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Design and Implementation of Haptic Sensing Interface for Ankle Rehabilitation Robotic Platform

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***Abstract*—To solve the problem of rapidly increasing of patients with movement disorders and the aging population, Many researchers pay attention to the design of human-computer interaction interface for rehabilitation training, which can provide patients with a humanized interactive environment for human-computer interaction. There are large individual differences in interactive interface based on biological signals, so the interaction interface based on haptic sensor for rehabilitation robot is studied in this paper. An interaction interface for an ankle rehabilitation robot based on haptic sensor is designed and implemented, which mainly including rehabilitation robot interaction interface hardware system, interactive information measurement and software control system. Experiments based on interaction interface verified the availability of the hardware circuit of each sensor module and the effectiveness of the interactive information measurement and software control system of the rehabilitation robot. It provides a solution for the rehabilitation training and interactive robot control based on haptic sensor.**

Keywords—human-computer interface; haptic sensor; rehabilitation robot; control system;

I. INTRODUCTION

The population aged 60 and above has reached 212 million in China [1] and the limb injury caused by various reasons has brought many troubles and inconveniences to people's work and life [2]. Faced with these problems, rehabilitation training is used as an effective method to restore body function. The interactive rehabilitation robot can help therapists to provide high repeatability, high strength and targeted training methods for these people. So the rehabilitation robot has gradually become an important tool to assist traditional physical therapists to help the patients with rehabilitation training [3].

Human-computer interaction (HCI) interface is a bridge that connects the users and the external devices, and is also a platform to help the devices understand user's motion intention. It should be able to help the robot determine the patient's motion intention accurately and provide intuitive, continuous and flexible motion control mode. The HCI interface should also be able to monitor the movement state and the patients' rehabilitation level in real time, realizing adjustable degree of robot assistance to satisfy different need of patients. There are three kinds of interaction interface technologies widely used: 1) interface technology based on electroencephalograph (EEG); 2) interface technology based on electromyography (EMG); 3) interface technology based on haptic signals.

In recent years, the brain computer interface (BCI) technologies are attracting more and more attentions. Through the motor imagery BCI combined with functional electrical stimulation (FFS), it can realize synchronous coupling of brain and muscle [4]. However due to the problem that noise-signal ratio of scalp EEG collected by BCI system is low, it is difficult to improve the information transmission rate. And it would lead to a series of technical bottlenecks, such as long self-calibration time, so that the popularization and commercialization of the research results are slow [5-7].

The EMG signal contains many key information of muscle activity, and can reflect the human movement behavior 30~100ms in advance [8]. They have been widely used in HCI. In recent years, a lot of methods that extract useful information from the EMG signal have been proposed [9]. However, most of the studies are carried out on the upper limb [10]. For example, Krebs et al. described a progressive therapy based on performance that triggered the robot assistance using EMG signal [11]. However, the potential problem of the EMG trigger auxiliary is that it does not consider the patients' participation degree, which is related to the interaction between the patient and the robot, that is, the HCI interface is very important for the participation degree. Therefore, the interaction interface technology based on EMG is still a research direction that needs further study.

Haptic interaction is based on human haptic perception mechanism. Haptic devices are used to simulate human perception of the actual objects, achieving perception and reproduction for virtual or remote sense [12, 13]. In contrast, interaction interface technology based on haptic signals is relatively mature and the most widely used. It is the first choice for HCI design and control. Shanghai Jiao Tong University has designed a complete exoskeleton robot rehabilitation system, which includes a monitoring system and an active compliance controller. The adaptive controller controls the HCI system based on interact information and hybrid dynamic model [8]. The BLEEX exoskeleton robot installs a pressure sensing system at the pelma to detect the ground reaction force for system control [14]. Schiele et al. control exoskeleton using force feedback through ropes driven way [15]. Banala et al. control the exoskeleton by collecting the interaction force between human and exoskeleton [16]. Haptic signals can be obtained by force sensors installed on the joints or pelma as the robot control information. And when human contacts with robot, it is bound to produce interaction force. Therefore, it is the most direct and effective method to study the interaction information as the input and feedback information of the system.

In this paper, an interaction interface system based on haptic sensor is studied through the ankle rehabilitation robot experimental platform. In order to measure the interactive information, hardware circuit of human computer interaction interface for each sensor is designed. To observe the patient's motion state information and intuitively control the robot, the HCI interface is designed. In addition, design of data processing program are conducted to make the information displayed on the interface easier to read.

The contributions of this paper are: (1) A HCI interface with low cost which can effectively control the robot and collect the motion signals of the rehabilitation training is designed; (2) Simple and intuitive data display provides a nice reference for the therapists to make a rehabilitation strategy; (3) The designed interface provides the possibility of the patients' active rehabilitation training and the interactive control of the robot. The rest of this paper is arranged as follows: Section 2 presents design details of the haptic sensing interface. The experiment is carried out to verify the performance of the interface in Section 3. Section 4 draws conclusion of the paper.

II. MATERIALS AND METHODS

A. *Mechanism design of ankle rehabilitation robot*

The ankle is one of the most complex skeleton structures of the human body, which plays an important role in maintaining the balance of human walking. The ankle is mainly composed of two joints, as shown in Fig. 1. The first is the ankle joint, consisting of the lower tibia, the fibula and the talus. The second joint is called the talus-calcaneal joint, which is composed of the talus and the calcaneal. The ankle joint can revolve around the X, Y, and Z axes, so many studies consider it as a spherical joint, and the form of motion is represented by Fig. 1. Mattacola et al. pointed out that the rotation of the ankle joint around the X axis and the Y axis played a major role in the ankle rehabilitation [17]. Therefore, aiming at the ankle movement model and the rehabilitation demand, a two degrees of freedom parallel rehabilitation robot driven by pneumatic muscles (PMs) is proposed in this paper.

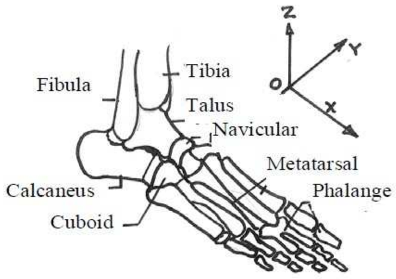


Fig. 1. Skeletal model of the ankle joint.

The mechanism chart of the ankle rehabilitation robot in this paper is shown in Fig. 2. The robot is composed of a movable platform, a fixed platform, a supporting rod, cable, pneumatic muscle and so on. It is driven by three pneumatic muscles. One end of the pneumatic muscle is connected with the flexible wire rope, and the flexible cable is connected with the movable platform through the hole of the fixed platform, so that the movable platform can be directly driven. The other end is connected with the force sensor and fixed on the platform frame, so the acquisition and control of the force signal can be carried out. The pneumatic muscle lets the wire rope flexible move in this way, and then drive the moving platform to complete the corresponding action. Since pneumatic muscle can only exert one way pull in parallel mechanism, a redundant drive must be added to achieve the force closure of the platform. Therefore, the two motion degrees of freedom are driven by three pneumatic muscles. The pneumatic muscle is also equipped with a displacement sensor at its moving end to measure the position information.

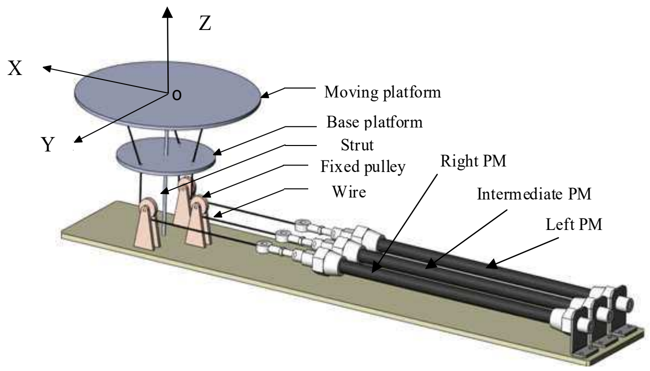


Fig. 2. Mechanism design of the ankle rehabilitation robot.

B. *Whole architecture of hardware system*

The hardware system consists of a variety of sensors and their peripheral circuits, including pressure sensors, angle sensors and displacement sensors. The original signals collected by these sensors are amplified and filtered by the corresponding peripheral circuit. And then these signal are transmitted to the computer through the RoboRIO to be processed and analyzed.

Pressure sensor

The pressure sensor converts pressure signals to electrical signals. In this paper, the pressure sensor module is used to measure the plantar pressure, so the pressure sensor must be measured on the sole of the foot. In order to measure the pressure, the pressure sensor requires small size with high flexibility and easy installation. In this paper, the Flexi Force A201-100 thin film pressure sensor is used. If the conductivity is $\sigma = 1/R_S$ and the interested force is F, The approximate relationship between conductivity and measured force is [18]:

$$\sigma = \frac{0.018\times10^{-3}}{120\times4.44}F \approx 3.378\times10^{-8} \qquad \text{□□□}$$

The pressure collected from the sensor is not conducive to the direct acquisition and transmission, so it is necessary to use the operational amplifier to amplify the signal to collect the output voltage signals. The physical map is shown in Fig. 3 and the principle diagram is shown in Fig. 4.

Fig. 3. Physical map of the pressure sensor.

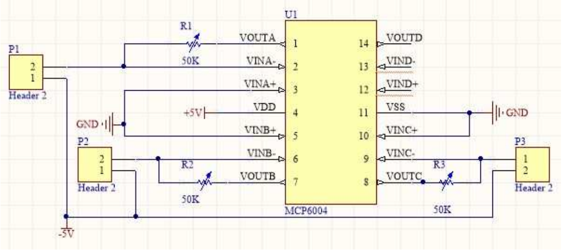


Fig. 4. Principle diagram of the pressure sensor.

In this circuit, the voltage of -5V is used as the excitation of the sensor, and the operational amplifier uses a reverse proportional amplification structure, so that the output is converted to a positive voltage signal output. Through the picture, we can get the relationship between the resistance of the sensor and the output voltage:

$$V_{OUT} = -V_T \frac{R_F}{R_S}$$

In this equation, R_F is not influenced by the pressure. When the voltage is determined, we can get the relationship between the input voltage and the out voltage according to the above equation.

Angle sensor

The tilt sensor module is used to measure ankle angle during patients movement. In order to accurately measure the movement angle of the ankle, it is necessary to install the tilt sensor on the moving platform of the ankle rehabilitation robot. Because two DOFs of this robot, the angle sensor needs to measure angles in at least two directions. In this paper, the SCA100T-D02 sensor is used. Its application circuit diagram and the physical map are shown in Fig. 5 and Fig. 6. According to the data manual, the equation between analog voltage and angle is:

$$\alpha = \arcsin\left(\frac{V_{OUT} - Offset}{Sensitivity}\right)$$

In this equation, $Offset$ is the output voltage at 0℃(5V). $Sensitivity$ is chip sensitivity (2V/g). V_{OUT} is the analog output of the chip.

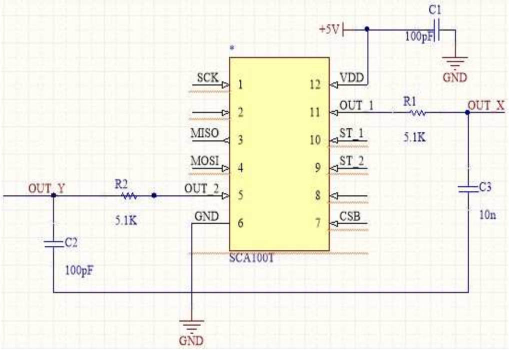


Fig. 5. Principle diagram of the angle sensor

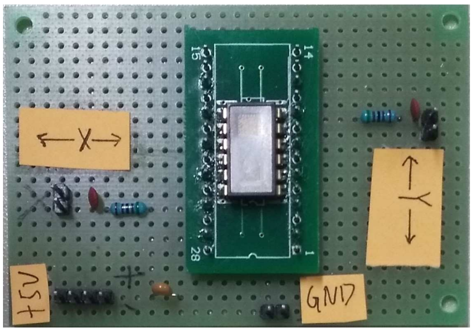


Fig. 6. Physical map of the angle sensor

Displacement sensor

The displacement sensor converts the displacement change into the voltage signal output, and the measurement can be divided into the physical size and the mechanical displacement. The displacement sensor in this paper is used to measure the position information of the pneumatic muscle. The adopted sensor is KTC150. As shown in Fig. 7, the sensor is used for accurate measurement of displacement or length, with a range of 1250mm, linearity of 0.08% and repeatability accuracy of 0.01mm. In order to ensure that the driving force is always toward the axial direction of the tie rod, the sensor rod is connected with a ball twist to overcome the partial torque generated by the tilt of the drive rod.

Fig. 7. Displacement sensor

C. *Robot software platform*

In this paper, LabVIEW is used to write the host computer software system. LabVIEW has a huge database, with data acquisition, serial control, data analysis, data storage, data display and other sub function sets. The software system in this paper is mainly composed of a data acquisition module, a HCI interface module and a control method implementation module. The data acquisition module processes the pressure signal, the angle signal and other original signal that are collected. The original signal collected by the sensor will have certain noise. The signal after processed needs to be calculated by some methods so that we can obtain the signals we need. The interface includes a real-time display module and a control module. The system can collect the angle signal in real time. Meanwhile the signal can be used as feedback to the patients on the interaction interface after processed data acquisition module. Patients can use the operation module to control the robot to realize the passive rehabilitation training. The interaction interface is shown in Fig. 8.

The main function of the ankle rehabilitation robot control module is to achieve the robot on/off control, the dorsiflexion/plantarflexion control and the inversion/eversion control. The trajectory tracking of rehabilitation robot is achieved by programming, realizing stable and smooth robot control. In order to control the movement of the robot, PID control method is applied in this paper.

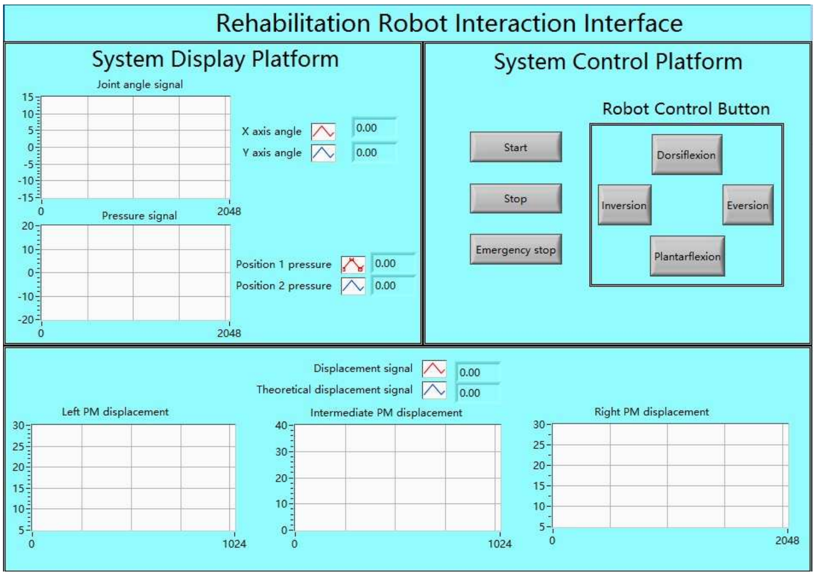


Fig. 8. Rehabilitation robot interaction interface.

III. EXPERIMENTS AND RESULTS

A. Experiment Setup

Based on the research of the interactive interface for rehabilitation robot, the performance of the designed human-machine interaction interface based on haptic sensor was tested on the rehabilitation robot experimental platform, so as to verify its practicability. Each sensor was installed at the corresponding position, and the sensor had been calibrated in a static state before the experiment. The corresponding position of the two pressure sensors at the foot bottom is shown in Fig. 9. The subject sat on a highly suitable chair and placed their right foot on the moving platform of the rehabilitation robot shown in Fig. 10. The robot and the RoboRIO controller was used to carry out the passive rehabilitation training for the subject. To ensure the safety of the subject, the maximum motion angle of the robot in all directions is 10 degrees. The movement of dorsiflexion-plantarflexion-eversion-inversion is a group of experiments in turn. At the same time, three kinds of signals: foot pressure, ankle movement angle and pneumatic muscle movement displacement were collected and analyzed, which can be used to verify the feasibility and effectiveness of the HCI interface.

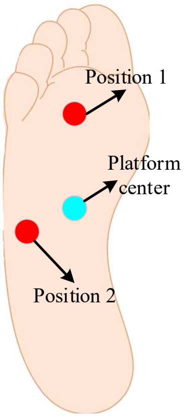


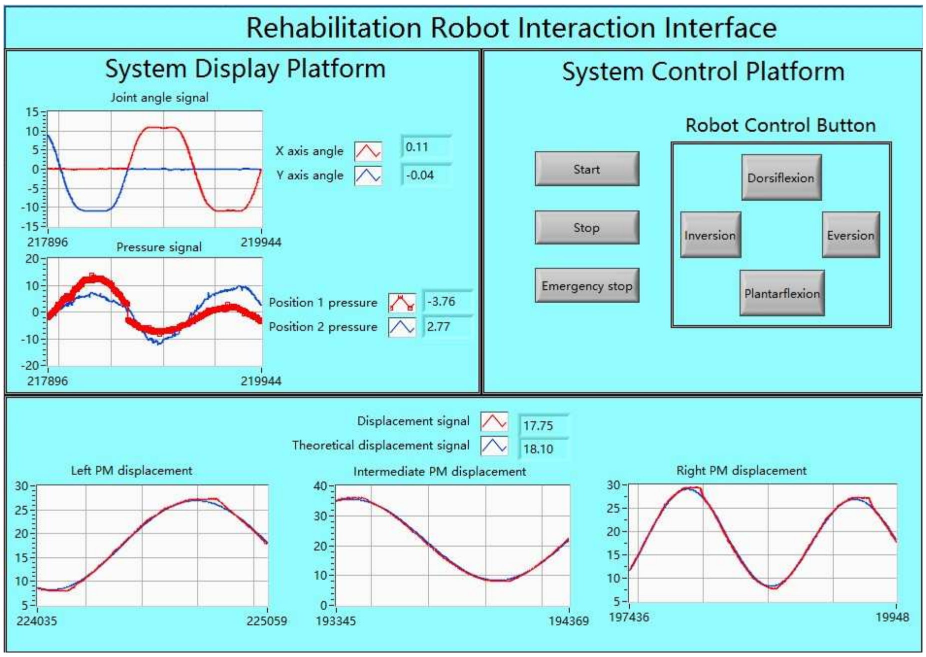
Fig. 9. Position of pressure sensors.

Fig. 10. Experiment setup.

B. Experimental Results

In the passive rehabilitation training, the subject's movement is in a completely passive state. The robot carries the corresponding movement with the subject. Experiment was conducted using the control button of dorsiflexion-plantarflexion-eversion-inversion. The waveforms in the experimental process of each movement can be displayed in real time on the human-computer interface as shown in Fig. 11. In the calibration, the inversion angle of X direction is negative, the eversion angle is positive; the dorsiflexion angle of Y direction is positive, and the plantarflexion angle is negative; and the pressure of the horizontal state is 0.

It can be seen from Fig. 11 that the control button can be used normally to control the robot performing the response movement, and the waveform can be displayed normally, which can provide intuitive data reference for therapists to formulate rehabilitation strategies. In order to better analyze the effectiveness of the interface, two sets of experimental data are taken to analyze and draw the waveform diagram, as shown in Fig.12 and Fig. 13.



X axis angle 0.11
Y axis angle -0.04
Position 1 pressure -3.76
Position 2 pressure 2.77
Displacement signal 17.75
Theoretical displacement signal 18.10

Fig. 11. Waveform display during experiment.

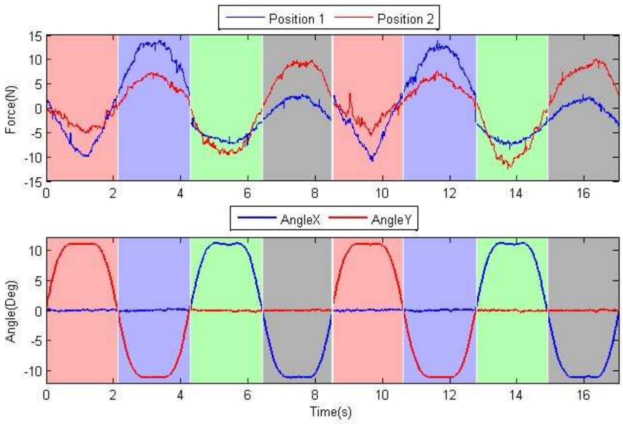


Fig. 12. Pressure and angle waveform display during experiment.

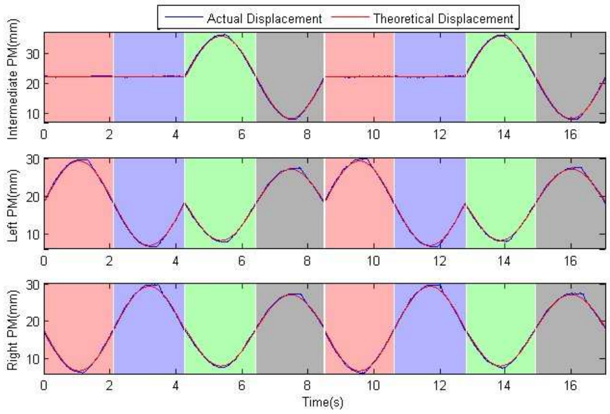


Fig. 13. Actual and theoretical displacement of three pneumatic muscles during experiment.

Fig. 12 is the signal collected by pressure sensor and angle sensor in two groups of movements of dorsiflexion-plantarflexion-eversion-inversion. Fig. 13 shows the actual and theoretical displacement of three pneumatic muscles collected from displacement sensors of the corresponding movement. It can be seen that the force amplitude of position 1 in the dorsolflexion and plantarflexion is larger than that in position 2. This is because position 1 has larger motion range, which leads to higher pressure changes. In the eversion/inversion movement, the pressure value of position 1 is less than the pressure value of position 2, because the effect of eversion/inversion movement on position 2 is greater. This is in accordance with the theoretical changes, indicating that the pressure sensor is designed to be effective. Angle data show that the angle changes of the X axis and the Y axis vary with different movements. The angle of Y axis in dorsiflexion/plantarflexion changes with the movement while the angle of X axis is basically unchanged. The angle of X axis also changes in eversion/inversion while the angle of the Y axis is basically the same, which explains the effectiveness of angle sensor design. From Fig. 13, it can be seen that the errors between actual displacement and theoretical displacement of three pneumatic muscles are all very small. The errors of three pneumatic muscle displacements of this group of data are 0.2544mm, 0.2932mm, 0.3133mm, respectively, which are very small, indicating that the theoretical displacement signals coincide with the actual displacement signals. Therefore, it can be verified that the planned trajectory is available and the PID control program is valid.

It can be seen from the above experimental results that the interaction interface system designed in this paper is effective and can be used to correctly obtain the patients' plantar pressure, the angle of ankle movement and the real-time displacement information of the PMs. These signals can be used as motion control signals and the reference for rehabilitation assessment, providing the basis of data analysis for the passive training of patients in the early stage of rehabilitation.

IV. DISCUSSION AND CONCLUSION

The research of HCI has occupied an important position in current field of rehabilitation robots. The HCI of rehabilitation robot mainly includes the HCI interface during rehabilitation, the information collection and analysis of the movement and the research of control method, so as to realize the auxiliary rehabilitation training. This paper starts from the ankle rehabilitation robot and makes a theoretical study on the HCI interface and control of rehabilitation robot. The hardware and software modules of the interaction interface system of the ankle rehabilitation robot are designed. The system mainly includes pressure sensor module, tilt sensor module and displacement sensor module. The pressure sensor module is used to collect the pressure information of the patients' foot. The tilt sensor is used to measure the movement angle information of the patients' ankle. The displacement sensor is used to measure the position information of the PMs. The information collected by the three sensor modules is displayed in real-time on the interface. The collected information will be analyzed and processed to provide reference for the rehabilitation training and system control.

In the future, the various information collected from the system can be fused to improve its effectiveness. The adaptive control method for rehabilitation robot will be studied and the robot trajectory parameters can be adjusted by the feedback of the fused information, so that the robot can automatically adjust the level of its assistance to make it more coordinated with human movement. In addition, EMG signals can be added into the interaction interface system, realizing real-time recognition of human motion intention. The EMG signals can be fused with motion signals for its advance to effectively compensate the hysteresis of the motion signals [19], realizing real-time robot control. In order to improve active participation of patients, virtual reality-based games can be introduced into rehabilitation training to increase its interest, improving the HCI between patients and rehabilitation robots.

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