Multi-mode Controller for Hemiplegia Rehabilitation

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Abstract. Patients with hemiplegia should receive different therapeutic exercises at different stages. This paper proposes a multi-mode controller with three control strategies, namely PID control, impedance control, and admittance control. Depending on the muscle strength of patients, the multi-mode controller can automatically switch to the best mode. When the muscle strength is below the lower threshold, the controller will switch to PID control and achieve passive position control. When the muscle strength is above the upper threshold, the controller will switch to admittance control and achieve active force control. When the muscle strength is between two thresholds, the controller will switch to impedance control and achieve passive force control. These control strategies can meet the needs of patients with hemiplegia at different stages, and the use of the multi-mode controller can speed up the rehabilitation process, which has great practical significance.

Keywords: Multi-mode Controller, Impedance Control, Admittance Control.

1. Introduction
Hemiplegia is a disease of dystonia and abnormal muscle coordination caused by the central nervous system losing control of the motor system, which leads to unilateral motor dysfunction [1]. The Swedish physical therapist Brunnstrom observed a large number of patients with hemiplegia and divided the recovery of hemiplegia into six stages [2]. Different therapeutic exercises are necessary for patients with hemiplegia at different stages because they are helpful to improve physical function and speed up the rehabilitation process [3]. Compared with traditional artificial rehabilitation, rehabilitation robots have better controllability, stability, and repeatability. Therefore, many rehabilitation robots have been developed, such as Lokomat [4], HAL-5 [5], Rewalk [6], and Motion Maker [7]. Many advanced control strategies have been applied to these robots.

Hogan proposed impedance control in 1985 [8], which is similar to admittance control proposed later. Both strategies link the force and position of the actuator by kinematics and dynamics. The difference is that the inner loop of impedance control is to control the force and the outer loop is to control the position, but the inner loop of admittance control is to control the position and the outer loop is to control the force [9]. The block diagrams of impedance control and admittance control are shown in Fig.1. Perez-Ibarra et al. [10] proposed an adaptive impedance control strategy, which can obtain motion information through
sensors and adaptively adjust system parameters. Ho et al. [11] proposed an impedance control strategy combining sliding mode and fuzzy neural network. This strategy has the advantages of high sensitivity, fast speed, and excellent tracking performance through verification on a CPM. Hussain et al. [12] proposed an adaptive impedance control strategy, which can provide adaptive force for pneumatic muscle actuators, and has been verified on a small group of normal people. Chen et al. [13] proposed an admittance control strategy based on fractional-order, which can effectively improve the response performance of the system compared with typical admittance control based on integer-order. Ott et al. [14] proposed a hybrid control strategy, which can switch between impedance control and admittance control, and has been verified on a DLR-KUKA lightweight robot.

Fig.1 The block diagrams of (a) impedance control and (b) admittance control

The main contribution of this paper is to design a multi-mode controller, which can switch to the best mode according to the muscle strength of patients with hemiplegia. Three control strategies are introduced in Chapter 2. Then in Chapter 3, the design of the multi-mode controller is explained. Next, simulations of impedance control and admittance control are presented in Chapter 4. Finally, the conclusion is put forward in Chapter 5.

2. Control Strategies

In the early stage of rehabilitation, the muscle strength of patients with hemiplegia is very low, which means that they cannot perform autonomous movements on their own and therefore require passive rehabilitation training. Due to fewer abnormal movements, force control is not required during this period. As a result, the passive position control strategy is adopted. PID control can form a control deviation according to expected output value and actual output value, and then form the control value by a combination of the proportional, integral, and differential deviations, thereby linearizing the controlled object. Therefore, it is suitable as the passive position control strategy.

In the middle stage of rehabilitation, although the muscle strength of patients with hemiplegia has recovered to a certain extent, it is still difficult for them to perform daily activities on their own, and there are more abnormal movements during this period. At this time, the passive force control strategy is adopted. Impedance control not only can control the position of the actuator but also can control the interaction force between the actuator and patients under passive movements of patients.

The expression of the impedance control model is shown in formula (1):

\[ F(s) = (ms^2 + bs + k)X(s) \]  

The kinematic equation considering the influence of friction is shown in formula (2):

\[ m\ddot{x} = F_c + F + F_f \]  

The expression of the environmental force is shown in formula (3):
The expression of the virtual environment force is shown in formula (4):

$$F_v = -k_v(x - x_o)$$  \hspace{1cm} (4)

The expression of the friction force is shown in formula (5):

$$F_f = -\text{sign}(\dot{x})(C_v \mid \dot{x} \mid + F_v)$$  \hspace{1cm} (5)

The controlled force is obtained as shown in formula (6) according to the above formulae:

$$F = m\ddot{x}_o - \frac{mD_f}{M_f}(\ddot{x}_o - \ddot{x}_o) - \frac{mK_f}{M_f}(x_o - x_o) + \text{sign}(\dot{x})(C_v \mid \dot{x} \mid + F_v)$$  \hspace{1cm} (6)

In summary, impedance control is composed of an internal force control loop and an external position control loop, but the focus is on force control. Therefore, it is suitable as the passive force control strategy.

In the late stage of rehabilitation, the muscle strength of patients with hemiplegia has been greatly recovered, but the gait characteristics of patients are still different from normal people. At this time, the active force control strategy is adopted. Admittance control not only can control the position of the actuator but also can control the interaction force between the actuator and patients under active movements of patients.

The expression of the admittance control model is shown in formula (7):

$$X(s) = \frac{1}{ms^2 + bs + k} F(s)$$  \hspace{1cm} (7)

The kinematic equation considering the influence of friction is the same with the formula (2). The expression of the virtual environment force is the same with the formula (4). The expression of the friction force is the same with the formula (5).

The expression of the environmental force is shown in formula (8):

$$F_e = M_f(\ddot{x}_f - \ddot{x}_o) + D_f(\dot{x}_f - \dot{x}_o) + K_f(x_f - x_o)$$  \hspace{1cm} (8)

The expression of the controlled force based on PD control is shown in formula (9):

$$F = k_v(x - x_o) + k_v(\dot{x} - \dot{x})$$  \hspace{1cm} (9)

The actual acceleration of the actuator under admittance control is obtained as shown in formula (10) according to the above formulae:

$$\ddot{x} = \frac{1}{m} [k_p(x - x) + k_v(\dot{x} - \dot{x}) - k_v(x - x_o) - \text{sign}(\dot{x})(C_v \mid \dot{x} \mid + F_v)]$$  \hspace{1cm} (10)

In summary, admittance control is composed of an internal position control loop and an external force control loop, but the focus is on position control. Therefore, it is suitable as the active force control strategy.

### 3. Design of the Multi-mode Controller

As shown in Fig.2, this paper designs a multi-mode controller for patients with hemiplegia at different stages. The controller consists of three control strategies and can switch between them according to the muscle strength of patients. When the muscle strength is detected below 5N, the controller will switch to PID control and realize passive position control. When the muscle strength is detected between 5N and
30N, the controller will switch to impedance control and realize passive force control. When the muscle strength is detected above 30N, the controller will switch to admittance control and realize active force control. The thresholds should be modified depending on professional advice.

**Fig. 2** The block diagram of the multi-mode controller

Under the normal rehabilitation process of patients, the controller will only switch from PID control to impedance control or from impedance control to admittance control. But under abnormal movements of patients, the controller may switch incorrectly due to sudden changes in the muscle strength of patients. At this time, the controller will switch to passive force control until the muscle strength is stabilized.

4. Simulation

Impedance control simulations of position and force are shown in Fig. 3. Both position and force change smoothly without overshoot, which can meet the requirements of passive force control, that is, impedance control can make patients feel soft interaction force despite the position is tracked slowly, and the focus is on ensuring patient safety.

**Fig. 3** Impedance control simulations of (a) position and (b) force

Admittance control simulations of position and force are shown in Fig. 4. Both position and force change rapidly with overshoot, which can meet the requirements of active force control, that is, admittance control can track the position quickly despite sudden changes on interaction force, and the focus is on tracking the position.
5. Conclusion
This paper proposes a multi-mode controller with three control strategies, namely PID control, impedance control, and admittance control, which can realize passive position control, passive force control, and active force control. According to the muscle strength of patients with hemiplegia, the controller will switch to the best mode. Simulations of impedance control and admittance control show that they can achieve the expected control effect. Next, the validity and reliability of the controller will be checked by experiments.

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