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From Mind to Motion: The Promise of Brain Computer Interfaces and Myoelectric Prosthetics for Stroke Neurorehabilitation

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Abstract - Stroke is one of the principal causes of mortality and disability internationally, with a more significant burden in third-world countries. Stroke survivors show various long-term sequelae, including motor defects, hemineglect, aphasia and limb weakness. Stroke is also associated with cognitive and emotional disturbances, which may complicate the process of recovery. Rehabilitation, therefore, is one of the most critical aspects of post-stroke care. Rehabilitative measures function on the principle of neuroplasticity, where repeated neural feedback promotes functional recovery. Brain-computer interfaces (BCIs) are external devices that allow communication between the user and external devices through invasive or non-invasive methods. Direct transmission between the user and the external machine can allow for real-time neural feedback, accelerating recovery. BCIs show potential not only in motor rehabilitation but also in emotional and cognitive recovery post-stroke. Myoelectric Prosthetics (MPs) are external devices that use surface electromyography (sEMG) signals to assist motor movement and rehabilitate affected limbs. Upper limb MPs are used mainly to improve fine motor function by providing real-time proprioceptive feedback to the patient. Lower limb MPs give patients mechanical assistance along with improvements to gait and speed. Even though technical limitations exist in both BCIs and MPs, they show immense rehabilitative potential in stroke survivors. This review aims to throw light on the burden of stroke, the state of current rehabilitative care, and the use of MPs and BCIs for stroke neurorehabilitation.

***Key Words*:** brain-computer interface, myoelectric prosthetics, neurorehabilitation, stroke, bionics

1.INTRODUCTION

A stroke or cerebrovascular accident (CVA) is characterised by an abrupt disruption of cerebral blood supply, precipitating a series of events culminating in the loss of neurological function (1). Recent statistics show that seventy per cent of CVA episodes occur within developing countries (2). India, in particular, has seen an increase in the burden of stroke, making it the fifth leading cause of disability and the fourth leading cause of mortality (3). The incidence of stroke in India ranges between 105 and 152 per hundred-thousand people per year (4). On a worldwide scale, stroke is the second-largest cause of mortality and the third-leading cause of death and disability combined (2,5). Between 1990 and 2019, there was a substantial increase in annual deaths due to stroke, the fastest-growing risk factor being increased body mass index (BMI) (6). Stroke and Ischemic heart disease are responsible for more than 80% of deaths due to cardiovascular diseases in India (7).

In cases of stroke, there is disruption of cerebral blood flow, leading to a diverse series of neurological manifestations dependent on the affected brain region. Patients who suffer from attacks of ischemic strokes often present with numbness, focal weakness, or aphasia corresponding to the infarcted area of the brain (8). Stroke of the dominant hemisphere of the brain may manifest as hemianopia and limb weakness of the dominant side. Non-dominant strokes, known as right hemisphere syndrome, may affect abstract functions like pattern recognition, emotion, perception, and personality (9). Hemi-neglect and attention deficits are also commonly observed features in stroke patients (10). Patients with stroke usually withstand the initial illness but are prone to long-term consequences. Even though massive leaps have been made in the medical management of stroke, rehabilitative strategies serve as the cornerstone for post-stroke care of patients (11). Stroke rehabilitation depends on the size of the ischemic lesion and the extent of post-stroke recovery. The recovery process is heterogeneous, and recovery patterns differ for different patients. Therefore, the rehabilitation process involves a multidisciplinary approach, addressing motor, sensory, cognitive and emotional components of post-stroke sequelae (12).

2. Fundamentals of BCIs

The brain-computer interface (BCI) systems directly connect the human brain to the outside environment in real time (13). The BCIs function by using the patient's EEG signals to allow communication between the computer and the user, which is further translated into the required output (3,13). It enables patients to operate external devices like prosthetic limbs and communication tools. Due to the inherent complexity of the human brain, thoughts generated by the brain are non-stationary, making the generated signals nonlinear (13). BCIs, therefore, need a system that enables the discovery of more profound insights from the brain, enabling the BCI to translate more complex signals.
The applications of BCIs for the rehabilitation of patients with severe motor impairments can potentially restore independence and improve quality of life (14).

BCIs function as complex neuro-translators. The process of signal translation can be simplified into five stages: signal acquisition, preprocessing, feature extraction, classification and command generation (15).
After raw electrophysiological data is acquired as an Electroencephalogram (EEG), filtering and noise reduction algorithms are applied to the signal. The signal acquisition stage improves the signal-to-noise ratio and removes any artifacting. The signal is then exposed to preprocessing, which prepares the acquired signal for effective processing. Feature extraction is performed on the preprocessed signal, identifying patterns within the processed signals. The brain signals are analysed to extract features representing the user's intent and mapped onto a vector containing discriminating features from the observed signal. This step is subject to data contamination due to bioelectrical activity, including electromyography (EMG) and electrooculography (EOG). To lessen the complexity of this stage, the feature vector should be of a lower dimension. The signal can be classified once the EEG data has been processed and feature extraction is complete. Machine learning algorithms are then used to identify feature-rich signal patterns associated with desired user actions. The BCI then decodes the intentions of the user based on classified neural signatures. These classified neural signatures are then translated to commands for connected devices, allowing the user to control them. The possibilities may range from controlling a computer cursor to moving a prosthetic limb.
Invasive and non-invasive methods acquire the brain's electrical signals. Invasive acquisition modes enable brain signal recording by surgically inserting electrodes inside the brain. Penetrating micro-electrodes and electrocorticography (ECoG) are invasive modes of acquisition(16). Non-invasive modes of acquisition include EEG, Functional Magnetic Resonance Imaging (fMRI), Magnetoencephalography (MEG), and Functional Near-Infrared Spectroscopy (fNIRS) (17–20).
Classification algorithms include neural networks, the concept of which has been derived from biological neural systems.

The inputs in a neural network are connected with positive or negative weights, which are then processed through processing units, ultimately connecting to the output. Commonly used neural networks include Convolutional Neural Networks (CNN), Perceptron Neural Network (PNN), and Probabilistic Neural Network (21–23).

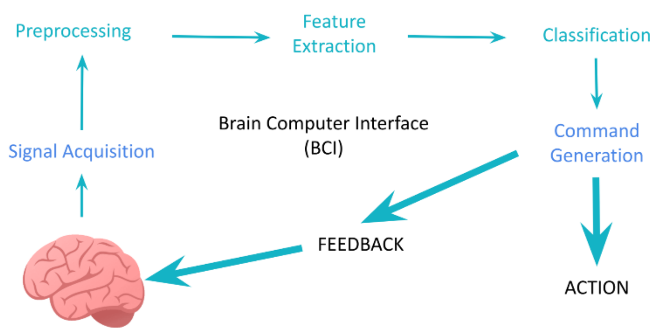

Fig -1: **A Simplified Illustration of Brain Computer Interfaces (BCIs)**

3. State of Neurorehabilitation

The recent headway in radiological imaging methods in stroke patients has revealed that the contralateral cortical hemisphere plays a vital role in recovery (24). Post-ischemic reorganisation of the somatosensory system occurs in the contralateral side of the brain, compensating for the loss of function due to an infarct (25).

Our understanding of the brain and neuroplasticity has grown significantly in recent years. It has been seen that the brain is intrinsically an exceedingly dynamic structure that can actively alter its neural connections. Recent studies on human and animal physiology suggest that cortical stimulation and motor learning can potentiate cortical remodelling of the brain (26). Cortical remodelling is of paramount importance in patients with stroke-related hemiplegia.

Various underlying mechanisms are responsible for the recovery of function in stroke patients, which, unfortunately, are still poorly understood. The spectrum of stroke recovery is a mosaic of compensation, substitution and restoration of lost functions (26). Recent radiological studies have shown that neural plasticity begins shortly after stroke and involves brain areas distant from the affected site. There is reduced lateralised activation of the lesional site, indicating increased activity of the contralateral hemisphere (27). This reduced lateralisation decreases the balance between the two hemispheres (28). The intact cortical regions associated with or close to the infarct also show somatotopic reorganisation. These intact regions gradually take over the lost function of the infarcted brain tissue (29).

The state of stroke neurorehabilitation can be assessed by reviewing recent animal and human trials. Animal trials have shown that exposure to locomotor exercise within 24-48 hours after stroke has better outcomes than controls (30,31). Better outcomes are attributed to decreased inflammatory cytokines, increased Brain-derived neurotrophic factor (BDNF), and improved neurogenesis (32–34).

Therefore, contrary to the conventional practice of forced bedrest after stroke, early mobilisation of patients has gained traction as a hypothesis for stroke rehabilitation (35). Various trials focusing on initiating early activity after an ischemic episode have challenged this hypothesis. The AVERT (A Very Early Rehabilitation Trial for Stroke) found that early, more frequent mobilisation was associated with poorer outcomes when compared to standard care and may even be potentially harmful (36). Only Constraint Induced Movement Therapy (CIMT) of the upper extremity was found to have favourable results when used in the early time window post-stroke (37). Studies also suggest that early intervention can prevent learned overuse of the unaffected side, which benefits cortical reorganisation (35).

4. BCI Neurorehabilitation

Neurorehabilitation using BCI aims to enhance the quality of life of stroke patients. Assistive BCI strategies target to bypass the infarcted neuronal networks through an alternative connection to external devices. These interfaces allow patients with motor deficits to perform limb movement without using the lesional segment (38). Rehabilitative BCIs, unlike assistive BCIs, provide feedback mechanisms to hasten neuroplasticity, helping in stroke recovery (39). Neurological deficits after a stroke may create a gap between the intention and the actual execution of the patient's motor commands (40). As the patient produces little to no limb movement, sensory feedback is reduced to the brain. Rehabilitative BCI aims to close this loop by providing feedback on the patient's intention, which may be haptic or robotic (41,42). It is assumed that the sensory-motor loops of stroke patients may be strengthened by providing prompt proprioceptive feedback through external devices, eventually accelerating the neuroplasticity and motor recovery process (43).

Neurofeedback training is another mechanism used in rehabilitation and involves the conscious modulation of visualised brain activity by the patient. Research has shown that neurofeedback training over time leads to sustained alterations in activation patterns and can reduce functional impairments post-stroke (44). Reinforcement can also be provided through operant conditioning, where the patients are rewarded upon eliciting the desired action successfully and are given null or negative feedback on failing (45). Positive feedback may include actual assisted movement of the stroke-affected limb by external BCI devices, hypothetically inducing neuroplastic changes (46).

To facilitate motor rehabilitation, recent data suggests that non-invasive brain stimulation (NIBS) can be used as adjuvant therapy with BCI. Transcranial direct current stimulation is used to administer inhibitory NIBS to the contralesional motor cortex, while excitatory NIBS is used on the ipsilateral side (47). NIBS combined with BCIs target the reduced motor excitations at the lesional side and counter the post-stroke increase in inter-hemispheric inhibition (48,49).

Several cognitive impairments are seen in stroke patients, along with motor and emotional features. Cognitive challenges post-stroke can significantly alter the outcomes of motor rehabilitation techniques, even when BCI technologies back them. Understanding the BCI interface's feedback and maintaining sustained attention for prolonged periods is paramount for neuroplasticity. A severe cognitive disability can remove the patient's ability to undergo motor rehabilitation programmes, severely affecting their quality of life. Traditional post-stroke rehabilitative cognitive training has seen improvements in the critical cognitive functions of patients, but the use of BCIs in this realm has been relatively less explored (50). The potential of BCI applications in cognitive rehabilitation, however, shows promise due to its fruitful applications in Attention Deficit Hyperactivity Disorder (ADHD) and Cognitive impairment (51,52). A randomised control trial tested a BCI-based training program for ADHD, where EEG-based neurofeedback therapy significantly improved attention and impulsivity symptoms in children (41,51). Even though BCI-cognitive rehabilitation is less explored, many case reports have shown improvements in patients with severe memory deficits (53,54).

Emotional disorders are also components of post-stroke distress, ranging from generalised anxiety disorders to Post-stroke depression (55–57). Due to the majority of focus on motor and cognitive defects in patients, the emotional component is often neglected despite its impact on rehabilitation. Emotional disturbances like lack of motivation and loss of interest can result in a lack of neurofeedback response by the patient, leading to reduced recovery of function. The patient might feel an immense challenge during neurorehabilitation activities, which may precipitate depression (58,59). Countering emotional disturbances in stroke survivors has been related to elevating the mood profile of the patients, where music therapy plays a pivotal role (60). Compared to conventional therapy without music, music therapy has seen significant improvements in the mood of patients, along with enhanced functional rehabilitation (61). The integration of BCIs with music therapy has also shown encouraging results in the regulation of emotions (62).

5. Myoelectric Prosthetics for Neurorehabilitation

Myoelectric prosthetics (MP) are external devices controlled by the electrical impulses generated by the muscles of the affected limb (63). Muscles that have not entirely lost their functional ability guide the movement of the non-functional segment of the lesional limb. Impulses are acquired from neurologically impaired muscles through surface electromyography (sEMG) (64). MP can allow users to perform basic daily tasks like lifting and grasping objects using only the surface leads of an EMG device. Continuous activation of muscles by the prosthesis can help delay muscular atrophy and enhance neuroplasticity. Some prostheses also include sensory-feedback mechanisms such as haptic feedback to improve proprioception. MP also contribute to the psychological rehabilitation of stroke patients by providing them with the ability to perform everyday tasks independently to some extent.

Studies suggest that more than 80% of post-stroke survivors have impairments in the upper limb, out of which only one-third gain full recovery (65). Braces or orthosis are often used to manage upper-limb impairment, which may or may not be powered (66). Several myoelectric robotic gloves have been used in recent years to enhance motor function and bimanual task performance in patients. One untethered robotic glove capable of providing five-finger extension and grip assistance detected user motor intentions with 84.7% accuracy (67). Another elbow-wrist-hand orthosis was found to improve the range of motion of the affected upper motor extremity (66). Several myoelectric prostheses have utilised EMG feedback to alter the coactivation of agonist-antagonist muscles during stroke rehabilitation, significantly changing the contraction of these muscle pairs (68,69).

Some studies have explored other rehabilitative uses of MP, which use myoelectric impulses as inputs for neurorehabilitation interfaces. To avoid the reintegration of pathological EMG signals from a lesional limb, some novel models mirrored EMG signals from the contralesional limb to assist movement and rehabilitation of the affected side (70).

Several studies have challenged the feasibility and effectiveness of myoelectric control in stroke rehabilitation. One such feasibility study reported an average classification accuracy of 84% using random cross-validation for recognising hand movements in stroke patients. The findings suggested that myoelectric pattern recognition for hand prosthesis control was feasible but could not be used as a template for all post-stroke patients (71). A new neural machine interface aims to improve the function of the prosthesis by targeted muscle reinnervation (TMR). TMR involves transferring the residual nerve fibres from a post-stroke or amputated limb onto an alternative muscle group, which are not functional due to the lesion (72,73). This process attempts to retrain the affected limb's proximal muscles and extract intent information from the remaining re-innervated muscles.

Prosthetics and exoskeletons have also been developed for lower limb lesions post-stroke. Some ankle exoskeletons have been found to provide increased walking speed and limb power to users (74). Another study presented an innovative approach to diagnosing and classifying leg movements in post-stroke foot drop, a commonly encountered feature. The paper proposed a new machine learning algorithm known as the Label Self-Advised Support Vector Machine (LSA-SVM), which improved the accuracy and efficiency of the EMG signals for post-stroke foot drop patients. The LSA-SVM achieved an accuracy of 99.60% in classifying the leg movements of the user, proving its potential for broader applications in lower limb myoelectric pattern recognition (75). Similar studies implemented a BCI-based neurofeedback machine to the lower limb and reported massive improvements in gait velocity and stance phase index (76,77).

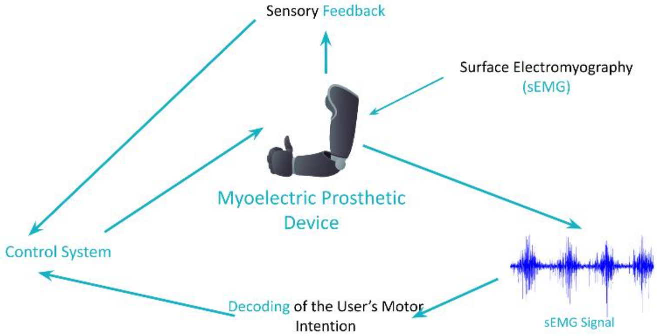

Fig -2: A Simplified Illustration of Myoelectric Prosthetics

6. Limitations of BCIs and MPs

Several limitations in effectiveness hinder the widespread use of BCIs and MPs. Limitations include but are not limited to usability, affordability, patient compliance and long-term effectiveness. The current affordability of MPs and BCIs is a concerning factor for their overall accessibility. Neurorehabilitation using BCIs is a long-term process that requires a substantial investment in both software and hardware, crippling the accessibility in resource-limited scenarios (78). The usability of BCIs is also under scrutiny as they require extended periods of training to achieve desired proficiency. User-level errors like external noise or a lack of motivation can negatively impact the practical usability of BCIs (79). Long-term compliance and patient acceptance of these technologies are also challenges to their overall effectiveness. Perceived benefit, comfort and aesthetics of these prosthetic devices and interfaces greatly influence the usability of these devices for substantial rehabilitation (80). One of the largest limitations, however, is the long-term effectiveness of BCIs and prosthetics. While studies do indicate short-term improvements in motor rehabilitation in stroke patients, sustaining benefits over prolonged durations is often difficult (81). Key factors influencing proper and prolonged usage of BCIs include device maintenance and a continuous need of motor engagement by the patient (82). A lack of consistent motor training sessions for the patient or degradation of device performance can alter the outcome of neurorehabilitation (83). Addressing these limitations, therefore, should be the top priority for BCIs and MPs to be harnessed for Stroke rehabilitation.

7. The Future of Rehabilitation

The future potential of BCIs and Myoelectric prostheses is extensive, promising to transform traditional rehabilitation techniques significantly. BCI rehabilitation in the future involves developing personalised and holistic systems that address motor, emotional and cognitive impairments of stroke survivors, taking advantage of restorative neuroplasticity (43). The future BCI systems are expected to integrate operant conditioning and advanced neurofeedback more effectively and with reduced latency (84). More efficient, real-time monitoring of brain activity can allow for dynamic adjustment of a patient's rehabilitation (38). However, several limitations are associated with BCI systems, which include the latency and methods of neurofeedback mechanisms used by the systems. The usability challenges of BCIs include the prolonged training time required and the lack of mobility for said time (85). Technical challenges that plague BCI systems include non-linearity of brain and muscle signals, loss of signal strength due to noise, and prolonged signal processing latency (86). These limitations will likely be reduced in the future, offering a more seamless experience to stroke survivors.

The integration of myoelectric control and virtual reality is an emerging avenue for neurorehabilitation, where virtual environments can provide training scenarios that are both engaging and immersive to the patient (63,87). Given the potential of myoelectric prostheses in the future, limitations like variability of surface EMG signals, control accuracy for different patients, and severity of post-stroke paralysis are still preventing the likely success of these machines. Adaptive control algorithms and approaches that are more personalised to the patients are essential for effective rehabilitation strategies in the future.

8. CONCLUSIONS

Brain-computer interfaces (BCI) and myoelectric prosthetics (MP) offer blooming potential in stroke neurorehabilitation. The burden of stroke is colossal and climbing, making rehabilitative strategies the need of the hour. BCIs induce neuroplasticity through real-time neural feedback and reinforcement, accelerating the recovery of function in stroke patients. These interfaces are also exploring new avenues like emotional and cognitive rehabilitation, which can provide a holistic and personalised rehabilitative experience in the future. Myoelectric prostheses for motor rehabilitation have gained tremendous traction recently, serving as powerful tools for restoring limb function. Prostheses have been developed for fine motor defects in the upper limb and for gait and speed improvement in the lower limb, boosting self-reliance and quality of life. Both modalities discussed have limitations, including signal acquisition, latency, and the inherent complexity of stroke lesions. Affordability, user acceptance, and long-term effectiveness are also key limitations of these technologies. The future of stroke rehabilitation must overcome these limitations to counter every patient's personalised rehabilitative need. With the eventual integration of BCIs and MPs along with traditional stroke-care therapies, neurorehabilitation can significantly improve the recovery of stroke survivors in the near future.

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