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Article

Application of Nerve Signal Tracking Technology in Rehabilitation of Spinal Cord Injury

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Abstract: Neural signal tracking technology plays an important role in the rehabilitation of spinal cord injury. This paper describes the basic concepts and technical solutions of neural signal tracking technology, including the key technologies of signal acquisition, brain computer interface, electrical stimulation repair and signal modeling, and discusses the application of this technology in FES training, TENS electrical stimulation, prosthetic limb and gait training, so as to improve the treatment accuracy and individual matching with the circular feedback mechanism, which brings new hope for nerve regeneration in patients with spinal cord injury.

Keywords: neural signal tracking; spinal cord injury; functional electrical stimulation; neurorehabilitation

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1. Introduction

Spinal cord injury causes severe and long-term physical and sensory impairment, which greatly impairs the daily life of patients. With the development of neuroscience and restorative therapy, neural signal tracking has become one of the important means to evaluate nervous system function. Neural tracking can obtain and analyze neural activity information and provide accurate rehabilitation information feedback and individual adjustment. This study mainly focuses on how to apply nerve signal tracking technology to the rehabilitation of patients with spinal cord injury, and provides scientific knowledge reserve and technical reference for the follow-up intelligent rehabilitation program.

2. Basic Concepts of Neural Signal Tracking Technology

Neural signal tracking is a comprehensive detection method for the central nervous system and peripheral nervous system, which is based on the acquisition and processing of the information exchange process between neurons to continuously monitor and evaluate their neural activity. This method is widely used in various interdisciplinary disciplines such as neuro-electrophysiology, signal processing, computational modeling and brain-computer interaction. It is a system engineering technology from "data acquisition" to "state judgment" and then to "reverse control". This is a new technology based on voltage changes in neural activity and nerve pulse activity, using non-invasive or micro-invasive tools (such as electroencephalograms, electrocorticograms, groups of micro-electrodes placed in the body, etc.) to obtain high-precision information in time or space, filter the raw data, remove interference, and extract important characteristics. This allows understanding of the specific neural circuits that are stimulated, the strength of their functional connections, and even predicting the incidence of dysfunction. In the process of clinical diagnosis, treatment and rehabilitation, nerve signal tracking is not only a diagnostic means to passively reflect nerve activity, but also through the integration with external stimulation equipment to achieve active, active and effective intervention, to achieve the purpose of regulating, improving nerve function and repair.

3. Methods of Neural Signal Tracking Technology

3.1. Neural Signal Acquisition

The basis of nerve signal tracking is nerve signal collection, the basic purpose of nerve signal collection is to sample and store the electrical signals related to the nervous system for further processing and analysis. Common methods of collecting nerve signals include electroencephalogram, electrocorticogram, functional magnetic resonance and multi-channel nerve electrode. EEG records the electrical activity of the cerebral cortex by placing an electrode array on the scalp surface. It can be used to detect neurological problems such as epilepsy or brain injury. It has the advantage of high temporal accuracy and the disadvantage of low spatial accuracy. ECoG is an invasive technique in which electrodes are placed under the scalp to achieve higher resolution and precise placement, and is therefore often used in neurosurgery. fMRI, which uses changes in blood flow to track signs of neural activity, has a high spatial resolution to clearly describe functional areas of the brain, but its low temporal resolution makes it impossible to track rapidly changing neural behavior. By implanting multiple neural electrodes into multiple neurons, the multi-channel neural electrode technology can record and study the electrical activity of multiple neurons, and is often used to treat neurological diseases such as Parkinson's disease and spinal cord injury [1]. Table 1 below shows common nerve signal acquisition methods.

Table 1. Common neural signal acquisition methods.

technology	Description	advantage	Application field
Electroencephalogram	Electrical activity in the brain is recorded using scalp electrodes	Non-invasive, real-time, easy to operate	Diagnosis of neurological diseases, monitoring of brain function
Electrocorticogram	Electrodes are placed on the surface of the brain to record local neural activity	High resolution, precise localization of neural activity	Brain surgery monitoring, neurological function research
Functional magnetic resonance imaging	Changes in blood flow reflect neural activity	High spatial resolution reveals functional areas of the brain	Brain function research, neurological rehabilitation

The above list shows a comparison of the most common neural signal collection techniques. EEG general neuromonitoring instruments commonly used, simple operation is suitable for general conditions of acquisition; ECoG provides more accurate data and is ideal for determining location during surgery. fMRI can provide the most accurate spatial resolution, which is very suitable for the investigation of brain function. Each technology has advantages and disadvantages, and the corresponding technology should be selected according to the actual situation when using.

3.2. Brain-Computer Interface Technology

As an emerging technology, brain-computer interface technology is a technology that directly connects human brain with external tools to control related devices (such as bionic hands, robots or computers) by decoding the electrical activity of human brain. It is a technology that realizes the direct operation of electronic devices by human brain, and has great potential for neurological rehabilitation of patients with spinal cord injury and quadriplegia. In general, BCI is a method of operation based on electroencephalogram or electrocorticogram, which collects the electronic activity of the brain and converts it into a method of manipulation command by a specific analytical device. This approach is very important in the application of neural recovery. The biggest bottleneck of BCI technology is how to analyze the signal more efficiently, accurately and quickly [2]. With the application of modern machine learning and artificial intelligence technology, it has gradually been solved, further making BCI more stable and accurate. Similarly, the feedback mechanism of BCI system will also affect the rehabilitation effect of patients. Appropriate sensory feedback (such as haptic feedback) can make it easier for patients to control these tools, so that patients can more quickly re-establish the connection between their brain and peripherals, thereby improving their motor ability and improving their quality of life. Figure 1 below is the BCI system framework diagram:

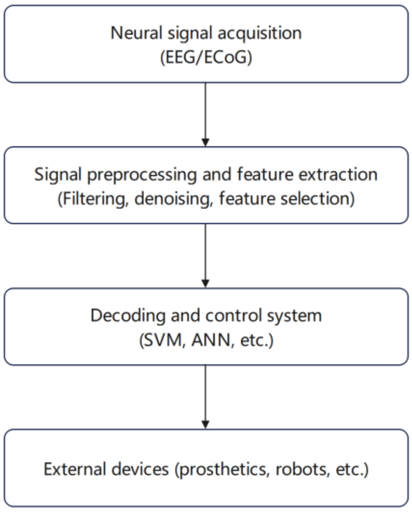

Figure 1. BCI system framework.

3.3. Electrical Stimulation Repair

Electrical stimulation is a commonly used method to repair nervous system injury, which is mostly used for spinal injury and peripheral nerve injury, etc. It can stimulate and re-establish damaged nerve fibers and restore some of their lost functions [3]. However, the choice of intensity and frequency of electrical stimulation can affect the activation effect of neurons. Common models of electrical stimulation can be expressed as follows:

$$I(t) = I_0 \, sin(2\pi f t + \varphi) \quad (1)$$

Where, $I(t)$ is the time of the electrical stimulation current, I_0 is the amplitude of the current, f is the frequency, and φ is the phase. There are three main types of electrical stimulation: functional electrical stimulation, transcutaneous electrical stimulation and spinal cord electrical stimulation. FES is the electrical stimulation of the spinal cord or peripheral nervous system through electric current, so that the muscle activity, and strengthen the strength of the muscle, usually suitable for spinal cord injury patients to restore the motor ability. At the same time, it can also adjust the stimulation parameters in real time according to the physiological information of patients, such as myoelectric information, and make personalized rehabilitation programs. TENS therapy reduces pain and promotes nerve regeneration by stimulating nerve afferent pathways due to the effect of its electrical current on the skin surface. In addition to pain management, the therapy can also promote nerve repair after spinal cord injury, and the importance of chronic pain management and neurological rehabilitation is self-evident. SCS is a method of embedding electrodes in the spinal cord and then electrical stimulation, which can relieve chronic pain and increase mobility. It has been proven to bring significant benefits to motor function recovery and nerve injury treatment, etc. Combining these electrical stimulation methods with nerve signal tracking technology can more accurately measure nerve growth process. The stimulation parameters can also be adjusted to obtain the best treatment results.

3.4. Neural Signal Processing and Modeling

In neural signal tracking technology, the important work of neural signal processing and modeling is to ensure that high-quality raw data is obtained and then analyzed. Firstly, due to the existence of noise and stray factors in the original neural signal, we need to de-noise, screen and extract features. Wavelet analysis and wavelet transform are commonly used to remove the artifacts and electronic interference of neural signals. By extracting the frequency domain and time domain of the original signal, valuable information will be extracted, so that researchers can find signals directly related to neural activity, and then apply them to subsequent analysis and interpretation. In the construction of neural signal models, the common models include neuron model, connectivity matrix model, brain network model, etc., which can be used to simulate the transmission process of neural activity and deepen the understanding of the function of the nervous system. Combined with the analysis of the dynamic system, the intervention effect of different treatment modes on nerve function can be estimated, especially the recovery effect of some nerve injuries after treatment, which can realize the optimization of treatment measures and rehabilitation strategies. Through the strategies of processing and modeling, the dynamic changes of the nervous system can be deeply explored, and the theoretical basis for the treatment of neurological diseases can be provided.

4. Application of Nerve Signal Tracking Technology in Rehabilitation of Spinal Cord Injury

4.1. Neural Signal Tracking and Fes Training

At present, in the spinal cord injury rehabilitation stage, FES has proved its great strength. By using information from the nervous system (such as EEG, ECoG, or EMG signals), it is possible to understand neuronal activity in real time and adjust stimulus parameters based on the feedback [4]. This feedback strategy can not only improve the efficiency of FES treatment, but also provide a basis for accurate regulation to avoid over-stimulation or under-stimulation. On the other hand, when FES technology is combined with neural activity monitoring technology, individualized treatment can be performed. By monitoring the state of the patient's neural activity, FES exercises can adjust the current value according to the needs of different stages of treatment, so that the patient's nervous system can gradually adapt and recover function. In the treatment of patients with spinal cord injury, neural activity monitoring technology can help determine the best trigger point and trigger timing, stimulate the formation of neural networks and restore function. FES needs to be regulated by signal changes, so a steady-state and closed loop management system must be established to ensure the correlation between neural input and neural output. Figure 2 below shows the closed-loop structure of FES-neural signal tracking system.

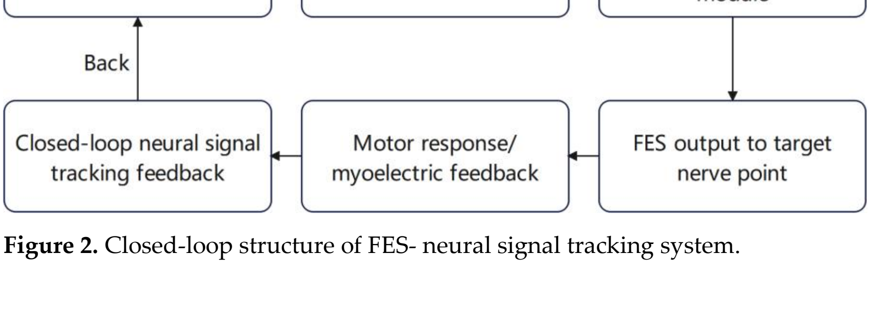

Figure 2. Closed-loop structure of FES- neural signal tracking system.

4.2. TENS Electrical Stimulation and Nerve Regeneration

Percutaneous electrical stimulation is a method that uses low-frequency electrical stimulation to stimulate the nerves on the skin surface to achieve pain relief and promote nerve repair. The following is the relationship function between electrical stimulation intensity and neural response (simplified model).

$$R(I) = \frac{1}{1+e^{-(I-\theta)/\beta}} \tag{2}$$

Where, $R(I)$ is the nerve response intensity, I is the current intensity, θ is the excitation threshold, and β is the parameter that regulates the slope of the curve.

At present, TENS technology has been widely used in relieving pain and promoting nerve regeneration in patients with spinal cord injury. It stimulates the peripheral nervous system and spine through electrical currents transmitted by external instruments to relieve poor blood flow, reduce pain, and trigger the self-healing function of the nervous system to promote nerve cell regrowth. The effect of electrical stimulation on patients' neural activity can be monitored in real time through nerve signal monitoring to ensure optimal stimulation parameter setting. These data help to understand the neurostructural changes and help doctors better adjust treatment plans. And neural signal monitoring technology makes TENS electrical stimulation application more accurate and more responsive. TENS technology is applied to monitor patients' neurobehavior, and current intensity, frequency and time can be adjusted according to patients' conditions to achieve the best effect. Meanwhile, combined with nerve signal tracking technology, adverse reactions such as excessive stimulation or inappropriate frequency can be avoided to ensure safety and effectiveness. Current studies have confirmed that different modes of TENS shock can play a regulatory role in neuronal activity and expression of nerve growth. Table 2 below shows the corresponding relationship between TENS parameter adjustment and neural recovery effect (theoretical model).

Table 2. Correlation between TENS parameter adjustment and neural recovery effect (theoretical model).

Parameter class	Recommended range	Influence mechanism	Application target
Frequency (Hz)	10-100	Regulate nerve excitability	Acute/chronic pain control
Pulse width (μs)	100-400	Determines the depth of nerve fiber recruitment	Neural activation and repair promotion
Current intensity (mA)	5-80	Provides effective nerve stimulation	Nerve regeneration/blood flow enhancement
Stimulus pattern	Intermittent/continuous	Control fatigue and adapt to change	Long-term rehabilitation intervention

The table lists the parameters commonly used in TENS electrical stimulation and their corresponding efficacy. Changes in frequency, pulse width and intensity will affect activation of the nerves, while the choice of stimulation mode will affect tolerance and adherence to the treatment process, which must be adjusted according to the specific conditions of the individual.

4.3. Brain-Computer Interface and Prosthesis Control

Brain-computer interface technology can directly read the electrical signals of the human brain and convert them into commands to control peripheral devices, which is of great significance for the rehabilitation of patients with spinal cord injury [5]. This method can take information from human brain activity signals (such as EEG or ECoG), and then convert it into control signals, and then use it to control artificial limbs or machines. For people with spinal injuries, this approach offers a new possibility for them to regain the use of their limbs, especially when traditional medical treatment has not been effective. If

BCI and neural signal tracking are combined, it is possible to understand human brain activity in real time, and thus better improve the accuracy and efficiency of human-computer interaction. Second, the improved decoding algorithm allows the BCI system to better understand and predict the patient's behavioral intentions, so that the patient can use the prosthesis more naturally and comfortably. In addition, the real-time feedback provided by the BCI can facilitate the mutual adaptation of the brain and the device to improve motor function and life. Neural signal tracking can be used in BCI systems to provide the necessary feedback support to ensure stable and reliable operation. Figure 3 shows the basic structure of the brain-computer interface system:

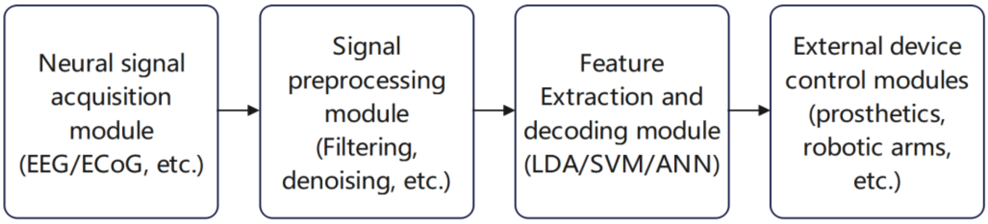

Figure 3. The basic structure of the brain-computer interface system.

4.4. Gaitsense System and Gait Training

Gait training is a key step in the recovery process of patients with spinal cord injury. GaitSense is a high-tech method that can monitor and optimize walking. GaitSense system is used to monitor the walking behavior of patients and respond to it to improve their motor ability. It is used together with neural signal tracking technology, so that the motor nerve and gait information can be continuously monitored, and the training plan can be changed in time, so as to strengthen the therapeutic effect. GaitSense uses sensors to obtain data about walking, such as walking speed, step length and balance posture, and analyzes its gait pattern. At the same time, the system can also integrate neural signals, such as EEG or ECoG, to track the activity of the brain and spinal cord in real time to ensure that gait training is carried out within the range allowed by neurophysiology. According to the input of neural signal feedback, gait sense can adjust the parameters related to gait training according to the patient's own neural state, so as to provide personalized rehabilitation planning for patients. By means of neural signal tracking, in addition to judging whether the patient's gait movement has problems such as shaking, the neural activity signal can also optimize the gait training strategy and promote the repair of neural structure more effectively. This real-time feedback mechanism is conducive to strengthening the patient's neural adaptability, so as to help improve their motor ability. Table 3 below shows the key sensing parameters of GaitSense and corresponding rehabilitation goals.

Table 3. GaitSense key sensing parameters and corresponding rehabilitation goals.

Sensing index	Representative meaning	Rehabilitation reference value	Feedback action
Step frequency (steps/min)	Gait rhythm	50-100	Detect gait asymmetry and adjust rhythm
Step size (cm)	Distance moved in a single step	≥50	Assess recovery of lower limb strength
Ground time (ms)	Length of foot contact with ground	600-800	Judge coordination and muscle control
Symmetry ratio	Left and right gait balance	0.9-1.1	Determine whether there is a deviation of gait

The data in the table reflect the routine gait analysis parameters in the GaitSense system and the important role of each parameter in the rehabilitation process. These parameters can comprehensively reflect the gait frequency, gait symmetry and lower limb function, and guide the effect of rehabilitation training and personalized gait recovery.

5. Conclusion

Neural signal tracking technology plays an accurate and real-time adjuvant role in the rehabilitation of spinal cord injury, and significantly improves the efficacy of nerve function assessment and rehabilitation training. This technology can be combined with a variety of treatment modalities such as FES, TENS, BCI and walkers to form a core loop rehabilitation technology based on real-time feedback. It is believed that this technology will also be more deeply explored in terms of personalized interventions and intelligent assistance systems, so that neurological rehabilitation will move forward to a higher level.

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