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RESEARCH ON ROPE-DRIVEN FLEXIBLE ROBOT FOR HAND REHABILITATION AND EXPERIMENTAL STUDY BASED ON EEG SIGNALS

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Dysfunction of hand after stroke can affect patients' ability to perform daily activities and social ability. This paper developed a flexible hand function rehabilitation robot based on sensory input. First, we designed a flexible external finger muscle based on rope drive, then we designed a special two-way output linear actuator to drive fingers for rehabilitation training. At the same time, we performed vibration stimulation on each finger of the patient and low-frequency electrical stimulation on the patient's wrist. Sensory stimulation mobilizes the active participation of the brain in rehabilitation training, thereby effectively promoting the rehabilitation effect of fine functions of fingers after stroke. We have completed the hardware design of the flexible hand robot and developed the control software of the flexible hand, thus completing the development of the hand function robot. Finally, experiments were carried out on the use of equipment by using EEG. Experiments show that when the flexible hand robot developed in this

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paper is used for training, it mobilizes the active participation of the brain in rehabilitation training.

Keywords: Hand rehabilitation; flexible robot; rope-driven; rehabilitation training.

1. Introduction

The rehabilitation of hand function requires the participation of fine motor and sensory functions of the fingers, as well as the active participation of patients. Therefore, the recovery of hand function is very slow after stroke, and the healing effect is not significant.[1,2] After stroke, the recovery of motor function mainly depends on the reorganization of the remaining cerebral cortex. Most robots used in stroke rehabilitation are based on this theory.[3–9]

The research and development of hand rehabilitation equipment is still in its infancy. Most exoskeleton-type hand robots focused on thick finger joints and increase of muscle strength, while ignoring the role of active brain participation and sensory function input in motor function. Therefore, the effect of fine motor rehabilitation on hand function is not obvious.

At present, the design of soft hand robot basically adopts an exoskeleton structure,[10,11] which mainly provides driving force through motors and pneumatics to complete finger muscle and joint flexion and extension. There are five main driving methods for soft hand robot, including hydraulic drive, motor, pneumatic artificial muscle, memory alloy and drive-flexible rope with linear actuator.[12–17]

Hand function rehabilitation robots that use motors and rigid transmission mechanisms are more common, and this structure has the characteristics of simple implementation. The first generation of robots used finger-driven passive motor training through motors.[18–21] However, because the hand function robot with this structure is a rigid structure, its weight and size are difficult to control, and the rigid transmission is likely to cause secondary damage to the user. Taheri *et al.* used a motor and a linkage mechanism to achieve a finger rehabilitation robot, as shown in Fig. 1, which has large size and weight.[22]

Fig. 1. Finger rehabilitation robot using motor and rigid transmission structure.[22]

Rehabilitation robots that use pneumatic artificial muscles are also a relatively common method, because pneumatic muscles have good safety.[23,24] However, the pneumatic bionic muscle needs to have a higher trachea placed on the back of the finger, which is not very convenient to wear. At the same time, there is a certain difference between the movement and the real finger. Al-Fahaam *et al.* studied a hand function robot based on pneumatic artificial muscles, as shown in Fig. 2. They made some rehabilitation training gestures based on pneumatic hand robots.[24]

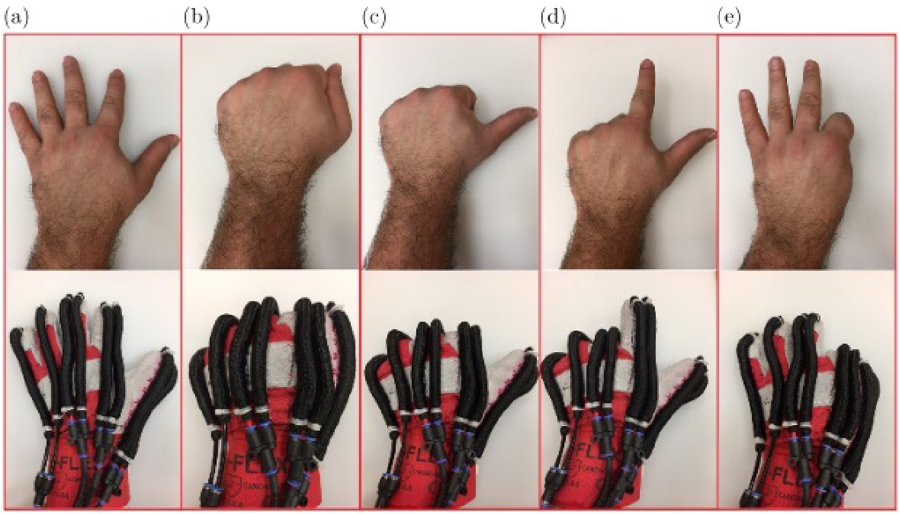

Fig. 2. The pneumatic artificial muscle hand robot with some rehabilitation movements.[24]

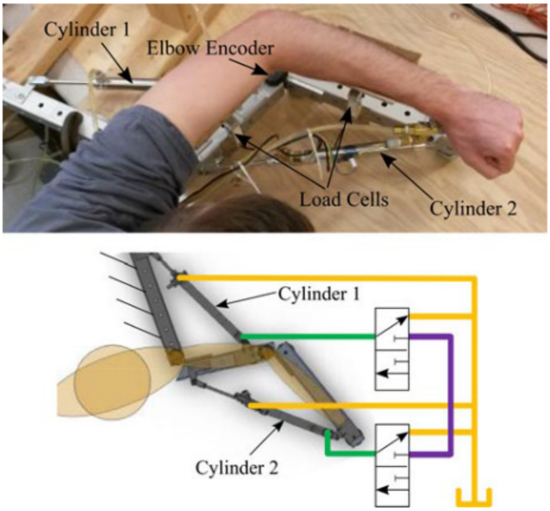

Fig. 3. Prototype of rehabilitation robot using hydraulic drive.[25]

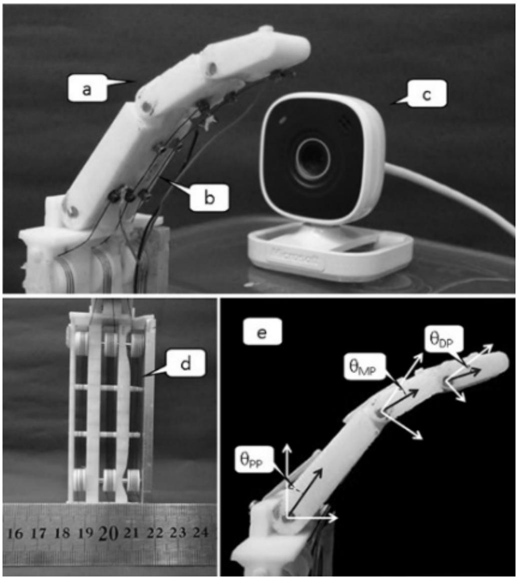

Fig. 4. Photograph of the SMA finger driven by memory alloy.[26]

The hydraulic drive has a larger output power, but due to the larger volume and heavier drive, it is difficult to achieve commercial use. Treadway *et al.* designed a hydraulically driven upper limb rehabilitation device for the arm of a stroke patient, as shown in Fig. 3.[25]

Memory alloy is a driving method that has appeared in recent years. Because its driving requires temperature changes, there are fewer products. Silva *et al.* used memory alloy to drive the finger, as shown in Fig. 4.[26]

Lasso drive is a flexible driving method. Because of being close to the real motion characteristics of human muscles, lasso-driven robots have become a research

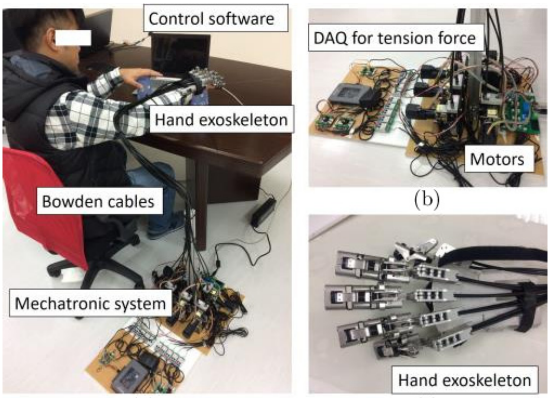

Fig. 5. The flexible hand robot developed by Pu *et al.*[20]

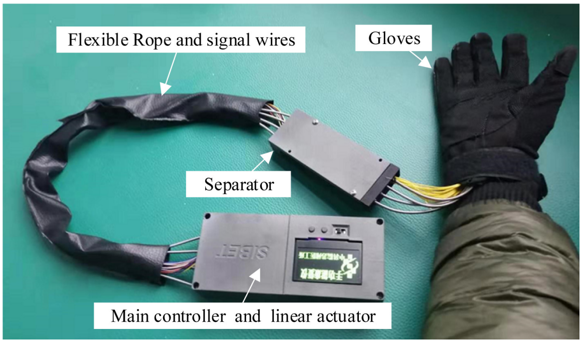

Fig. 6. The rope-driven flexible robot for hand rehabilitation developed in this paper.

hotspot in recent years. Usually, the lasso drive is driven by a linear drive to move the intermediate rope to produce the required movement. Pu *et al.* developed a hand function robot using a lasso transmission, as shown in Fig. 5. The rehabilitation robot they developed uses a lasso transmission method, but the finger body part still uses a rigid exoskeleton method.[20]

In this paper, we designed a new drive unit of the flexible hand robot, completed the design of the control hardware of the flexible hand robot and designed a modular flexible drive structure. Through engineering research and development, we have completed a new flexible hand robot prototype. For the researched flexible hand robot, we used 64-lead electroencephalogram (EEG) device to collect the user's EEG signals to explore the effect of flexible hand robot on the user. The robot device we developed is shown in Fig. 6.

2. Materials and Methods

The rehabilitation gloves based on flexible lasso transmission can realize hand function rehabilitation. At the same time, they can assist patients to achieve normal work and life, and enhance patients' confidence.[27,28] The flexible rope driving method has the advantages like simple structure, light weight, strong flexibility, comfortable wearing and convenient use. It can be the future development direction of hand function robots.

The hand function rehabilitation robot is mainly composed of the main control module, a separation module/glove connection module and wearing gloves. The main system composition is shown in Fig. 7.

2.1. *Structure and hardware of the main controller*

Considering the portability of hand rehabilitation robots, linear actuators were used as the power source for rope-driven robots. The main structure and hardware components of the controller part are shown in Fig. 8.

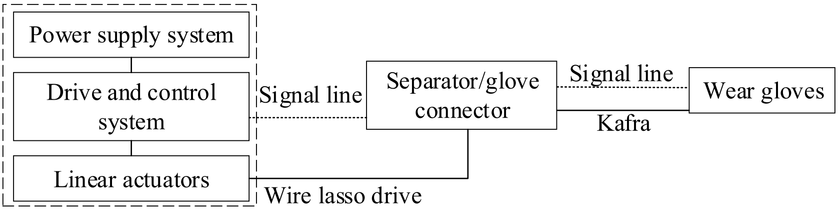

Fig. 7. The system composition of hand function rehabilitation robot.

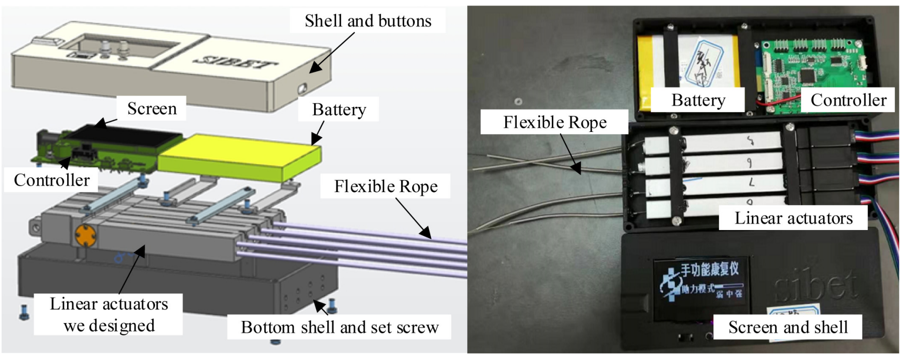

Fig. 8. The controller part of rope-driven hand rehabilitation robot.

The transmission components driven by flexible ropes were in the form of spring wire lasso. The outer spring was used to ensure relative position between the controller and the separation structure. In the middle, there was a transparent Teflon sleeve, which was used to reduce friction between the spring sleeve and moving wire, and it could also simplify the assembly process. The internal execution device was a moving wire, which pulled a finger for reciprocating motion under the action of a linear actuator. The composition of the flexible steel wire lasso driving system is shown in Fig. 9.

The controller hardware of the flexible hand rehabilitation robot was based on STM32. The hardware used a 12-V lithium battery to provide power and drive the

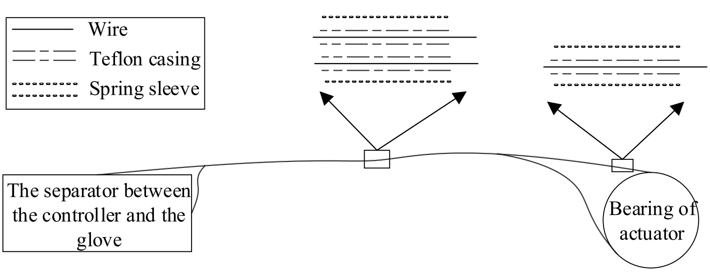

Fig. 9. The composition of the flexible steel wire lasso driving system.

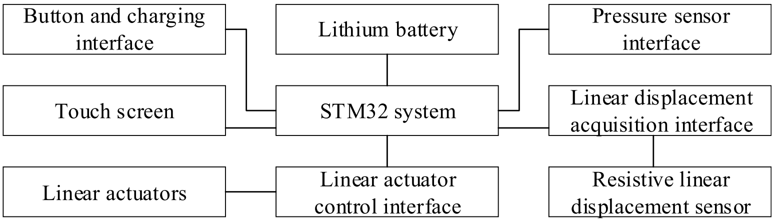

Fig. 10. Hardware composition of the controller system.

actuators. The serial touch screen was used to communicate with the main control hardware through serial interface. At the same time, the switch buttons, mode selection and intensity adjustment buttons were designed for rehabilitation mode selection. The hardware composition of the controller is shown in Fig. 10.

The STM32 core module obtains the corresponding finger movement intention through the pressure sensor. The position of the linear actuator was obtained by a linear displacement feedback device. Then, according to the rehabilitation training mode and the training intensity level, the reciprocating exercise fingers of the linear actuator were controlled to perform flexion and extension exercises.

The multifunctional flexible hand function rehabilitation robot has two working modes: assist mode and active mode. In the passive mode, the patient can select a rehabilitation training intensity level based on finger rehabilitation. After obtaining the bending motion intention of the finger, the linear actuator was controlled to perform a reciprocating motion, and the finger with the motion intention was driven to complete a flexion and extension movement through the rope mechanism.

In active mode, a flexion and extension movement was set to 20 s by a timer, and the patient actively performed a finger flexion and extension movement periodically to achieve fingers' exercising. The rehabilitation training control process is shown in Fig. 11.

We fixed the spring sleeve on the shell, so that the movement of the wire could be used as the power output of the hand function robot. We fixed four linear actuators,

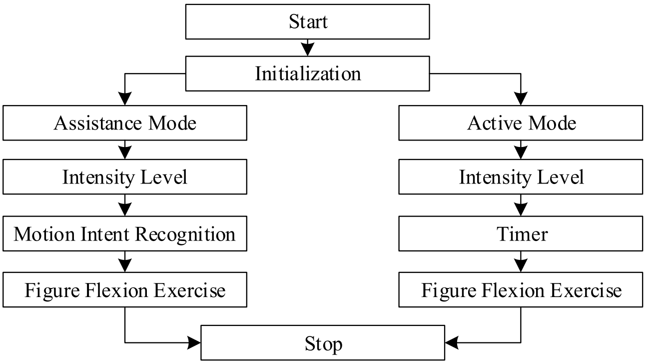

Fig. 11. The rehabilitation training control process.

battery, hardware and screen in the housing as a portable robot main control module. The main control module and the rehabilitation gloves were effectively combined by the separator.

2.2. *The separator as the connection between the controller and the gloves*

Consider the decoupling design between the main control module and the glove module of the hand rehabilitation robots. In this paper, a separator was designed between the main control module and the glove module, so that the movement could be decoupled. The splitter made the signal transmission part of the sensor separable through spring pins and contacts on the circuit board. The structure and hardware composition of the separator are shown in Fig. 12.

The motion coupling structure was completed by a T-type device and a groove-type device. The T-type components and the glove end were connected by Kevlar wires, and the groove-type components and the main control module were connected by wire. The steel ribbon caused the grooved components to move, thereby driving the T-shaped components.

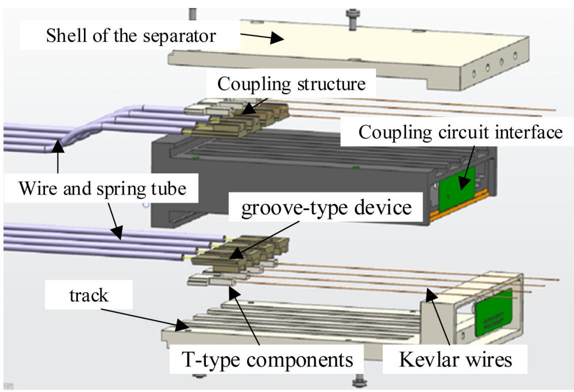

Fig. 12. The structure and composition of the separator.

Fig. 13. Main part of hand function rehabilitation robot.

The hand function rehabilitation robot was flexibly connected to the decoupling structure, as shown in Fig. 13. The left and right hand gloves can be adapted through the decoupling structure.

2.3. *Linear actuator with bidirectional output*

Each finger of the patient needed to be driven forward and backward. So, we designed a wire spring lasso to ensure that the stroke is closed. We also designed a reciprocating linear actuator to drive two-way fingers. The bidirectional linear actuator designed in this paper is shown in Fig. 14.

A linear motor was used for motion actuation of the linear actuator. The screw rod was connected to the motor through a reducer, thereby controlling the driving block on the screw rod to make a reciprocating linear motion. The steel wire formed a closed loop in the linear actuator through a miniature bearing, and the driving block drove the wire to move. Therefore, there were two wires in the output part of the linear actuator. The two wires output in opposite directions and the absolute travel values were equal.

2.4. *Structural design of gloves part*

The flexible rope from the splitter to the hand drive used a softer Kevlar wire. A fixed structure was designed on the palms and wrists and was fixed on the gloves, so as to ensure the relative position relationship of the spring lasso between the gloves and the main controller. When the linear actuator drove the wire to move, the wire would transmit the movement to the Kevlar wire through the separator, and then the Kevlar wire would drive the fingers for reciprocating training. The flexible transmission structure between the finger and the separator is shown in Fig. 15.

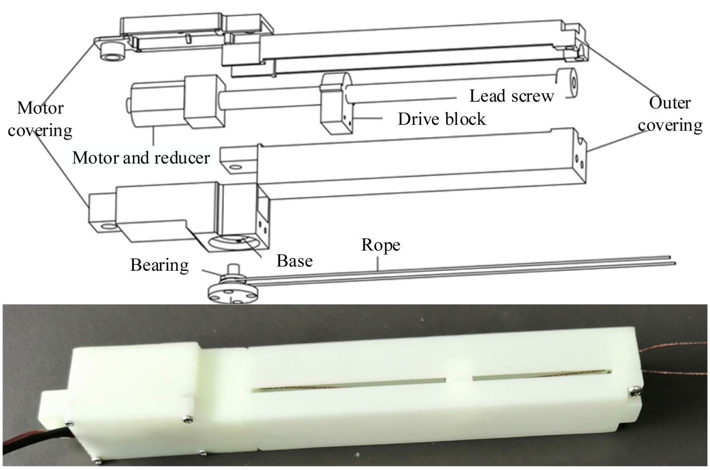

Fig. 14. The structure of linear actuator with bidirectional output.

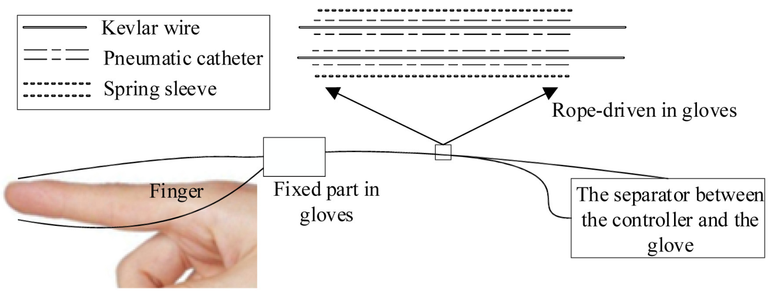

Fig. 15. The flexible transmission structure between the finger and the separator.

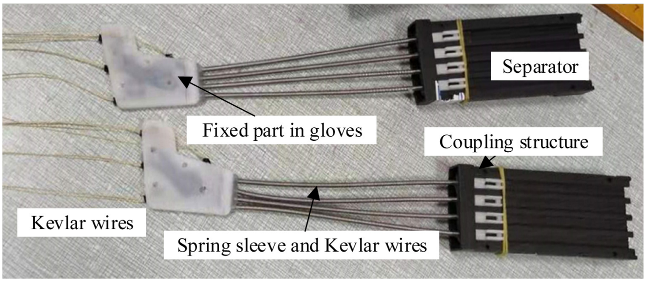

Fig. 16. The flexible transmission connection and the fixed part in gloves.

Between the Kevlar wire and the outer spring sleeve, we used a pneumatic tube to reduce friction. A wire sleeve fixing structure was used inside the palm. Considering the interference with finger movement, we designed the casing fixing device and flexible transmission connection as shown in Fig. 16.

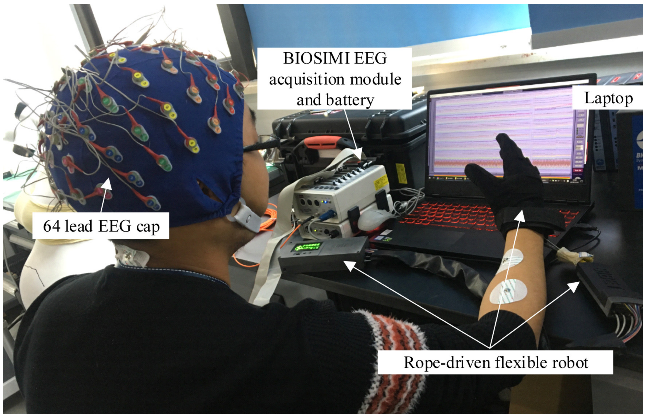

Fig. 17. Experiments based on EEG signals.

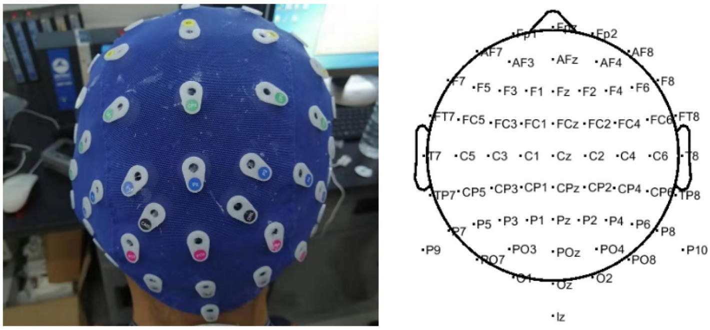

Fig. 18. EEG visualization channel location diagrams.

2.5. *Experiment of flexible hand robot based on electric signal*

Surface electromyography (sEMG), EEG and brain functional imaging (fMRI) were usually used in limb rehabilitation training and effect evaluation.[29–34] For the hand function rehabilitation robot developed in this paper, EEG was used for part of the test and analysis.

As shown in Fig. 17, a 64-lead EEG device from BIOSIMI was used to collect EEG activity data in different states.

The EEG cap wearing diagram and the visualization channel location diagram are shown in Fig. 18.

3. Results

Independent Component Analysis (ICA) is a new signal analysis method that has emerged with the development of Blind Source Separation technology in the past 10 years. It has become a research hotspot in the field of signal analysis and processing in the world, and the ICA function has been integrated in the EEGLAB toolbox.[35–37] We use ICA in the EEGLAB toolbox to decompose the data to obtain the scalp distribution of each independent component, as shown in Fig. 19.

The 3D scalp map can be used to draw the properties of each component by clicking the rectangular button above the scalp map of each component. Clicking the rectangle under the component, an interface will next appear, as shown in Fig. 20. Some eye artifacts can be viewed in that interface. Eye artifacts (almost) always appear in EEG datasets. They were usually at the top of the component array (because they tend to be large).

In order to better understand the cortical modification related to motor preparation and execution after robot-assisted training, it is helpful to improve the rehabilitation treatment program for stroke patients.

Time–frequency event-related electroencephalogram and task-related coherence (trcoh) were used to evaluate the EEG changes of cortical activity in healthy subjects. Three subjects wearing functional robots with flexible hands were studied.

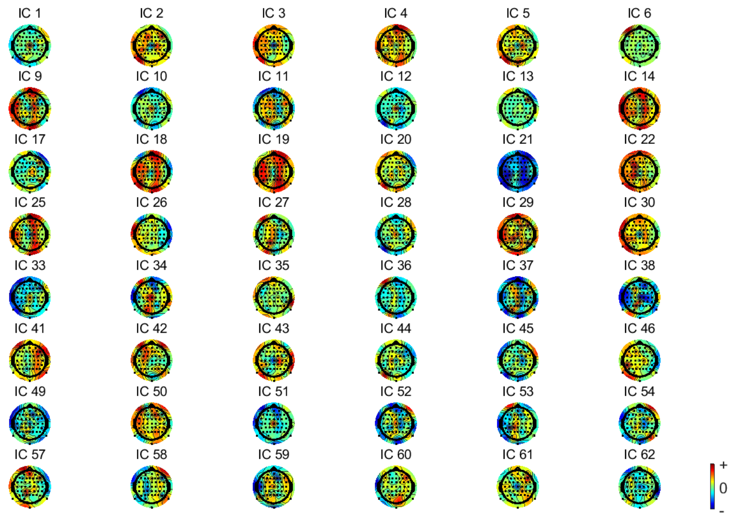

Fig. 19. Scalp distribution of each individual component.

The EEG activities of the subjects were recorded during active activities. We used time–frequency event-related synchronization/desynchronization (ERS/ERD) and trcoh methods to study the local location of motion-related power degradation and the functional relationship between regions, as shown in Fig. 21. We analyzed a total of 15 s, and there there was no movement in the first 10 s. After that, there is a time of 5 s for moving the flexible hand robot.

The results showed the ERD of bilateral sensorimotor area before exercise and bilateral ERD during the exercise. The ERD during passive exercise was similar in topography to that observed in voluntary exercise, but there was no pre-exercise component. There was no significant difference in the time courses of the two regions.

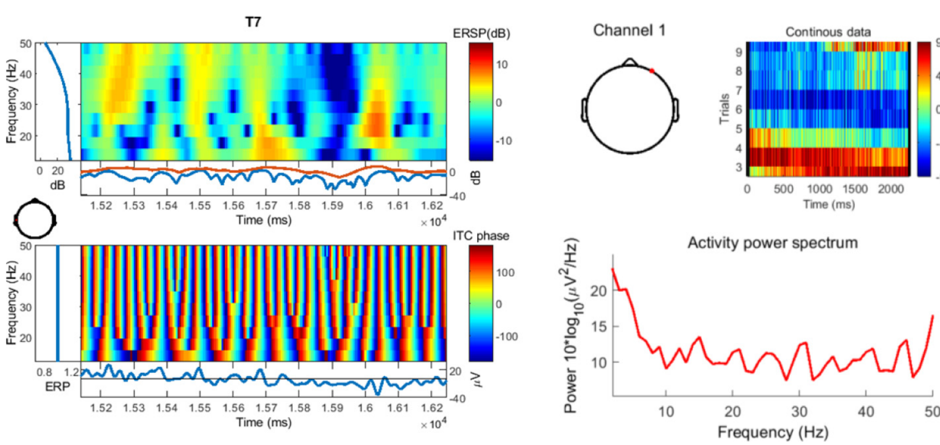

Fig. 20. Activity power spectrum of channel.

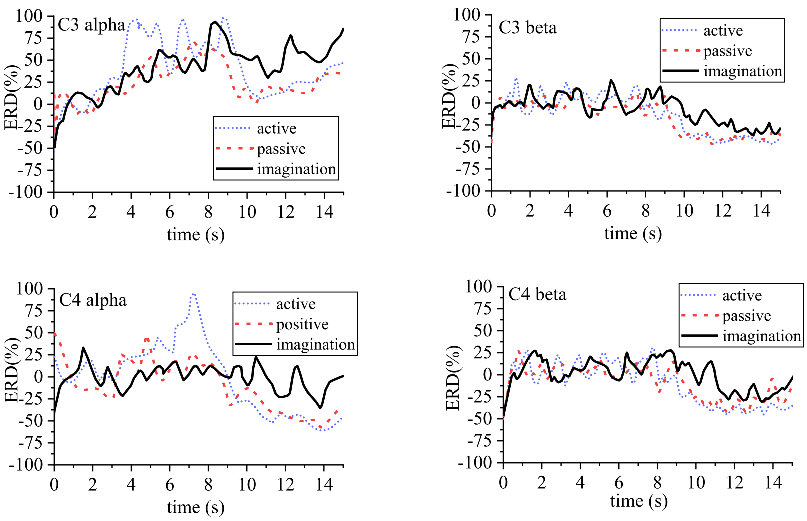

Fig. 21. ERDs of different channels.

The terrain of trcoh was similar to those of active motion and imaginary motion; before passive motion, frontal region was uncoupled from the SM region, and had no contribution to task execution.

This provides a new perspective for EEG evaluation of hand function movement, in order to better understand the planning and implementation of exercise.

4. Discussion

This paper studies the prototype development of a flexible hand robot, and explores the development of a fully flexible hand robot device. The paper mainly shows the driver design, control circuit design, flexible transmission mechanism design and glove design involved in the development of flexible robots.

Through the use of lasso drive, combined with the design of the drive structure of the glove part, the flexibility and lightness of the hand robot were realized. Although the development is still a prototype, it explores a way to develop a flexible hand functional robot. By using the developed actuator and flexible driver, the flexible connection between the controller and the robot is realized. It provides an idea for the fully flexible development of hand function robots.

Through the use of EEG equipment, we are exploring the application of EEG signals to the study of the exercise training effect of the hands. Of course, there is still a lot of research in this area.

The flexible hand robot prototype developed now also has certain functional deficiencies. Because there is no drive for the wrist part, when the wrist of some patients is curled up, the fingers cannot complete the normal movement. Of course, when we further the research and development of hand rehabilitation robots, it is possible to add the driver of the wrist part to solve this shortcoming.

5. Conclusions

This paper mainly introduced a flexible hand rehabilitation robot based on steel wire transmission. By designing a flexible drive combined with a fixed structure, the movement control of fingers was realized. Separate structures and probe contact hardware were used to realize the interchangeability of left and right gloves. A linear motor with a screw structure was designed to realize the positive and negative linear motion outputs of a linear motor. A flexible drive was designed into gloves to create the rehabilitation gloves based on flexible robot technology. For the flexible hand functional rehabilitation robot completed in the early stage, the brain electrical activity signals in the states of use and nonuse were collected. In the later stage, we hope to verify the performance of the flexible hand functional rehabilitation robot in more different ways.

Acknowledgments

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Author Contributions

Conceptualization was made by Hongbo Yang and Kai Guo. Methodology was designed by Kai Guo and Mostafa Orban. Software was developed by Kai Guo. Validation and formal analysis were made by Mostafa Orban. Resources were organized by Hongbo Yang and Zhenlan Li. Data curation was made by Mostafa Orban. While writing this paper, the original draft preparation was made by Kai Guo and Mostafa Orban, review and editing by Kai Guo, visualization by Mostafa Orban, supervision by Hongbo Yang, project administration by Kai Guo and funding acquisition by Hongbo Yang. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

The data presented in this study are available upon reasonable request from the corresponding author.

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