Application and Future Prospects of Brain-Computer Interface in Neurological Diseases

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Abstract:

Brain-computer interface(BCI) is becoming into a panacea for people with neurological disorders,which can help people control the machine with their minds and help them restore their body function.It has the promise of becoming the next generation of hardware for humanity.This article elaborates on the definition of brain-computer interfaces, pointing out the mainstream types (invasive, semi-invasive, non-invasive),then it explained the application status of this technology,demonstrated the wonderful use of brain-computrer interface in the treatment of neurological diseases and mental diseases by quoting true examples. In medical treatment,BCI could help Auxiliary limb disorders, neurodevelopmental abnormalities and other types of patients.In the field of rehabilitation,It can help people with nerve damage,improve the ability to live and help in the treatment of mental illness.Moreover,The article also analyzes how brain-computer interfaces work when used for such purposes.At the same time, the current development bottlenecks and limitations of brain-computer interfaces are revealed, including insufficient transmission efficiency, information security and privacy risks. Finally,this article analyzes the direction of future advances through technology.It looked forward to the future of the technology and mentioned possible technological breakthroughs.

Keywords: Brain-computer interface; Neurological Diseases; Depression.

1. Introduction

For hundreds of years, patients with amyotrophic lateral sclerosis(ALS) face the dilemma of progressive muscle atrophy and loss of function, patients with sequelae of stroke are often limited by severe movement disorders caused by spastic paralysis, and spinal cord injury patients often have permanent loss of motor and sensory functions.Brain-computer interfaces have become the hope of saving these patients in this

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context.As the communicating passage between brain and the external machinery,it directly changes the way patients interact with the world by capturing brain intentions, allowing patients to manipulate prosthetics with their minds, type and communicate, and even restore some motor functions.Brain-computer interfaces have the potential to be the perfect lifesaver for all neurocompromised patients in the future.Moreover,BCI shows brand new future,it may provide lower barriers to operation,higher operation efficiency,stronger body or even a brain that learns faster and thinks more quickly.It will be the next generation of hardware for mankind after mobile phones and computers. BCI has gradually moved from theoretical exploration to clinical practice in the medical field, covering many aspects from helping patients with atresia syndrome achieve electroencephalogram(EEG) spelling to relieving tremor in patients with Parkinson‘s disease through deep brain stimulation (DBS).However,the technology has certain limitations, such as signal transmission speed, long-term implant safety, and high price, which limit its ability to benefit more patients.

2. BCI Definition

BCI is a new communication method which is designed to establish a direct connection between brains and machines, and enable the human brain to directly operate external machinery [1].At present, there are three main types of mainstream brain-computer interfaces: invasive, non-invasive and semi-invasive, just as their names, invasive brain-computer interface refers to the direct implantation of electrodes into the cerebral cortex through surgery to directly record the activity of neurons, but it is prone to infection. Therefore, it is characterized by high signal accuracy, which may face high surgical risks and high maintenance costs. The non-invasive brain-computer interface does not require surgery, only the electrode is attached to the scalp, and the signal is collected through the electrode cap or sensor covering the surface of the scalp, which is convenient and fast, low cost, but low signal quality, semi-invasive brain-computer interfaces are somewhere in between and are designed to implant electrodes under the scalp, above the dura mater, without passing through the cerebral cortex, so they are characterized by high signal accuracy and high maintenance costs.

3. Application status of BCI

The main target population of brain-computer interfaces includes patients with physical disabilities, patients with neurodevelopmental abnormalities, patients with mental disorders, and patients with abnormal consciousness and cognition. Brain-computer interfaces can help patients with physical disabilities enhance neuronal connections and assist in connecting and controlling external devices. When targeting other patients,BCI can assist in detecting neurological states, making it convenient to observe patients‘ emotions, EEG signals and consciousness states. In the field of therapy, brain-computer interfaces basically follow the brain-to-machine model, but BCI is actually a two-way window, which can be both brain-to-machine and machine-to-brain, which may enable rapid training for the brain.

4. Application of BCI in Neurological Diseases

4.1 BCI in Patients with Nerve Damage

At present, there are three main ways in clinical rehabilitation medicine to repair or assist the interaction control between patients with cranial nerve damage and the outside world.1,Replacing damaged nerve pathways or muscles with functional nerve pathways or muscles (e.g., people can communicate with the outside world through eye movements or body movements instead of speech),this method is cheap and easy,but it could be easily limited by the disease type.2,Installing external devices that match the nerves or muscles of the injured area and can replace the corresponding functions (such as neuroprostheses that help patients with spinal cord injury restore limb motor function) which must be backed by fine surgical skills and precision instrument manufacturing skills, which is difficult to implement.3,Providing a new non-neuromuscular output channel (i.e., BCI) for the brain to replace, repair, enhance, supplement or improve the corresponding functions of the CNS by detecting the activity of the brain CNS and directly converting its thinking will into control instructions for external device operation.

BCI‘s research was originally intended to establish a way to allow people with disabilities to communicate with the outside world.However,with the advancement of its technology, the concept of BCI robots was born.BCI robots allow humans to directly operate robots to complete tasks using their brain signals.People with paralysis and ALS can use BCI robots to directly and significantly improve their self-care ability and quality of life [2].Or even regain the ability to exercise. For example, ALS patients can walk again with the help of BCI robots, and can even assist special occupations to complete the corresponding work.Elon Musk‘s company Neuralink accomplished such a feat by implanting an N1 brain-computer interface for a government measurement technician with ALS, and now patients can manipulate CAD software with their minds to continue surveying and mapping at home, bringing income to their families.

4.2 Application of BCI in Mental Illness

Depression is a mental disorder with high incidence, high clinical cure rate but low treatment acceptance rate and high recurrence rate, and its distinctive characteristics are significant and persistent depression [3].The function of antidepressant is Adjusts neurotransmitter levels in the brain and improves nerve signaling.Although it could greatly eliminate pathological depression and improve mood, but in fact depression cannot be completely cured through this way.Some studies have observed the hippocampus of depressed patients through magnetic resonance imaging(MRI), and it has been found that the core area of the brain responsible for cognition and memory has shrunk significantly.In addition, the reward circuits responsible for emotional regulation, ruminative thinking, lack of interest, and self-awareness are more or less abnormal in the brains of depressed patients, that is, the amygdala of the brain of depressed patients will be more active and connected, the activity of the anterior cingulate gyrus below the knee will increase, and the activity of the insula and dorsal prefrontal lobe will decrease.

Brain-computer interfaces are quite effective in treating depression, and people have found deep brain stimulation areas for depression. A case report showed that 32-year-old Mr. Wu had been mired in depression since he was a teenager, and all conventional treatments such as medication and electroconvulsive treatment were ineffective, and he even developed memory loss and suicidal tendencies. Through multimodal imaging and neuroelectrophysiological monitoring, Sun Bomin‘s team accurately located the core lesion of the brain‘s „emotional loop“ - the combined region of the terminal bed nucleus and nucleus accumbens. The 16-contact electrodes implanted during the operation can not only release electrical stimulation, but also collect nerve signals in real time and dynamically adjust parameters through the mobile app. At the moment of starting the machine after the operation, the patient reported that „the brain was unlocked“ and the feeling of heaviness disappeared; After personalized parameter debugging, its depressive symptoms were significantly alleviated, its social skills and quality of life were greatly improved, and it even actively participated in community activities.In recent years, with the development of science and technology, augmented reality technology (VR&AR) has been gradually promoted as a therapy for mental disorders, which mainly targets anxiety disorders and pain relief.Placing depressed patients in a VR environment allows them to immerse themselves in a virtual environment, utilizing the unique experience of virtual reality for antidepressant treatment. Brain-computer interfaces provide a reliable way to understand neural signals.However,How to better combine the two technologies is the focus of current consideration.First of all, the brain-computer interface itself has a more intuitive ability than augmented reality technology, which can be regarded as the interaction control between the senses and the virtual environment. Secondly, extended reality systems will also become useful information feedback tools in brain-computer interface systems. Traditional research uses stimulus materials such as sound, text, and two-dimensional images, which are quite different from real life scenarios, while the environment generated by extended reality can create a variety of sensory stimuli, and patients can generate higher-quality electroencephalograms (EEG) in a virtual environment closer to reality, thereby improving the performance of brain-computer interfaces.

Moreover, as a neurological disorder, autism may accompany patients throughout their lives, and its incidence rate is increasing year by year.New treatment modalities make neurofeedback therapy using brain-computer interfaces play an important role in rehabilitation training for children with autism.Carlos et al. found that the symptom performance and related physiological indicators of children with high-functioning autism were significantly improved by conducting a four-month P300 brain-computer interface attention intervention training in a virtual reality scenario [4].The P300 potential is an event-related potential(Event Related Potential,ERP),and its peak occurs approximately in the correlation300ms after the event.Theoretical research shows the probability of related events. The smaller the P300 potential, the more significant the P300 potential caused, and use each alternative target in the matrix Element representation, let these elements flash at different frequencies, stimulate people‘s vision, production,then corresponding P300 potential is generated [5].

5. Current Limitations of BCI and Future Challenges

5.1 Limited Transfer Speed

Although the performance of brain-computer interfaces has been significantly improved with the development of technology, the transmission efficiency of brain-computer interfaces is still far from enough to achieve the final goal, that is, normal and natural human-computer interaction.Transmission efficiency refers to the ability to convert brain activity into effective information output

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per minute,which is measured in bits/min, which refers to how many bits of data the brain-computer interface can transmit per minute.Intrusive brain-computer interfaces can obtain brain signals more directly and usually have high transmission efficiency,For example, the brain-computer interface team of Stanford University in the United States realizes high-speed recognition of handwritten characters based on neural signals in motor brain regions, and the equivalent information transmission rate of each electrode is about 2 bits/minute, while the equivalent information transmission rate of each electrode of the minimally invasive implanted brain-computer interface of Tsinghua University reaches 20 bits/minute.Non-intrusive brain-computer interfaces are relatively inefficient and generally provide a maximum information transfer rate of up to 5-25 bits/minute.At the 2019 World Robot Competition-BCI Brain-Controlled Robot Competition and the 3rd China Brain-Computer Interface Competition, the ideal information transmission rate of 691.55 bit/min was achieved, setting the highest record for brain-controlled typing in the previous World Robot Conference. Neuralink also successfully doubled the bandwidth of brain-computer interfaces in July 2025. The communication rate of brain-computer interfaces is greatly improved through brain signal decoding technology.After all, the key to achieving high-performance brain-computer interfaces is to establish high-speed and effective information channels between the brain and the machine.At present, how to use advanced algorithms to interact with the brain has attracted widespread attention from brain-computer interface researchers. In this regard, new tools such as machine learning and quantum computing will help make brain-computer interfaces a reality [6].

5.2 Information Security and Privacy Restrictions

Information security is also a major challenge for brain-computer interfaces in the future, George Washington University and a collaborative research team studied the security of home EEG systems and found that 156 brain-computer interface applications in the NeuroSky App store are vulnerable to short-range attacks, and 31 free applications are vulnerable to at least one remote attack.In addition, the team proposed a deep learning model of a combined recurrent convolutional neural network that can infer user activity from EEG data with reduced features stolen from the NeuroSky EEG device with an estimated accuracy of up to 70.55%[4]Therefore, how to effectively control the leakage of personal information is a crucial part of whether brain-computer interfaces can be used safely.Fortunately, at present, no brain-computer interface has successfully moved from the laboratory to commercialization, and the invasive method is focusing on reducing the rejection reaction, and the non-invasive method is focusing on reducing the size of the machine. Both require better algorithms to increase their signal transmission speed.

5.3 Expensive price

The high cost of brain-computer interfaces may also become a possibility of limiting their future development. For example, the treatment of Parkinson‘s disease costs about $130,000 for a 10-year course, while for the more difficult paralysis treatment, the initial cost of experimental implanted devices alone is $490,000, and the technology is not currently included in medical insurance, so it is now only exclusive to a small number of wealthy people. Musk has said that the price of this technology can be as low as $5,000 after mass production in the future, but it is still a luxury item at this stage. In Germany, DBS surgery costs as much as 3-60,000 euros, about 3.2-64,000 US dollars, and although public health insurance has covered some of the costs, the proportion of out-of-pocket expenses in private hospitals is still high. In the United Kingdom and France, BCI is not included in the national health insurance, and the government will only cover part of the cost during some clinical trials.

6. Future Possibilities of BCI

In science fiction works, there are often scenes where brain-computer interfaces are used to transmit knowledge, skills, information, etc. into the human brain, and brain-computer interfaces can not only be from the brain to the machine, but also from the machine to the brain. Blind people can regain their sight through brain-computer interfaces, and paralyzed people can stand up again through brain-computer interfaces. Normal people can also use external mechanical prosthetics to enhance their bodies.The transmission efficiency of brain-computer interfaces is getting higher and higher, and the machine‘s interpretation of the human brain can become faster and faster, and the therapeutic effect of brain-computer interfaces on humans will become better and better.At the same time, China has set the lowest price for brain-computer interface therapy in the world, and fully included brain-computer interface in medical insurance, with an invasive implantation fee of only US$936 and a non-invasive brain-computer interface adaptation fee of only US$138,whcih has become the lowest price in the world. With technological advancements, such as material innovation and surgical robots, the price of invasive devices is expected to drop by 50% in the next five to ten years, and non-invasive brain-computer interfaces are moving closer to the „ChatGPT“ of the neural world, and products under $500 will dominate. Therefore, BCI technology is progressing in the direction of being more affordable and economical.As brain-computer interface technology becomes more and more popular, more and more organizations are investing in this field. With the advancement of machine learning technology, brain-computer interfaces are iterating faster and faster. The technological explosion of brain-computer interfaces will come.

7. Conclusion

With the continuous breakthroughs in brain-computer interface-related technologies in recent years, the theoretical research, hardware components, and theoretical algorithms of brain-computer interfaces have made revolutionary progress.These advances can accomplish things that were previously not clinically possible and cure some incurable diseases, such as paralysis, ALS,etc. At the same time, brain-computer interfaces are not limited to physical medicine, but are also reliable channels for curing neuropsychological diseases, whether it is depression, autism, or other types of mental disorders, reality-expanded psychotherapy with the participation of brain-computer interfaces is gradually proving its reliability. Despite the promising prospects of brain-computer interfaces, humans are still facing problems such as slow transmission rate, low resolution efficiency, and expensive installation and maintenance of brain-computer interfaces.Moreover, the leakage of personal information that may be caused by brain-computer interfaces will become a security hazard that cannot be ignored, and people must be prepared to prevent information leakage.In general, brain-computer interfaces provide highly effective medical methods for people and reveal the prospects of next-generation hardware, but while bringing a high degree of convenience, people also need to be aware of and prepare for the risks under the good appearance.

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