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Design of a Rehabilitation Robotic System Based on Physiological Electrical Signals

Luoluo Wang[*], Hui Yang, Junliang Chen, Jiexin Zhou

Zhuhai City Polytechnic, Zhuhai, Guangdong, China
**Corresponding author*

Abstract: *This paper proposes the design of a rehabilitation robot for upper limb rehabilitation based on physiological electrical signals. The system uses surface electromyography (sEMG) and electroencephalography (EEG) signals to control the robot's movements. The rehabilitation robot has a modular structure consisting of a mechanical hand, a control system, and a data acquisition system. The control system uses a STM32 microcontroller and a Bluetooth module for real-time data transmission and control. The data acquisition system collects sEMG and EEG signals from the user's arm and head respectively, and processes the signals to extract features for controlling the robot. The rehabilitation robot also incorporates a virtual reality system to provide a more immersive and engaging rehabilitation experience.*

Keywords: *physiological electrical signals; EEG; EMG; rehabilitation robot*

1. Introduction

1.1 The Significance of Rehabilitation Robots

The rehabilitation robot, consisting of a mechanical arm and various sensors, is a device designed to aid patients in recovering their motor ability through the use of electronic, mechanical, and computer technology. This device can be used to treat various types of motor disorders and injuries, such as stroke, brain damage, and amputation. The significance of the rehabilitation robot lies in its ability to provide patients with an extremely effective method of rehabilitation[1]. By using the robot to perform repetitive movements, patients can gradually regain the function of their damaged muscles and joints, increase their muscle strength, and improve their movement coordination and balance.

Furthermore, the rehabilitation robot provides a personalized treatment method that can accelerate the rehabilitation process while reducing the risk of further injury caused by incorrect postures and movements during rehabilitation. The rehabilitation robot can also help patients rebuild their confidence and autonomy. Many motor disorders and injuries can cause patients to lose their ability to care for themselves, leaving them feeling helpless and hopeless. The rehabilitation robot allows patients to exercise independently, helping them regain a sense of control and self-confidence.

The rehabilitation robot also provides a monitoring method during the patient's rehabilitation process. Through the use of sensors, doctors can monitor the patient's movements and progress, making timely adjustments to the rehabilitation plan. This monitoring method can ensure that patients receive the best treatment outcomes while helping doctors and rehabilitation therapists better understand the patient's condition and progress[2].

In summary, the rehabilitation robot is a highly meaningful device that provides an effective rehabilitation method for patients. It can aid in the recovery of muscle and joint function, restore patient confidence and autonomy, provide precise treatment methods, and monitoring during the rehabilitation process.

1.2 Research Status of Rehabilitation Robotic Systems

The human hand is one of the most dexterous and frequently used parts of the body, capable of performing a variety of complex movements. As a result, the structure of the hand is also very complex, leading to a wide variety of rehabilitation robotic hand designs. Although there is controversy over the classification of rehabilitation robotic hand designs, they can generally be divided into the following

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categories based on their structure and driving method.

In terms of structure, rehabilitation robotic hands can be divided into exoskeleton and wearable types. Exoskeleton robotic hands typically use rigid structures, while wearable types use flexible structures. In terms of driving method[3], rehabilitation robotic hands can be divided into rigid and flexible driving types. Rigid driving types usually use electrical equipment such as motors, while flexible driving types use popular materials such as pneumatics and shape memory alloys.

With the increasing emphasis on and investment in the rehabilitation medical industry in China, research on rehabilitation robotic hands has also been developing more and more deeply. Although research in China started relatively late, driven by policies and demand, researchers from rehabilitation medical institutions and universities have achieved some research results. For example, as shown in Figure 1, a rehabilitation exoskeleton hand device developed by Beihang University in China, which uses passive control based on PID and active control with resistance compensation. The device can also achieve active and passive switching through program control and integrate force sensors to measure the pressure on human fingertips[4]. At the same time, the device can not only handle free space but also constrained space. To avoid the structural complexity of driving devices and the separation of exoskeletons, Yang et al. designed a jointless muscle-driven rehabilitation robotic hand at Northeastern University, as shown in Figure 2. They explored the coupling mode of finger joints and applied it to the motion mode of rehabilitation robotic hands, making it more in line with the normal trajectory of finger movement.

Regarding the control methods of rehabilitation robotic hands, current research can be divided into several categories[5], including open-loop control, bio-signal-based perception control such as brain and muscle electrical signals, virtual scene-induced control, master-slave correspondence control, and closed-loop control, etc. Specifically, control methods of rehabilitation robotic hands include impedance control, admittance control, force control, and position control, etc.

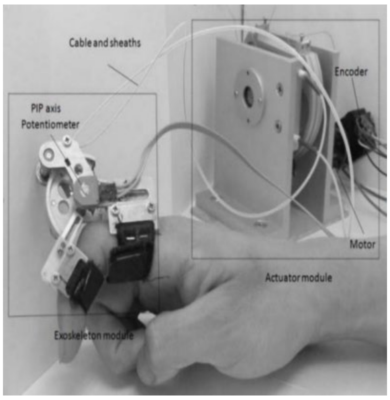

Figure 1: Exoskeleton Hand Rehabilitation Device developed by Beihang University

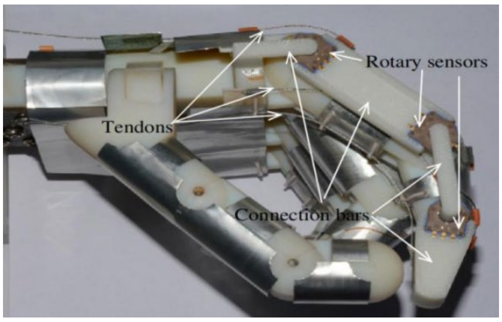

Figure 2: Rehabilitation Mechanical Hand Driven by Jointless Muscle and Tendon

Huazhong University of Science and Technology has designed a robotic hand (shown in Figure 3) whose driving device uses pneumatic muscles and torsion springs to achieve bi-directional movement of the fingers, thus achieving the desired therapeutic effect. In addition, a variable integral PID controller has been designed to improve control accuracy. However, this rehabilitation robotic hand uses open-loop control and may experience instability in control. Although it can be used for home therapy, its shortcomings should be noted.

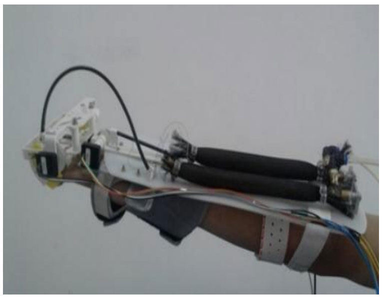

Figure 3: Huazhong University of Science and Technology's pneumatic mechanical hand

2. Principles of Physiological Electrical Signals

2.1 Principles of Electroencephalography (EEG) Signals

When a subject intends to perform or actually performs a limb movement, the corresponding motor cortex in the brain exhibits clear rhythmic changes in EEG energy, which is referred to as event-related desynchronization (ERD) or event-related synchronization (ERS). Specifically, the energy of the contralateral hemisphere decreases significantly, while that of the ipsilateral hemisphere increases significantly[6]. The ERD/ERS phenomenon essentially refers to the enhancement and reduction of EEG signal energy. Due to the weak, non-stationary, and non-linear nature of EEG signals, specialized EEG acquisition equipment is required for signal acquisition.

2.2 Principles of Electromyography (EMG) Signals

The control intention of human limbs is generated by the pulse control signals produced by the central nervous system, which are transmitted to muscle fibers through the limb nerves. Once the muscle fibers receive pulse signals that exceed a certain threshold, the fibers contract or stretch, and the electric potential changes produced by the contraction or stretching of a large number of muscle fibers are superimposed to form an EMG signal[7]. With the continuous stimulation of pulse signals, the muscle fibers release calcium ions, and the increase in calcium ion concentration further increases the energy of the pulse signal, resulting in more intense muscle fiber activity. The collective activity of a large number of muscle fibers manifests as an increase in muscle contraction or stretching force, thereby making the EMG signal more prominent[8].

3. Rehabilitation robot hand design

3.1 Overall design of rehabilitation robot hand

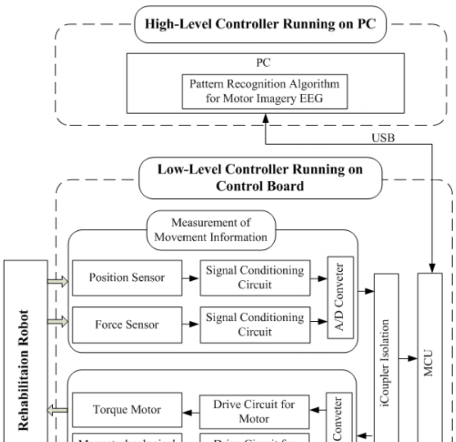

Figure 4: Rehabilitation robot hand system

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Figure 4 shows the rehabilitation robot hand system, which consists of three main components: a flexible wearable rehabilitation robot arm structure, physiological signal acquisition and processing, and corresponding hardware control circuits.

3.2 Structural design of rehabilitation robot hand

Our hand is composed of three parts: bones, ligaments, and joints, which work together to complete various hand movements through the drive of muscles and tendons. Muscles are the main power source of the hand, and their contraction and relaxation can generate the energy required for movement. Tendons are located between muscles and bones, playing a role in connecting and transmitting forces, and helping the hand to complete various fine movements. The synergy of these components gives our hand rich functionality and flexibility. The muscles of the human hand are mainly located in the forearm, including flexor and extensor muscles. The flexion and extension movements of the fingers are achieved by pulling tendons when the forearm muscles contract. To achieve basic functionality, the human hand needs to include the starting and ending points of muscles and tendons, tendons and annular ligaments, etc. The annular ligament is similar to a pulley, determining the direction of the tendon while stabilizing the muscles and tendons as well as transmitting the energy of muscle contraction to induce finger movement.

3.3 Rehabilitation Robotic Hand Circuit Design

Our rehabilitation robotic hand control system adopts a modular design approach. In order to meet different control requirements, we have divided the entire circuit into several parts, including data acquisition, signal transmission, microcontroller main control chip, and power control system. The hardware circuit diagram is shown in Figure 5.

In the control system of the flexible rehabilitation robotic hand, the STM32 microcontroller minimum system is responsible for overall control. The signal acquisition module of the system needs to real-time collect the angle and force information of the installed bending sensor and pressure sensor on the robotic hand. At the same time, the Bluetooth module needs to send control instructions from the upper computer to the rehabilitation robotic hand and return the collected data to the upper computer. In addition, the power control module provides the power supply required by the entire control system, including the microcontroller, drive push rod motor, Bluetooth module, and sensors.

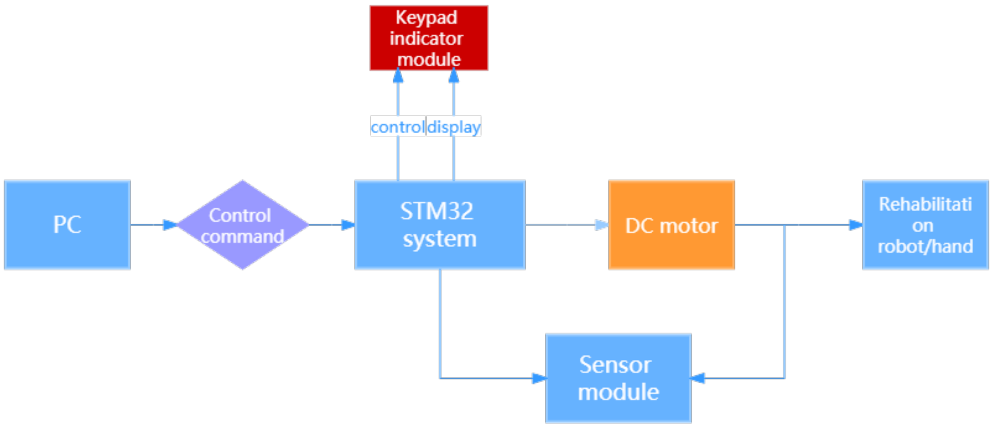

Figure 5: Hardware circuit diagram of the control system

4. Design of physiological signal control algorithms

4.1 Brain-computer interface (BCI) algorithm for controlling physiological signals

ERD/ERS is a commonly used method for analyzing EEG signals, which can extract temporal and spatial features of neural activity related to specific tasks from EEG signals. Specifically, ERD (Event-Related Desynchronization) and ERS (Event-Related Synchronization) refer to the decrease or increase in the energy of EEG signals within specific frequency ranges before and after certain events or tasks. This decrease or increase phenomenon can be used as a feature of EEG signals for task classification or behavior recognition.

The principle of the ERD/ERS method is based on the changes in the frequency components of EEG signals, i.e., when a brain region is activated, the neurons in that region fire synchronously, producing oscillations at specific frequencies that can be analyzed using methods such as fast Fourier transform (FFT) or wavelet transform. In the ERD/ERS method, a baseline signal before the task is usually used as a reference, and the power spectrum of the EEG signal in different frequency bands during the task is calculated. Then, ERD or ERS values are calculated by comparing the task signal with the baseline signal. Specifically, ERD refers to the decrease in the energy of EEG signals within specific frequency ranges before or after the task, while ERS refers to the increase in the energy of EEG signals within specific frequency ranges during the task.

The formulas for calculating ERD and ERS are:

$$ERD(t,f)=(Pbaseline(f)-Ptask(t,f))/Pbaseline(f)\times 100\% \quad (1)$$

$$ERS(t,f)=(Ptask(t,f)-Pbaseline(f))/Pbaseline(f)\times 100\% \quad (2)$$

Here, ERD(t,f) and ERS(t,f) represent the ERD and ERS values at time point t and frequency f, respectively, and Pbaseline(f) and Ptask(t,f) represent the power spectra of the baseline signal and the task signal in frequency f, respectively.

In summary, the ERD/ERS method can extract neural activity features related to specific tasks by comparing the changes in the frequency components of EEG signals during the task and the baseline period, providing a powerful tool for brain-computer interfaces and other neuroscience applications.

4.2 Electromyography (EMG) signal control algorithm

EMG signal is a biological electrical signal generated by muscle contraction during human movement, and its amplitude and frequency can reflect the degree of muscle contraction and fatigue state. EMG signal feature extraction is an important step in achieving brain-muscle signal fusion, which can be used in limb movement recognition and control. This article introduces a method of using the time-domain integrated electromyogram (iEMG) as the EMG feature and designs an EMG signal feature extraction method based on wavelet transform algorithm.

The formula for the electromyographic (EMG) signal feature, integrated EMG (iEMG), is the integral of the absolute EMG amplitude over time, which reflects the degree of muscle contraction and fatigue status. The calculation formula of iEMG is as follows:

$$iEMG = \int |EMG(t)|\, dt \quad (3)$$

Here, EMG(t) represents the amplitude of the EMG signal at time t.

Wavelet transform is a multi-resolution analysis method that decomposes signals into wavelet coefficients of different frequency ranges to extract time-frequency features of the signal. In the feature extraction of electromyography (EMG) signals, wavelet transform can be used to reduce signal noise and improve feature stability and reliability. Specifically, the basic steps of wavelet transform include selecting wavelet functions, decomposing signals, filtering, reconstructing signals, and repeating the above steps until the analysis requirements are met. Through wavelet transform, EMG signals can be decomposed into wavelet coefficients of different frequencies, which can be used to extract stable and reliable features of the signal, and then applied in fields such as limb movement recognition and control.

The specific calculation formula and process of the wavelet transform algorithm can be referred to the following steps:

Perform wavelet decomposition on the original signal to obtain the wavelet coefficient matrix:

$$C(j,k) = \int x(t)\, \psi\, [2\text{^}(j)t - k]\, dt \quad (4)$$

where x(t) is the original signal, ψ is the wavelet basis function, j is the decomposition level, and k is the shift factor.

Select the wavelet coefficients related to muscle contraction to obtain a new wavelet coefficient matrix:

$$C'(j,k) = C(j,k) * S(j,k) \quad (5)$$

where S(j,k) is the selection function of wavelet coefficients, which can be selected according to actual needs.

Reconstruct the signal from the new wavelet coefficients to obtain the reconstructed signal:

$$x'(t) = \Sigma C'(j,k)\ \psi \tag{6}$$

As a result, by using appropriate methods to extract features from EEG and EMG signals and designing suitable algorithms, physiological signals can be integrated as indicators and control signals into the operation of rehabilitation robotic hands, thereby achieving a rehabilitation effect.

5. Conclusions

This article introduces a rehabilitation robot system designed based on physiological signals, which achieves rehabilitation treatment through the analysis of brain waves and electromyography signals. The system adopts an STM32 microcontroller as the control board, equipped with sensor modules, drive modules, Bluetooth modules, power control modules, etc., to achieve complete control of the mechanical hand. The experimental results show that the system can effectively help patients with limb rehabilitation training and has good application value.

In the design process of the rehabilitation robot, the analysis of brain waves and electromyography signals is very important. By collecting and processing these physiological signals, relevant information on patient limb movements can be obtained, thereby achieving automatic control of the mechanical hand. In this article, we successfully extracted relevant features by using frequency domain feature algorithms for brain wave signals and time domain feature algorithms for electromyography signals, providing reliable data basis for mechanical hand control.

In addition, this article also detailed the hardware design and control algorithm design of the rehabilitation robot system, including data acquisition, signal transmission, microcontroller main control chip, power control system, and other aspects. Through modular design thinking, the reliability and stability of the entire system are realized, which can adapt to different control needs. At the same time, communication between the upper computer and the mechanical hand is facilitated through the Bluetooth module, making it convenient for patient-doctor interaction and control.

In the experimental part, we conducted relevant tests on the system, and the results show that the system can successfully achieve patient limb rehabilitation training with high reliability and effectiveness. This provides a good reference and reference for the future development of rehabilitation robot systems. Through continuous improvement and perfection, this rehabilitation robot system based on physiological signals is expected to be more widely used in clinical practice.

In summary, the rehabilitation robot system designed based on physiological signals introduced in this article is a very effective method for limb rehabilitation. By analyzing and processing brain waves and electromyography signals, as well as optimizing hardware system design and algorithm control, effective rehabilitation training for patients can be achieved. In future research, we will continue to improve and perfect the system to enhance its performance and application value.

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