Study on Force Interaction System of Upper Limb Rehabilitation Robot

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Abstract. This paper designed a novel human-machine interaction system for a Center-control upper limb rehabilitation robot. This proposed system integrates control system, force interaction system, the graphical user interface and virtual reality system based on motion intention recognition technology, control technology and servo drive technology. Emphasis is placed on the research of force interaction system, which can identify the patient's motion intention and provide the required torque for rehabilitation training. Two functional tests have been done to verify that the human-machine interaction system of the upper limb rehabilitation robot can safely and effectively complete the assistance function in the active training, and can assist patients with certain muscle strength to complete the active rehabilitation training.

1. Introduction
Stroke is an acute cerebrovascular disease which can seriously affected the patient's ability to move\textsuperscript{[1]}. Hemiplegia has become the most common stroke sequelae and about 85% stroke hemiplegia patients have upper limb dysfunction\textsuperscript{[2]}. With the continuous development of medicine and engineering, it has become a hotspot and difficulty to use upper limb rehabilitation robot to assist stroke patients with hemiplegia to complete rehabilitation training treatment\textsuperscript{[3]}.

There is a general problem in existing upper limb rehabilitation robot, that is the force interaction is simple, only the collection and judgment of motion intention can be realized. Such as the MIT-Manus upper limb rehabilitation robot, designed by the Massachusetts Institute of Technology\textsuperscript{[4]}, after the target position is given, the execution of the motor will detect the patient's motion intention. But the robot can only control the position, not meet the requirements of force control in active rehabilitation training. The 4-DOF upper limb rehabilitation robot designed by the Japan’s Saga University\textsuperscript{[5]} can estimate whether a task is performed by detecting the force signal generated by the force sensor at the user's wrist, which can only identify the current task, plan and carry out task trajectory, and fail to achieve rehabilitation training based on force interaction\textsuperscript{[6]}. Therefore, it is urgent to make breakthroughs and innovations in torque interaction mode and force feedback regulation in rehabilitation robot research.
Aiming at the above problems, this paper puts forward a kind of upper limb rehabilitation robot based on the force interaction mode of human motion intention recognition by using motion intention recognition technology, control technology, servo drive technology and rehabilitation training theory, and its system structure can be mainly divided into control system, force interaction system, graphical user interface system and virtual reality system four parts, as shown in figure 1. This paper focuses on the force interaction system.

![Figure 1. Structure block diagram of upper limb rehabilitation robot system.](image1)

2. Overall Design Scheme

The force interaction system proposed in this study can not only identify the motion intention of patients, but also provide patients with the torque needed for rehabilitation training. In this study, the corresponding software functions are completed on the basis of the hardware scheme, the required torque for balancing the gravity of the manipulator is calculated according to the angle of each joint and the weight of the manipulator by the dynamic analysis of the three-DOF manipulator, and the specific torque of the patient’s limb is applied according to the patient’s motion intention in a gravity-balanced state to achieve the goal of assisting movement. It can also effectively improve the patient’s participation and enthusiasm in the process of rehabilitation training, which can facilitate the rehabilitation of patients.

3. Hardware System Design

The overall structure of the force interaction system using the servo motor is shown in figure 2. The whole system consists of two parts: the motion intention acquisition module and the servo torque control module. Specifically, the motion intention acquisition module consists of a torque sensor and a signal amplifier, and the servo torque control module consists of a servo motor, a servo driver, an encoder, a speed reducer and a precision resistor.

![Figure 2. Structure block diagram of force interaction system.](image2)
3.1 Motion Intention Acquisition Module

The principle of the motion intention acquisition module is shown in figure 3. Comparing to other methods of motion intention acquisition, such as surface EMG or EEG signal, the torque sensor has the advantages of good detection stability, strong anti-jamming ability and high acquisition accuracy, and the user do not need to wear the corresponding acquisition device, which eliminates the tedious process of wearing the acquisition equipment[7].

![Schematic diagram of signal amplifiers](image)

Figure 3. Schematic diagram of signal amplifiers.

3.2 Servo Torque Control Module

For DC Servo motors, the relationship between the output torque of the motor passing through the speed reducer $T_O$ and the motor current $I$ is shown in the formula (1). $K_T$ is the torque constant of the motor, unit N/A ; $I$ is the operating current of the motor, unit A; $\eta$ is the transmission efficiency for the speed reducer; $n$ is the deceleration ratio for the speed reducer.

$$T_O = K_T \times I \times \eta \times n \tag{1}$$

According to the formula (1), the output torque of the motor $T_O$ is proportional to the current of the motor $I$ when the operating voltage of the motor $U$ remains constant. The current closed-loop composed of the servo motor and the drive can keep the operating current of the motor at the set value[8].

The relationship between the measured voltage $V_{out}$ of the torque sensor and the measured torque $T_{det}$ is shown in formula (2). $K_c$ is the proportional constant of the torque and voltage. In this paper, $K_c = 50/(3 - 1.65) \approx 37$.

$$T_{det} = K_c \times (V_{out} - 1.65) \tag{2}$$

4. Software System Design

4.1 Force Interaction Algorithm

![Upper limb rehabilitation robot coordinates](image)

Figure 4. Upper limb rehabilitation robot coordinates.

The coordinate system shown in figure 4 is established with the origin at the shoulder joint. $\theta_1$ is the shoulder joint’s flexion/extension angle; $\theta_2$ is the shoulder joint’s internal/external angle; $\theta_3$ is the elbow joint’s flexion/extension angle. The rod length is $L_1$ and $L_2$ while the distance of the center of mass from the center of the joint rotation is respectively $r_1$ and $r_2$. The dynamic equation of the robot is shown in formula (3):

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) = T_O - \tau_f \tag{3}$$
In the formula, \( q, \dot{q}, \ddot{q} \) are respectively angle, angular velocity and angular acceleration of each joint of the robot; \( M(q) \) is the positive symmetric inertial torque; \( C(q, \dot{q})\dot{q} \) is the non-linear coupling that includes Coriolis Force, centrifugal forces and so on; \( G(q) \) is the gravity term; \( T_D \) is the output torque of the motor when passing through the speed reducer; \( T_f \) is the friction term. 

In the left end of the equation, because of the upper limb rehabilitation robot must operate in a low-speed, smooth conditions, \( \dot{q}, \ddot{q} \) must be set in a very small range, so \( M(q)\dot{q} \), \( C(q, \dot{q})\dot{q} \ll G(q) \). This study only considers overcoming the gravity of the manipulator \( G(q) \) when the manipulator is under gravity. And in the right end of the equation, the friction force created from the speed reducer output shaft to the end of the joint \( T_f \approx 0.03T_D \) according to theoretical calculation, which is far less than the output torque of the motor. 

The formula can be simplified and written as \( G_1 = 0.97 \times T_{O1}. \) \( T_{O1} \) is the output torque of the shoulder joint flexion/extension motor passing through the speed reducer, \( G_1 \) is shown in the formula (4), while \( M_1 \) and \( M_2 \) is the weight of the upper arm and forearm respectively.

\[
G_1 = M_1g \sin \theta_1 + M_2g(L_1 \sin \theta_1 + r_2 \cos \theta_3) \tag{4}
\]

The degree of freedom of shoulder joint’s internal/external degree is only affected by friction. Using Coulomb Friction Model to model the friction force, \( G_2 \) is obtained as shown in the formula (5), \( \lambda \) is the friction coefficient.

\[
G_2 = \lambda \left( M_1g \sin \theta_1 + M_2g(L_1 \sin \theta_1 + r_2 \cos \theta_3) \right) = 0.97 \times T_{O2} \tag{5}
\]

\( T_{O2} \) is the output torque of the shoulder joint flexion/extension motor passing through the speed reducer. Analyzing the degree of freedom of flexor/elongation of elbow joint, \( G_3 \) is shown in formula (6).

\[
G_3 = M_2 \times g \times r_2 \times \cos \theta_3 = 0.97 \times T_{O3} \tag{6}
\]

According to the torque of three degrees of freedom, load compensator of \( G_1, G_2, \) and \( G_3 \) can be designed. The steering torque which is discussed farther below is being called in the active training, using it’s result to superimpose with the compensation torque of the load compensator to work as the target torque of the servo driver, the overall control block diagram is shown in the figure 5.

![Active training block diagram of upper limb rehabilitation robot.](image-url)

The main controller can obtain \( V_{out}(i=1,2,3) \) by the motion intention acquisition module, and the measuring torque \( T_{det} \) \((i=1,2,3)\) of the torque sensor can be calculated by the formula (2) According to the designed load compensator, the load compensation torque \( G_t(i=1,2,3) \) under the current position of each degree of freedom can be calculated. An additional booster torque \( T_i(i=1,2,3) \) will be added on the basis of \( G_t(i=1,2,3) \) and should change with the change of the calculation period. \( T_i = k \times (T_{det} \cdot G_t) \) is set in this paper. Therefore, the target torque of the servo torque control module is \( T_A = G_t + T_i \). \( K \) is the booster coefficient and can be adjusted according to the required booster level. Considering the
noise and fluctuation in the operation of the system, the threshold setting is being set on the trigger program of the active training. The value of Torq_Threshold depends on each degree of freedom, the smaller the value, the higher the sensitivity of the system to identify the motion intention. But if the value is too small it will judge the system noise as the motion intention, resulting in the false recognition of the motion intention. Here Torq_Threshold are set to: Shoulder flexion/extension 1.14Nm, shoulder joint internal / external move 0.45Nm, elbow flexion/extension 0.59Nm.

According to the measurement torque \( T_{\text{deti}} \), the incremental PID algorithm is used to control the target torque \( T_A \), and the control variable of the incremental PID algorithm is the increment of the input amount of the system\[10][11]. Taking the degree of freedom of shoulder joint flexion /extension as an example, the specific PID algorithm program is as follows:

```c
float kp=200;  
float ki=0.008;  
float kd=0;  
float PID_Control(float setvalue,float feedback)
{
    float pError=0,iError=0,dError=0; //Scale, integral, differential error
    ek = setvalue - feedback;//Deviation of target value from measured value
    pError = ek - ek1;// Calculate proportional Error
    iError= ek; // Calculate Integral errors
    dError = (ek - ek1)-( ek1-ek2); // Calculate differential errors
    ek2 = ek1;
    ek1 = ek;
    out = kp * pError +ki * iError + kd *dError + outlast;//Call PID algorithm to calculate the input amount
    outlast = out;//Save the last calculation result
    return out;
}
```

In the above PID algorithm, \( k_p \), \( k_i \) and \( k_d \) will be adjusted accordingly according to different degrees of freedom. The PID algorithm is called to calculate the target torque of each degree of freedom, and the target current of the motor \( I_A \) is obtained by the formula (1), which will be written to the current register of the servo drive\[12]. The control process is shown in the figure 6.

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**Figure 6. Servo motor torque control flow diagram.**

**Figure 7. Experimental prototype.**

**Figure 8. Motion intention experiment.**
5. Experiments and Verification

5.1 Experimental Platform
The experimental platform of upper limb rehabilitation robot mainly includes four parts: mechanical structure, control system, Force interaction system and computer installed with graphical user interface and virtual reality system. The prototype of the upper limb rehabilitation robot in this experiment is shown in figure 7.

5.2 Motion Intention Experiment
This experiment mainly tests the shoulder joint’s flexion/extension in the active training and the detection and mistake identification of the motion intention of the upper limb rehabilitation robot when the user intends to trigger the active mode.

In the course of the experiment, the torque of motion intention was applied by the subjects to the freedom of shoulder joint’s flexion/extension (as shown in figure 8), and trigger torque threshold of the active mode was set to 1.4Nm, 1.3Nm, 1.2Nm, 1.1Nm, 1.0Nm, 0.9Nm and 0.8Nm respectively. In such cases, the effect of motion intent recognition is tested separately, and 30 experiments are carried out each torque threshold, the experimental results are shown in table 1.

| Trigger torque threshold (Nm) | Number of successful times | Number of failed time | Success rate (%) |
|-------------------------------|----------------------------|----------------------|------------------|
| 1.4                           | 25                         | 5                    | 83.33%           |
| 1.3                           | 26                         | 4                    | 86.67%           |
| 1.2                           | 27                         | 3                    | 90.00%           |
| 1.1                           | 29                         | 1                    | 96.67%           |
| 1.0                           | 29                         | 1                    | 96.67%           |
| 0.9                           | 28                         | 2                    | 93.33%           |
| 0.8                           | 27                         | 3                    | 90.00%           |

As seen from the table above, with the decrease of the torque threshold of the trigger active mode, the probability of success of motion intention detection increases correspondingly, but when reduced to 0.8Nm, the probability of success of motion intention detection decreases. The main reason for this phenomenon is that the smaller the torque threshold is setting, the smaller the trigger torque that the user needs to apply, the easier it is for the user to trigger the active mode, and the more sensitive the upper limb rehabilitation robot is to detect the motion intention.

5.3 Gravity Balance Experiment
In the design of this study, the active training mode is realized on the basis of balancing the gravity of the manipulator itself. Therefore, it is particularly important for the servo torque control module to be used to balance the torque of the manipulator's own gravity according to the attitude output of the manipulator, in order to verify the gravity effect of the balanced manipulator itself, the experiment shown in figure 9 is designed. The gravity equilibrium problem of the degree of freedom of shoulder joint’s flexion/extension is tested in this experiment. In order to facilitate the calculation and statistics, the degree of freedom of shoulder joint’s flexion/extension is recorded as 0° when vertically down in this experiment. At the same time, the upper arm and forearm remain straight state. Within the range of 30°~150° of shoulder’s flexion/extension activity, the torque of the torque sensor is measured and compared with the torque calculated by the theory each15°, and the experimental results are shown in the figure 10.
The experimental results show that the servo torque control module can balance the self-gravity of the manipulator well. The error of the torque increases with the increase of the angle, and become greatest at the 90°. The main reason for the errors is that when the angle of the shoulder joint is bend/stretch is 90 degree, and the upper arm and forearm of the manipulator are just at the front extension state, the influence that gravity of the manipulator applied to the torque sensor is the greatest, resulting in the greatest disturbance and noise, which make the error of gravity balance increase. At the same time, the average error rate of the output torque is 3.83%, and the effect is that when the motion intention is detected, the motion intention of the shoulder joint stretching direction is easier to identify than the motion intention in the buckling direction. But from the motion intention detection experiment, it can be concluded that the torque error used to balance the gravity of the manipulator does not have a significant effect on the detection of motion intention.

6. Conclusions and Prospects
According to the functional requirements of human-computer interaction, the human-computer interaction system of upper limb rehabilitation robot proposed in this study can be divided into four parts of control system, force interaction system, graphical user interface system and virtual reality system. And the force interaction system focused research has been carried out. In this study, servo motor was used to complete the boost function in active training, which can assist patients with certain muscle strength to complete active rehabilitation training. In the later stage, we should make full use of the function of servo motor to increase resistance training and balance the arm weight of patients. In addition, the control algorithm of upper limb rehabilitation robot will be further optimized in the later stage, the dynamic characteristics of upper limb rehabilitation robot should be calculated accurately to provide precise parameters for the control system.

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