Progress in the Application of Brain-Computer Interface in the Diagnosis and Treatment of Parkinson's Disease

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Abstract. Parkinson's disease (PD) is a common neurodegenerative disease, whose main features include movement disorders, cognitive impairment and other non-motor symptoms. With the aging of the population, the incidence of PD has increased year by year, seriously affecting the quality of life of patients. At present, although treatments such as levodopa, deep brain stimulation (DBS) and rehabilitation training can relieve some symptoms, it is difficult to prevent the progression of the disease, and the demand for personalized treatment is increasing. Therefore, neuroregulatory technology based on brain-computer interface (BCI) has become an important research direction in the diagnosis and treatment of PD. BCI technology has shown important application value in disease diagnosis, motor function rehabilitation and cognitive intervention of PD. BCI technology based on electroencephalogram (EEG) can be used to detect abnormal EEG signal patterns in PD patients and assist in early screening of the disease; combined with neuroregulatory technology (such as transcranial magnetic stimulation TMS and functional electrical stimulation FES), BCI can effectively improve the motor function of PD patients. However, the current application of BCI in PD still faces challenges such as insufficient signal decoding accuracy, unstable data quality and poor patient adaptability. Therefore, this article reviews the latest research progress of BCI in the field of PD diagnosis and treatment, and explores its technical bottlenecks and future development directions, in order to provide valuable reference for research in this field.

Keywords: Parkinson's disease; Brain-computer Interface; diagnosis; treatment.

1. Introduction

Parkinson's disease (PD) is a common neurodegenerative disease (NND) whose main features include movement disorders, cognitive impairments and other non-motor symptoms. With the aging of the population, the incidence of PD is increasing year by year, which seriously affects the quality of life of patients. Although the current main treatments such as levodopa medication, deep brain electrical stimulation (DBS), and rehabilitation can relieve some of the symptoms, it is still difficult to stop the progression of the disease, while the need for individualized treatment is increasing [1].Therefore, exploring new diagnostic and therapeutic techniques, especially neuromodulation techniques based on Brain-Computer Interface (BCI), to provide more precise and personalized treatment plans for PD patients has become a key direction of current research [1].

BCI is a technology that establishes an information pathway directly between the human brain and external devices, which can decode brain electrical signals and translate them into control commands for external devices, thus helping patients to restore some motor functions or perform neuromodulation [1]. In the diagnosis and treatment of PD, the application of BCI technology is mainly focused on disease diagnosis, motor function rehabilitation, and cognitive intervention. For example, Electroencephalography (EEG)-based BCI technology can be used to detect abnormal EEG signal patterns in PD patients and assist in the early screening of the disease [1]. In addition, BCI combined with neuromodulation techniques (e.g., transcranial magnetic stimulation TMS and functional electrical stimulation FES) has been shown to be effective in improving motor function in PD patients [1].

Traditional neurorehabilitation means face many challenges in PD treatment, such as large inter-individual differences, unstable training effects, and low patient compliance [1]. In contrast, BCI-

based rehabilitation training is able to provide personalized feedback mechanisms by decoding the patient's brain activity in real time, thus optimizing the rehabilitation effect. For example, studies have shown that EEG-BCI can be used to monitor changes in neural activity during motor performance and cognitive tasks in PD patients, providing data support for the development of individualized rehabilitation programs [1].

Although BCI shows great potential in PD diagnosis and treatment, it still faces challenges such as insufficient signal decoding accuracy, unstable data quality, and poor patient adaptability. Therefore, this article will review the latest progress of BCI application in the diagnosis and treatment of PD, and explore its technical bottleneck and future development direction, with a view to providing valuable references for research in this field.

2. Pathological Mechanisms of PD

2.1. Neurotransmitters

Dopamine's Role and Mechanisms in PD

PD is primarily characterized by the progressive loss of dopaminergic neurons in the substantia nigra, leading to major clinical and pharmacological abnormalities. The death of these neurons messes up the normal flow of dopamine in the nigrostriatal pathway. This causes the three main motor symptoms of PD: bradykinesia, rigidity, and resting tremor [2]. However, the pathology extends beyond dopaminergic dysfunction.

Other Relevant Neurotransmitter Systems

Other research recognizes that not all motor and non-motor features of PD can be attributed solely to dopaminergic dysfunction [3]. Multiple neurotransmitter systems show significant alterations:

The cholinergic system is notably affected, with imbalances between dopaminergic and cholinergic neurotransmission contributing to motor symptoms. The glutamatergic system's dysregulation may lead to excitotoxicity, potentially accelerating neuronal death in vulnerable regions. Additionally, disturbances in GABAergic and serotonergic systems contribute to both motor and non-motor manifestations of PD, including mood disorders and sleep disturbances [3].

2.2. Neuronal degeneration and pathological changes

Nigrostriatal Neuronal Degeneration

The neurodegenerative process in PD is characterized by selective vulnerability in certain neuronal populations. Loss of dopaminergic neurons in the substantia nigra is a characteristic feature, but the damage also occurs in other parts of the brain, such as the entorhinal region, certain parts of Ammon's horn, and key subnuclei of the amygdala [4].

2.2.1 α-synuclein aggregation and lewy body formation

Lewy bodies in neuronal perikarya and Lewy neurites in neuronal processes are two of the most important signs of PD. These inclusions contain abnormal aggregates of α-synuclein, with morphologies ranging from inconspicuous dot-like forms to voluminous types [4]. The formation of Lewy bodies may represent a protective mechanism against age-related dysfunction and degeneration of the nervous system [5].

2.2.2 Oxidative stress, mitochondrial dysfunction, and cell death pathways

Multiple cellular mechanisms contribute to neuronal death in PD. The ubiquitin-proteasome pathway doesn't work right, mitochondria are damaged, oxidative stress happens, the c-Jun N-terminal kinase pathway is activated, and there is neuroinflammation [6]. The accumulation of age-related somatic damage, combined with a failure of compensatory mechanisms, may accelerate PD progression with age [5].

2.2.3 Interaction between genetic and environmental factors

About 3 to 5 percent of PD cases are caused by a single gene, but about 90 genetic risk variants explain 16 to 36 percent of the heritable risk of non-monogenic PD [2]. Additionally, having a family member with PD or tremor, suffering from chronic constipation, and never smoking all more than doubled the relative risk of developing PD [2]. The presence of both genetic and environmental factors potentially lies at the heart of the intricate pathogenesis of this multifaceted neurodegenerative disorder.

3. Technical Principles of BCI

A BCI serves as a direct communication channel between a user and external technology, enabling control of the latter without relying on the user's neuromuscular systems [7]. This technology has developed as a possible aid for people suffering from motor disabilities of high degree and provides them with more freedom as well as participation in the surrounding world [8].

The method of signal acquisition primarily divides BCIs into two types: invasive and non-invasive. Invasive BCIs need electrodes to be directly implanted into the brain or placed on the surface of the cortical tissues. Non-invasive BCI systems, on the other hand, get their signals from outside the body without surgery [7]. Each technique comes with its own set of benefits and drawbacks with reference to signal quality, spatial resolution, and applicability [9].

3.1. BCI Signal Acquisition and Processing Principles

As foundations for BCI systems, several modalities provide neuroimaging data. EEG remains the most practiced due to its ease of use, mobility, and ability to measure time [8]. Other methods include functional Magnetic Resonance Imaging (fMRI), Magnetoencephalography (MEG), and Near Infrared Spectroscopy (NIRS), all of which have specific strengths in detecting neuronal signals [10].

Processing of signals constitutes crucial communication between components of a system. It usually includes preprocessing (cleaning noise and artifacts), feature extraction (signal characteristics), and classification (recognizing neural patterns) [11]. Out of the numerous EEG signals implemented in BCI, the P300 potentials, SSVEP, and motor imagery signals are the most practical for real-life applications [10].

3.2. Implementation and Application Process of BCI Systems

An entire BCI system consists of hardware for signal acquisition, a processing system for computing, and software algorithms for interpretation and command execution [7]. The working principle is based on machine learning paradigms, where the system learns to identify certain patterns of neural activity corresponding to a user’s will [8].

In transitioning from laboratory investigation to clinical practice, there are major problems to solve. BCI systems are implemented in three basic areas: motion therapy for people with limited mobility, speech therapy, and controlling virtual environments [10]. In spite of promising achievements, many challenges remain, such as variability in signals, ease of external disruption, and the level of user training needed to achieve any degree of control [9].

Forward-looking plans focus on the improvement of real-time performance, artificial signal processing, and more natural interaction with users. The introduction of modern prerequisites, in particular deep learning, is promising for solving certain classification problems [11]. From a general perspective, as the technology changes, the BCI is expected to profoundly affect the field of neurorehabilitation and disability assistance and one day serve as an everyday device for people with neurological disorders [10].

4. BCI in the Treatment of PD

PD is a common NND, and its main pathological mechanism involves degenerative damage to nigrostriatal dopaminergic neurons, leading to abnormal function of the basal ganglia circuits, which in turn affects motor control and cognitive function [1].In recent years, Brain-Computer Interface (BCI) technology has shown great promise in the diagnosis and treatment of PD. BCI is able to decode brain signals in real time and provide patients with personalized neuromodulation means to improve motor function and neuroadaptation [1]. Currently, the application of BCI in PD mainly focuses on three aspects: disease diagnosis, neuromodulation and motor rehabilitation.

4.1. BCI in the Early Diagnosis of PD

BCI can be used for the early diagnosis of PD by recording brain activity through EEG and cortical electroencephalography (ECoG) and extracting specific neural signaling features. It has been found that beta oscillations (13-30 Hz) in PD patients are abnormally enhanced in the STN (thalamus primordial nucleus) and GPe (external to the globus pallidus), and are closely associated with motor dysfunction [1]. EEG-based BCI can be used as a biomarker for PD by decoding these abnormal neural oscillation patterns, improving the early screening of the disease [1].

In addition, BCI combined with machine learning algorithms is able to analyze movement-related neural activities to identify abnormalities in motor control in PD patients with higher precision [12]. Compared with traditional clinical diagnostic methods, such as clinical assessment scales (e.g., UPDRS), the BCI system can provide more objective data support and reduce subjective errors [12]. In the future, the combination of BCI and artificial intelligence (AI) is expected to further optimize the early detection of PD and achieve personalized disease monitoring [13].

4.2. Neuromodulation of BCI in PD

The core goals of BCI in PD neuromodulation are to reduce abnormal beta oscillations and optimize the functional connectivity of neural networks. In recent years, the closed-loop BCI-DBS (deep brain stimulation) system has become a research hotspot. Conventional DBS uses continuous electrical stimulation, which may lead to side effects such as speech impairment and cognitive decline. The closed-loop BCI-DBS system, on the other hand, dynamically adjusts the DBS parameters by monitoring the patient's β oscillation level in real time, making neuromodulation more precise and personalized [13].

It has been found that β oscillations in the STN and GPe are abnormally enhanced in PD patients, which may be the main cause of motor retardation [13]. The ECoG-BCI-based closed-loop neuromodulation system can detect abnormal β-rhythms in real time and inhibit pathological oscillations by adjusting the frequency of DBS stimulation, thus improving motor function in PD patients [13]. Compared with traditional DBS, BCI-DBS can reduce unnecessary electrical stimulation, improve efficacy and reduce side effects [13].

In addition, BCI can be combined with transcranial magnetic stimulation (TMS) and transcranial electrical stimulation (tACS) for non-invasive neuromodulation in order to promote plasticity in the cortico-basal ganglia loop to optimize motor control [13]. Studies have shown that tACS can improve motor initiation in PD patients by regulating the synchronization of β oscillations, providing a new therapeutic strategy for non-invasive BCI [13].

4.3. BCI in Motor Rehabilitation for PD

BCI technology has also demonstrated an important role in motor rehabilitation training in PD, especially the neurofeedback-based motor training system. Recording the patient's motor intention by EEG-BCI and training with external devices (e.g., robotic arms or electrical stimulation systems) can enhance the patient's motor control [13]. It has been found that motor imagery training (Motor Imagery, MI) using BCI enhances cortical excitability and improves motor function in PD patients [13].

In addition, BCI combined with functional electrical stimulation (FES) has been used for gait training in PD patients. Studies have shown that the BCI-FES system can improve the gait and walking stability of PD patients by decoding the movement-related neural signals and activating the corresponding muscle groups [13]. This technology has great potential in motor rehabilitation of PD, especially for advanced patients, and it can be used as an auxiliary means of rehabilitation training to help patients recover some of their motor functions [13].

In the future, the combination of BCI with electromyography (EMG) and virtual reality (VR) is expected to further improve the training effect of motor rehabilitation and enable neurorehabilitation of PD patients in a more natural interactive environment [13].

5. Conclusion

BCI technology shows broad application prospects in the diagnosis, treatment and rehabilitation of PD. The EEG-based BCI system can identify abnormal neural signal patterns in PD patients and improve the early screening ability of the disease, thereby achieving earlier and more accurate intervention. In addition, BCI combined with neural control methods (such as DBS, TMS and tACS) can optimize the function of neural circuits, reduce abnormal β oscillations, and improve motor control ability. In particular, the application of closed-loop BCI-DBS system makes neural control more precise, which is expected to improve the side effects of traditional DBS and improve the treatment effect. At the same time, the application of BCI in PD motor rehabilitation has also made significant progress. For example, BCI-based motor imagery training and BCI-FES system can enhance cortical plasticity and improve patients' motor ability and gait stability. In the future, BCI is expected to be deeply integrated with technologies such as electromyography (EMG) and virtual reality (VR) to further improve the training effect of motor rehabilitation. However, the current BCI technology still faces problems such as unstable data quality, insufficient signal decoding accuracy and poor patient adaptability. Therefore, future research should focus on optimizing signal processing algorithms, improving the real-time performance and user experience of BCI systems, and strengthening the application research of BCI in clinical environments to promote its development in the direction of personalization and intelligence, thereby providing PD patients with more accurate and efficient diagnosis and treatment plans.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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