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REVIEW

Research Status and Prospects of Brain-Computer Interface Technology in Motor Function Rehabilitation After Stroke

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Abstract

Stroke is one of the leading causes of death and disability worldwide, and it places an enormous burden on health systems and on society. Brain-computer interface technology connects the brain to external devices, controlling those devices by decoding neural signals. Research on brain-computer interface technology in motor function rehabilitation after stroke has already made marked progress in three areas: experimental paradigms, decoding algorithms, and clinical application. In future it will incorporate more precise methods of analysing brain activity and more immersive virtual reality technology to deliver sensitive real-time feedback, and it is expected to offer patients with stroke more flexible and more effective ways of recovering motor function.

Stroke is a common disease caused by haemorrhagic or ischaemic brain injury, and it has a high incidence and a high disability rate[1]. One study[2] reports that by 2020 the number of patients with stroke in China had exceeded 17 million, and that the trend is towards a younger age at onset. At the same time, 55%–75% of patients with stroke still have motor dysfunction several months after rehabilitation[3], manifest as muscle weakness and loss of motor coordination[4]. Motor function rehabilitation for patients with stroke has therefore remained a central and difficult problem in medical rehabilitation.

In recent years, as research in biomedicine, neuroscience and computer science has deepened, brain-computer interface (BCI) technology has gradually become a new tool for improving the recovery of patients with stroke. The basic idea of a BCI system is to establish a new pathway between the brain and an external device that does not depend on muscle tissue or peripheral nerves. A BCI system acquires brain signals using sensor and computer technology, analyses and recognises the EEG in real time through signal processing and pattern-recognition algorithms, and then transmits the recognition result to the external device as a control command, so achieving communication and control between the human brain and the external device[5]. This technology offers patients with stroke an entirely new route to motor function rehabilitation. By examining the research status of BCI technology in motor function rehabilitation after stroke, this paper aims to offer new thinking for improving motor function rehabilitation in patients with stroke.

Keywords: brain-computer interface; stroke; medical rehabilitation

1 The BCI system

According to the way brain signals are acquired, BCI systems fall into two classes, invasive and non-invasive. Invasive BCIs are found mainly in neurosurgery: a probe is implanted in direct contact with the cerebral cortex to obtain high-precision, low-interference signals. Because invasive acquisition does some harm to the patient's body, it is generally used in animals and in patients with epilepsy. The non-invasive BCI is therefore the type in common use: it measures the various signals associated with brain activity through electrodes placed on the scalp. The electroencephalogram (EEG) is the physiological signal most widely used in BCI systems; it is inexpensive, quick to record and easy to obtain, and by recording EEG changes in different regions of the brain[6] it can display the activity patterns of the human brain objectively. A typical EEG-BCI system is of one of the following types. (1) The motor imagery (MI)-BCI system. An MI-based BCI drives the BCI system through the characteristic change of the sensory motor rhythm (SMR), and is usually implemented with an MI task. (2) The event-related potential (ERP)-BCI system. An ERP is a transient response potential evoked by a specific stimulus event. An ERP-BCI system presents different stimuli at different times and so determines the corresponding stimulus target from the characteristics of the response. (3) The steady-state visual evoked potential (SSVEP)-BCI system. The SSVEP is the neural response of the brain to a visual stimulus of constant frequency, and is a special type of EEG signal.

Among these, the MI-BCI system has several advantages in motor function rehabilitation after stroke. Through the MI task, patients can repair, rebuild and strengthen damaged neural pathways and the associated functional areas of the brain,

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and so promote the recovery of motor function. For patients with stroke whose actual movement is limited — those with hemiplegia, for instance — MI offers a way of rehabilitating that requires no actual movement and yet allows active participation; it strengthens the patient's motivation to recover and greatly increases their willingness to take part in rehabilitation training.

2 Research status of BCI technology in motor function rehabilitation after stroke

2.1 Paradigm research

Given the superiority of MI in motor function rehabilitation after stroke, the MI-BCI paradigm has attracted widespread attention. In the MI-BCI paradigm the patient is asked to simulate the performance of a specific motor task through a thinking process — an upper-limb movement or a lower-limb movement, say — and the choice of task is usually based on the patient's rehabilitation goals and needs. The patient trains within the MI paradigm, repeatedly simulating the thought of a particular movement in order to strengthen the neural pathways associated with it. The commonest form of training displays an arrow on a screen and guides the subject to imagine the movement of the corresponding limb. To improve the effect of MI training further, researchers have proposed a series of ways of refining the MI-BCI paradigm.

2.1.1 Incorporating familiar motor tasks

For speakers of Chinese, for example, one study[7] set a Chinese-character writing MI task, which offered a training method better suited to the subjects' habits and at the same time showed that the paradigm could effectively guide subjects in regulating their brain activity and improve the accuracy with which MI tasks were recognised. Subjects take to a familiar MI task more readily, find it more interesting and are more willing to take an active part in training. A familiar MI task helps the subject to understand the goal of the task and eases the anxiety and disturbance that may arise while it is being performed, and so builds a positive training experience.

2.1.2 Introducing multimodal stimulation

One study[8] used a hybrid BCI paradigm based on MI and ERP to improve the reliability of feedback in the initial stage of training, and its results were markedly better than those of a single modality. Another study[9] incorporated virtual reality (VR) technology into the MI-BCI paradigm and demonstrated the positive effect of VR stimulation on the subject's level of neural activation and on the accuracy of MI task recognition. Multimodal stimulation activates several sensory channels at once, widening the subject's perceptual range so as to supply fuller and richer task information, which makes the target movement easier to understand and simulate and so raises the subject's attention to and engagement with the task. Multimodal stimulation can also elicit more integrated and more varied neural responses in the brain, which helps to promote neuroplasticity and so supports rehabilitation more effectively.

2.1.3 Achieving closed-loop feedback

One study[10] used functional electrical stimulation (FES) as feedback, activating the FES system while the subject performed the MI task and producing hand movement by stimulating muscle contraction. An exoskeleton device can likewise serve as the peripheral control equipment of the MI-BCI paradigm, assisting the subject to complete the action corresponding to the MI task[11]. A closed-loop feedback paradigm can process neural signals and return the MI classification result at once, and can monitor the subject's neural activity in real time, so that the system can correct the subject's MI pattern promptly. By observing the result of neural signal processing, the subject also gains a real-time understanding of their own state, which increases their involvement in rehabilitation training. With the help of FES and the exoskeleton the subject can carry out the actual limb movement, and so receives more intuitive feedback and a more genuine and complete sensory experience during MI, which strengthens the effect of training.

2.2 Algorithm research

The EEG is the aggregate expression of the electrical activity of brain neurons, and it carries a great deal of physiological and pathological information. Many factors, however — individual differences, noise interference from electromyographic activity and eye movement, and cross-influence between brain regions — make it complicated to extract useful information from the EEG. Machine-learning algorithms play a key part in BCI algorithm research: through their powerful capacity for data processing and pattern recognition they can handle a complex feature space effectively and learn the different patterns in the EEG, and so improve the performance of the BCI system and lay the foundation for putting BCI technology to effective use in motor function rehabilitation after stroke. The following are representative BCI recognition algorithms applied to motor function rehabilitation after stroke.

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2.2.1 The common spatial pattern (CSP) algorithm and its refinements

The CSP algorithm is widely used to extract features from the EEG. It seeks the optimal spatial filter, so that after projection the variance difference between the two classes of signal — left-hand MI and right-hand MI, say — is maximised, and features of high discriminative power for the classification task are thereby extracted. As research has advanced, many refined versions of the CSP algorithm have been proposed, the methods of refinement including optimisation of the objective function[12], optimisation of the time window[13] and the introduction of sparse learning[14]. These refinements have all had a positive effect on the performance, adaptability and generalisation of the CSP algorithm.

2.2.2 Convolutional neural networks (CNN)

Through the stacking of successive convolutional and pooling layers, a CNN obtains a hierarchical feature representation. This helps to capture information at different levels of abstraction in the EEG and improves the capacity to handle models and complex information. In recent years the multi-scale CNN has been applied increasingly to EEG recognition, because it can combine different scales to obtain fuller information, and it can effectively capture the dynamic change and temporal correlation in EEG features[15].

2.2.3 Graph neural networks (GNN)

The EEG is usually multidimensional data over many channels and many time points. The GNN takes graph theory as its foundation: by constructing nodes at different channels and time points and building an adjacency matrix between the nodes, it makes it possible to understand the spatio-temporal dynamics of brain activity comprehensively[16]. A GNN can also handle multimodal information well — biological signals other than the EEG, such as the electromyogram. Fusing information from different modalities into a single GNN can improve the robustness of the system.

2.3 Application

Conventional methods of limb rehabilitation after stroke usually progress slowly, and long periods of repetitive training readily leave the patient fatigued and losing interest in training. BCI-based rehabilitation therapy for stroke has clear advantages in stimulating neuroplasticity, raising patient participation and improving individualised rehabilitation outcomes, and it is being used increasingly in motor function rehabilitation after stroke.

2.3.1 BCI technology in upper-limb functional rehabilitation after stroke

In upper-limb functional rehabilitation, BCI technology can achieve more precise motor control, allowing the patient to train specific muscles and joints and so strengthening the strength and flexibility of the upper limb. One study[17] used FES as the feedback of a BCI system in the grouped treatment of patients with post-stroke shoulder subluxation, and assessed the distance of shoulder subluxation, the degree of pain and manual function after treatment; the BCI-FES group improved significantly by comparison with the conventional treatment group. Another study[18] combined BCI and VR technology to intervene in hand motor disorder in patients with stroke, and showed that the hand rehabilitation system it proposed could activate more of the cerebral cortex in the course of rehabilitation.

2.3.2 BCI technology in lower-limb functional rehabilitation after stroke

In lower-limb functional rehabilitation, a BCI can train the patient in gait-related tasks and so help them to recover the ability to walk. One study[19] examined the effect of a lower-limb rehabilitation robot on functional recovery after stroke, dividing patients into a treatment group and a control group that received BCI lower-limb robot training and lower-limb pedal training respectively; after training, the treatment group scored significantly better than the control group on the leg score of the Fugl-Meyer Assessment and on the National Institutes of Health Stroke Scale (NIHSS). Another study[20] used a BCI system with visual and motor feedback to rehabilitate patients with post-stroke hemiplegia, and found that both the lower-limb Fugl-Meyer score and the 6-min walk distance improved considerably.

Taken together, these results show that BCI training can effectively promote neural reconstruction in the brain, improve the patient's motor attention and concentration, consolidate motor memory, and so bring about the recovery of motor function.

3 Prospects

BCI technology has already shown great potential in the field of motor function rehabilitation after stroke. On the basis of the research reviewed above, several lines of development suggest themselves. First, as BCI technology advances, more advanced and more precise analysis of neural information will become possible. This will not only improve the accuracy with which the patient's motor intention is recognised; analysis of the EEG will also allow more individualised

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rehabilitation plans to be drawn up, and so improve the outcome of motor rehabilitation. Second, BCI technology may accelerate motor rehabilitation through a more sensitive real-time neural feedback mechanism. By monitoring the patient's brain activity in real time and returning that information to the patient, the BCI system helps the patient to adapt to rehabilitation training more quickly and to master motor skills more effectively, and it can also adjust the difficulty of the rehabilitation task adaptively on the basis of the feedback. In addition, combined more deeply with VR technology, BCI can provide a more interactive and more immersive rehabilitation environment, which increases both the interest and the initiative of patients with stroke during rehabilitation. Future development may also include remote monitoring by BCI systems in stroke rehabilitation: given the imbalance in rehabilitation resources between regions, a medical team could obtain EEG data through the cloud, adjust the rehabilitation plan promptly and so achieve remote rehabilitation management for the patient. Despite its promise in motor function rehabilitation after stroke, BCI technology has still to overcome several challenges — the stability of the system, individual variability, and the sustainability of long-term use among them. It is to be hoped that further development of BCI technology will give patients with stroke more effective rehabilitation programmes, a friendlier rehabilitation experience and a better quality of life.

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