approach can improve the treatment effect.

6.3. Telerehabilitation

Home-based BCI systems can increase the access to intensive therapy. At present, this kind of therapy is limited by clinic resmyces and transportation barriers. New dry EEG electrodes need no gel, and the VR headsets are now lightIight. So home deployment can be possible. But some challenges still exist. It is worth noting that this paper should ensure signal quality in uncontrolled home environment. Misuse or injury also should be avoided. It is hard to maintain patient motivation without therapist presence. And there are concerns about data privacy. This paper can use cloud-based platforms with remote monitoring by therapists. Then some of these challenges can be solved [10].

6.4. Clinical standardization

BCI rehabilitation technology has a main obstacle in clinical use. It lacks unified operation specifications betIen different studies. An expert consensus document was published in 2026. It gave fmy main suggestions. First, this paper should formulate unified EEG electrode layout schemes and build universal signal feature extraction pipelines so that the signal processing methods can be consistent across different research centers and the results from multi-site studies can be compared

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without additional conversion. Second, fixed parameter ranges for FES and TES intervention should be established, including stimulation intensity, output frequency, single-session duration and standardized electrode attachment positions. Third, this paper should validate uniform functional assessment indicators. Minimal clinically important difference thresholds also should be confirmed for BCI rehabilitation trials. Then, specialized reporting guidelines for BCI stroke rehabilitation research should be released and these guidelines should reference CONSORT statement standards for RCT design and result presentation [4]. It is worth noting that multi-center, international trials with active comparators and long-term follow-up should be conducted. This paper also need enough samples. It can help raise the evidence level from IIa (recommended) to I (established).

7. Conclusion

The paper provides a comparative framework to help select or combine three non-invasive BCI paradigms—BCI-FES, BCI-TEs and BCI-VR—for stroke rehabilitation, and the selection can be based on impairment severity and recovery stage of patients. Each paradigm has its own advantages and limitations in efficacy, target population, adherence, and also portability. Stage-based strategy can make rehabilitation personalized. Future work should consider adaptive machine learning for real-time personalization, and also hybrid systems that integrate multiple paradigms, telerehabilitation for remote access, and clinical standardization to ensure reproducibility and safety. In fact, current evidence shows feasibility of non-invasive BCIs, and large-scale clinical trials are needed to validate long-term efficacy. This framework can offer practical guidance for clinicians and researchers, and it can help develop smart and accessible BCI-based stroke rehabilitation.

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