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STUDY ON THE INTERFACE BETWEEN THE NERVOUS SYSTEM AND ELECTRONIC DEVICES; CASE STUDY IN DEEP BRAIN STIMULATION WITH BRAIN COMPUTER INTERFACE

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ABSTRACT

The recent developments in brain-computer interface technology for the purpose of restoring and rehabilitating neurologic function have the objective of enabling individuals who are afflicted with neurologic disorders that are incapacitating to communicate, engage with their surroundings, and accomplish other essential activities of daily living and personal goals. Taking into consideration the field of neuro-rehabilitation, this article provides an analysis of the fundamentals, advantages, difficulties, and potential future directions of brain-computer interfaces. Following this, we investigate the therapeutic application of these technologies and offer a method for easing the processes involved in the development of brain-computer interfaces for individuals who suffer from neurologic conditions.

Keywords: *Brain-computer interface, neuro-recovery, neuro-rehabilitation, neuro-technology, brain-machine interface*

INTRODUCTION

Over the course of the last twenty years, the simultaneous development of computer technology, bioengineering, and neuroscience has made it possible to conceive of the possibility of making extraordinary advancements in the field of brain-computer interfaces (BCI), which are used to facilitate neurorecovery. For physicians who are attempting to provide the best possible treatment to patients who have long-term functional deficits as a result of neurologic disease or neurotrauma, the fast expanding field of brain-computer interface (BCI) technology and its implications for clinical research and practice are becoming increasingly important. By facilitating the restoration or replacement of lost function, brain-computer interfaces (BCIs) have the potential to improve quality of life. This can be accomplished by boosting the autonomy and agency of users, reducing feelings of isolation, and encourage reintegration into society. This article presents a practical approach to facilitating access to brain-computer interfaces (BCIs) for people with neurologic disease who are in different phases of care. This comes after a review of the fundamentals, benefits, challenges, and opportunities associated with brain-computer interfaces (BCIs) in the context of neurorecovery. In this context, the word "neurorestoration" is used to refer to the function that is quickly restored as a direct result of the utilization of a technology (in this case, a brain-computer interface). The process by which the residual or undamaged neurological system regains the ability to perform a function is referred to as "neurorehabilitation," and the term is applied to describe the process. The phrase "neurorecovery" is our more general term for the objective, which is not dependent on any particular method.

Brain-Computer Interface

The term "brain-computer interface" (BCI) refers to a system that converts signals from the central nervous system (CNS) into command signals that may be used by either an external or an internal application. Beginning in the 1800s, pioneering research conducted by Richard Caton, Adolf Beck, and Hans Berger laid the historical framework for the development of brain-computer interface (BCI) technology. These researchers made discoveries concerning continuous electrical activity in the brain, which gave a substrate for the detection and manipulation of signals from the nervous system. These discoveries laid the groundwork for the most important study on non-human primates, as well as the eventual creation and implementation of EEG neurofeedback and the first prototypes of brain-computer interfaces. Since then, the term brain-computer interface (BCI) has expanded to embrace a wide range of technologies that interact with the neurological system. These technologies include cochlear implants, which are used to restore hearing, as well as the NeuroPace device, which is a responsive neurostimulator used to treat epilepsy that is medically resistant. In its broadest sense, brain-computer interfaces (BCIs) are designed to revive or rehabilitate function, with the ultimate objective of enhancing the capabilities of users to communicate, engage with their surroundings, and accomplish other personal objectives.

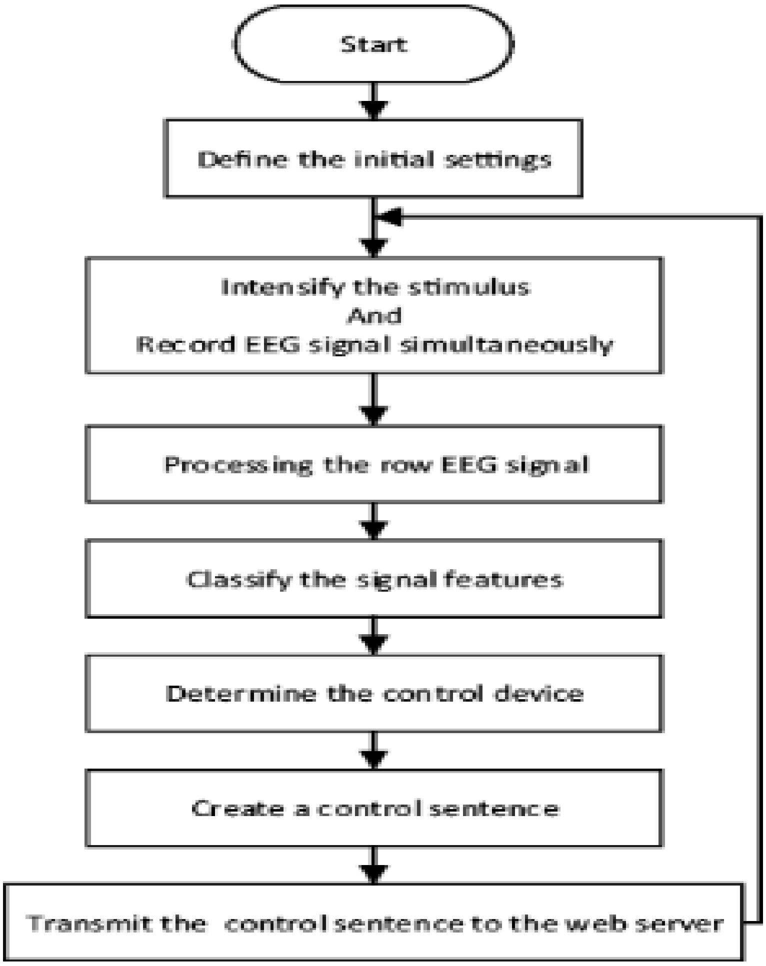

Figure 1 Flowchart of brain computer interface

Bypassing a lesion that has been caused by disease or damage is often required in order to restore lost function. The objective of this procedure is to directly replace the function that has been missing. For instance, a brain-computer interface (BCI) that enables prosthetic arm control to replace lost limb function or BCI that enables typing or voice to replace compromised verbal communication capabilities are cases that illustrate this concept. Such technologies, by virtue of their ability to permit novel means of doing an activity in a manner that circumvents the lesioned area that is normally engaged in executing that function, are examples of such technologies.

Neurofeedback, with or without neural stimulation, is often utilized in the process of rehabilitating function through the use of brain-computer interfaces (BCIs). The purpose of this practice is to encourage plasticity and make it possible to re-learn a function that has been lost. With rehabilitative brain-computer interfaces (BCIs), the goal is not to circumvent a deficit-producing lesion but rather to enhance the nervous system's capacity to re-learn function that was previously lost or impaired. Training on a brain-computer interface (BCI) orthosis system is one example. The ultimate objective of this training is to restore native upper extremity function for individuals who have hemiparesis as a result of a stroke. It is possible to combine restorative brain-computer interface (BCI) systems with rehabilitative BCI techniques that attempt to shape or engage cortical, subcortical, and spinal plasticity in order to assist neural re-learning and re-mapping. This would result in a synergistic effect.

The ability of brain-computer interfaces (BCIs) to increase diagnostic precision in disorders of consciousness, consequently shedding light on neurological rehabilitation chances, is another developing application of BCIs. People who have disorders of consciousness are frequently misdiagnosed using traditional behavioral assessments, which rely heavily on intact motor systems or higher-order cognitive abilities to infer level of awareness. Brain-computer interfaces (BCIs) may be able to help in assessing covert responsiveness, which is defined as responsiveness that is not detectable on a bedside neurologic exam. For instance, one brain-computer interface (BCI) system has been utilized to supplement the evaluation of visual fixation. This system combines a computer-based visual fixation task with electroencephalography (EEG) in order to identify event-related potentials that occur in conjunction with visual fixation. The system's objective is to assist in the detection of awareness, which can sometimes be missed by bedside behavioral assessment.

People who suffer from disorders that are caused by the disconnection of the routes to peripheral neuromotor targets and who have severe speech and motor deficits as a consequence are among the populations that neurologists typically treat and who may benefit from brain-computer interfaces (BCIs). Those who have suffered functional deficits as a result of a stroke, spinal cord injury, traumatic brain injury, motor neuron disease, multiple sclerosis, locked in syndrome, cerebral palsy, or disorders of consciousness are included in this category.

The Components of a BCI: Actuating Cognition

Sensor, decoder, and effector are the three components that make up brain-computer interfaces (BCIs). The BCI sensor is responsible for detecting and recording neural input. After that, a decoder processes and translates this data into a command signal, which is then sent to an effector so that it can carry out the function that is relevant to the situation. Particularly important is the fact that the user receives sensory feedback, which is typically presented in the form of visual feedback. Additionally, approaches including auditory and tactile feedback are being investigated.

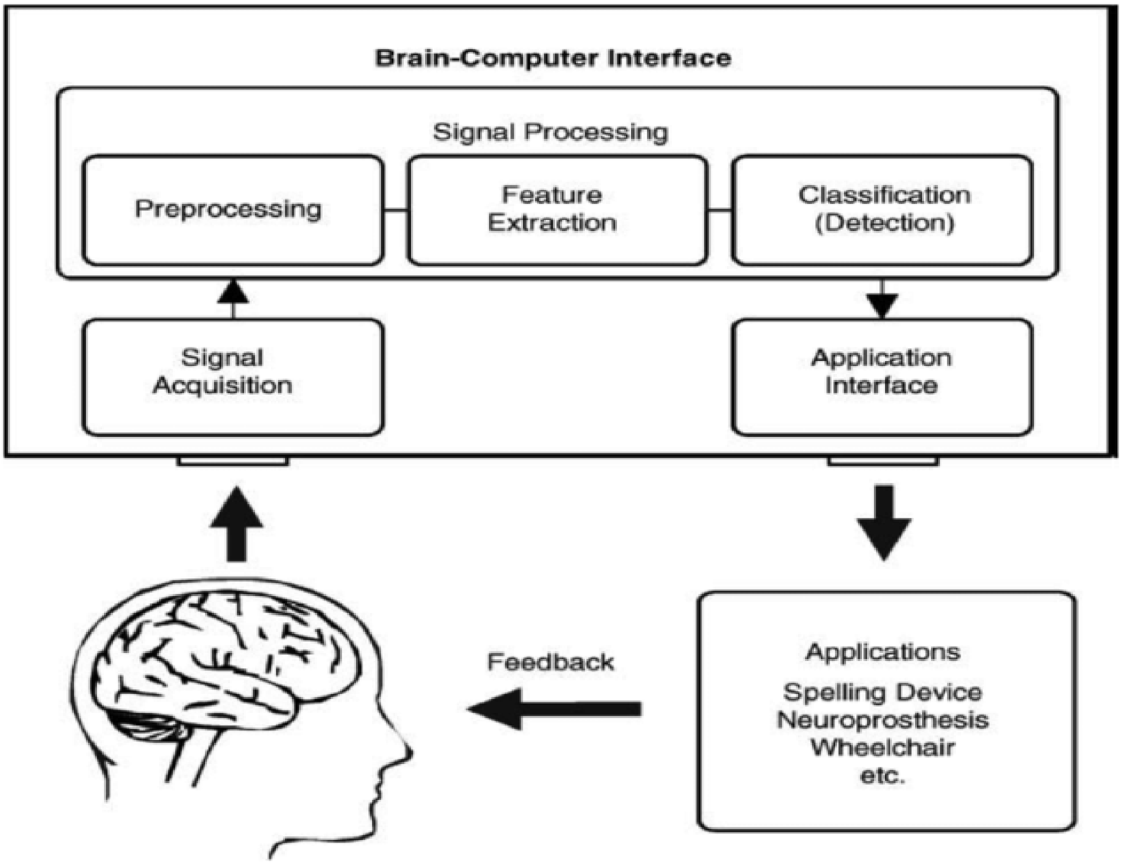

Figure 2 Components of a BCI system

BCI Sensors: Capturing Intention

BCI sensors are primarily able to detect signals from the central nervous system that are either electrical, hemodynamic, or magnetic in nature. Electroencephalography (EEG) based on the scalp, electrocorticography (ECoG) based on the surface of the brain, and intracortical microelectrodes are some of the ways that are utilized by sensors that are meant to detect electrical impulses. Sensors that are designed to detect hemodynamic signals make use of techniques such as functional magnetic resonance imaging (fMRI) and functional near-infrared spectroscopy (fNIR), both of which rely on variations in blood oxygenation to locate neuronal activity of interest. A basic modality that is utilized for the purpose of detecting magnetic brain signals that are created by synchronized neuronal currents is known as magnetoencephalography (MEG). It is possible for multimodal sensors to integrate the detection of many signals in order to improve their performance. Combinations of electroencephalography (EEG) and magnetoencephalography (MEG) or fMRI are two examples of multimodal sensors. Sensors can be differentiated from one another based on their location (for example, implanted within deep brain structures, or within cortex, or subdural, epidural, intracranial, or epicranial, on the scalp, or external to the head), temporal resolution (i.e., sensing speed), spatial resolution (i.e., sensing detail), signal-to-noise ratio, sensor size, and the capacity to record signals for an extended period of time. The two most prevalent forms of brain-computer interface (BCI) sensors that are used to restore movement and communication for persons who have neurologic disease are electrical sensors, and more specifically, electroencephalograms (EEGs) and magnetoencephalograms (MEGs).

Neural Decoding: Translating Neural Information

When brain activity or its proxy is detected and recorded by a sensor, a BCI decoder employs an algorithm to process this information and generate a signal that can be sent to an effector to trigger a beneficial output. This signal can then be communicated to the effector. Associating patterns of brain activity with the behavior that is intended for the user is the goal of neural decoding algorithms. When neural decoding algorithms were first developed, they depended on linear statistical analyses (such the Kalman filter, which is also known as linear quadratic estimation). However, recent developments in processing power and artificial intelligence are leading to improvements in the performance of brain-computer interfaces (BCI) through the use of machine learning techniques. The advancements that have been made in neural decoding offer the potential to improve the performance of brain-computer interfaces (BCIs) by taking into account the variability in neural activity, which has traditionally been a difficulty for some BCIs in terms of their consistency in inferring the intended user action.

Neural effector and Feedback: Bringing Intention to Action

The signals that are received by a neural decoder are processed by BCI effectors, which then provide the intended output. Computer cursors, robotic orthoses, exoskeletons, wheelchairs, virtual reality settings (i.e., computer-generated simulations that allow users to interactively practice activities), artificial voice, flash spellers, and reanimation of one's own limb are all examples of effectors that are used in brain-computer interfaces (BCI).

When it comes to both the restoration of function (also known as closed-loop control) and the rehabilitation of function, neurofeedback is recognized as an essential component. Audiovisual (AV) feedback has been the neurofeedback approach that has been used the most frequently. It has been investigated whether or not providing individuals with real-time AV feedback can assist with task-specific training and recovery. Neurofeedback strategies also include neuromodulation techniques, such as adaptive deep brain stimulation and non-invasive brain stimulation. These approaches are aimed at altering the neural system in order to attain enhanced motor, cognitive, and affective goals. As an illustration, individuals who have limb weakness as a consequence of a stroke may be able to learn how to increase ipsilesional mu-rhythm activation and upregulate ipsilesional sensorimotor networks by utilizing haptic or behavioral feedback strategies.

In brain-computer interfaces (BCIs), the feedback that is delivered is an essential component since it "closes the loop" between the user and the device. This could be accomplished by the use of pure visual feedback, such as the control of a cursor in two dimensions on a computer screen or the movement of a robot arm in three dimensions, or through the use of visual and sensory input during the movement of one's own arm and wrist that is caused by functional electrical stimulation (FES). In a notion known as closed-loop neural adaptation, it has been demonstrated that this feedback has the ability to affect the tuning qualities of individual neurons and cortical networks that are involved in BCI control activities. It has been demonstrated that brain-computer interface (BCI) neurofeedback can alter the properties of the neurons and groups of neurons that are engaged in BCI control. The implications of these changes for closed-loop BCI control are currently becoming more thoroughly investigated. Current research is being conducted to investigate neurofeedback paradigms at the systems-neuroscience level in order to improve neurorehabilitation..

BCIs in Neuro-recovery and Neuro-rehabilitation

A brain-computer interface (BCI) may be used in the context of neurorecovery and neurorehabilitation with the intention of restoring a capacity that has been lost as a result of an accident or disease. Communication, muscular function, mobility, autonomic systems (bowel, bladder, and sexual functions), hearing (via cochlear implants), and vision (retinal prosthesis) are some of the capacities that brain-computer interfaces (BCIs) have the potential to return to affected individuals.

It is also possible that brain-computer interfaces (BCIs) could be used to promote plasticity in neural circuits in order to restore natural function following neural injury. Donald Hebb, a neuropsychologist, conducted research and formulated a theory regarding the capacity of the brain to undergo structural reorganization. He proposed that "when an axon of cell A is near enough to excite a cell B and repeatedly or persistently takes part in firing it, some growth process or metabolic change takes place in one or both cells such that A's efficiency, as one of the cells firing B, is increased...Any two cells or systems of cells that are routinely active at the same time will have a tendency to become "associated," which means that activity in one cell or system will enhance activity in the other cell or system. A principle that is now known as Hebbian plasticity is the idea that cells that are co-active have the potential to create stronger synaptic connections in settings that are rich in learning opportunities. The phrase "neurons that fire together wire together" is the short mantra that is being used. The goal of some brain-computer interfaces (BCIs) is to strengthen synaptic connections that provide functions that have been disrupted owing to neurological injury. This is accomplished by inducing programmed recruitment of neurons, which is in keeping with this idea. Repetitive stimulation of a neural pathway, paired stimulation of multiple points in a neural pathway, and closed-loop stimulation are all methods that can be utilized to induce neural plasticity. Closed-loop stimulation is a technique that utilizes endogenous activity at one point in a pathway to trigger activation of a second point in a neural pathway.

OBJECTIVES

1. To study the interface between the nervous system and electronic devices.
2. To study deep brain stimulation with brain computer interface.

Interfacing with the deep brain

Before, the majority of the research that has been done on BMI has concentrated on decoding the brain signal and then using that information to encode an external device. Modulation of the brain, on the other hand, might be of greater significance in DBMIs. In this section, deep interface technologies and their applications are discussed.

Interface technology

Deep Brain Stimulation (DBS) is a form of electrical neuromodulation therapy that involves the implantation of a deep brain electrode in a process that is minimally invasive. The current generation of deep brain stimulation (DBS) devices often consist of two intracranial electrodes that are linked to an implanted pulse generator (IPG) by means of extended wires. Four to eight cylindrical connections, each measuring around 1.5 millimeters in length, 1.2 millimeters in diameter, and 0.5 to 1.5 millimeters in inter-contact space, are included in a conventional electrode. Electrodes of the deep brain stimulation (DBS) are inserted into the targeted deep brain using preoperative magnetic resonance imaging (MRI)-based targeting and intra-operative electrophysiological testing. Electrical stimulation is produced in the intraperitoneal space (IPG) and administered through electrodes that have been implanted. The contact selection, amplitude, frequency, and pulse width are the factors that determine the shape of the applied electric field.

Recent developments in deep brain stimulation (DBS) include the optimization of the electrode, the design of the IPG and programming system, as well as the creation of technology that is MRI-compactable and features sensing capabilities. As a result of the implementation of directed electrodes, the top and bottom contacts continue to be cylindrical. However, each of the middle two contacts is divided into three segments, resulting in a total of eight connections for a lead. By utilizing segmented contacts, it is possible to generate a wider variety of electric fields. The infraclavicular subcutaneous pocket is the primary location where the IPG is placed. This procedure requires the incision of the chest and the tunneling of the neck tissue. Because of a new design for the IPG, its size has been lowered such that it can be implanted in the skull (NCT03837314). Additionally, the technology that allows for the management of numerous independent currents permits the automatic modification of stimulating parameters in accordance with variations in impedance. This results in a more precise delivery of therapeutic agents with fewer adverse effects. A number of different approaches to waveform design and temporal pattern selection have been contemplated and implemented in the programming system. The waveform of stimulation, which is a function of the current or voltage with respect to time, is typically asymmetrical. This results in a cathodic phase of stimulation that lasts for a short period of time and an anodic phase of recharge that lasts for a longer period of time. Due to the fact that both the cathodic and anodic phases contribute to the effectiveness of neuromodulation, recently developed stimuli with symmetrical waveforms may lead to greater suppression of motor symptoms in patients suffering from Parkinson's disease and essential tremor. There is also a complex setup associated with the temporal pattern of DBS. Investigations are being conducted using computational models and algorithms in order to ascertain the contact combinations and stimulus frequencies used.

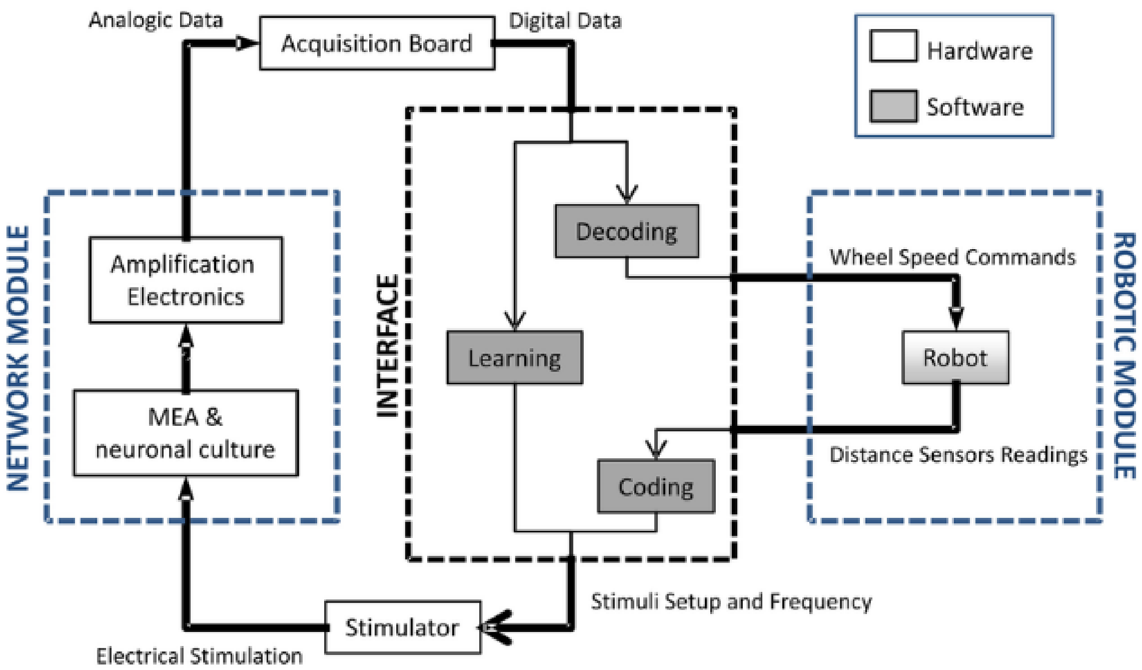

Figure 3 Block diagram of the neuro-robotic architecture

Providing more possibilities for clinical application and promoting research on human brain network dynamics are two of the goals of the development of sensing and MRI-compatible deep brain stimulation (DBS), which is an important trend in medical imaging technology. Implantable pacing devices (IPGs) that are equipped with sensing capabilities are able to retrieve electrophysiological signals from implanted electrodes. The local field potential (LFP), which is the summing of the electrical activity of neurons in the target location, comprise the majority of the signals that were captured. Chronic sensing makes it possible to identify biomarkers for closed-loop neuromodulation, which will be covered in the section titled "Closed-loop deep brain-machine interface." A number of potential complications, including device heating, current induction, IPG dysfunction, and magnetic field-induced device movement, have been associated with previous DBS systems, which have prohibited patients from undergoing MRI scanning. When it comes to MRI compatibility, heating presents a significant safety challenge. As a result of the interaction between the conducting wires of the DBS lead and the radio frequency fields in the MRI, there is a possibility that the lead tip will experience excessive heating. As a result of recent advancements in MRI-compatible deep brain stimulation (DBS) devices, it is now possible to do simultaneous MRI scanning and electrical stimulation. This makes it possible to uncover the effects that deep brain stimulation has on neuronal activity at the whole-brain level. There are new designs that are being offered for the lead structure in order to reduce the amount of radio frequency heating and to raise the intrinsic safety of the device. These ideas include a braided shield that can change the resonance behavior or wire winding with varying diameters that can increase the outflow area of the currently induced currents.

Clinical applications

Pain relief and the treatment of psychiatric conditions, such as depression and anorexia, were the initial applications of deep brain stimulation (DBS). The use of deep brain stimulation (DBS) for the treatment of movement disorders began in the 1970s. Benabid et al.'s successful treatment of essential tremor marked the beginning of the contemporary age for deep brain stimulation (DBS). Movement disorders such as Parkinson's disease, essential tremor, and dystonia are among the conditions that are treated with deep brain stimulation (DBS) nowadays. Among these movement disorders, PD is the most common indication for DBS. Other neurological conditions, such as epilepsy and Alzheimer's disease, have emerged as new frontiers for the application of deep brain stimulation (DBS) in recent years. Movement disorders are not yet included in this category. A number of other mental conditions, such as obsessive-compulsive disorder, Tourette syndrome, major depressive disorder, addiction, anorexia nervosa, and others, are also potential indications for deep brain stimulation (DBS).

Defining the epileptogenic network in the brain is a significant application of the electroencephalogram (EEG). The direct method involves recording the electrical changes that occur in various regions of the brain during ictal and interictal periods. This allows for the mapping of the level of seizures and their propagation, as well as the identification of scattered regions that are implicated in seizures. In addition, functional connectivity can be analyzed through the use of linear or non-linear methods, which involve assessing the correlation between various regions in the temporal and frequency domains. Furthermore, there is the possibility of discussing both local and global characteristics of epileptogenic networks through the use of graph theory-based analysis. The electroencephalogram (EEG) is utilized as a functional mapping interface for the purpose of determining the function of various regions of the brain and determining the degree of susceptibility to epileptic seizures that are triggered by stimulation. Low-frequency stimulation, which targets portions of the lower after-discharge threshold, and high-frequency stimulation are both components of the paradigm of stimulation. Additionally, SEEG could be utilized in the assessment of comorbidities that are present in individuals who have epilepsy, as well as in the direction of following interventional operations. In this context, the first applications have reported the location of long-term modulation targets for depression that is resistant to treatment. There is a significant possibility that SEEG will be utilized in the future for the purpose of neurophysiological research as well as tailored treatment for a variety of neurological and psychiatric conditions.

DBMI as a research platform for brain connectivity

Understanding deep brain processes, particularly those associated with diseased conditions, is one of the most significant functions of the DBMI. A prior understanding of neuroanatomy and neuropathophysiology has been of great use in providing direction for the sensing and interpretation of deep brain activity. Technological advancements in the field of artificial intelligence and brain-machine interface have the potential to capture the dynamic activity of the brain network. DBMI technology that is compatible with magnetic resonance imaging (MRI) offers a platform that allows for the direct investigation of changes in brain connectivity both before and after modulation. Another factor that has contributed to an improvement in the temporal resolution of brain network dynamics is the development of sensing techniques in DBMIS, as well as the simultaneous recording of electrophysiological signals from several sites. Through these investigations, we get additional knowledge for neural network modulation and are able to gain a deeper understanding of illness mechanisms. This, in turn, will lead to the optimization of biomarkers, implantation targets, and modulation patterns, which will ultimately lead to the construction of next-generation closed-loop systems.

There are two prominent methods for modeling the structural tractography and functional connectivity of the active human brain. These methods include diffusion magnetic resonance imaging (dMRI) and functional magnetic resonance imaging (fMRI). dMRI and fMRI, when combined with deep brain stimulation (DBS) and other advanced computational tools, have the ability to highlight the influence that DBS has on the connection patterns of the human brain. These patterns of brain connection have been investigated in relation to the effects of deep brain stimulation (DBS) using high-quality normative connectivity data generated by diffusion weighted imaging or resting-state functional magnetic resonance imaging (fMRI) from healthy participants. For structural connectivity, the volume of tissue activated (VTA) by deep brain stimulation (DBS) is used as a seed to generate the probabilistic tractography map. On the other hand, for functional connectivity, temporal correlation analysis is performed among voxels sampled from VTA and every other voxel in the brain. This analysis is based on the normative connectome. It is then possible to utilize a variety of statistical methodologies and machine-learning algorithms to evaluate the relevance and predictability of particular connections with clinical results, which ultimately leads to the selection of the most effective target networks for neuromodulation. These research paradigms have been utilized in the treatment of a variety of pathological conditions, such as Parkinson's disease, essential tremor, dystonia, Tourette syndrome, obsessive-compulsive disorder, epilepsy, treatment-resistant depression, and Alzheimer's disease. As a result, new research avenues have been opened in the hope of optimizing pre-surgical targeting and post-surgical modulation.

In the past, attempts to provide simultaneous MRI scanning and DBS have primarily been made with 1.5T MRI. This is because of safety concerns. The stimulation is able to function with 3T MRI thanks to recent developments in DBS that are compatible with MRI. An investigation of the On/Off stimulation paradigm, in conjunction with a number of different frequency or electrode combinations, has been carried out during MRI scanning, and the results have been quite intriguing. The frequency-dependent activation of the GPi-thalamus-cerebellar circuit and the deactivation of the M1-putamen-cerebellum were demonstrated, and both of these phenomena were found to correspond with improvements in motor function in long-term observations. When applied to the same patient, the activation levels of monopolar and bipolar stimulation are substantially distinct from one another. The results of this study reveal that it is possible to achieve precise modulation on an individual level through the use of DBS.

Closed-Loop Deep Brain-Machine Interface

The study on brain-machine interfaces faces a significant obstacle in the form of the closure of the sensory-control loop. The two common clinical DBMIs, deep brain stimulation (DBS) and surface electroencephalography (SEEG), offer safe and persistent interfaces for decoding and modifying neuronal processes. In order to address the disordered brain activity that are the root cause of neurological and psychiatric illnesses, several systems have been developed.

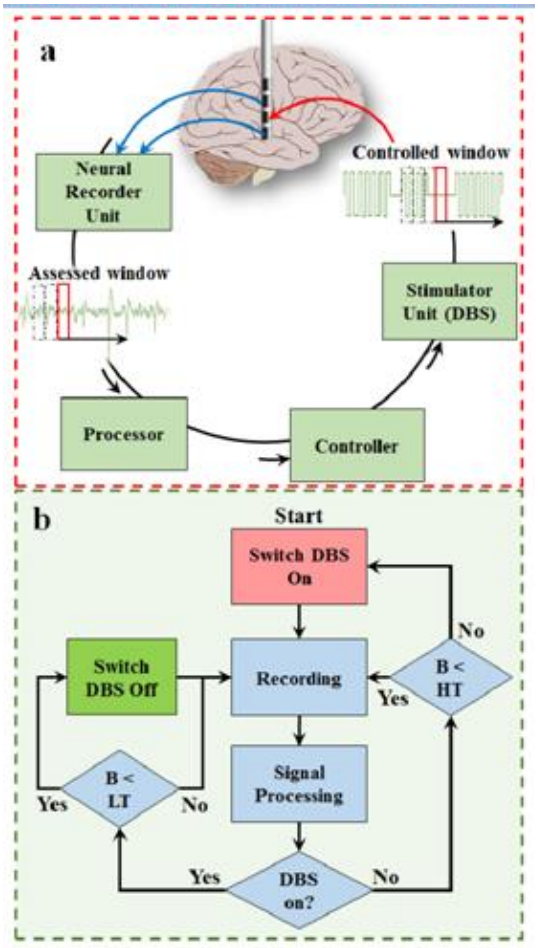

Figure 4 (a) Closed-loop control algorithm. (b) Flowchart of the closed-loop control logic. Here B, HT, and LT represents the beta power level, high threshold and low threshold values, respectively.

The clinical procedures that are typically used for the utilization of these systems are open-loop, which means that the stimulation of these systems does not react to disease-related indicators. Closed-loop applications are becoming more apparent as deep brain stimulation (DBS) and surface electroencephalography (SEEG) technologies become more frequently used in clinical treatments. With the help of closed-loop neurostimulation, it is possible to achieve both an improvement in efficacy in real time and a reduction in adverse effects. The temporal adjustment of neuromodulation in therapy is necessary because the neural target population may adapt to prolonged stimulation, for example through neuroplastic changes. If this occurs, then the treatment will need to be adjusted accordingly. DBMIs have the potential to regulate brain activity based on time feedback if the sensing-modulation loop involving them is closed.

Current system and applications

Under normal circumstances, a closed-loop DBMI system is composed of three modules:

(i) internal and exterior disease-related biomarkers are measured using a sensor module that serves as the input.

(ii) an output that is a stimulation module that delivers stimulation patterns in order to influence activity in the deep brain.

(iii) An algorithmic module that maps input sensing signals to output stimulations is referred to as control. The construction of closed-loop DBMI systems begins with the first phase, which is the development of a technique that combines simultaneous sensing and stimulation.

As was just indicated, numerous DBS systems that are capable of stimulation and sensing have been developed over the course of the past few years. Initial investigations into closed-loop modulation were carried out with the assistance of an external IPG. Local field potentials from the subthalamus nucleus with a predetermined threshold were employed as the biomarker for bradykinesia and rigidity in the majority of the closed-loop modulation that was performed on Parkinson's disease patients. The stimulation amplitude was automatically adjusted. A paradigm like this was compared to standard treatment, and the results showed that it was more effective and suffered from fewer adverse effects. On the other hand, because these investigations were conducted in experimental settings, additional proof is necessary before the clinical application is carried out on a wide scale. Recent developments include the creation of sensor and modulating devices for longitudinal brain signal recording, as well as the potential of these systems to serve as a platform for decoding and regulating human cognitive and motor states. In a recent study, it was observed that five patients who were implanted with sensing-enabled deep brain stimulation (DBS) were able to achieve long-term wireless recording and adaptive stimulation over a period of fifteen months or more. Furthermore, the initial outcome of a preliminary cohort of patients with Parkinson's disease who were treated with bilateral dual target bidirectional deep brain stimulation (Summit RC + S) has been published to demonstrate the long-term efficacy of adaptive deep brain stimulation with dual targets.

The responsive neurostimulation (RNS) device is yet another closed-loop DBMI system that can be utilized. This device was granted approval in 2013 for the treatment of partial-onset drug refractory epilepsy. It continuously monitors neural activities at the epileptic foci or through an electrocorticography strip on the surface of the brain, and it provides therapeutic stimulation when it detects the beginning of a seizure. The RNS system has been used more frequently, which has resulted in the accumulation of long-term data, which includes treatment verification in medication-resistant epilepsy. This has led to more accurate prediction, tailored stimulation, and successful network identification. Not only has closed-loop modulation been established for treatment-resistant major depression, but it has also been demonstrated for epilepsy in recent research, which has led to an expansion of indications.

The difficulties associated with closed-loop database management systems can be broken down into three categories. The initial step involves the detection and interpretation of deep brain signals, which is where the most difficult task lies: the identification of biomarkers. The encoding and stimulation portion is the second half, and the optimization of the stimulation parameters is the primary focus of this section. Control is the final component, which focuses on how to stimulate in an appropriate manner depending on the decoded signals (Figure 1).

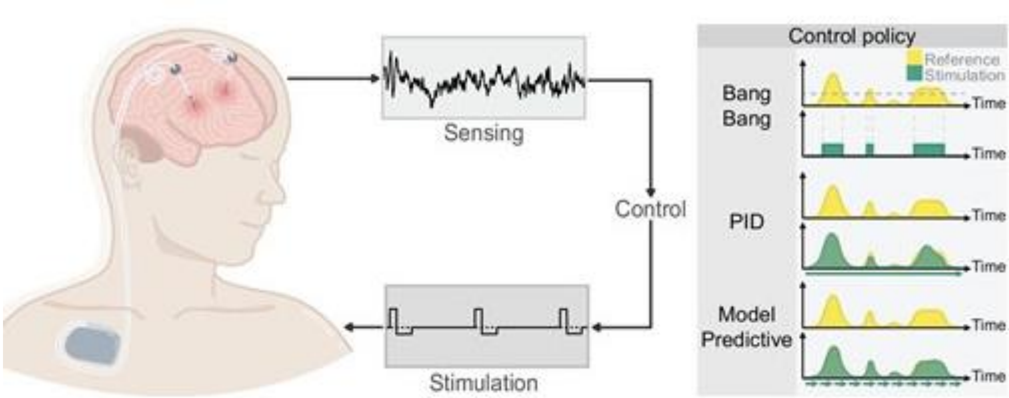

Figure 5 Sensing and modulation via a deep brain-machine interface. The implanted deep brain stimulator can record LFP signals and apply stimulation based on the sensing signals and the control policy. Control policies for current closed-loop deep brain stimulation can be categorized as Bang-Bang control, PID control and model predictive control.

Sensing and decoding

The sensing mechanisms utilized by DBMIs make it possible to perform recordings of brain events under a variety of conditions. In a closed-loop DBMI, biomarkers can be classified into two categories: those that are disease-specific and those that are state-related. When it comes to LFP, the oscillation rhythms are the biomarkers that are examined the most frequently. An identification of disease conditions in patients has been accomplished by the utilization of frequency-specific oscillations. The beta band power in the subthalamic nucleus (STN) in persons with Parkinson's disease is the one that is utilized the most frequently. This kind of power has been demonstrated to be a concrete biomarker for brady-rigidity, and it has also demonstrated long-term validity in follow-up studies [84,89]. Other characteristics of oscillation include an increase in the power of the theta band in STN, which exists between 4 and 8 Hz and is significant to impulse control problems. In Tourette syndrome, motor tics are indicated by increased theta band activity in the GPi nucleus and the centromedian-parafascicular thalamus. Additionally, high beta and gamma oscillations in the GPi were deemed to be resistant to tics in the syndrome. In addition to these pathogenic biomarkers, state-related biomarkers have also been the subject of research. The LFP delta band that was recorded from STN in the entire sleep state was more significant in the non-REM sleep stage than it was in the awake stage. On the other hand, the beta band was more important in both the awake period and the REM sleep stage, with high individual heterogeneity. There were also other research that sought to build sleep staging models based on STN local field potentials. These models offered a promising basis for state-related regulation. More recently, a study was conducted that deciphered the beginning, ending, and intensity of leg muscle activation from STN LFPS. Additionally, this study predicted the occurrence of freezing of gait in individuals with Parkinson's disease, which might be applied to motor. stimulus that is based on intentions.

Not only does the frequency domain play a significant role, but the phase of oscillations also plays a significant component. Phase-lock encoding, which is enabled by oscillation biomarkers derived from local field potentials, has the potential to provide a more accurate and comprehensive portrayal of the illness states. An increased number of network-related characteristics have been explored as a result of the development of multi-site recording techniques. Patients diagnosed with Parkinson's disease who are in the 'OFF' state have been discovered to have phase-amplitude coupling of beta and gamma bands in their primary motor cortex. It has also been discovered that patients who demonstrate freezing of gait exhibit phase-amplitude coupling. An illustration of cortical response patterns that are elicited by deep brain stimulation (DBS) was presented in a recent study. These qualities are strongly related to the hyperdirect channel that the STN uses to receive input signals from cortical areas. A different study investigated the use of intraoperative H-reflex monitoring as a possible biomarker for determining the appropriate location of electrodes. There are closed-loop systems that have the capability of utilizing multi-modal signals as biomarkers. These signals include acceleration and heart rate. In order to manage essential tremor with thalamus deep brain stimulation (DBS), the tremor-phase monitored method might be utilized. The progress that has been made in deep brain decoding for a closed-loop DBMI is demonstrated by these attempts.

Encoding and stimulation

The waveform and the arrangement of the electrical field are both components of stimulation patterns. Regarding the former, we have already talked about it in the section titled "Interfacing with the Deep Brain." During this section, we will mostly talk about the setup of the electrical field, which can be manually altered during the programming process. A number of parameters have an effect on the construction of the electrical field. These parameters include the selection of contact and polarity, amplitude, frequency, and pulse width. Among these parameters, frequency, also known as the temporal pattern, is strongly associated with brain oscillation and pathology. For the most part, the parameters of the current DBS are set to constant frequencies. There is a frequency of 130 Hz that is often utilized in deep brain stimulation (DBS) for Parkinson's disease (PD), which can obviously relieve symptoms of parkinsonism. It is possible, however, that in the long run, it will lead to a worsening of axial symptoms such as gait, balance, and speech difficulties. It was in order to strike a balance between the various therapy effects that variable frequency stimulation was developed. It is capable of switching between several frequency patterns at intervals that are chosen by the user. Studies have demonstrated that people with Parkinson's disease can experience a reduction in the number of freezing episodes, an increase in gait speed, and relief from the symptoms of parkinsonism when they receive variable frequency stimulation.

On the basis of the concept that the temporal pattern, which refers to the precise timing of the stimulation pulse sequence, plays a crucial role in neuronal coding, an additional endeavor has been made to optimize the stimulation frequency for irregular stimulation. The conventional iterative adjustment that physicians would normally perform is rendered difficult by such a perception, which brings parameter settings into a vast space. In this area of study, algorithmic approaches to machine learning and computational models are taken into consideration. The highly complex optimization of non-linear systems can be accomplished with the help of a genetic algorithm, which is a sequential optimization method that is drawn from the principles of biological evolution. In order to forecast the most effective non-regular pulse sequence for the purpose of regulating parkinsonism, a genetic algorithm is utilized in conjunction with computational models for the purpose of temporal pattern discovery.

In addition to an investigation into frequency modulation, a more comprehensive investigation into parameter optimization has been carried out. In recent years, the difficulty of programming stimulation parameters has greatly grown due to the growing popularity of directed leads for deep brain stimulation (DBS). Accurate mapping of the location of each electrode contact in the brain is possible with the use of technology that is compatible with magnetic resonance imaging (MRI). Additionally, techniques for machine learning have been utilized in order to analyze clinical data in order to optimize stimulation parameters. There is a widespread utilization of supervised learning algorithms, including random forest, support vector machines, Naïve Bayes, and deep neural networks, for the purpose of learning stimulation parameters and medicine dosages for patients based on clinical ratings. Electrophysiological and imaging analyses are utilized in conjunction with sensing and imaging techniques in order to modify stimulation parameters through the application of machine learning techniques. In a prior investigation with patient data, support vector machines were used to a STN-LFP signal, and the results showed that the optimal contact of stimulation was established with an accuracy of 91%. A learning model that was based on FMRI screening in Parkinson's disease patients with optimal and non-optimal DBS settings was established with the use of linear discriminant analysis. This model also predicted the optimal settings of contacts and amplitudes in data sets that had not yet been seen.

CONCLUSION

Neurorecovery and neurorehabilitation are two areas that could benefit tremendously from the utilization of brain-computer interfaces for patients suffering from neurologic conditions. It is possible for brain-computer interfaces (BCIs) to quantify and restore capacities that have been lost as a result of neurologic injury or disease, or to induce plasticity in order to improve learning and remapping following neurological injury. It is possible to identify a wide range of challenges and opportunities in the process of successful clinical translation throughout the whole lifespan of brain-computer interface (BCI) research. These include the early stages of design and discovery, clinical trials, regulatory approval, and clinical implementation. In order to provide care for patients who have neurologic impairments, clinicians should be knowledgeable of the present landscape of brain-computer interfaces (BCIs) across the various stages of the development lifecycle and have an understanding of how to match BCI technologies with patients who are eligible for them. To ensure that the promises of brain-computer interfaces (BCIs) for neurorecovery are captured and maintained in this rapidly developing era of novel neurotechnologies, it will be vital for researchers, engineers, doctors, patient advocates, regulatory bodies, bioethicists, payers, and other stakeholders to continue working together.

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