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Brain–Computer Interfaces in Functional Recovery from Severe Motor Disabilities: A Focus on ALS and High-Level Paraplegia

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Abstract. Motor disabilities like amyotrophic lateral sclerosis (ALS), or high-level paraplegia severely affect patient's interaction with their environment and independence. Brain-computer interfaces (BCIs) are an essential technology linking neural activity to external devices to recover lost functions. Advances in signal acquisition and decoding algorithms have greatly enhanced the accuracy and stability of BCIs; however, there remains much room for improvement concerning long-term biocompatibility and seamless integration within everyday life. This review analyzes the present role of BCIs in functional recovery among patients suffering from severe motor impairments, summarizing recent results obtained using both invasive and non-invasive modalities about motor rehabilitation and communication restoration. This analysis shows that although BCIs provide significant benefits in regaining autonomy they face technical hurdles and lack standardization in evaluation metrics. This paper provides here a comprehensive reference towards further BCI developments and highlight open issues related to system robustness and user adaptability. Further efforts should be directed toward optimization of closed-loop neuromodulation strategies and large-scale longitudinal clinical trials to enable wide practical use.

Keywords: Brain-Computer Interfaces (BCI), Severe Motor Disabilities, Amyotrophic Lateral Sclerosis (ALS), Closed-Loop Neuromodulation

1. Introduction

Amyotrophic Lateral Sclerosis (ALS) and high-level paraplegia/tetraplegia are two prototypical diseases that cause severe motor impairments caused by an irreversible injury of upper/lower motor neurons/spinal cord pathways. Advanced ALS patients may eventually develop a locked-in state (LIS) where they retain minimal control over their eyes/face muscles; similarly, those suffering from high cervical spinal cord injuries (C4 and above) usually have quadriplegia and profound caregiver dependency. Traditional neurorehabilitation approaches including physical therapy, occupational therapy and traditional assistive devices do not offer any effective functional restoration in these severely affected cases, resulting in significant physiological, psychological and socioeconomic burden for patients/families/society.

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Emergence of brain–computer interface (BCI) technology provides an innovative solution: by providing a direct connection between neural activity and external devices, it bypasses damaged peripheral nerves and muscles allowing for expression of intent and controlling external systems with no involvement of skeletal muscle. Advances over the last 20 years in neurophysiological signal acquisition, machine learning–based decoding algorithms, and robotics have propelled the evolution of BCI from lab prototypes into clinical trials and early commercial use [1]: For the ALS population, invasive or semi-invasive BCI has allowed text spelling and speech synthesis in completely locked-in patients; for high-level paraplegia, BCI-controlled exoskeletons and functional electrical stimulation (FES) systems restore complex motor function like grasping and ambulation in small-scale clinical studies.

In light of that, it becomes crucial to systematically review the mechanism, application, and challenges of BCI for severe motor disability to determine its role in modern neurorehabilitation as well as direct future research directions. Therefore, this paper addresses ALS and high-level paraplegia by presenting the basic principle and technical taxonomy of BCI; reviewing their specific applications and clinical outcomes in these two groups; and discussing current limitations and future development trajectories.

2. Fundamental principles and technical architecture of BCI

2.1. Signal acquisition modalities: invasive, semi-invasive, and non-invasive BCI

A key determinant of BCI efficacy is neural signal acquisition quality/stability. Modalities can be classified according to distance from cortical tissue. Most non-invasive BCIs rely on electroencephalography (EEG); they are the most commonly used clinically because of its safety, low cost, and ease of use. It records scalp potentials related to motor imagery (e.g., event-related desynchronization/synchronization, ERD/ERS) or evoked potentials (e.g., P300). Nonetheless, EEG has poor spatial resolution, sensitivity to electromagnetic artifacts, and attenuates signal passing through the skull and scalp.Invasive BCIs (iBCI), including intracortical microelectrode arrays (e.g., Utah array) or electrocorticography (ECoG) grids, penetrate the dura mater or pia mater to capture action potentials (spikes) or local field potentials (LFPs). Delving further: EEG mostly functions within the low-frequency spectrum, recording mu (8–13 Hz) and beta (13–30 Hz) desynchronization while executing motor actions and P300 evoked potentials for target detection – making it ideal for low-bandwidth applications like assistive communication in late-stage ALS. On the other hand, ECoG excels at the high frequency domain, recording broadband gamma (30–200 Hz) signals and local field potentials providing superior signal fidelity and spatial resolution – which are critical for high-bandwidth, real-time control of advanced prosthetic limbs in paraplegia.Conversely, semi-invasive BCIs (e.g., ECoG or stereoelectroencephalography, sEEG) position electrodes under the skull but not inside the dura. These provide a compromise between biocompatibility and signal fidelity, capturing broadband gamma activity without risk of gliosis as seen with fully implanted microelectrodes. Modality selection is dependent upon the patient's remaining motor function/cognitive status and desired application - ranging from basic communication in late-stage ALS to sophisticated robotic limb control in paraplegia.

2.2. Neural decoding algorithms: from feature extraction to machine learning

Neural decoding is a process that translates raw electrophysiological signals into actionable device commands. This generally includes steps: preprocessing, feature extraction, dimensionality

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reduction, and classification. Traditionally, linear algorithms like Linear Discriminant Analysis (LDA) or Support Vector Machines (SVM) are used to classify discrete mental states (e.g., imagining left vs. right hand movement). Due to the non-stationary properties of neural signals exacerbated by electrode drift, neuroplasticity, and changes in brain state, solutions. Recent advances use deep learning architectures, e.g., Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs), which are adept at capturing complex spatiotemporal dynamics in high-dimensional neural data. Interestingly, recurrent models like Long Short-Term Memory (LSTM) networks can predict continuous kinematic parameters (e.g., velocity, trajectory) for prosthetic control. Unlike traditional linear methods such as LDA or SVM—which only support discrete classification tasks (e.g., left vs. right hand movement [1, 2]), deep learning models especially LSTMs and CNNs excels at modeling temporal dynamics needed for continuous control [3, 4]. For example, Willett et al. reported high-performance decoding of imagined handwriting through LSTM-based decoders [1] whereas Moses et al. achieved fluent speech synthesis from cortical signals using RNN architectures [3]. Additionally, Milekovic et al. reported stable long-term communication in ALS patients using LFP-based decoders demonstrating the robustness of adaptive recurrent models compared to static classifiers [5]. Transfer learning techniques also address the 'cold start' problem by initializing decoders with pre-existing datasets dramatically shortening calibration time--a crucial aspect when dealing with rapidly progressive conditions such as ALS [6, 7]. Real-time artifact rejection and co-adaptive training paradigms wherein both the user and the algorithm learn together enhances decoding robustness and user experience [8, 9].

2.3. Output modalities and application paradigms: substitution, assistance, and restoration

The output modalities of BCIs specify how the decoded intent manifests itself and are broadly categorized in three therapeutic paradigms: substitution replaces lost motor functions using other effectors – e.g., BCI-driven communication software (virtual keyboards or speech synthesizer) enables expressing one's thoughts without engaging any muscle activity. Assistance uses BCIs to control external devices supporting residual capabilities like smart wheelchairs, environmental control systems (lights, doors) or robotic arms attached to wheelchairs. Shared control architectures enable the BCI to perform high-level goal selection whereas automation handles low-level execution details, thus alleviating cognitive load. Restoration attempts to reanimate paralyzed limbs with neuromodulation or neuroprostheses. It can be achieved either by triggering Functional Electrical Stimulation (FES) with the BCI to activate peripheral nerves and muscles in an orchestrated manner, restoring grasping or stepping movements. Or, it can be realized by bidirectional BCIs combining recording electrodes with stimulation capabilities to form closed-loops providing sensory feedback (proprioceptive or tactile cues) through intracortical microstimulation, addressing the sensory deficit inherent in motor paralysis and improving the embodiment of the prosthetic limb. Sensory feedback provided within these bidirectional systems comes from delivering precisely-timed electrical stimuli–either through intracortical microstimulation (ICMS) evoking artificial tactile or proprioceptive sensations in the somatosensory cortex, or through FES activating residual sensory pathways in the periphery. Functionally speaking, this makes the BCI a closed-loop control system. As opposed to open-loop architectures issuing the 'brain-to-machine' command without verifying its success, closed-loop systems constantly monitor their outcomes feeding the discrepancy (error signal) back to the controller. Immediate feedback provides for continuous recalibration of the decoding algorithm, essential for mitigating accumulated error due to signal drift, fatigue, or external disturbances. Open-loop systems inevitably accumulate errors since there exists no way to verify if the desired action has been successfully performed and the user must rely entirely upon

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slow visual feedback to correct the error. Ultimately, the closed loop approach not only compensates for the sensory loss but leverages Hebbian learning principles whereby the simultaneous activation of motor commands and artificial sensory feedback strengthens neural pathways leading towards a more efficient, accurate, and biologically plausible control process.

3. Applications of BCI in ALS

3.1. Neuropathological characteristics of ALS and mechanisms of communication impairment

ALS is a relentlessly progressive neurodegenerative disease involving the select destruction of both upper motor neurons (UMNs) within the motor cortex and lower motor neurons (LMNs) from the brainstem and spinal cord. Although primarily targeting motor systems, increasing evidence indicates that there are also frontotemporal network involvements in some cases which can affect executive functions and language processing. The clinical consequences include muscle atrophy, spasticity and eventually paralysis. Importantly, the corticobulbar tracts responsible for innervating cranial nerves are often affected early resulting in dysarthria (slurred speech) and dysphagia (difficulty swallowing); when ALS progresses into the completely locked-in state (CLIS), patients lose all voluntary muscle control apart from occasional vertical eye movements or residual facial twitches; this results in a dramatic dissociation between intact cognition and lack of ability to communicate ("anarthria"); conventional augmentative and alternative communication (AAC) devices based on eye-tracking or switch scanning become unusable upon deterioration of oculomotor control. This paradox, where patients lose all peripheral motor output yet retain the capacity for communication, is explained by the neurophysiological fact that the cortical circuitry underlying generation of motor intentions remains largely intact even though its downstream effector pathways degenerate: specifically, the premotor and primary motor cortices and supplementary motor areas involved in movement planning and execution often contain neuronal populations able to generate distinct activation patterns corresponding to specific intent (e.g., imagining limb movement or syllable articulation); these intention-related cortical signals exist independent of the corticospinal and corticobulbar tracts that have suffered axonal degeneration and demyelination. Therefore, BCI becomes not just an assistive device but a vital communication lifeline that accesses preserved cortical function despite widespread neuromuscular collapse.

3.2. Clinical advances in BCI-based augmentative and alternative communication systems

There have been substantial strides towards using BCI for communication in ALS: early EEG-based systems used the P300 speller wherein users focus on characters that flash within a grid, producing a P300 evoked potential when they detect them. Though successful in LIS, these systems suffer performance degradation in CLIS because of attentional fluctuations. Recently, slow cortical potential (SCP), and sensorimotor rhythm (SMR) modulation based BCIs showed sustained efficacy. On the invasive side, the Stentrode™ system –a minimally invasive sensor deployed through cerebral angiography– allowed a patient with ALS to achieve high-speed text entry by decoding motor cortex signals related to attempted handwriting movements. Additionally, attempts at "speech neuroprostheses" are groundbreaking, with Willett et al demonstrating real-time synthesis of intelligible speech from neural activity recorded in the speech motor cortex of a paralyzed individual, achieving word error rates as low as 25% [1], indicating an emerging path towards restoring naturalistic, high-bandwidth communication beyond existing typing-based interfaces.

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3.3. Impact of BCI on quality of life and long-term prognosis in ALS patients

In addition to their functional utility, BCIs profoundly impact psychological well-being and quality of life (QoL); studies using standardized scales (e.g., ALS Assessment Questionnaire, ALSAQ-40) show significant improvement in psychological scores after adopting a BCI due largely to regained autonomy and social connectedness; being able to start conversations, manipulate environment controls, or communicate needs decreases caregiver burden and alleviates feelings of helplessness and depression–comorbidities common with advanced ALS. Longitudinal evidence for survival benefit is equivocal: although retrospective analyses indicate that BCI users may experience slowed functional decline (possibly mediated by increased engagement and decreased stress), there are no randomized controlled trials definitively linking BCI use to an extension of lifespan. Challenges exist related to small sample size, heterogeneity of disease progression rate, and ethical considerations which prevent withdrawing BCI access from control groups. Large-scale, multi-center registries should be prioritized to quantify long-term biopsychosocial impacts of BCI—including possible neuroprotective effects via sustained cognitive engagement.

4. Applications of BCI in high-level paraplegia

4.1. Characteristics of sensorimotor pathway damage in high-level spinal cord injury

A high cervical spinal cord injury (C4 and above typically), interrupts both descending corticospinal and reticulospinal tracts and ascending somatosensory pathways causing tetraplegia characterized by loss of volitional motor output and peripheral sensory feedback [9]. Motor cortex and supplementary motor areas are generally structurally intact during chronic stages offering a decodable cortical substrate that differs from the progressive cortical involvement observed in ALS [9, 10]. The separation of preservation of central motor planning versus interruption of peripheral conduction is the neurophysiologic foundation of BCI intervention in this population [9]. Patients have complete or incomplete sensorimotor paralysis below their lesion and heavy caregiver dependence; there exists a clear indication for restorative rather than merely communicative BCI paradigms [9].

4.2. Motor function reconstruction via BCI-driven exoskeletons and functional electrical stimulation

The use of intracortical BCI together with functional electrical stimulation (BCI-FES) can recover functionally meaningful upper-limb movement in chronic tetraplegia. Ajiboye et al. described a C4 AIS-A subject who was able to perform brain-controlled reaching and grasping through the use of two intracortical microelectrode arrays connected to multi-channel FES – a proof-of-concept for cortical-to-peripheral motor reconstruction [10]. Bouton et al., decoded attempted grasp/open states from epidural ECoG which drove proportional FES to reanimate paralyzed forearm muscles [4]. In addition to invasive methods, researchers have investigated integrating BCI with exoskeletons to allow gait-like training in high-level paraplegia; domestic literature summarizes progress and technical bottlenecks of these strategies in spinal cord injury rehabilitation [9]. Yang et al. also reviews implantable BCI architectures for restoring motor functions in paralysis including high-density electrode arrays, deep-learning decoding and hybrid interfaces [8], illustrating this translation gradient where BCI-FES focuses on physiological re-animation of native musculature while BCI-exoskeleton systems focus on external kinematic restoration with less surgical risk [8, 9].

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4.3. Closed-loop system design integrating motor intent decoding and sensory feedback

Lack of somatosensory feedback hinders fine motor control and embodiment within BCI prostheses. Bidirectional systems that integrate both cortical recording and stimulation were proposed to provide artificial tactile or proprioceptive cues [10]. Requirements for a closed loop design involve low latency intent decoding and alignment between decoded state and stimulation parameter [4]. In China, Yin et al., emphasize "intent–action–feedback" loops in BCI applications for spinal cord injury; Yang et al. discusses closed-loop neuromodulatory paradigms and hybrid EEG/EMG interfaces as avenues for implantable systems [8, 9], which aligns with the restorative paradigm described in Section 2.3, seen recently in Chinese review literature about BCI and spinal cord injury [9].

5. Challenges and future perspectives

5.1. Technical bottlenecks: signal stability, decoding accuracy, and long-term biosafety

Invasive electrodes gradually degrade from gliosis, impedance drift, and material fatigue: few multi-year human data exist [8]. Semi-invasive (ECoG), non-invasive (EEG): sacrifice bandwidth for biocompatibility – susceptible to artifact and inter-session variability [4, 10]; improved decoding via deep learning shows patient-specific non-stationarity; poor cross-subject generalization, heavy calibration burden in rapidly progressing ALS [6, 7]. Considerations include biosafety including chronic tissue response and infection risk [9]. Both Yin et al., and Yang et al.: long-term stability and biocompatibility of signal acquisition, and individualized decoding adaptability are rate-limiting steps towards clinical scalability [8, 9].

5.2. Clinical translation: individual adaptation, ethical considerations, and commercialization pathways

Adaptation at an individual level includes neurophysiology/cognition variation by disease stage: Li et al., suggest matching BCI paradigm choice (P300, SMR, invasive motor/speech cortex decoding), with remaining oculomotor/attentional capacity in ALS. For spinal cord injury, Yin et al., observe that electrode form/signals modalities and effectors are personalized based on lesion level and rehabilitation goals [7, 9]. Ethically, neural data privacy, and responsibility allocation if there is malfunction [8, 9]; Yang et al. place this in the larger context of implantable BCI translation, Yin et al., place it in contrast to domestic clinical/regulatory realities [8, 9]. Nascent commercialization; Yang et al., and Yin et al., call for multidisciplinary governance, standardize outcome metrics, and staged industrial roadmaps [8, 9]. Future progress will rely upon converging advances in flexible electrodes, low-power integrated circuits, adaptive artificial intelligence, and regenerative neurobiology placing BCI as part of personalized medicine instead of a pure device paradigm.

6. Conclusion

This paper conducted systematic review on the role and application progress of brain–computer interface in the functional recovery of patients suffering from severe motor disabilities (amyotrophic lateral sclerosis and high-level paraplegia). It found that BCI successfully bypasses the constraints of peripheral nerve and muscle damage via directly decoding neural activities within motor- or language-related cortical areas. It shows great promise in augmentative communication, motor substitution and environmental control. For ALS patients it is an indispensable means of preserving

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their social interactions and autonomous expressions at advanced stages. For high-level paraplegia, BCI-integrated exoskeletons and closed-loop feedback systems provide viable avenues towards near-natural limb movements. Nevertheless, there exist some challenges related to long-term stability, algorithm adaptability, system complexity, and ethics regarding BCI technology. Advances in materials science, artificial intelligence, and neurobiology will allow us to develop personalized, multifunctional, and clinically applicable BCI systems.

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