The Application of Brain-computer Interface (BCI) based Functional Electrical Stimulation (FES)

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Abstract. Rehabilitation medicine has developed rapidly in recent years. Brain computer interface and functional electrical stimulation are very cutting-edge technologies in this field. Because brain computer interface provides a real-time operation platform for patients to operate their limbs according to their intention for functional electrical stimulation, the research on BCI based FES has gradually increased in recent years. This paper discusses the current development status and technical application of FES and BCI. The research status of BCI based FES is discussed, and the existing problems of various research are summarized. According to the research findings, this field is a new technology with great application prospects in the field of modern rehabilitation engineering.

1. Introduction

Functional electrical stimulation (FES)’s principle is to stimulate nerves or muscles through low-frequency pulse current, cause muscle contraction, and then improve or restore the function of stimulated muscles or muscle groups. In the past decades, FES technology has been applied in many different aspects of the medical field. Such as the recovery of bladder function after spinal cord injury, the treatment of respiratory and swallowing disorders caused by stroke, the improvement of motor function in patients with paralysis, and the well-known cardiac pacemaker. However, it should be pointed out that FES treatment is most suitable for the human body with a complete nerve conduction pathway, that is, muscle dysfunction caused by central nervous system (brain and spinal cord) injury, while it has a poor effect on muscle weakness caused by peripheral nerve injury without complete nerve conduction pathway [1], but it can be used to promote the regeneration of injured peripheral nerve and prevent denervated atrophy of skeletal muscle. BCI (Brain computer interface) is a new communication and control technology established between the human brain and external devices (such as computers or other electronic devices). It does not depend on the normal output pathway of brain-peripheral nerve-muscle. The expression of will and the manipulation of equipment can be realized by collecting and analyzing EEG signals.

The control of its stimulation signal restricts the further development of FES. Because if we can't find the appropriate stimulation signal, FES can't achieve a good treatment effect, and its motion control of the residual limb can only be carried out according to the preset mode, and can't carry out the limb motion control at will in real-time according to the wishes of the patient. Thus, BCI technology provides a very good operation interface, the combination of BCI and FES technology in the treatment of patients with nerve or muscle injury is the latest application in the field of rehabilitation. I summarize all the application fields and technical problems of BCI based FES so far.
It provides a reference for future researchers in this field.

2. BCI based FES technique

2.1. Working system of BCI based FES

Generally, the working system of BCI based FES is divided into two modules. The first part is BCI, the module includes collecting signals from the skin surface and amplifying them for signal conditioning. Then, it classifies the required signals through filters, and finally records and transmits these signals. The second module is FES. Signals produced by the BCI will be transmitted to FES equipment. These FES devices will read the signal and generate corresponding electrical pulses. These electrical pulses are sent to the muscle surface, and the muscle will contract.

![Figure 1. Block system for the working system of BCI based FES [2]](image)

In 2003, the combination of brain computer interface and functional electrical stimulation was applied for the first time, which brought hope to paralyzed patients and attracted the attention of many researchers. The basic principle of the system is: the brain computer interface is used as the control source to analyze people’s intentions; Functional electrical stimulation technology is used as the driving source to stimulate muscles and make paralyzed limbs move [3].

EEG is the most important technique used in brain computer interface to collect brain signals caused by neuron activity. Its non-invasive interface, economy, convenience, and high time resolution make it popular for all researchers. Lin et al pointed out that Brain computer interface based on EEG can be divided into four categories: steady-state visual evoked potential (SSVEP), slow cortical potential (SCP), P300 and Mu and beta rhythm of motor imagery [4]. Therefore, all papers related to BCI based FES so far use SSVEP and p300 as their method to collect EEG signals.

2.1.1. SSVEP based FES

Based on the urgent practical application, Gollee et al consider the brain computer interface based on SSVEP, which has higher information transmission speed, simpler training and relatively small individual differences compared with other EEG acquisition methods [5]. SSVEP is a low-level response with a constant frequency [6]. If there are a large number of visual stimuli that oscillate at different frequencies, the selected stimulus can be detected by matching the SSVEP response frequency to one of the stimulus frequencies. In the literature [7, 8, 9], the SSVEP response is usually described as reliable.

In Lin’s paper, patients should look at the black-and-white flashing boxes with different frequencies on the screen according to their wishes, to select different upper extremity movement modes. The function of brain computer interface of steady-state visual evoked potential is to collect EEG signals of the scalp when the eyes are looking at a flashing area, extract and classify the signals, identify the flashing frequency of the patient's staring area, and then translate the patient's intention [4].

![Figure 2](image)
corresponding area setting an intention is transmitted to the electric stimulator through the interface, so as to realize the switching between different electric stimulation modes, control different actions.

Figure 2. Black and white flashing boxes [4]  Figure 3. Experimental setup to achieve FES [10]

Another system, shown in Figure 3, uses SSVEP based BCI to achieve functional electrical stimulation. Zhao et al. designed a similar system with the former one [10]. In order to achieve the rehabilitation of the upper extremity, the integrated system has three upper limb operation modes: fast mode, medium speed mode and low speed mode. The three flickering squares are mapped to three motion modes. The square of 20 Hz represents the fast mode, the square of 15 Hz represents the medium speed mode, and the square of 12 Hz represents the slow mode. In addition, a square without flickering in the center corresponds to an idle state.

2.1.2. P300 based FES. Visual or auditory mental images and external stimuli can generate EEG signals. By using auditory stimuli (such as headphones) to generate P300, the user's brain supplement activities are more focused, and it is not like visual stimuli that distract patients from hill [11]. This signal control method also does not require the extensive training required by mental imaging techniques, and the resulting equipment is not user-specific.

A method combining PCA and ICA technology has been proven effective in processing data, but it has not yet been implemented in the auditory P300 BCI. Alexander et al. conducted experiments on this issue. They conducted 6 experiments on 15 participants. Six of the 180 trials were performed on 15 subjects (right-handed men between the ages of 21 and 30) using the high-resolution system [12].

In the end, it was found that the accuracy of EEG signal with p300 as the carrier was as high as 78%, but the training time was long and it was not easy to experiment.

2.2. Classification of BCI based FES

2.2.1. Upper extremity. The technology of BCI based FES to help the rehabilitation of upper limb movement is very promising, such as upper limb hemiplegia caused by stroke. The combination of FES and BCI can help elbow or shoulder voluntary flexion and extension, forearm rotation or finger movement. The following are the relevant literature, as well as their research methods and processes.

Nourhan et al. conducted an experiment on recovering the activities of paralyzed upper limbs through BCI based FES [2]. The system uses a certain method. ANT neuro headphones collect data, carry out signal processing and feature extraction, and connect FES stimulators. However, in this experiment, the FES module selected transcutaneous electrical stimulation (TENS). But at the same time, this method uses the medium frequency modulation composite waveform, which can stimulate the deeper muscle tissue and make the muscle contract. The experiment successfully achieved arm extension and bending.

Muller-Putz et al. conducted a case study of connecting an EEG-based BCI with an implantable FES device freehand system. In the study, the patients were first trained for a short period of time in order to make them produce obvious EEG patterns by imagining the movements of the disabled hand. This mode is further classified by BCI, and then the output signal generated by the BCI simulated shoulder joystick is provided to the freehand system of different gripping stages. With continuous imaging, the patient can move a simple object from one place to another [13]. Zhou Peng et al. used
the left and right hand motion imaginary potential as the input signal of BCI, and used it in conjunction with FES to develop an intelligent rehabilitation system for paralyzed patients to control the movement of their residual limbs according to their own motion wishes. This system can bypass the damaged nerve pathway in the body of the paralyzed patient, directly convey the person's movement intention to the FES instrument through the external pathway, stimulate the corresponding neuromuscular, and complete the patient's direct control of the residual limb. Preliminary experiments have shown that this system can analyze people's movement intentions with a correct rate of more than 95%, control the FES instrument to complete the predetermined stimulation tasks, and resume hand grasping actions [14]. Tan et al. completed the rehabilitation training experiment of wrist and finger of stroke patients with BCI based NMES. The motor image of μ rhythm (8-12Hz) was used in this experiment. When a person wants to exercise, mu rhythm will decay, which is used to trigger NMES on the wrist [15].

However, the experiment requires a lot of training for participants to maintain a high degree of concentration. Goniometer at the joint to provide feedback to determine the completion of NMES. Once NMES is activated, BCI will immediately stop detecting brain waves. Until the goniometer detects that the arm is fully extended, the electrical stimulation stops.

2.2.2. Lower extremity. Lower extremity has more restrictions when designing the whole BCI based FES system compared with upper extremity. Because EEG signals can be extremely unstable because the large movement degree when walking or standing. In order to get stable EEG signals, active shielding electrodes needed [16]. Due to the high difficulty, there is less research on the system serving the lower limbs.

An et al realized ankle rotation by stimulating foot dorsiflexion with BCI based FES, which provided a rehabilitation way for those people with chronic gait impairment caused by foot ptosis [16]. But different from other experiments, volunteers need to accept the computer model prediction first. Five healthy volunteers participated in the experiment. The reaction delay was about 1.4-3.1 seconds, but all volunteers successfully achieved dorsiflexion. When one lower limb performs 10 alternating ankle neutral and dorsiflexion positions, it can trigger the lower limb with BCI-FES on the other side to step on dorsiflexion, which indicates that BCI-FES may be an effective rehabilitation method to solve foot ptosis caused by stroke and brain trauma. It is proved in this paper that BCI and FES is a novel and feasible treatment for patients with lower limb paralysis. Chung et al. conducted EEG-BCI-FES ankle dorsiflexion training for 5 days in 5 stroke patients, the results showed that the score of Berg Balance Scale and walking speed were significantly improved [17]. In addition, he also compared the patients with foot ptosis with FES training alone and BCI FES training respectively. The results showed that the curative effect of the latter was significantly better than the former, indicating that the application of BCI can effectively improve the rehabilitation of patients' lower limb function.

Christine et al. conducted an experiment to control functional electrical stimulation to walk on the ground based on a brain-computer interface [18]. The experiment recruited a patient suffering from spinal cord injury. The patient was first trained in BCI. In order to evaluate the performance of BCI, they used a laser rangefinder gyroscope and video recording data. Followed by FES training until the patient can complete the ground walk completely autonomously. Finally, it is the BCIFES system experiment. The step rate and current stimulation amplitude are programmed into the microcontroller in advance, so that the left and right steps can be automatically cycled. Participants also need to participate in the suspended walking experiment and the ground walking experiment. In the end, the study showed that participants can initially operate under a suspension, then transfer their skills to walking on the ground and achieve a high level of control. The research provides a recovery treatment for paraplegic patients.

3. Existing technical problems
Due to the short development time of BCI based FES, the research and technology in this area are not very complete. Previous studies have pointed out the existing problems in the experimental process and the aspects that can be improved. But the most important thing is that the system is based on BCI and FES, so the development of BCI and FES has a great influence on the perfection of this system. Peter et al. pointed out that the movement of artificial limb and the increase of muscle and eye activities lead to the application of neural artificial limb, which may cause artifacts in EEG, which will
have a bad impact on feature extraction and FES signal transmission [19]. At the same time, many experiments are recruiting healthy volunteers. The differences of brain waves between those with SCI and healthy volunteers may lead to accuracy of the experiment.

Taehoon et al. pointed out that their current research only applied a simple action sequence to participants, which should be completed by themselves [20]. Then, although they determined that the effect of BCI FES on the arm of patients with paraplegia was obvious within 4 weeks, there was no long-term monitoring or investigation effect.

Christine et al. pointed out in the experiment that the error rate of volunteers during walking on the ground is higher than the discontinuous movement of pausing walking [18]. This performance is due to the increase of EEG noise caused by the movement of volunteers, such as the movement of center of gravity and unbalanced shaking of posture. The second point is that the current noninvasive BCI FES system is very cumbersome. In addition, the system has a great impact on the comfort of other parts of volunteers, affecting the activities of brain and nerves and the movement of parts.

For SSVEP based BCI, Zhao et al. showed that SSVEP can only deal with decentralized intentions [10]. The conversion between continuous control and different motion modes cannot be realized. Due to too many unstable factors of EEG signals, such as human factors such as concentration difference and individual difference of subjects, it will directly affect the recognition rate of EEG signals, and further affect the response speed of the whole BCI based FES system, so some subjects may feel uncomfortable such as dazzling, which will also increase the false recognition rate.

Tan et al. emphasized that the use of EEG will bring some disadvantages [15]. The impedance matching phase takes a long time, and it will always lead to brain fatigue and affect volunteers' attention. Although there were no other side effects, participants usually felt headache after the experiment.

4. Conclusion
This paper discusses the current technical status of BCI and FES, as well as the research status of BCI based FES. Although the application of BCI based FES in limb control and medical rehabilitation is only in the preliminary stage, most of the literature shows that the system is very feasible. It is found that there are fewer studies on BCI based FES for lower limbs. First, there is a stronger demand for recovering the movement of paralyzed upper limbs, while the movement of patients with lower limb paralysis can be completed with the help of auxiliary equipment such as wheelchairs; second, the movement of lower limbs (such as walking) will interfere with electroencephalogram (EEG), so special brain computer interface equipment is required, such as active shielded electrode [16]; third, the position of the cerebral cortex controlling the walking movement of the lower limbs is deep, and the collected EEG signal information is relatively weak, which brings difficulties to the later signal processing and recognition.

In view of the feedback from previous studies, future studies should be more inclined to optimize the experimental scheme and reduce the impact of external factors on patients' brain activities; try to use patients with SCI to carry out the experiment; BCI based FES at present, the experimental equipment is too heavy, and the device should be simplified; Improve the response rate of BCI and FES.

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