Position-based Adaptive Impedance Controller Design for Lower Limb Rehabilitation Robot

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Abstract. Aiming at the tracking problem of human-computer interaction force in active rehabilitation training mode, the position-based adaptive impedance controller is used to control the human-computer interaction force in the training process. The control rate of the adaptive impedance controller is first derived. The position controller and impedance controller simulation model are established based on MATLAB software, and the impedance control effect is simulated. The experimentally proven position-based adaptive impedance controller can realize the resistance following requirements in the active training process.

Introduction
The number of patients with lower extremity dyskinesia caused by stroke, spinal injury and brain trauma has increased year by year. Lower extremity dyskinesia seriously affects patients' daily life and imposes a heavy burden on patients. In recent years, with the rapid development of robotics, many scholars have combined intelligent robot technology with rehabilitation medicine, using the characteristics of high robot motion precision, strong interaction, intelligent automatic to assist or replace the rehabilitation physician to complete the exercise treatment [1].

Medical research has shown that patients with limb dyskinesia caused by nerve damage and healthy limbs can help them recover their athletic ability through scientific and effective exercise rehabilitation training. After the patient completes the initial passive training, the lower limbs have certain athletic ability, and the patient can perform some active output training. In active training, the rehabilitation robot tracks the desired human-machine contact force and follows the patient’s active motion trajectory. Therefore, in order to meet the requirements of resistance following in the active rehabilitation training, the position-based adaptive impedance controller designed in this paper is used in the active rehabilitation training process.

Adaptive Impedance Algorithm for Active Rehabilitation Training

Lower Limb Rehabilitation Robot
The overall structure of the pedal-type lower limb rehabilitation robot described in this paper is shown in Figure 1. It mainly includes drive and transmission structure, rotating crank, limb protection structure, fixed frame and so on.
Active Rehabilitation Training Mode

The purpose of active training of the affected limb is to strengthen the muscle strength and endurance of the affected limb. In the control process, the impedance control algorithm with better human-computer flexibility is used to control the interaction between the robot and the patient. In the active training, it is necessary to formulate a suitable human-computer interaction trajectory according to the comprehensive assessment results of the patient's physical state, so that the patient can prolong the exercise time of the patient as much as possible and ensure the rehabilitation training effect. The normal person's lower limb output trajectory approximates the sinusoidal curve trajectory during treadmill exercise. This trajectory is the most comfortable trajectory of the human body after optimal adjustment of the human brain. Therefore, in this paper, the resistance of the lower limbs of the patient is set to the trajectory in the form of sine and cosine.

Position-based Adaptive Impedance Controller Design

Impedance control can be divided into position-based impedance control and force-based impedance control. The force-based impedance control must make the robot joint drive motor in the torque working mode, and directly calculate the required torque to the driver through the system dynamics model. The accuracy of the dynamic model is higher and the calculation amount is larger. The rehabilitation robot in this paper can accurately control the position. Therefore, the position-based impedance control is used to realize the control of human-computer interaction in active training, that is, the change of position can achieve the purpose of interactive force control.

In the actual movement of the robot, it can be divided into a free state and a restrained state according to whether it is in contact with the environment. The working process of the rehabilitation robot in this paper has only the constraint state, so this paper only analyzes the constraint state, and since the robot is a single joint, only the single joint space is analyzed. When the robot comes into contact with the environment, it forms a comprehensive dynamic system with the environment. In the analysis process, the contact model corresponding to the dynamic system is usually simplified into a linear spring system, as shown in Figure 2, where \( x_e \) is the environmental position, \( x \) is the actual position of the robot, \( k_e \) is the environmental stiffness, and \( f \) is the interaction force[2].

According to the principle of impedance control, the impedance model corresponding to the dynamic system is:
\[ m_d \ddot{e} + b_d \dot{e} + k_d e = f_e - f_d \]  \hspace{1cm} (1)

Where:  
\( e \) — the correction amount of the current robot position under impedance control /m;  
\( f_e \) — the force /N that the environment actually applies to the end of the robot;  
\( f_d \) — the desired contact force /N.

When the target stiffness \( K_d=0 \), it shows some robustness to the force tracking of any stiffness environment, but when \( f_d, \dot{e}, \) and \( \Delta \dot{e} \) are time-varying functions, the force following error will appear. The rehabilitation robot in this paper uses the adaptive impedance control proposed by Seul to reduce the tracking error of the force [3]. The control law is:

\[
\begin{align*}
\dot{m}_d \ddot{e} + b_d \dot{e} + \dot{f}_d(t - \lambda) &= f_e - f_d, \\
\ddot{\Omega}(t) &= \ddot{\Omega}(t - \lambda) + \eta \frac{f_d(t - \lambda) - f_e(t - \lambda)}{b_d} \\
\end{align*}
\]  \hspace{1cm} (2)

Where:  
\( \dot{\Omega} \) — based on the adaptive adjustment of the force error;  
\( \eta \) — update coefficient;  
\( \lambda \) — the sampling period of the controller.

**Simulation Analysis of Position-Based Adaptive Impedance Control**

**Position Controller Design and Simulation**

In this paper, the speed control simulation model is established in MATLAB, and the double closed loop PID control system of speed inner loop and position outer loop is established to realize the position control of the rehabilitation robot. In the simulation, the transmission system inertia is equivalent to the motor rotor inertia, and the sampling control period is set to 2 ms. The simulation model is shown in Figure 3. After the speed loop PID parameters are adjusted, \( K_p, K_i \) and \( K_d \) are 60, 0, and 700. In order to avoid damage to the patient, the position loop control should reduce overshoot and oscillation, set the position loop output limit [-30, 30], and the position PID parameters are adjusted to obtain \( K_p, K_i \) and \( K_d \) respectively 8, 0, 20.

![Figure 3. Position speed double closed loop PID control matlab simulation model.](image)

The rectangular position following simulation is performed when the motor shaft load is 0.2 N·m. The matlab solver is ode23tb, and the simulation result is shown in Figure 4(a). It can be seen from the figure that the transitions under different steps are relatively stable, no overshoot occurs, and the response time increases with the increase of the step amount. In order to analyze the response effect of the position control loop to the disturbance load, the simulation results of the motor shaft end step disturbance torques of 0.25 N·m, 0.5 N·m, and 0.8 N·m are shown in Figure 4(b). It can be seen from the figure that the larger the disturbance torque, the larger the sudden change in position, and the small stability deviation after stabilization is about 0.01°. The simulation results show that the double closed loop PID controller can achieve stable control of angular position.
Impedance Controller Design and Simulation

It is assumed that the patient's lower limbs have a certain stiffness and can generate a certain trajectory. The positional impedance Simulink simulation model is established according to the position impedance control schematic. The motor model is packaged separately, and the final simulation model is shown in Figure 5. When the 60kg human body actively treads, the maximum treadmill force is about 20% of the weight. When the crank is 170mm, the corresponding mid-axis torque is 20N\cdot m. The actual treadmill force is very similar to the sinusoidal curve, taking medium target resistance (average resistance 10N\cdot m).

Set the desired contact torque trajectory between the human body and the robot as \( \tau_r = 10 + 5\sin(4t) \), and set the lower limb to pedal at a constant speed. The simulation results are shown in Figure 6.
From the above simulation results, at the initial and end, the mutation tracking response has a turbulent phenomenon, which has a slight impact on the human leg. In actual control, the expected resistance should be avoided as a step change. After reaching the steady state, there will be a dynamic fluctuation error with a maximum value of 0.1 N·m, and the error is relatively small. Therefore, the adaptive impedance control algorithm can adaptively adjust the crank position to stabilize the human-machine interaction force near the expected value.

Active Training Interactive Resistance Tracking Experiment

Position Control Experiment

In the experiment, the speed loop PID parameters are set to $K_p=100$, $K_i=0$, $K_d=100$, the position loop PID parameters are $K_p=2.5$, $K_i=0.01$, $K_d=0.5$, and the position loop output is limited to $\pm 50 \text{ r/s}$. The incremental step response of different positions when the robot is unloaded is shown in Figure 7. It can be seen from the figure that the transitions under different incremental steps are relatively stable, the overshoot is small, the steady-state error increases with the increase of the step, and the maximum steady-state error is about 1°. After the impedance controller is debugged, the position and speed loop have better force tracking performance under this parameter.

![Figure 7. Control step response curve.](image)

Impedance Controller Performance Experiment

During active training, the rehabilitation robot tracks the trajectory of the affected limb and provides a certain resistance to the affected limb. The human trajectory is completely generated by the patient's active motion. It is expected that the human body position trajectory is the same as the crank position trajectory. $K_d=0$ is set in the interaction tracking. The control effect is compared with traditional impedance control and adaptive impedance control. First, the traditional impedance control experiment is carried out to adjust the impedance parameters. The experimental results are shown in Figure 8(a) when the tracking force is set to 0 mA. Adjust the adaptive adjustment rate based on the above impedance parameters. When $\eta=0.05$, the force tracking effect is better. The experimental results are shown in Figure 8(b) when the tracking force is set to 0 mA.
Comparing Figure 8(a) and Figure 8(b), it can be seen that there is a static deviation in the conventional impedance control force tracking, and the larger the rotation speed, the larger the static deviation. Although traditional impedance control can achieve the purpose of force tracking, the effect is poor. Adaptive impedance control can effectively reduce the effects of velocity and acceleration. In interactive force tracking, there is almost no static deviation. In addition, there is still a dynamic error in the adaptive impedance control, because the drive current itself has a large noise in the motor control operation, and it is difficult to filter out all of it in the control. But overall, adaptive impedance control algorithms can already achieve resistance tracking requirements.

**Summary**

In this paper, by designing the position-based adaptive impedance controller, the tracking control of human-computer interaction force in the process of active rehabilitation training is realized. Compared with the traditional impedance controller, the adaptive impedance controller has better force tracking effect, which can effectively reduce the influence of velocity and acceleration. There is almost no static deviation in the interactive force tracking. From the simulation analysis and experimental results, it can be seen that the adaptive impedance controller can fully meet the resistance tracking requirements in active rehabilitation training.

**References**

