Control Strategy of Upper Limb Rehabilitation Exoskeleton based on Impedance Control and Position Feedback

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Abstract: The upper limb rehabilitation exoskeleton was designed based on the human movement mode, and the kinematics and dynamics of the exoskeleton were modeled by simulink. The double closed-loop control system composed of impedance controller and position feedback was designed according to the control requirements. Based on the movement requirements, The parameters were adjusted adaptively to meet the design needs, and the conclusion was proved through simulation experiments.

1 INTRODUCTION

At present, with the improvement of living standards and the increase of average life expectancy, the number of people with movement disorders caused by strokes and other causes is increasing rapidly(Cheng 2019). Rehabilitation training is an important recovery method for people with movement disorders (Zhuo 2003), but traditional rehabilitation training is highly dependent on professionals (Sun 2019). The training method assisted by rehabilitation robots has developed rapidly in recent years (Lo 2010, Klamroth-Marganska 2014). Studies have shown that rehabilitation robots such as exoskeleton can play a very helpful role in the rehabilitation training of patients with movement disorders caused by stroke (Connell 2014). The rehabilitation exoskeleton can realize different types of rehabilitation training, such as active and passive, through the cooperation of man and machine. By simulating the daily motion behavior of the human body, it helps patients to realize the recurrence of daily activities, and helps users to achieve muscle and nervous system recovery by providing impedance or exercise assistance, and restore the corresponding motor functions (Yao 2019). In this regard, scholars have conducted a lot of researches on rehabilitation exoskeleton, the focus of which is the human-computer interaction control method of exoskeleton (Li 2008).

Due to the non-linear characteristics of the man-machine coupling system, many scholars have proposed different control strategies based on different control theories. According to the extracted human-computer interaction information, it can be divided into two types: bio-signal-based human-computer interaction and force/position information-based human-computer interaction (Du 2018). Since human body signals are difficult to extract and susceptible to interference, signal processing in this way is relatively cumbersome. The human-computer interaction method based on force/position information has the advantages of simple extraction and clear physical meaning. The current research is relatively mature. For example, Saglia et al. used impedance control to adjust the compliance of the ankle rehabilitation robot to achieve patient-assisted training (Saglia 2013). However, the traditional impedance control control method has fixed control parameters and is effective for a single training target, but it is difficult to meet different training requirements. Aiming at the above problems, this paper designs an exoskeleton control system that adaptively adjusts impedance control parameters.

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2 EXOSKELETON MODEL

2.1 Exoskeleton Kinematics Model

In order to ensure the coordination of human-machine movement, the exoskeleton and the human body should adopt similar movement patterns and structural designs. The upper limb exoskeleton model with 2 rigid bodies and 4 free in series is used as the research object. The shoulder joint and elbow joint are used as the main joints for exercise assistance. The four degrees of freedom of shoulder internal rotation/external rotation, forward flexion/posterior extension, outward swing/adduction, and elbow joint flexion/posterior extension are the design degrees of freedom. The schematic diagram is shown in Fig 1. Among them, the X_0-Y_0-Z_0 coordinate system is the base coordinate system, and its coordinate origin coincides with the shoulder joint point.

The exoskeleton uses flat extension to the right as the initial state of motion, and the joint angle θ_{1-4} represents the angle between it and the initial state, where θ_{1-4} corresponds to the flexion/extension, extension/adduction, and rotation of the shoulder joint, respectively. Internal/external rotation, elbow flexion/extension four degrees of freedom. Since there are two rotating shafts that coincide with the joints, it is difficult to model with the D-H parameter method. The kinematics model is established directly by the principle of coordinate change. The transformation method is shown in Table 1.

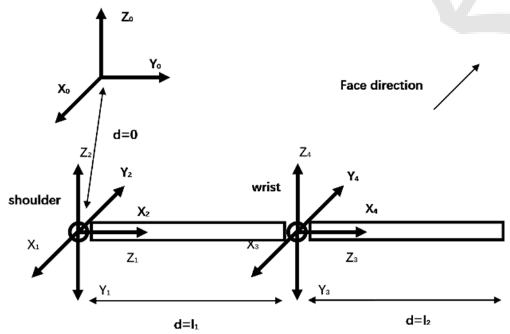

Figure 1: Schematic diagram of exoskeleton.

Table 1: Coordinate system change table.

Coordinate system	0→1	1→2
Coordinate system change method	Rotate around the X-axis square -pi/2 → rotate around the Z-axis square θ_1	Rotate around the Y-axis square -pi/2→ rotate around the X-axis square pi/2→ rotate around the Z-axis square θ2

Table 1 (CONTINUED)

Coordinate system	2→3	3→4
Coordinate system change method	Rotate around the Z-axis square -pi/2→ rotate around the X-axis square -pi/2→ translate along the Z-axis square l1→ rotate around the Z-axis square θ3	Rotate square around Y axis -pi/2→ rotate pi/2 around X axis→ rotate square around Z axis θ4

$$ {}^1_0T = Rot(X,-pi/2)Rot(Z,\theta_1) \quad (1)$$

$$ {}^2_1T = Rot(Y,-pi/2)Rot(X,pi/2)Rot(Z,\theta_2) \quad (2)$$

$$ {}^3_2T = Rot(Z,-pi/2)Rot(X,-pi/2)\cdot Trans(Z,l_1)Rot(Z,\theta_3) \quad (3)$$

$$ {}^4_3T = Rot(Y,-pi/2)Rot(X,pi/2)Rot(Z,\theta_4) \quad (4)$$

Where, ${}^{n+1}_{n}T$ represents the coordinate transformation matrix from the coordinate to the nth coordinate in the n+1 coordinate system. $Rot(a,\theta)$ represents the transformation matrix that rotates θ degrees around the coordinate axis a, and $Trans(Z,l_1)$ represents the transformation matrix that translates l1 toward the Z axis. Then the spatial coordinates of the elbow joint and wrist joint in the base coordinate system are

$$[X_1,Y_1,Z_1,1]^T = {}^1_0T\,{}^2_1T[l_1,0,0,1]^T \quad (5)$$

$$[X_2,Y_2,Z_2,1]^T = {}^1_0T\,{}^2_1T\,{}^3_2T\,{}^4_3T[l_2,0,0,1]^T \quad (6)$$

Where, $[X_1,Y_1,Z_1]$ is the coordinate of the elbow joint, $[X_2,Y_2,Z_2]$ is the coordinate of the wrist joint, and the speed of the joint points is

$$V = \partial X/\partial\theta \cdot d\theta/dt \quad (7)$$

2.2 Exoskeleton Dynamic Model

In this paper, Lagrangian equations are used to establish the exoskeleton dynamics model. The model ignores the joint friction damping and the movement deviation caused by the mechanism mismatch. At the same time, the exoskeleton is regarded as a pure rigid mechanism. Take the shoulder joint as the origin of motion, and the o-xy plane of the base coordinate system as the zero potential energy surface. Assuming that the weight of the boom mechanism is m1, the center of mass and the origin of motion are l_1, the weight of the forearm mechanism is m_2, and the distance between the center of mass and the elbow joint is l_2. From the Lagrangian equation

$$T = \frac{d}{dt}\frac{\partial L}{\partial \dot{\theta}} - \frac{\partial L}{\partial \theta} \quad (8)$$

Among them, T is the joint torque and L is the Lagrangian function, which is the difference between the kinetic energy and the potential energy of the system, namely

$$L(\dot{\theta}, \theta) = K(\dot{\theta}, \theta) - P(\theta) \quad (9)$$

Among them, K is the total kinetic energy of the system, and P is the total potential energy of the system. The exoskeleton is regarded as a homogeneous rigid body to reduce the complexity of the system. Then the rigid body can be equivalent to the mass point at the center of mass of the rigid body. From equation (7), the speed of the mass point in various directions can be known, and the negative semi-axis direction of the base coordinate Z axis is taken as the gravity direction. Then

$$L(\dot{\theta}, \theta) = (m_1 V_1^2(\dot{\theta}, \theta) + m_2 V_2^2(\dot{\theta}, \theta))/2 - \left(m_1 Z_1(\theta) + m_2 Z_2(\theta)\right) g \quad (10)$$

The standard form of its kinetic equation can be expressed as

$$M(\theta)\ddot{\theta} + C(\dot{\theta}, \theta)\dot{\theta} + G(\theta) = T \quad (11)$$

Among them, $M(\theta)$ represents the moment of inertia of the exoskeleton, $C(\dot{\theta}, \theta)$ represents the Geese force and centrifugal force terms of the system, and $G(\theta)$ represents the gravity term

2.3 Human Body Impedance Model

The paper (Duchaine 2009) uses a spring model to describe the human body impedance, and proposes a human body impedance model. The concept is that when the human body remains stationary in space, the distance between the moving unit and the force is linear. Namely

$$F = Kx + b \quad (12)$$

This article uses this method to obtain the contact force between the human body and the exoskeleton. In the preliminary work of this research group, the repeatability of human motion was verified, and the results proved that for the same moving target, the human body's multiple motion trajectories have a high degree of similarity. The movement was planned. Based on the above assumptions, it can be considered that during movement, when the actual route of the human body deviates from the movement intention, a force will be applied in the opposite direction of the deviation direction. Based on the results of literature (Duchaine 2009), it is assumed that the force of the device has a linear relationship with the actual route and the size of the motion intention, thereby simulating the human-machine contact force in actual motion.

3 EXOSKELETON CONTROLLER DESIGN

3.1 Design Requirements

The control design of the human rehabilitation exoskeleton should meet the active and passive training requirements of rehabilitation training, that is, when the user is completely or partially disabled, the exoskeleton provides additional torque to help the patient complete the exercise goal. When the user has active exercise ability, he should follow the user's movement. At the same time, safety requirements should be met, and when the contact force is large, stop in time to ensure the safety of users. In addition, it should have a certain degree of flexibility to meet the needs of human-computer interaction.

3.2 Impedance Control

Impedance control is a way to achieve indirect force control by controlling the movement of the robot. Its ultimate goal is neither to directly control the movement of the system nor the contact force between the system and the outside world, but the dynamic relationship between the two. Make the motion joints of the mechanical system exhibit the dynamic characteristics of the second-order system composed of spring-damping-mass, namely:

$$M_d \ddot{\tilde{\theta}} + D_d \dot{\tilde{\theta}} + K_d \tilde{\theta} = \tau_{ext} \quad (13)$$

Among them, M_d , D_d , K_d correspond to the set mass, damping, and elastic coefficient respectively. In order to make the impedance characteristics of each joint independent of each other, M_d,D_d,K_d are generally designed as diagonal arrays, and $\tilde{\theta}$ is the movement deviation angle. Combine it with equation (11) to obtain a motion model including impedance control.

$$\tau = M(\theta)\ddot{\theta}_d + C(\dot{\theta},\theta)\dot{\theta} + G(\theta) + M(\theta){M_d}^{-1}\left(D_d\dot{\tilde{\theta}} + K_d\tilde{\theta}\right) + \left(I - M(\theta){M_d}^{-1}\right)\tau_{ext} \quad (14)$$

Among them, θ_d is the set joint angle, θ is the actual joint angle, and I is the identity matrix.

3.3 Position Feedback

Because the feedback torque of the impedance control part of the design controller is determined by the actual joint angle and the user's own planned joint angle. For the set trajectory and the actual trajectory, it is actually an open-loop control. In this case, in order to improve the controllability of the exoskeleton, the joint angle and joint angular velocity feedback are used to realize the position feedback of the controller.

$$\tau_1 = K_1\dot{\theta} + K_1\theta \quad (15)$$

The controller block diagram is shown as in Fig. 2.

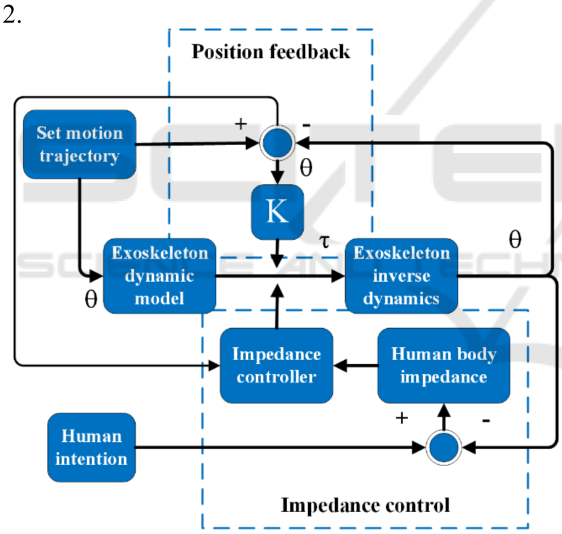

Figure 2. System control block diagram

3.4 Control Parameter Design

Based on the design function realization requirements, the designed control model should satisfy different motion feedback under different motion assistance requirements. The overall system feedback can be divided into impedance control feedback based on contact force and position feedback based on position information, namely

$$\tau_t = \tau + \tau_1 + \tau_{ext1} \quad (16)$$

Where, τ_t is the total input of the controlled torque, τ is the input of the calculation based on the kinematics model, τ_1 is the position feedback, and τ_{ext1} is the equivalent feedback of impedance control. Based on the principle of impedance control, under the influence of τ_{ext1}, the motion trajectory will have an offset that tends to the human body motion intention, and τ_1 will cause the motion trajectory to have an offset close to the set value. Therefore, the feedback of τ_1 can be controlled by increasing the coefficient K. Control the strength of the position feedback to affect the overall control effect, thereby meeting the design requirements.

4 EXPERIMENT

Assuming that the length l1 of the exoskeleton arm part is 0.35m, the weight is 4kg, the length l1 of the forearm part is 0.25m, the weight is 4kg, and the human body impedance coefficient is 6000N/m, the exoskeleton model is established. Use simulink to establish a dynamic model, as shown in Fig.3, build a control model from the control structure shown in Fig.2, as shown in Fig. 4

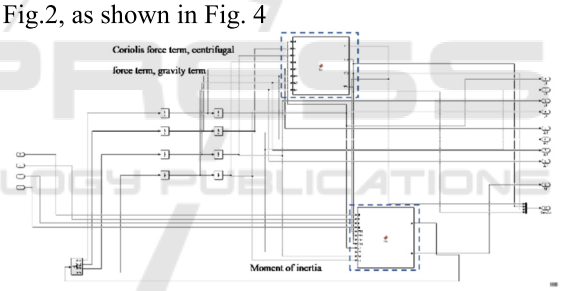

Figure 3. Exoskeleton dynamic model.

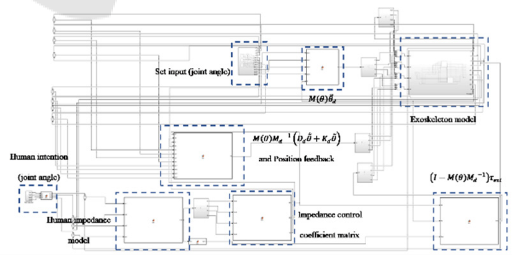

Figure 4. Overall control model.

The result of setting a larger position feedback coefficient is shown in Fig 5. The actual motion curve is close to the set value, and the contact force is larger. The result of setting a smaller position feedback coefficient is shown in Fig 6. The actual motion curve is close to the intention curve, and the contact force is small. The result of setting the position feedback coefficient in the middle is shown in Fig 7. The actual motion curve is between the intention curve and the set curve, and the contact force is moderate.

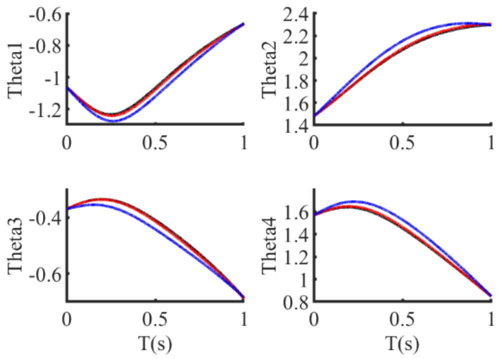

Figure 5. Oscilloscope waveform (from top to bottom are θ1-4, the black curve is the set rotation angle, the red is the actual rotation angle, and the blue line is the intention of the human body)

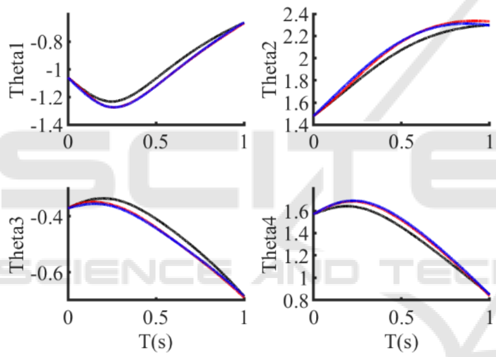

Figure 6. Oscilloscope waveform

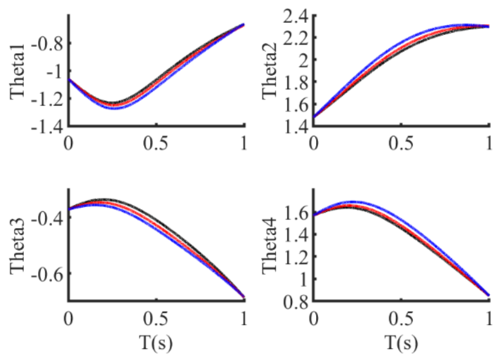

Figure 7. Oscilloscope waveform

5 CONCLUSIONS

The simulation experiment proves that by adjusting the position feedback coefficient, the control can be switched between different performances. The impedance control coefficient determines the upper limit of the closeness between the actual motion curve and the human body intention curve. The position feedback coefficient can be adjusted to adjust the closeness between the actual curve and the intention curve or the set curve to achieve different human-computer interaction requirements.

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