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Neural Bypass via Brain-Computer Interfaces: Restoring Function after Spinal Cord Injury

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Abstract. Spinal cord injury (SCI) frequently leads to enduring motor and sensory impairments, significantly diminishing patients' autonomy and quality of life. Recent advancements in brain-computer interface (BCI) technology have brought the concept of a neural bypass, wherein motor goals are decoded directly from cerebral activity and redirected to peripheral effectors, thereby bypassing impaired spinal connections. This review encapsulates the theoretical underpinnings and contemporary developments of BCI-based neural bypass devices, emphasising invasive electrocorticography (ECoG) recording. This paper emphasises signal acquisition, feature extraction, and decoding methodologies, including linear discriminant analysis (LDA), support vector machines (SVM), and contemporary deep learning techniques such as CNN–LSTM frameworks, which provide precise prediction of motor intents. Functional electrical stimulation (FES) is presented as a principal output modality for the restoration of limb movements, in conjunction with epidural electrical stimulation (EES) aimed at spinal motor pools. Exemplary case studies—such as the restoration of natural ambulation via a brain-spine interface, brain-mediated reaching and grasping utilizing FES, and EEG-based BCI FES gait training. This paper examines present problems including signal stability, long-term implant safety, and ethical considerations, and we delineate future trajectories for scalable neurotechnology in spinal cord injury rehabilitation. Collectively, our data suggest that BCI-enabled neural bypasses signify a promising transition from functional compensation to functional restoration in spinal cord injury therapy.

Keywords: BCI, Spinal cord injury, Functional electrical stimulation, Electroencephalogram

1. Introduction

The debilitating neurological condition known as SCI severely reduces a patient's quality of life and sense of autonomy by frequently causing irreversible movement and sensory impairments. For incomplete injuries, traditional therapies like physical therapy, medication, and neurosurgical restoration can be effective treatment, but in cases of complete spinal injuries, these therapies usually do not provide functional improvement [1].

Recent developments in neurotechnology have changed the focus of rehabilitation from functional compensation to functional restoration in order to get over this restriction. Researchers

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want to use developing technology to restore native control pathways instead of depending on external assistive devices to get around impairments. BCIs are becoming one of the most promising technologies. In order to directly activate muscles or peripheral nerves, BCI decode the user's movement intention from motor-related neural signals that are extracted from the cerebral cortex. This method creates a "neural bypass" by avoiding injured spinal segments [2].

Clinical research has shown that BCI-based systems can help paralysed patients accomplish arm raising, grasping skills, and even supported walking, underscoring the technology's revolutionary potential. The viability of BCI as an artificial communication pathway keeps getting better thanks to ongoing advancements in brain signal capture, decoding algorithms, and closed-loop control.

The present status of neural bridging systems enabled by BCI is described in this review. Start with outlining the pathophysiology of SCI and the foundations of BCI. Then look at example experimental experiments and clinical investigations that confirm the viability of the system. Finally conclude by talking about the field's future directions, ethical issues, and lingering technological difficulties.

2. Theoretical foundation analysis

2.1. SCI

SCI can be categorized as traumatic spinal cord injury (TSCI) and non-traumatic spinal cord injury (NTSCI) based on aetiology. TSCI results from direct and immediate mechanical injuries, including spinal fractures or dislocations, as well as spinal cord contusions, compressions, and/or lacerations. The majority of patients experience enduring motor dysfunction (weakness or paralysis), sensory impairment, and autonomic dysfunction. The predominant cause of NTSCI is degenerative cervical myelopathy (DCM), arising from intervertebral disc protrusion, ligamentum flavum hypertrophy or infoldings, and spinal cord shear and tethering generated by cervical motion, signifying a gradual degenerative condition [3].

Approximately 61.6% of spinal cord injury patients are non-traumatic instances, and due to a substantial rise in mortality with age, the total mortality rate among non-traumatic spinal cord injury patients exceeds that of traumatic spinal cord injury patients [4].

The American Spinal Injury Association (ASIA) Impairment Scale (AIS) is the globally acknowledged instrument for assessing the severity of SCI and is integrated into the International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI). The AIS relies on the preservation of sensory and motor functions below the lesion level, particularly focusing on the sacral segments (S4–S5): AIS A (Complete injury): Absence of sensory and motor function in S4–S5 (no sacral sparing). AIS B (Sensory incomplete): Sensory function is maintained below the level of injury (including S4–S5), but motor function is absent. AIS C (Motor incomplete – weak): Motor function is retained, although over fifty percent of the essential muscles below the affected level exhibit a muscle grade of three or lower. AIS D (Motor incomplete – strong): Motor function is retained, with at least fifty per cent of the major muscles below the injury level exhibiting a muscle grade of ≥3. AIS E (Normal): A history of spinal cord injury with full restoration of sensory and motor functions [5].

The global annual incidence of spinal cord injury is estimated to be between 80 and 116 million new cases, with a prevalence of approximately 27 million individuals. The incidence exhibits significant regional variation, spanning from 8 to 246 instances per million individuals [6–9]. Men face a markedly elevated risk compared to women, with falls and road traffic accidents being the primary causes.

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Despite the potential benefits of acute-phase decompressive surgery, stabilization, pharmaceutical therapies, and rehabilitation training in facilitating partial recovery, the probability of achieving significant motor and sensory function restoration in individuals with total spinal cord injury is exceedingly low. Long-term impairment not only limits everyday activities and social engagement but also creates a substantial economic and caregiving burden [1].

From a positive standpoint cortical region that have experienced functional loss for years due to high-level spinal cord injury can nevertheless yield reliable brain-computer interface signals from a positive standpoint [10]. As non-invasive and invasive BCI technology, neural decoding algorithms, and neuromuscular stimulation devices/electrodes progress, the electronic circumvention of impaired spinal pathways may become feasible. The electronic neural bypass is an innovative approach for functional rehabilitation following SCI [11]. Consequently, the development of procedures that circumvent the damaged spinal cord and directly restore neuronal signal transmission has emerged as a prominent area of research.

2.2. BCI

BCI is a communication system that operates independently of peripheral nerves and muscles. It captures electrical or other signals associated with brain activity from the scalp, cortical surface, or intracortical acrfreas. Through the analysis of these signals and the extraction of pertinent information, BCIs convert them into commands for applications that engage with external devices or the body itself. Such applications can replace, restore, augment, complement, or enhance the normal functions of the central nervous system. For instance, in individuals with spinal cord injury-induced paralysis of the upper limbs, an implanted brain-computer interface-controlled electrode can activate paralysed muscles to restore grasping ability [10].

BCIs can be classified by Invasiveness levels: non-invasive (EEG, fNIRS), semi-invasive (ECoG), and invasive (intracortical microelectrodes). Functional objectives: substitution (replacing lost functions), restoration (recovering compromised functions), and augmentation (augmenting intact capabilities). Signal paradigm: motor imagery (MI), event-related potentials (ERP, such as P300), and steady-state visual evoked potentials (SSVEP). Each modality possesses distinct advantages, and the selection relies on experimental comparison to ascertain which signals most effectively attain the desired outcome [10].

3. Methods

3.1. Type of BCI technology using

This review concentrates on BCIs utilising invasive recording techniques, including ECoG [12, 13]. ECoG is an invasive neural recording method that involves the placement of flexible electrode grids or strips beneath the skull, on the cortical surface (either epidural or subdural), to directly capture local field potentials (LFPs) [14]. It offers millimeter-scale spatial resolution and an extensive frequency bandwidth (0–500 Hz). Compared to EEG, ECoG provides more distinct and multidimensional signals, encompassing larger cortical areas and facilitating high-resolution mapping of cortical functions, such as the differentiation of motor and sensory regions for individual fingers [15].

Clinically, ECoG electrodes are typically platinum discs approximately 4 millimetres in diameter with a surface area of 2.3 square millimetres. Macro-ECoG arrays possess an inter-electrode spacing of approximately 10 mm, whereas micro-ECoG arrays can be minimised to around 1 mm [12, 16].

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Common configurations consist of 8×8 grids or 4 to 6 electrode strips. Most arrays are implanted for therapeutic purposes, with their position, number, and implantation length dictated by medical necessities rather than research design, and most BCI systems rely on EEG to record brain electrical signals to determine electrode placement [12, 14].

At the neurophysiological level, high-frequency gamma activity (60–120 Hz) is intricately associated with local neuronal firing during motor execution, motor imagery, and cognitive tasks, offering substantial insights into motor, sensory, and linguistic processes [17]. Conversely, low-frequency μ (8–12 Hz) and β (18–26 Hz) rhythms are linked to thalamo–cortical modulation of the motor cortex, commonly displaying event-related desynchronization (ERD) or synchronization (ERS) during motor planning and execution [14].

The commonly retrieved characteristics of ECoG signals encompass: Spectral characteristics: Event-related desynchronization/synchronization of μ/β rhythms, alterations in high-gamma band power, and power spectral density (PSD) for measuring energy fluctuations in specified bands. Temporal characteristics: average amplitude, variations in signal envelope, and peak latency. Time-frequency characteristics: wavelet transform or short-time Fourier transform (STFT) can capture concurrent time-frequency dynamics, particularly swift high-frequency activity. Spatial characteristics: spatial filtering techniques (e.g., common spatial patterns, CSP) to improve the signal-to-noise ratio and cortical mapping to pinpoint functional hotspots, such as individual finger motor regions in the primary motor cortex.

3.2. Decoding

These multimodal properties are supplied into various decoding models (e.g., LDA, SVM, CNN, RNN) to turn brain signals into motor intentions or control orders.

Initial research often utilized linear techniques, including LDA and SVM, which gained popularity for their rapid training and clear interpretability [18]. For example, an LDA-based two-step classification utilizing high-gamma band power (72–110 Hz) was executed: the initial classifier discerned movement presence, while the subsequent classifier specified finger movements, facilitating real-time prosthesis control. The online detection accuracy for finger movements attained 92%, with classification accuracies ranging from 76% to 88% [19]. Additional research utilised the CSP method to effectively differentiate hand extension from flexion with minimal error rates [16].

Due to the augmentation of data accessibility and computing capabilities, nonlinear models like convolutional neural networks (CNNs) and recurrent neural networks (RNNs/LSTMs) have been included into ECoG decoding. These models may autonomously extract hierarchical features and encapsulate the temporal dynamics of brain activity. The integration of CNNs and RNNs yielded substantial enhancements in finger trajectory prediction and motor intention categorization [20]. Moreover, probabilistic graphical models, including conditional random fields (CRFs), have been utilised in multi-class classification tasks, attaining superior performance in five-finger movement decoding on the BCI Competition IV dataset [16].

The decoding efficacy of ECoG is significantly influenced by the alignment of feature selection and model selection. Although deep learning-based end-to-end methods demonstrate significant promise, conventional linear techniques continue to be the predominant selection in contemporary clinical closed-loop BCI systems owing to their reliability in small-sample contexts.

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3.3. Using FES as the output

In addition to traditional physical and occupational therapy, the predominant technology employed to restore motor function in spinal cord injury patients is FES, which was first introduced in the 1960s for gait and motor rehabilitation. The core premise is to administer brief electrical pulses to stimulate muscular contractions, allowing paralyzed muscles to contract and execute functionally significant movements [21]. The stimulation targets encompass the spinal cord, peripheral nerves, and the muscles themselves. EES at the spinal level can influence the dorsal root entry zone (DREZ), hence modifying local spinal networks to activate specific motor neurone pools. By optimizing anode-cathode configurations, the electric field can be accurately directed to specific DREZ subsets, thus enabling independent control of hip, knee, and ankle flexion and extension [14]. Typical stimulation parameters include 20–40 Hz frequency, 0–120 mA amplitude, and 0–300 μs pulse width, employing biphasic waveforms to avoid electrochemical tissue damage [22]. These configurations are input to a microcontroller to achieve automated gait cycling, synchronised with motion sensors to facilitate performance assessment [23]. A stimulation-to-contraction latency of 10–50ms is typically noted, contingent upon the equipment and the specific muscle units addressed [22].

FES devices are classified into surface electrodes (cutaneous patches), percutaneous electrodes (needle-based), epimysial electrodes (implanted on the muscle surface), and cuff electrodes (encircling peripheral nerves) [22]. Surface systems are extensively utilized in rehabilitation because to their straightforward setup, albeit they provide limited selectivity. Conversely, implanted devices provide accurate stimulation of deep nerves and muscles, rendering them especially appropriate for prolonged use. Fully implanted devices can attain more natural gait patterns and enhanced control accuracy by directly targeting motor neurone pools or specific nerve trunks [21]. For example, activating hip flexors can commence walking, or engaging ankle dorsiflexors reduces foot drop during the swing phase, so facilitating stable locomotion.

Functionally, FES has been extensively utilized for the rehabilitation of both upper and lower limbs in patients with spinal cord injury. Electrical stimulation of targeted nerves or muscle groups in the upper limb allows patients, following training, to recover grasping abilities and even precise control of individual fingers. FESC for the lower limb focusses on the quadriceps, peroneal nerves, and ankle musculature to rehabilitate gait [21]. A prominent example is the FDA-approved Parastep system, which uses surface electrodes to stimulate quadriceps and peroneal nerves, allowing patients to perform alternating stepping motions [23]. Numerous studies demonstrate that focused FES not only improves ambulation and muscle strength but also boosts cardiovascular fitness and mitigates secondary problems induced by prolonged immobility [24]. Schematic representation of the BCI system is shown in Figure 1.

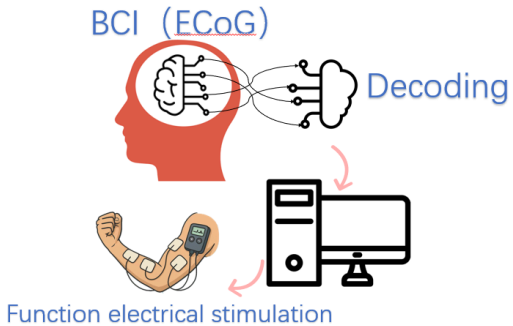


Figure 1. Schematic representation of the BCI system (picture credit: original)

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ECoG signals are recorded from the motor cortex, than decoded by computational algorithms, and subsequently used to drive FES of paralyzed muscles, enabling restoration of motor function.

4. Case study

4.1. STIMO-BSI

In Lorach et al. under the context of the STIMO-BSI clinical trial (NCT04632290), the research team recruited a 38-year-old male patient who sustained an incomplete cervical spinal cord injury (C5/C6) due to a cycling accident ten years earlier. Research team are using the WIMAGINE system, ECoG signals were recorded, while CT and MEG imaging were applied to localize cortical hotspots associated with lower limb motor intentions. Two ECoG arrays were implanted to decode right and left leg movements. A recursive exponentially weighted Aksenova/Markov-switching multilinear algorithm was employed to link these cortical signals to the parameters of EES, thereby enabling a closed-loop BSI. Remarkably, after just five minutes of calibration, the system provided continuous control of hip flexor activation, and significantly enhancing muscle activity. With further training, the participant regained the ability to walk overground with stimulation, although still requiring compensatory strategies. This study demonstrates the feasibility of directly using brain signals to control spinal cord stimulation via FES and restore natural walking in people with spinal cord injuries [13].

4.2. Rehabilitation of upper-limb

In Ajiboye et al. this study examined the rehabilitation of upper-limb functionality in a 53-year-old individual with a chronic cervical spinal cord injury (C4, AIS grade A). Intracortical microelectrode arrays were implanted in the motor cortex, and after 311 days, the subject achieved high accuracy (80–100%) in point-to-point reaching tasks, initially using a virtual arm and subsequently with FES of his paralyzed limb. Over time, significant clinical milestones were attained: by day 463, the participant successfully reached for and consumed coffee in 11 out of 12 attempts, and by day 717, he was capable of feeding himself autonomously.

Neural decoding was accomplished by daily recalibration to address session-to-session variability, utilising threshold crossing rates and high-frequency power (250–3000 Hz) obtained from each electrode. A linear transformation function akin to a Kalman filter translated brain activity into control signals for virtual or functional electrical stimulation-driven arm movements. The combination of iBCI with implanted FES and an arm support device facilitated voluntary control of reaching and grasping utilizing the participant's own limb.

This work revealed that an iBCI-FES methodology can bypass spinal cord injury to reinstate natural and self-initiated upper-limb motions in an individual with total quadriplegia, signifying a significant advancement beyond previous BCI applications restricted to cursor or robotic manipulation [24].

4.3. BCI restoration of walking

King et al. enlisted a 26-year-old male participant with a chronic traumatic spinal cord injury at the T6 level (AIS grade B), showing an absence of voluntary lower-limb motor function and sensory perception below the lesion level, except for minimal awareness of bladder fullness. The subject received training on an EEG-based BCI utilising a walking/idle attempted movement approach and underwent muscle retraining to facilitate integration with a commercial FES system.

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The BCI system analysed EEG signals divided into 4-second intervals of "idle" versus "walking attempt." Spectral power characteristics (6–40 Hz, at 2 Hz intervals) were derived from the EEG, thereafter undergoing dimensionality reduction via classwise principal component analysis (CPCA). Discriminative characteristics were subsequently derived by approximation information discriminant analysis (AIDA). Real-time decoding facilitated binary categorisation between idle and walking attempt states.

During a 19-week interval, the subject engaged in 30 real-time BCI-FES controlled ambulation sessions. The BCI was integrated with FES-induced muscle contractions, allowing the individual to complete both suspended and terrestrial walking assessments. The performance was measured by comparing the decoded BCI state to the actual task conditions, with the subject attaining an information transfer rate exceeding 3 bits/s and a correlation more than 0.9, indicating consistent and intentional BCI-FES control in response to verbal prompts.

No adverse events associated with the trial were noted. The incorporation of BCI training with virtual reality (VR) was proposed to enhance the reactivation of supraspinal locomotor regions inhibited following chronic SCI, hence bolstering the participant's capacity to achieve purposeful walking movements with BCI-FES [23].

5. Conclusion

This study emphasizes current advancements in BCI-based neural bypass systems aimed at restoring motor function following SCI. Three exemplary case studies demonstrate the feasibility of bypassing damaged spinal networks by direct cortical decoding and targeted stimulation. These studies collectively illustrate complementary techniques that include non-invasive EEG, ECoG, and intracortical microelectrodes, which can significantly achieve improvements in signal resolution, control precision, and functional results. They also emphasize the adaptability of output techniques, direct muscle stimulation and epidural spinal stimulation, in the restoration of motor function.

SCI persists in inflicting significant physical, psychological, and financial challenges, with traditional treatments providing minimal potential for substantial recovery, particularly in cases with full lesions. Recent advancements in BCI technologies have established the concept of a neural bypass, allowing for the decoding of cortical motor intentions and their direct translation into commands for FES of muscles. This technique has transformed the rehabilitation paradigm from functional compensation to genuine functional restoration.

The examined case studies—spanning non-invasive EEG-based BCI-FES to ECoG and intracortical systems—illustrate that neural bypass methodologies can reinstate fundamental activities such as gripping, reaching, and ambulation, even in chronic SCI. The analyzed research collectively indicate that BCI-enabled neural bypasses can reinstate significant motor functions in persons with spinal cord injury, signifying a transition from conventional functional compensation to direct functional restoration.

Nonetheless, significant challenges persist, such as brain signal stability, muscular fatigue generated by functional electrical stimulation, implant safety, and the restricted generalizability of single-case studies. Future research must prioritize extensive multi-center investigations, adaptive decoding algorithms, closed-loop sensory feedback, and hybrid stimulation schemes that use both peripheral and spinal channels to facilitate clinical adoption.

In conclusion, BCI-enabled neural bypass systems signify a hopeful advancement in spinal cord injury rehabilitation. By re-establishing interrupted communication between the brain and body, to restore lost functions and facilitate neurological recovery, resulting in considerable progress in neurorehabilitation.

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