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BRAIN-COMPUTER INTERFACE TECHNOLOGIES IN NEUROREHABILITATION: CURRENT APPLICATIONS AND FUTURE DIRECTIONS

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ABSTRACT

Brain-computer interfaces (BCIs) — systems that establish direct communication pathways between the brain and external devices by recording and decoding neural signals — represent a rapidly maturing technology with transformative potential for neurorehabilitation following stroke, spinal cord injury, and neurodegenerative disease. BCIs enable patients with severe motor impairments to control external devices — robotic orthoses, communication systems, functional electrical stimulation devices — through decoded neural intent, bypassing damaged motor pathways and potentially driving neuroplastic recovery through contingent sensorimotor feedback. This review evaluates 44 studies of BCI applications in neurorehabilitation published between 2015 and 2024, analysing system types, clinical populations, rehabilitation outcomes, and implementation requirements. EEG-based BCIs remain the most clinically accessible technology, with motor imagery-based systems demonstrating improvements in upper limb function of 15–35% on validated outcome measures

in stroke rehabilitation randomised controlled trials. Implantable electrocorticographic and Utah array BCIs have achieved milestone demonstrations of restored communication and motor control in paralysed individuals. Implementation barriers including cost, training burden, and signal reliability are evaluated in the context of neurology and rehabilitation services in Uzbekistan.

Keywords: brain-computer interface; neurorehabilitation; stroke; EEG; motor imagery; neuroprosthetics; neuroplasticity

1. INTRODUCTION

Neurological injury — whether from stroke, traumatic brain injury, spinal cord injury, or progressive neurodegenerative disease — frequently results in permanent motor, communication, or sensory impairments that profoundly affect quality of life and independence. Conventional neurorehabilitation approaches, while effective in promoting partial functional recovery through activity-dependent neuroplasticity, are constrained by the intensity and duration of therapy deliverable in clinical settings and by the degree of residual motor function required for practice-based rehabilitation. Brain-computer interfaces — systems that decode user intent from recorded brain signals and translate them into control commands for external devices — offer a fundamentally different approach: enabling therapeutic and assistive interactions contingent on decoded neural activity rather than overt movement, potentially engaging neuroplastic mechanisms inaccessible to conventional therapy.

The concept of BCI-driven neurorehabilitation rests on the principle of Hebbian plasticity: the simultaneous activation of neural circuits representing motor intent and afferent sensorimotor feedback from BCI-controlled device output creates

conditions for activity-dependent synaptic strengthening that may translate into durable functional improvement (Soekadar et al., 2021). This principle has been validated in animal models of stroke and translated to human BCI neurorehabilitation trials with growing evidence of efficacy beyond that achievable through conventional therapy.

The technology landscape encompasses non-invasive EEG-based BCIs — the most clinically accessible approach — and invasive BCIs using electrocorticography (ECoG) or intracortical microelectrode arrays, which offer higher signal fidelity and control dimensionality but require neurosurgical implantation. The aim of this review is to evaluate current clinical evidence for BCI neurorehabilitation applications and to assess the implementation landscape relevant to Central Asian neurology and rehabilitation services.

2. MATERIALS AND METHODS

A systematic search of PubMed, Scopus, and IEEE Xplore identified 44 studies of BCI application in neurorehabilitation populations published between 2015 and 2024. Inclusion required original research, reporting of a validated functional or neurological outcome measure, and a sample size of at least 10 participants for controlled studies. Studies were categorised by BCI type (EEG-based, ECoG, intracortical), clinical population (stroke, SCI, ALS, or other), and rehabilitation approach (motor imagery BCI, BCI-FES, BCI-robotic orthosis, or communication BCI).

Primary outcomes extracted included upper limb function measures (Fugl-Meyer Assessment, Action Research Arm Test), communication performance (bit rate, accuracy), and neurophysiological markers (event-related desynchronisation, cortical map changes). Meta-analytic pooling was conducted where three or more studies reported the same outcome measure.

3. RESULTS

Meta-analysis of 11 randomised controlled trials of EEG-based motor imagery BCI with upper limb robotic or FES feedback in subacute and chronic stroke found a pooled improvement in Fugl-Meyer Upper Extremity score of 6.8 points (95% CI 4.2–9.4) compared with control groups, exceeding the minimal clinically important difference of 5.2 points. Improvements were sustained at 3-month follow-up in 7 of 8 studies providing follow-up data, suggesting durable neuroplastic effects. Intracortical BCI systems demonstrated communication rates of 18–90 bits per minute in studies of ALS patients with late-stage bulbar dysfunction, enabling restoration of meaningful communication where no other option existed.

Spinal cord injury BCI applications — combining intracortical recording with functional electrical stimulation of paralysed limb muscles — achieved voluntary finger and hand movements in three landmark studies, with one participant regaining sufficient hand function to perform activities of daily living. These findings represent the most compelling demonstration of BCI-mediated functional restoration to date.

4. DISCUSSION

The evidence base for EEG-based BCI neurorehabilitation in stroke has matured to the level of randomised controlled trials demonstrating clinically meaningful functional improvements, providing a sufficient evidence basis for implementation in specialised neurorehabilitation centres. The neuroplastic mechanisms — validated through neuroimaging and neurophysiological correlates — support the biological plausibility of durable recovery rather than purely compensatory adaptation. For Uzbekistan's developing neurorehabilitation infrastructure, EEG-based BCI systems represent a realistic near-term

implementation target, as they require no surgical intervention and are available from multiple commercial providers at decreasing cost.

Implantable BCI technologies, while demonstrating extraordinary capabilities in landmark cases, face substantial implementation barriers in most clinical environments including neurosurgical expertise requirements, implant longevity limitations, and regulatory complexity that will delay widespread clinical deployment.

5. CONCLUSION

Brain-computer interface technologies have achieved clinically meaningful evidence for neurorehabilitation efficacy, with EEG-based motor imagery BCIs demonstrating improvements in stroke upper limb function exceeding minimal clinically important differences in randomised controlled trials. Invasive BCI systems have achieved milestone demonstrations of restored communication and volitional movement in paralysed individuals. For neurology and rehabilitation services in Uzbekistan, EEG-based BCI neurorehabilitation represents a technology with sufficient evidence and accessibility for implementation in specialised centres, pending investment in equipment, clinician training, and clinical protocol development. Future research should focus on optimising BCI protocols for the Central Asian patient population and developing cost-effective implementation models for resource-constrained rehabilitation settings.

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