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Neural rehabilitation based on brain computer interface

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Abstract. BCI is a newly developed technology that can be used for neurological rehabilitation of brain injuries and paralysis. This article first reviews the history of BCI, and then introduces two major neurorehabilitation BCI technologies for neurorecording and neuromodulation, invasive and non-invasive. For each technology, we describe the challenges of each technology, analyzing the current state and future development trends. In terms of non-invasive technology, the most mature and extensive EEG brain signal analysis methods and two brain regulation technologies, transcranial magnetic stimulation (TMS) and transcranial electrical stimulation (tES), as well as the application of brain signal analysis techniques such as functional magnetic resonance imaging (fMRI) and functional near-infrared spectroscopy fNIRS) were also discussed. In terms of invasive technology, the implantable neural interface technology focuses on implantable neural interface technology, which collects cortical electrical brain signals (ECoG), which can obtain more original neural information and has high temporal and spatial resolution characteristics. In recent years, with the development of microelectronics technology and material technology, invasive BCI technology has made a lot of cutting-edge progress, which is an important future development direction of neurorehabilitation technology.

Keywords: component, BCI, Function, non-invasive, invasive.

1. Introduction

Brain-computer interfaces have a garnered attention as a potential communication and control interfaces for populations with a variety of nervous system disease including stroke, epilepsy,and Parkinson's disease. It can also be used to restore sensory functions such as vision, hearing or touch and measure and optimize human cognitive load, emotional state, attention, and other factors.

The development of brain computer interfaces originated in the 1950s, when researchers began using EEG to observe the electrical activity of humans' brains. In the 1960s, researchers discovered that EEG signals is capable of being applied to control external machine equipments such as electric wheelchairs and robotic arms. And in the 1980s, with the rapid development of computer technology, researchers have begun to explore the application of EEG signals in controlling computer games and other applications, marking the official launch of brain computer interface technology. Then in the 1990s ,BCI technology developed rapidly due to the neural and computer science. Researchers have started using technologies such as fMRI, MRI, and MEG to obtain more accurate EEG signals, thereby improving the accuracy and reliability of brain computer interface technology. In the 2000s, researchers obtains more accurate neural signals. Simultaneously, researchers began to explore applications such as rehabilitation therapy and neural feedback training based on brain computer interface technology.

Direct measurement of intra-cortical nerve cells' activity can be realized through electrode arrays that are often installed at the motor cortex. The disadvantage of the technology is that brain surgery is needed. All of the experiments are impossible to apply to our daily life even the case is less servere, such as the people whose high spinal cord is injured. Then it comes to ECoG. It records the activity of large nerve cell assemblies on the cortical surface and less invasive. It has been used as pre-treating to patients so that surgery for epilepsy and demonstratation of impressive communication rates can be implemented smoothly. Recently, it can be used by persons who are lying on the bed because of motion disabilities and even at home. Finally, EEG is one of the most widely used method for observing brain activity. Althouugh it is of low cost, excellent time resolution and ease of setup as well as rejects motion artifacts which allows its reliable use even during walking, it consipicuous drawbacks that ow spatial resolution is still considerable.[1].

In BCI, measurable changes in brain activity can occur only by considering task execution. Signals can be read, evaluated, and converted into control signals through machine learning systems, which can then be used to operate computers. Firstly, BCI technology can monitor and evaluate the state of the brain, cooperate with rehabilitation training, improve upper and lower limb motor dysfunction, and promote neural plasticity of the cerebral motor cortex. BCI technology also has immeasurable prospects in the neuroregulatory layer. BCI technology can promote tNhe positive development of abnormal brain structure or function, and is suitable for treating mental disorders such as Alzheimer's disease, anxiety disorder, and depression. In the non medical field, BCI technology also has strong potential application value, such as the brain control technology required in the military field and the intelligence of household appliances. Brain computer interface technology is a promising technology in modern scientific research, depicting a new blueprint for the future life of human society[2].

This paper contains the details of invasive and non-invasive BCI, including the function, application, and future. And there are explanations for the principle and applications of EEG, fNIR and fMRI and their development and future. The applications of different devices in our daily life and how they ncontact with human's brain are illustrated in this paper. What's more, talks about the challenges will meet and the potentials in it's futrue development.

2. Non-Invaisive Brain Computer Interface

2.1. Non-invasive BCI'S Challenge

Neural cells are permanent cells and have non-renewable properties. Therefore, damage to neural tissue will result in permanent loss, which the human body itself cannot repair. In this context, a new technology called Brain-Computer Interface (BCI) has been invented to rebuild the neutral tissues' functions and connections. A BCI interprets brain activities such as neural signals or patterns. Then it translates these activities into commands that a machine can understand. Conversely, a BMI could also provide sensory feedback to the brain by converting external information into electrical signals that the brain can understandCurrently, the BCI technology's main challenge has been listed below. To begin with, one of the main problems faced with this technology is that current study on the brain is still at junior phase. Most brain's activities' mechanism and detail are still remained unknown.As a result, the BCI's effectiveness and pertinence will be affected. For example, in addition to dimensionality reduction for high-dimensional neural data, there is a lack of more effective analysis methods, so the process of neural coding is still poorly understood. Secondly, BCI may incompatible with the human body because outer substance in the body may cause immune activity, which may lead to inflammation. Therefore,

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non-invasive BCI's interface such as electroencephalography(EEG), near-infrared spectroscopy(fNIRS) and functional magnetic resonance Imaging(fMRI) were developed Third, BCI's two main parts--recording and modulating--not only need signal detecting methods that are of high space and time resolution, but also a large detecting scale. One can increase the number of electrodes in order to achieve high detecting scale (but if there are too many electrodes, the damage to brain tissue will be greater) or can increase a single electrode's recording sites' number (i.e., the number of channels). Currently, NeuraLink can detect 3072 channels. Neuropixel2 can observe 5000 channels, and Argo can even reach an astonishing 65536 channels. But Neuropixel cannot cover the brains of monkeys or humans, except for rodents, at most covering several adjacent brain regions. And there are also a few laboratories that can afford Neuropixel because the cost is too high. It is said that Neuropixel costs several hundred thousand yuan, and electrode arrays with thousands of channels are even more exorbitant. What's more, high space and time resolution are often incompatible.For example, although the techniques for recording electrical signals (single electrode, electrode array, cortical electroencephalogram (ECOG), electroencephalogram (EEG)) have high temporal resolution, they are of low space resolution. The ECOG and EEG electrodes are too large, and a single electrode may record signals of millions of neurons mixed together. Even fMRI's voxel (smallest unit) size is at the cubic millimeter level, so one voxel may be a mixed signal of 100,000 neurons, which is still unable to meet the requirement.

2.2. Arm and Leg motion Rehabilitation

By using non-invasive BCI, rehabilitation can be realized through detecting and analyzing the motion-imagining EEG signals. In 1995, the MIT team developed the MIT-MANUS, an upper limb rehabilitation robot that was first fully defined by the world [3]. This machine can porvide assistance to stroke patients trying to completing their rehabilitation training tasks in disabled body parts such as the shoulder and elbow. During the rehabilitation training process, the patient fixes their arms on the robotic arm and follows the planned route of the system to complete rehabilitation training for shoulder and elbow areas. At the same time, the computer can elvaluate the patient's shoulder rehabilitation and elbow movement trajectory, helping the patient have a clearer understanding of the rehabilitation training task. [4]. In neural rehabilitation training, effective feedback can adjust and improve corresponding brain activities [5]. Today's most widely-used algorithm used in rehabilitation training is the Common Spatial Pattern(CSP). However, it is not good at categorizing the motion-imaging signals on certain patients such as stoke, whose signals' difference is low. In order to better stimulate peripheral nerves and muscles, the BCI rehabilitation system based on CSP-SVM adopts three different feedback methods: visual, auditory, and tactile, forming a three-dimensional feedback stimulation network [6]. By using WEB-VR technology, a light VR system which can provide training scene and ways that are not affective to patients can be developed. In immersive VR context, simulated sensory stimuli can have a more significant regulatory effect on neurons, enhancing patient performance [7].

2.3. Hands motion Rehabilitation

Current people's lifestyle and high working pressure have produced many stoke patients. To these patients, their hand can often lost several functions led to hand disability. It has been proved that non-invasive BCI can have considerable effect in helping these patients recovering. Traditional therapies on rehabilitating finger movement function only focus on movements and gaits without particularly training on fingers' particular movement functions such as counting on one's fingers. Therefore, the therapy's effects are of low levels [8]. Scientists introduced brain computer interface technology Art to enable these patients to perform the correct active rehabilitation training. In the 2018 Journal of the American Neurological Society, Neurology, it was pointed out that in clinical trials over the past 10 years, patients who received training in brain computer interfaces compared to other rehabilitation treatments such as mirror therapy, the motor function score of patients has the most significant improvement. This indicates that brain computer interface technology has great advantages [7]. BCI combines the method of changing peripheral behavior through neural activity intervention with inducing neural level changes in peripheral body nerves, achieving closed-loop training of the neuromuscular circuit. In BCI finger rehabilitation, high degree of freedom exoskeleton robot is seen as a assistance to helping patients recover upper limb distal movement. In 2018, Norman group used finger exoskeleton to help stoke patients recovering fingers' sketching. This intervention training was conducted on 8 patients for 4 weeks [8].

2.4. Future

Although non-invasive BCI can solve many problems and help patients' recovery, it still has several shortcomings. EEG is sensitive to time-varying, and can be easily mixed with Eye movement artifacts, electrocardiogram, electromyography, and power frequency interference. In order to solve the interfaces, necessary pre-processing signals is important. When analyzing Exercise Imagination EEG Signal, the band-pass or the band-block filters' limit and fixed features in the feature selection stage number is fixed.[9] What's more, limited information content of non-invasive signals, signal drift and correction on different training days, neural interfaces poor anti-interference ability and muscle coordination issues in neural control are also key factors restricting the development of BCI. [3]For example, in order to improve flexibility, accuracy, and safety in the training assistance process, the rehabilitation process needs to ensure muscle coordination as much as possible, which is crucial for dynamic modeling, motion trajectory planning, and force control calculations. Moreover, precise rehabilitation treatment plans also have high requirements for sensory motor function assessment standardisation and accuracy.

3. Invasive Brain-Computer Interfaces

Invasive Brain-Computer Interfaces represent a cutting-edge technology that has garnered significant attention for its potential to bridge the gap between the human brain and computers. These interfaces have shown enormous potential across various domains, but they also come with their unique set of challenges and ethical considerations. This section aims to introduce the applications, challenges, and future potential of invasive BCIs.

3.1. Invasive BCIs Application

Invasive BCIs are advanced systems that interface with the brain through implanted electrodes. They enable precise control and communication between the brain and external devices [10]. They measure neural activities of the brain using electrodes or chips under the scalp. Invasive BCIs provide direct contact between eletrods and brain cortexs, which makes invasive BCIs can offer the most accurate temporal and spatial resolution [11]. These interfaces provide neuroscientists with precise neural data, enhancing our understanding of the brain and neurological conditions in neuroscientific research [12]. One of the most promising and established applications of invasive BCIs is in the field of medicine. They are utilized to restore lost sensory or motor functions in individuals with paralysis, enabling them to control prosthetic limbs or computer interfaces with their thoughts. Research in this area has shown remarkable progress, including assisting individuals with paralysis to regain mobility and independence, advancing neuroscientific research by providing precise neural data, and aiding in communication for individuals with severe disabilities [10].

3.2. Challenges

Although invasive BCIs can offer high time and spatial resolution, several significant concerns needed to be addressed before massive application.

Surgical Risks: Invasive BMIs require surgical implantation of electrodes into the brain, which carries inherent surgical risks and can lead to infections or complications

Ethical Considerations: The ethical implications of BMIs are complex. Issues such as privacy, consent, and the potential misuse of this technology raise important questions that need careful examination [13].

Technical Hurdles: Developing reliable and efficient algorithms for decoding neural signals is a formidable technical challenge. The accuracy and speed of data processing are critical for practical BMI applications [13].

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Long-Term Stability: Ensuring implantable devices' long-term stability and durability remains a challenge. Over time, electrodes can degrade or become less effective, requiring additional surgeries.

3.3. Invasive BCIs Future Potential

In 2023, BMIs are considered a groundbreaking technology, with promising developments such as brain-to-text communication [12] and flexible electronics to address mechanical challenges and immune responses. Moreover, invasive BCIs are expected to receive information from computers and help brain execuate some activities, for example, invasive BCIs may restore or enhance memory functions. Also, with the accurate data that invasive BCIs can offer, researchers can have the valuable chance to learn more about our brain mechanism [12].

In conclusion, invasive BMIs represent a cutting-edge technology with vast potential to transform medicine, communication, and cognition. However, addressing challenges, including ethical considerations and technological advancements, is crucial to realizing this potential.

4. User Comfort

Current brain-computer interface research aims to develop an ideal interface without affecting users' comfort and mobility. Although current technology cannot have no influence on users' comfort, significant progress is being made in innovating interfaces that both sound ergonomically and are capable of being used in a wider range of human activities, including whole-body movements. For EEGs, this is problematic because degenerate motion artifact interactions are introduced or cause them to collapse completely. In fact, in most cases BCI study users are instructed to sit and remain still for the duration of the experiment.

Steady-state visual evoked potentials (SSVEPs) that are the brain's electrical response to repeated visual stimuli are one of the most popular event-related potentials (ERPs) for implementing EEG-based brain-computer interfaces. The target stimulus, which a user is gazing at, can be reliably identified by frequency component in elicited SSVEPs. Therefore, it is easy to be disturbed by the user's own transaction. As we know, head motion or other artifacts can influence SSVEP performance, for example, Lin did an experiment on the feasibility of detecting SSVEP in free-walking participants was validated using a treadmill with a wireless EEG headset, and it comes that their quality was deteriorated while walking (head motion)[14]. The authors r ultimately reported that there is a moderate drop of performance between sitting and walking conditions (both based on single trial recording). Another experiment by Yao also suggested that extracting the SSVEPs from the contaminated EEG signals is difficult [15]. Because in a mobile virtual reality (VR) environment, it is impossible to that EEG signals are completely not contaminated by muscular artifacts generated in their necks because their viewing angle depends on their direction pointed by their heads. This dependence leads to the MI modality's disability (at least in real-time) to practical cases without movement restrictions. Due to the great difficulties related to evaluating the effect of head movements on SSVEPs both systematicly and quantitatively, it still has a long way to go to develop the practical and commercial BCI applications of which functions can be competent in our daily life.

Assuming that BCI is now in use, users also need to go through special training and system calibration (usually done together). And the user needs to stay still during the experiment time since the same brain areas used for movement are leveraged to achieve control. In summary, the user experience at this stage is still not up to the level that the public can use.

5. Conclusion

Brain Computer Interface is a fascinating and promising research field that has the potential to completely change the interaction between humans and technology. This technology has broad application prospects in many fields, especially in the field of nerve repair. Currently, many studies are dedicated to developing treatment plans for nerve repair using BCI. For example, research on paralyzed patients has achieved significant results. By using BCI, patients can control assistive devices such as prostheses and wheelchairs through their own thinking, thereby restoring autonomous movement and life independence. In addition, studies have shown that BCI can help improve symptoms in patients with Parkinson's disease and epilepsy. With the continuous progress of technology, we believe that the application prospects of BCI in the field of nerve repair are very broad. In the future, BCI may be used to treat more diseases, such as stroke and Alzheimer's disease. In addition, with the popularity of smartphones and wearable devices, BCI is also expected to combine with these devices to provide people with more convenient and efficient health management services.

From our analysis, it can be concluded that brain computer interfaces are rapidly developing in terms of accuracy, robustness, and usability. We have seen significant improvements in data acquisition technology, signal processing algorithms, and machine learning methods, collectively improving performance in various tasks such as motion control, communication assistance, gaming, and even mental health therapy.

In addition, we found that non-invasive brain computer interfaces based on EEG and EMG signals have great prospects due to their ease of use and low risk. These systems allow users to directly interact with computers through thinking alone, providing them with new means of self-expression, education, entertainment, and rehabilitation. Finally, further progress in this domain will require interdisciplinary collaboration among neuroscientists, engineers, computer scientists, clinicians, and other professionals. Together, they should strive towards more intuitive interfaces, improved training protocols, higher portability, and broader accessibility so everyone can benefit from these remarkable technologies.

In summary, brain-computer interfaces represent an exciting frontier at the intersection of biology and technology. With continued innovation and refinement, it seems likely that BCIs will play an increasingly central role in shaping our society's relationship with machines in the years ahead.

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