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Impedance Control of a Pneumatic Muscles-Driven Ankle Rehabilitation Robot

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Abstract. Pneumatic muscle is a new type of flexible actuator with advantages in terms of light weight, large output power/weight ratio, good security, low price and clean. In this paper, an ankle rehabilitation robot with two degrees of freedom driven by pneumatic muscle is studied. The force control method with an impedance controller in outer loop and a position inner loop is proposed. The demand of rehabilitation torque is ensured through tracking forces of three pneumatic muscle actuators. In the simulation, the constant force and variable force are tracked with error less than 10N. In the experiment, the force control method also achieved satisfactory results, which provides a good support for the application of the robot in the ankle rehabilitation.

Keywords: Pneumatic Muscle, Ankle Rehabilitation, Impedance Control.

1 Introduction

With the gradual growth of population over the age of 60 years, China has entered the aging society. The aged people have a significant decline in the degree of physical activity of limbs, which brings a lot of inconvenience to their daily life. In addition, the number of patients with joint and muscle injury is increasing rapidly and their rehabilitation problems are becoming more and more serious. Medical theory has proved that appropriate amount of scientific rehabilitation training can improve the recovery effect for ankle injury patients after the completion of surgery [1]. Traditional ankle rehabilitation needs high physical demanding work from therapists. However, because of the lack of rehabilitation surgeons, patients can not get enough rehabilitation training, which reduces the rehabilitation effect. The assistance of ankle robot can reduce the burden of rehabilitation physicians and help ankle injury patients speed up the recovery. The parameters in ankle rehabilitation training can also be recorded to provide the basis for physicians to develop a rehabilitation plan for next stage.

Pneumatic muscle is a new type of pneumatic actuator with output characteristics to human muscle. It is composed of an inner rubber tube and an almost non elongated diamond braid wrapped around the rubber. The two ends have packaging and fixing devices(see Fig.). The internal rubber tube expanding under the gas pressure leads to the increase of pneumatic muscle diameter and the decrease of its length [2]. And the external braided mesh limits pneumatic muscles to be shortened without limitation. If the end is subjected to the external tension, the pneumatic muscle can produce the tension. Pneumatic muscle has the advantages of light weight, large output power/dead-weight ratio, good safety, cleanness, low price and so on [3]. Based on these characteristics, the application in rehabilitation field has been studied and many rehabilitation robots using pneumatic muscles as actuators have been developed [4]. However, due to the flexible rubber material, friction of woven web [5], nonlinear of compressed air and the uncertainty of robot model, the robot control system is very complex with strong nonlinearity and parts of time-varying parameters [6].

Fig. 1. PESTO pneumatic muscle

TU Diep Cong Thanh et al. used nonlinear PID controller to improve the control performance of the two axis pneumatic muscle mechanical arm. They combined the traditional PID controller and neural network and proposed a neural network nonlinear PID controller, which was suitable for the control object with strong nonlinearity, uncertainty and disturbance. The experimental results showed that the controller had good control performance and anti external interference [7]. Lin Chih-Jer et al. studied the hysteresis characteristics of pneumatic muscles. They established the double pneumatic muscle system PI model used as the feedforward compensation of a sliding mode controller to reduce the tracking error [8]. Shameek Ganguly et al. studied the position control of a single freedom degree manipulator driven by pneumatic muscle and put forward a new method to establish an accurate model for the system [9].

Patients can move along the predetermined trajectory through these position control methods to improve the patients' movement ability and the joints' mobility [10]. However, the simple position control will put the patients in a passive state and the output torque can not be given quantitatively, which may lead to secondary damage. The impedance control can enhance the interaction between patients and robots during the rehabilitation training, so that patients can participate in the rehabilitation training more actively.

2 The Ankle Rehabilitation Robot

2.1 Ankle Model

In this paper, the robot platform driven by pneumatic muscle is mainly used for ankle rehabilitation. The ankle joint is one of the most complex skeletal structures of human(see Fig.). The ankle model has three rotational freedom: the varus and valgus motions around the X axis, the plantar flexion and dorsiflexion motions around the Y axis and the adduction and abduction motions around the Z axis. Carl Mattacola, University of Kentucky, deeply studied the rehabilitation courses of ankle injury patients and pointed out that the rotational motions around X and Y axis played a major role in ankle rehabilitation. In this paper, the robot platform just right has these two freedom and the workspace of the robot can reach the ankle motion range in these two directions.

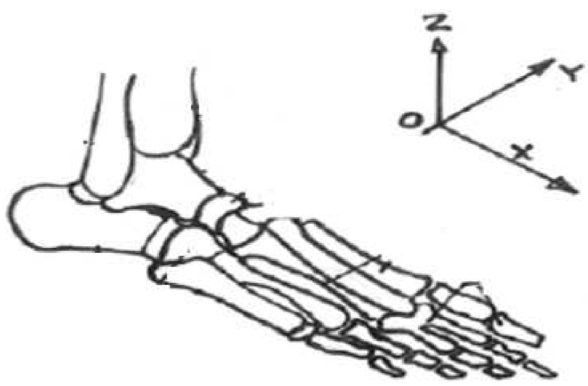

Fig. 2. Ankle joint

2.2 Robot Platform

The effect figure and practicality picture of this ankle rehabilitation robot is shown in Fig. 3. The robot is driven by three pneumatic muscles that pull the wire rope. In order to reduce the height of the robot platform and facilitate the rehabilitation training of patients, the pneumatic muscles are placed in horizon. One end of the pneumatic muscle is connected with the force sensor, which is also fixed on the platform frame. The other end is connected with the wire rope. After changing directions through the fixed pulley and then passing through the three holes on the fixed platform, the three wire ropes are connected with the moving platform. Pneumatic muscle drives the wire rope in this way and then drives the platform to complete the corresponding action. The fixed hole on the fixed platform is made of plastic material with smooth surface to reduce the friction between the wire rope and the hole. A rigid supporting rod is vertically arranged between the moving platform and the fixed platform. The lower end is fixed with the fixed platform and the upper end is connected with the moving platform through a Hooke hinge. The Hooke hinge limits the rotational motion of the moving platform in the Z axis direction to ensure that the moving platform has only two degree of freedom. The robot is also equipped with displacement sensors and force sensors to measure the position and force information of three pneumatic muscle actuators during operation.

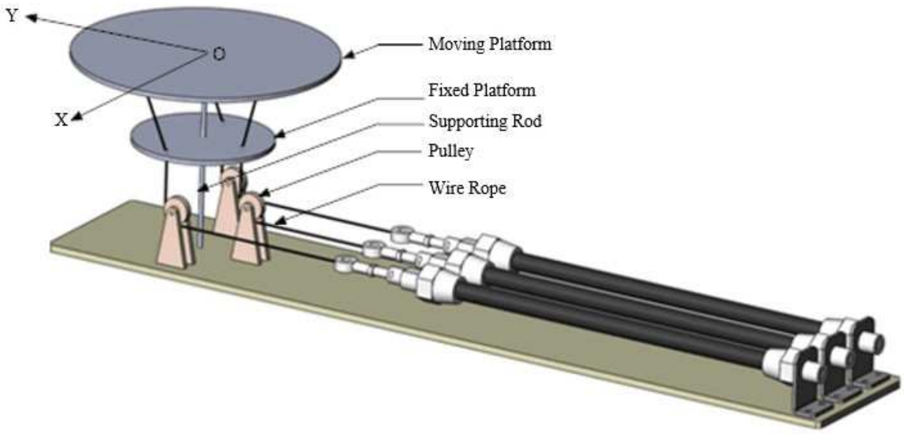

Fig. 3(a). Effect figure

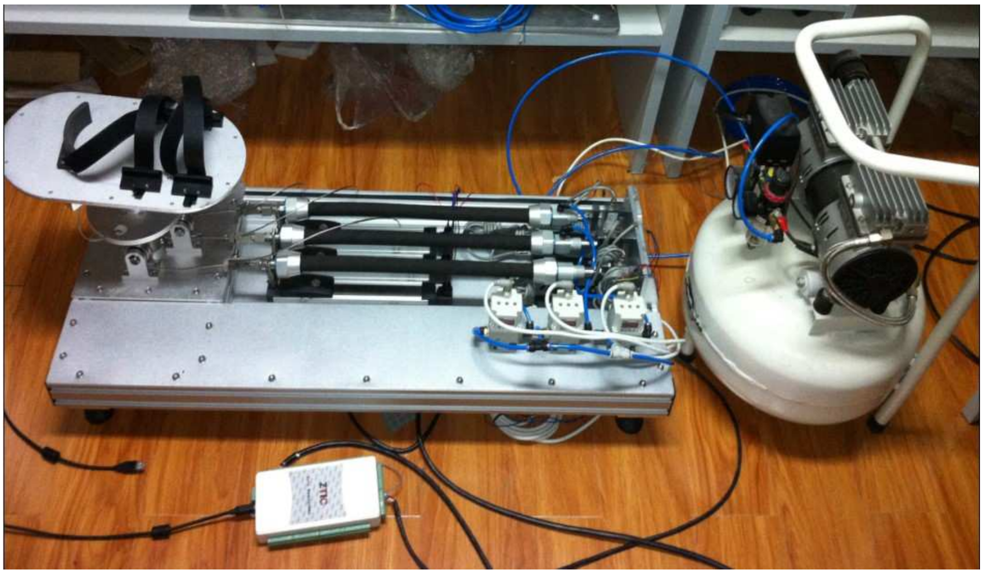

Fig. 3(b). Practicality picture

The system schematic diagram of the robot is shown in Fig 4. The robot communicates with the host computer written by LabView through the data acquisition card. The pneumatic muscle's gas is supplied by the air source and the quantity is determined by the input voltage of the proportional valve. The data acquisition card is connected with the host computer through USB interface. On the one hand, it can convert the analog signals from displacement sensors and force sensors into digital signals through A/D and then send the signal to the host computer to process. On the other hand, it can convert the digital control signal calculated by the control algorithm into analog voltage input signal through D/A and then send the signal to the proportional valve. The proportional valve can adjust the air input of the pneumatic muscle according to the voltage signal and then achieve corresponding movement.

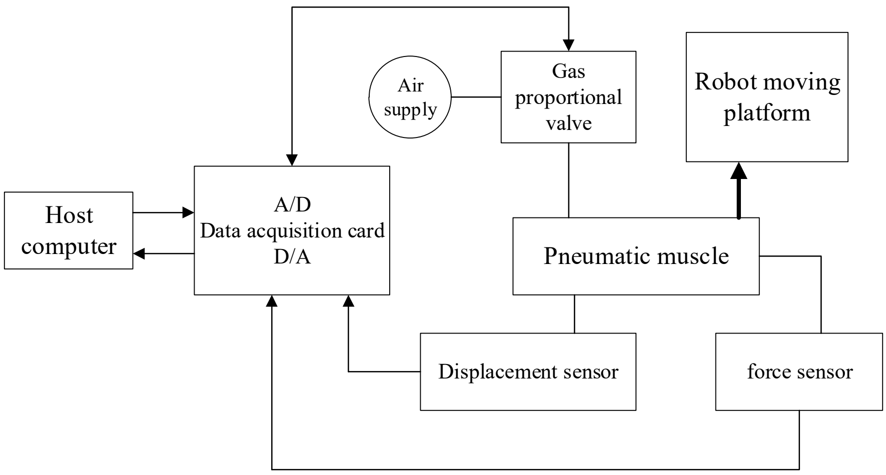

Fig. 4. System working principle diagram

3 Impedance Control of Ankle Rehabilitation Robot

3.1 Impedance Control Model of Pneumatic Muscle

The impedance controller is comprised of an inlayer position control unit and an outlayer impedance control unit [11]. In this paper, the ankle rehabilitation robot only installs the force sensors in each pneumatic muscle, the interaction force between the robot and the external environment can be reflected by the force in joint space. Therefore, we can track the output force of each pneumatic muscle through impedance control of each driven branch to realize the force control [12].

Equation (1) is a commonly used target impedance model, which describes the relationship between the interaction force and the position [13].

$$M_d(\ddot{X}-\ddot{X}_d)+B_d(\dot{X}-\dot{X}_d)+K_d(X-X_d)=F-F_e \tag{1}$$

Because the single pneumatic muscle only moves in one direction, the equation can be simplified as one-dimensional form [14].

$$m_d(\ddot{x}-\ddot{x}_d)+b_d(\dot{x}-\dot{x}_d)+k_d(x-x_d)=f_d-f_e \quad (2)$$

m_d b_d k_d, respectively, are the inertia parameter, damping parameter and stiffness parameter. f_d f_e, respectively, are the desired interaction force and actual interaction force. x is the pneumatic muscle trajectory. When the pneumatic muscle moves in the free space without load, the interaction force f_e is 0.

$$m_d(\ddot{x}-\ddot{x}_d)+b_d(\dot{x}-\dot{x}_d)+k_d(x-x_d)=f_d \quad (3)$$

If $f_d=0$, when $t\to\infty, x-x_d\to 0$, x continuously approaches x_d. So when there is no interaction force in the pneumatic muscle, only position control will exist and the force control is meaningless [15]. However, when the pneumatic muscle interacts with the outside world and drives the robot to move, the interaction force f_e must be considered, which can be measured by the force sensor of each driven joint. In the process of impedance control, the pneumatic muscle and the external environment are regarded as one system [16]. The main function of the position based on impedance model is to convert the force error to the position correction x_f. In the actual conversion process, x_f satisfies the following equation:

$$m_d\ddot{x}_f+b_d\dot{x}_f+k_dx_f=f_d-f_e \quad (4)$$

Equation (4) is transformed into frequency domain:

$$X_f(s)=\frac{F_d(s)-F_e(s)}{m_ds^2+b_ds+k_d} \quad (5)$$

In the target impedance model, m_d, b_d, k_d, respectively, correspond to the acceleration, velocity and position of the control object. They can be adjusted in the actual control process, which can improve the dynamic response speed and steady-state tracking effect of the control system. The stiffness parameter k_d is mainly related to the input pressure. And the relationship between them can be expressed as:

$$k=\alpha_1p+n\frac{dp}{dL}+\alpha_0 \quad (6)$$

P is the pneumatic input pressure and it corresponds to the input voltage of the proportional valve. α_1, n, α_0, need to be adjusted by experiment. block diagram of the Pneumatic muscle impedance controller is shown in Fig. 5.

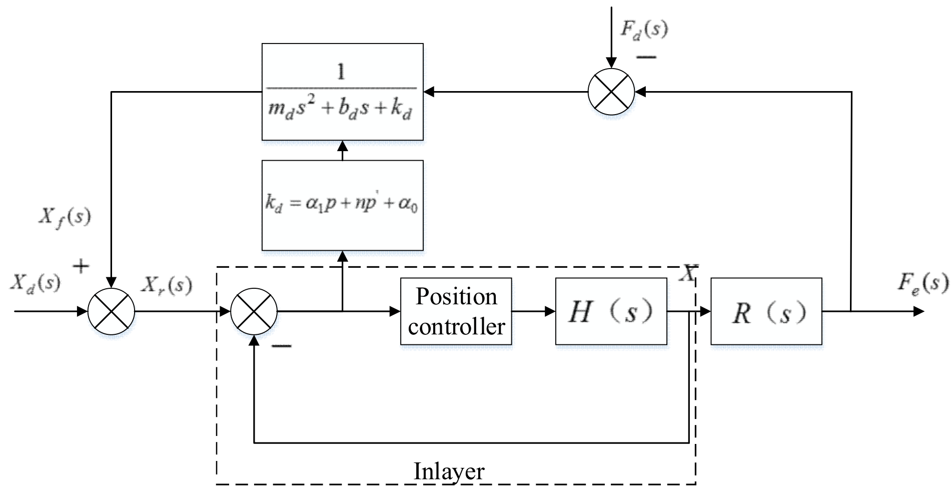

Fig. 5. Block diagram of control principle

Impedance control can provide a suitable impedance force based on the patient's rehabilitation status. Patients need to overcome this force in rehabilitation training so as to achieve the purpose of active rehabilitation. This method is suitable for patients with a certain ability to exercise.

When the actual impedance control is carried out on the robot platform, firstly, the output force should be determined according to the recovery status of the ankle. After the force is determined, the desired output force is tracked by establishing pneumatic muscle impedance control.

4 Experiment

4.1 Simulation

Considering that the actual control object is a single pneumatic muscle, Simulink is used to simulate the impedance control of the model.

In the simulation model, in order to simulate the force model in the real environment, the contact environment between the robot and the patient's lower limb is simplified to the stiffness and damping system. The relationship between the contact force and the motion of the platform is established as follows:

$$f_e = k(x - x_0) - d(\dot{x} - \dot{x}_0) \tag{7}$$

In the equation, k is the simulation stiffness of contact environment, d is the damping coefficient, $x - x_0$ denotes the position variation of the robot platform and $\dot{x} - \dot{x}_0$ denotes the velocity variation.

Generally, the desired acceleration $\ddot{x}_d$ is 0. So the equation(1) can be deformed as follows:

$$\ddot{x} = m_d[f_d - f_e + b_d(\dot{x}_d - \dot{x}) + k_d(x_d - x)] \quad (8)$$

In this impedance control model, we can obtain the correction of acceleration $\ddot{x}$ by desired interaction force f_d, actual interaction force f_e, actual displacement x_e and desired displacement x_d. Then displacement correction will be calculated through two integration. The impedance controller used in this model can get better simulation results. Constant force tracking simulation was done and the desired driving force was set to 20N. The simulation result was shown in Fig. 6.

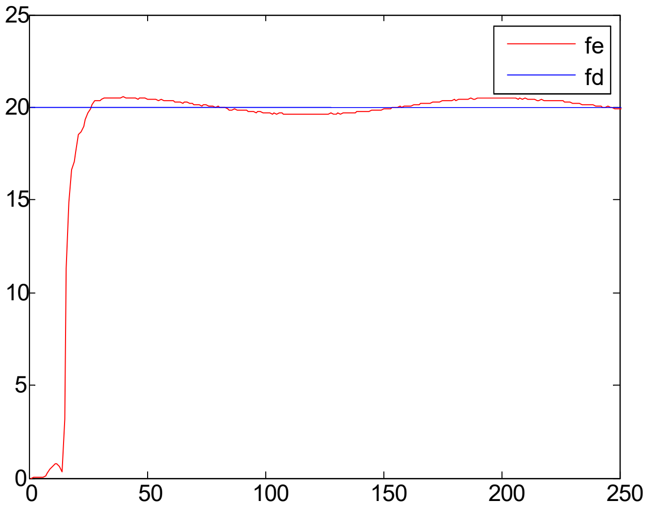

Fig. 6. Constant force tracking

Then variable force tracking simulation was done and the force was set to:

$$y = 20 * \sin t \quad (9)$$

The simulation result was shown in Fig. 7.

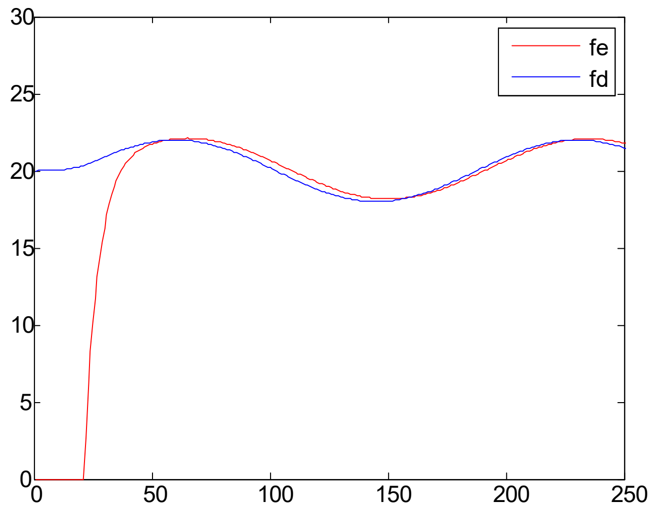

Fig. 7. Variable force tracking

4.2 Impedance Control Experiment

Based on impedance control method of the pneumatic muscle, the experiment is carried out on the physical robot platform. Because of the characteristics of pneumatic muscle and the application background of ankle rehabilitation, in experiment, the inertia parameter m_d and the damping parameter b_d use fixed value. The stiffness parameter k_d is adjusted in real time according to the output voltage of the controller.

In the constant force tracking experiment, the desired forces of three pneumatic muscles are set 60N, 70N, 85N, respectively.

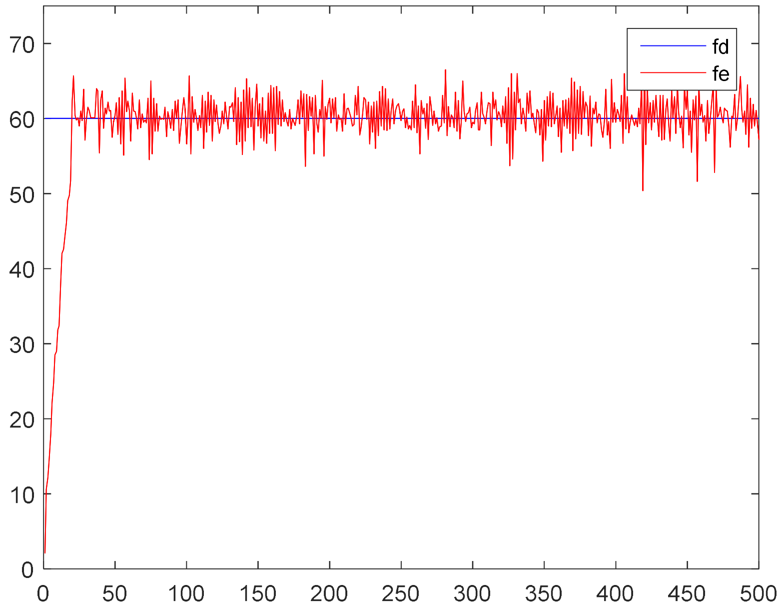

Fig. 8. 60N tracking graph

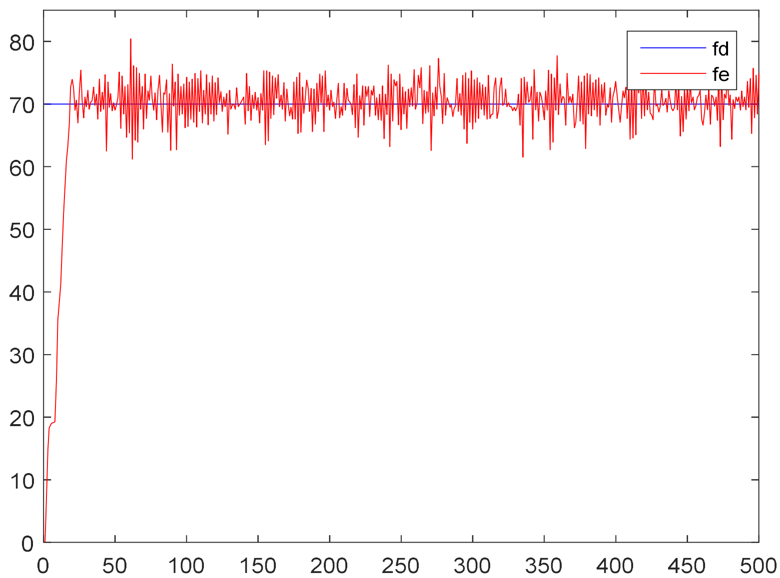

Fig. 9. 70N tracking graph

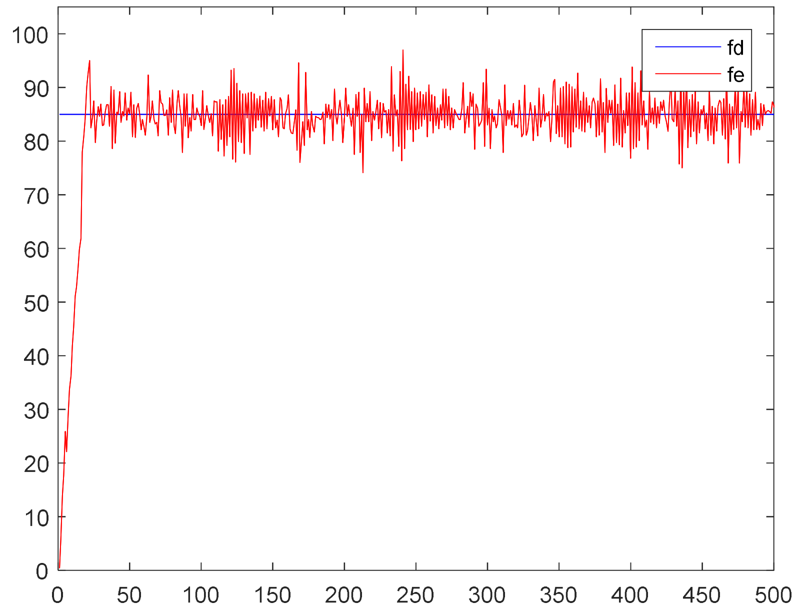

Fig. 10. 85N tracking graph

The results show that the response time is a little long when the robot tracks the constant force. After that, the tracking force will gradually stabilize. But there are still some fluctuations, and the range of the force error is less than 10N. This is mainly because in the initial stage of impedance control, actuator output force is almost 0, which leads to the great force deviation. The impedance model adjusts the actuator to achieve desired output force through converting the force error to the displacement correction. This conversion process takes a long time, resulting in a longer response time. It is also an important reason for the force fluctuation.

Conclusion

In this paper, the ankle rehabilitation robot driven by three pneumatic muscles is presented as an experimental platform. An impedance control method based on position inner loop is proposed as the control method. The force control is realized through the force tracking of three pneumatic muscles. This control strategy makes up for the lack of human-computer interaction defect because of only position control. In the actual experiment, the force tracking in the error range of 10N is realized, which proves the feasibility of this method.

Acknowledgments

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