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Damping Control Based Speed Adjustment Strategy for a Lower Limb Rehabilitation Robot

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***Abstract*—Active rehabilitation training based on recognition of motion intention can effectively improve the patient's engagement in rehabilitation training, and thus improve the training effect. In this paper, a speed adjustment strategy for active training based on multi-joint damping control is proposed for bicycle training. The active force applied by patient can be calculated by the dynamic model of human-robot system, and then converted into the tangential force at the pedal of robot along the forward direction of bicycle. The tangential force is converted into the adjustment term of joint angular speed by damping control to dynamically adjust the riding speed. When the tangential force is larger than the threshold value, the pedal will deviate from the reference circular trajectory. Therefor, a speed vector pointing to the circular center is added to pull the end-effector back to the reference trajectory. Moreover, a fuzzy impedance parameter regulator is designed to adjust the training intensity, by which the impedance parameters can be regulated according to the magnitude of the patient's active force and the deviation from the reference trajectory. Finally, in order to increase the patient's engagement, Unity3D software is used to design the virtual scene of cycling on the road. The experimental results show that the active compliant rehabilitation training can be realized by the proposed method.**

***Keywords*—speed adjustment strategy; active training; compliant control; rehabilitation robot.**

I. Introduction

Studies have shown that rehabilitation robots play a significant role in the recovery of stroke patients with hemiplegia [1]–[3], and can be used in various periods of stroke recovery [4]. Specific function training assisted by rehabilitation robot can promote the functional compensation and reorganization of central nervous system [5], strengthen the limb function of patients with hemiplegia and improve their daily living activities [6]. The application of exoskeleton robots in rehabilitation can provide high-intensitive, repetitive, task-oriented and interactive treatment for the affected limbs. Objective and reliable monitoring will greatly facilitate the work of rehabilitation physicians, and help to cope with the grim situation that China has become an aging society over time. Active training emphasizes the patient-guided rehabilitation training [7]. On the one hand, guidance is provided by robot to correct the wrong motion mode of patient, and on the other hand, assistance is provided to compensate for the patient's insufficient athletic ability so as to complete training tasks. Since active training is triggered and adjusted by patients, it has stronger stimulation to the motor nervous system compared with passive training. As a result, active training has better effects on rehabilitation training [8]. However, active training is relatively difficult to realize, and the key is how to obtain the patient's motion intention.

The force/position sensor based method is a commonly used method for calculating the active force applied by human [9], [10]. In the establishment of the dynamic model, the mechanical leg and the lower limb are considered as a whole in this paper. Meanwhile, the relatively minor influence factors are neglected. So that a more compact dynamic model can be obtained.

The active interactive training method is usually used to provide a compliant and safe interaction interface for the patient. Reference [11] refers to the concept of "force field", which is an implementation of impedance control. A "virtual wall" is established along the reference trajectory, and the off-track will be subjected to a resistive force. It can well realize the comfortable interaction between robot and human limbs.

The virtual reality scene can enhance the interaction and entertainment between the patient and robot, and stimulate the patient to actively engage in rehabilitation training. For example, a game task that can be completed by the patient on his own efforts, can make the patients feel more fulfilled, thereby enhancing their confidence and determination in recovering. Virtual reality technology plays an increasingly important role in the development and design of rehabilitation robots.

In this paper, a speed adjustment strategy based on damping

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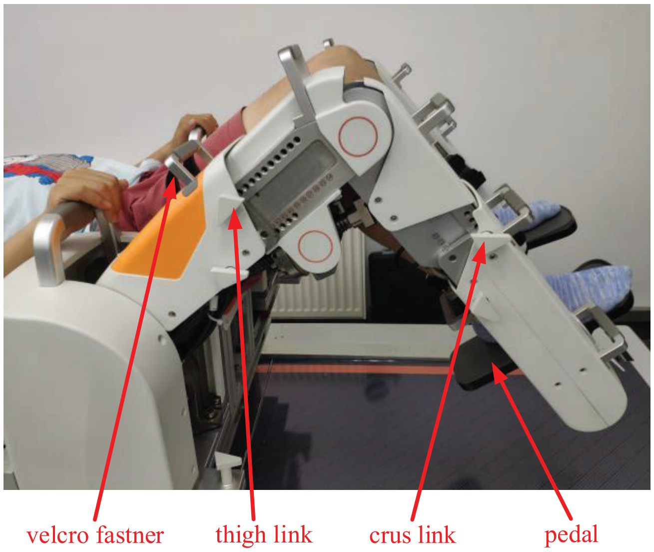

Fig. 1: Experiment setup.

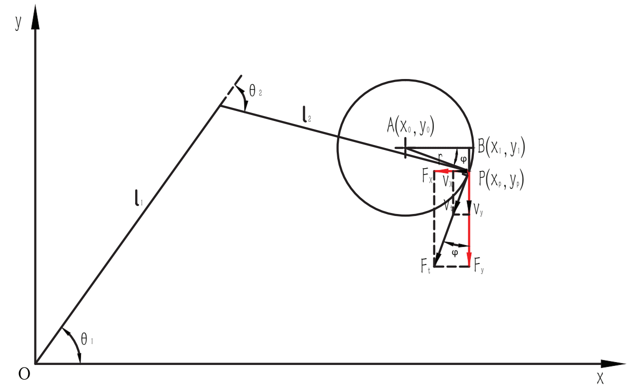

Fig. 2: Simplified schematic of bicycle movement for human-robot system.

control is proposed to realize active training with compliance. The speed adjustment strategy is used to generate speed commands of bicycle and damping control is used to convert the active force applied by the patient to the adjustment term of joint angular speed. Finally, the effectiveness of the proposed method is verified by experiments.

II. Method

A. Human-Robot System Dynamic Model

In the process of using the lower limb rehabilitation robot for exercise, the lower limb of patient can be attached to the mechanical leg by velcro faster, as shown in Fig. 1. The hip, knee and ankle joints of the mechanical leg are aligned with that of the human's lower limb by adjusting the lengths of the thigh link and crus link, respectively. Since the ankle joint contributes less to the motion range of end-effector, the human-robot interaction system can be simplified as a two-bar linkage mechanism.

The standard dynamic model of human-robot interaction system can be derived by the Lagrange equation. It should be noted that the knee joint of the robot developed at our laboratory is driven by lead screw. The force sensor installed at the end of lead screw can measure the thrust, f_2, which acts on the crus link. Then, f_2 is converted to the torque at the knee joint, τ_2, by the principle of virtual work. The standard dynamic model of human-robot system has a linear property, that is, its mathematical model is linear to physical parameters. In result, there is a parameter vector that makes the following equation hold.

$$D(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\dot{\theta} + G(\theta) + \tau_f = Y\phi \tag{1}$$

Where Y is a known matrix of the generalized coordinates of robot and its derivatives. ϕ is an unknown constant parameter vector, describing the mass characteristics of robot, and it can be calculated through the method of system identification.

B. Speed Adjustment Strategy for Bicycle Training

The human-robot interaction force can be used to realize active and compliant rehabilitation training, in which patients can control the training intensity autonomously. Cycling exercise can mobilize the active contraction of relevant muscles of lower limbs. It can help strengthen the corresponding muscles and increase the motion range of affected limbs. At the same time, cycling exercise can also enhance the stability and coordination of the knee, ankle and hip joints, thereby improving the patient's balance ability. Therefore, bicycle exercise is chosen as an implementation form of active training in this paper.

The speed adjustment strategy for bicycle training is designed to dynamically adjust the speed of bicycle according to the magnitude of the patient's active force, so as to encourage the patient to complete the training tasks on his own power. As shown in equation 2, when the active force is larger and the ordinate of point P is greater than that of point A, the center of the circular, the bicycle speed will be faster; when the patient is slacking or lazy without actively applying any force, the bicycle will gradually slow down until it stops. So, the patient needs to continuously exert the active force in order to keep the bicycle running, which is consistent with the actual riding experience. When the patient does not apply any force, the training will turn to passive exercise in the traditional strategy. The difference between the proposed and traditional strategies is that the proposed strategy can effectively avoid the occurrence of patient inertia.

$$\begin{cases} w\uparrow & y_p > y_0 \; and \; \tau_h > 0 \\ w\downarrow & \tau_h \leq 0 \end{cases} \tag{2}$$

The end-effector moves along a circular path, as shown in Fig. 2. The human-robot interaction force in the joint space obtained in the section II-A needs to be converted to the force in the Cartesian space at the end of robot. The tangential force is the source of power for bicycle acceleration, and it can be obtained according to the calculated force at robot's pedal.

The coordinates of point B are as follows.

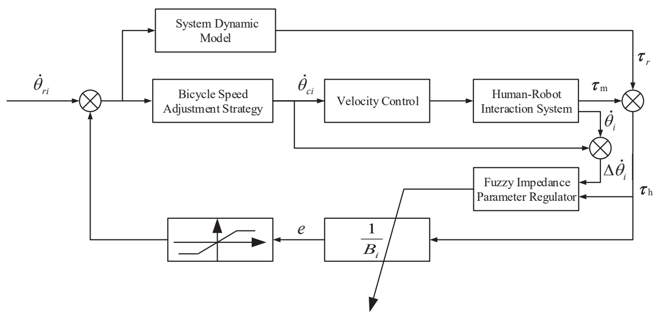

Fig. 3: Control structure of active training strategy.

$$\begin{cases} x_1 = x_0 + r \\ y_1 = y_0 \end{cases} \tag{3}$$

The tangential force is converted to the adjustment term of joint angular speed through impedance control method. When the tangential force along the motion direction of circular is large, the pedal will deviate from the reference circular trajectory. In order to pull the pedal back to the circular path, a speed vector directed to the circular center will be added.

C. Compliant Control-Variable Impedance Control

The adjustment term between the patient's active applied force and the bicycle speed can be obtained by impedance control. The impedance control method focuses on realizing the active compliant interaction between patient and robot, avoiding excessive confrontation between the mechanism and lower limb, so as to create a safe, comfortable and natural human-robot interaction tactile interface, of which the advantage is to avoid the risk of re-injury to the affected limb. In addition, the implementation of impedance control does not depend on a priori knowledge of the motion constraints of external environments. Therefore, multi-joint damping training strategy based on the patient's active force is proposed to realize compliance control, which means that the adjustment term of joint angular speed is proportional to the magnitude of active force applied by the patient. Damping control is a simplified impedance control method, which is to make the inertia and stiffness coefficients in impedance equation zero. The control structure of the proposed active training strategy is shown in Fig. 3, which is a double closed loop system. The inner loop is used to realize the compliant speed control of bicycle, wherein the speed adjustment strategy is utilized to generate an angular speed command for velocity controller, as described in section II-B. The velocity controller is implemented by a matured commercial servo system. The outer loop is damping control. The simplified impedance equation is employed to realize the conversion between the active force applied by patient and the adjustment term of joint angular speed.

Fig. 4: Virtual scene of cycling on the road.

D. Immersion Human-Robot Interaction Training-Virtual Reality

The human-robot interaction game has positive psychological hints to the patients, which can further improve the recovery efficiency of the patient's motor function. The virtual scene enables the patient to interact with the robot in a friendly manner, allowing the patient to immerse in the virtual training. Meanwhile, real-time imaging using the motion information fed back by the robot, such as angle, angular velocity and pressure force, enables the patient to rectify wrong training pattern in real time, giving the patient optimal and objective motion feedback and rehabilitation evaluation. As a result, the enthusiasm of patients for actively participating in rehabilitation training is effectively enhanced.

The TCP/IP is used to realize the communication between the host computer and the virtual scene. In this way, communication for multiple machines can be realized at the same time, so we can use another customized displayer to play a virtual scene. On the host computer, we can carry out various operations such as opening, closing, and controlling the virtual scene. In this paper, the virtual scene of cycling on the road is designed according to the training task of lower limb rehabilitation robot, as shown in Fig. 4, where the speed of bicycle on the left is controlled by the patient, while the speed of bicycle on the right is a fixed value for comparison.

The speed of bicycle is controlled by the patient's motion intention, depending on the angular velocity command generated by the speed adjustment strategy, as described in section II-B. In the virtual scene, the bicycle moves according to the data transmitted back, meanwhile, the environment model is rendered in real time using Unity3D.

In addition, in order to increase the patient interest, a reward mechanism is set in the virtual scene. For example, when there is effective interaction force between the patient and virtual scene, the speed of the bicycle in the virtual scene will increase, and an applause will appear. Such feedback information can improve the interactivity of the human-robot system.

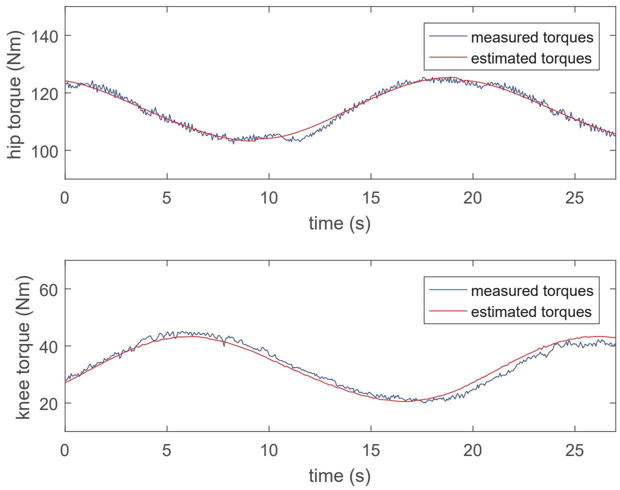

Fig. 5: Validation experiment for human-robot dynamic model.

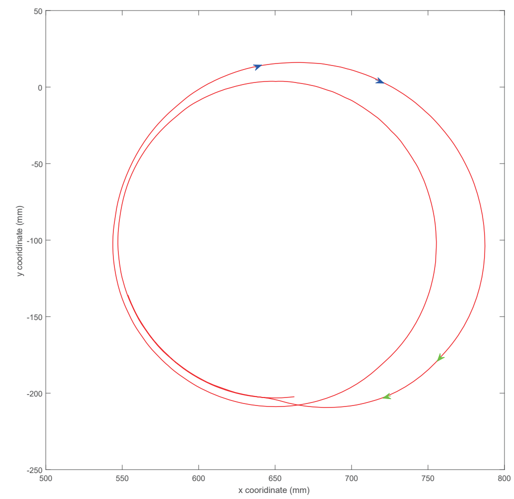

Fig. 6: The bicycle trajectory using active training strategy.

III. Experiments and Results

A. Experiment for Identification and Validation of Dynamic Model

In order to obtain the human-robot interaction force, it is necessary to recognize the unknown kinetic parameters in the dynamic model, which can be identified by using the least squares method. In order to improve the stability and anti-interference of the least squares estimation method, it is necessary to fully stimulate the dynamic model of the human-robot interaction system. In this paper, the stochastic particle swarm optimization algorithm is adopted to solve the optimization problem of excitation trajectory [12]. In the parameter identification experiment, the position control in the joint space was utilized, so that the human-robot system passively tracks the optimal excitation trajectory. In order to verify the validity of the dynamic model, a reference trajectory different from the optimal excitation trajectory was designed. The validation results is illustrated in Fig. 5. The root mean square error at the hip and knee joints are $0.3562Nm$ and $0.4396Nm$, respectively, which indicates that the established dynamic model of human-robot interaction system is effective.

The active force of subject, τ_h, can be obtained by the following formula, as shown in Fig. 3.

$$\tau_h = \tau_m - \tau_r = \tau_m - Y\phi \tag{4}$$

B. Experiment for Bicycle Speed Adjustment Strategy

Cycling can fully mobilize the active contraction of lower limb muscles, promote blood circulation to strengthen microvascular tissue, and improve heart and lung function. Meanwhile, it can also enhance the stability and coordination of the knee, ankle and hip joints and improve patient balance. What's more, the torso is well supported when riding a bicycle, which effectively avoids the body's large pressure on the joints of lower limbs, thereby greatly reducing the joint extrusion and abrasion caused by the weight-bearing movement.

The active training trajectory of bicycle is shown in Fig. 6. It can be seen from the experimental results that when $y_p > y_0$, if the patient actively applies force, the bicycle speed will be increased, so that it will deviate from the reference circular path along the direction of blue arrow. When $y_p < y_0$, the patient's active force does not work. According to the speed adjustment strategy, the bicycle speed will gradually decrease. At the same time, the speed vector pointing to the circular center, V_r, is added. As a result, the bicycle will gradually move toward the reference circular trajectory along the yellow arrow. The time it takes to pull the bicycle back into the circular trajectory is related to the magnitude and duration of active force applied by subject when $y_p > y_0$.

C. Experiment for Compliant Control

In the actual rehabilitation training process, the training difficulty needs to be adjusted according to the recovery of the patient's limb function. When the muscle strength of the affected limb is weak, it is difficult for the patient to complete the high-intensity training. At this time, it is necessary to reduce the challenge of training plan, so that the patient can easily complete the training task, thereby obtaining a sense of accomplishment. After a period of rehabilitation training, if the patient's muscle strength is enhanced, the therapist can increase the difficulty of training to avoid the patient's slack. Therefore, a fuzzy impedance parameter regulator is designed to realize the above functions, which adjusts the impedance parameters according to the magnitude of the patient's active force and the deviation from the reference circular trajectory. The relationship between the patient's active force and the adjustment term of angular frequency under different impedance parameters is shown in Fig. 7. When the patient's active force is small, the impedance parameter can be set to a small value, such as 300, to reduce the training difficulty. When the patient actively exerts a large force, if the path of bicycle significantly deviates from the reference trajectory, the

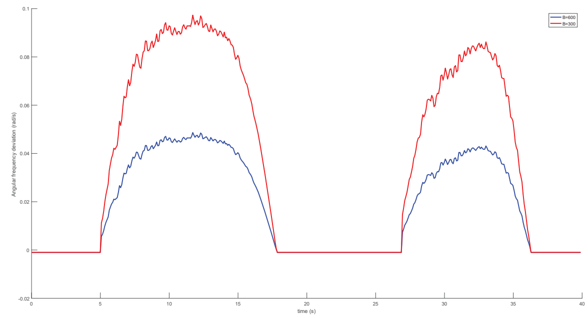

Fig. 7: The relationship between the patient's active force and the adjustment term of angular frequency under different impedance parameters.

Fig. 8: Result of virtual reality based active training strategy.

impedance parameter can be set to a larger value, such as 600, to increase the challenge of training tasks.

D. Experiment for Virtual Reality

In the built virtual scenario, the patient can interact with himself through the sensors installed on the robot. In order to transfer the patient's actual motion information to the virtual environment, the mechanism of shared memory is employed to realize the real-time reading and writing function of motion parameters of the lower limb rehabilitation robot. The main program exchanges the hip and knee joints' motion data with the lower limb rehabilitation robot in real time through CAN communication protocol, and converts them into motion command of the hip and knee joints in the virtual scene through the mapping relation, so that the subject in the virtual scene performs corresponding movements in the world coordinate system.

The experimental results are shown in Fig. 8. It can be seen that the speed of bicycle controlled by the subject on the left is significantly faster than that on the right, indicating that the subject actively continuously exerts an interactive force during the training, thereby avoiding the occurrence of patient inertia. In consequence, the active training strategy based on the virtual reality can effectively stimulate the enthusiasm of patients to participate in active training and improve the effect of rehabilitation.

IV. Conclusion

In this paper, a speed adjustment strategy based on damping control is proposed to realize the active compliant training. It is a double closed-loop control strategy. The outer loop is damping control, which is used to convert the tangential force into the adjustment term of joint angular speed to dynamically regulate the riding speed. The tangential force is derived from the active force applied by patient, which can be obtained by the dynamic model of human-robot system. The inner loop is used to realize the active compliant speed control of the bicycle, wherein the speed adjustment strategy is designed for generating a speed command for the bicycle. The experiments are carried out on the lower limb rehabilitation robot. The results show that when the patient exerts a large force, the corresponding speed of bicycle will be faster, and the pedal will easily deviate from the reference circular trajectory. By adding a speed vector pointing to the circular center, the end-effector can be pulled back the reference trajectory. The proposed strategy can be used to not only realize active training driven by patients, but also correct the abnormal motion trajectory. When the patient is slacked or lazy without actively applying force, the pedal will gradually slow down until it stops. So the proposed strategy can effectively avoid the patient's inertia during the training. Meanwhile, different intensity of training can be provided by adjusting the impedance parameters. Moreover, the virtual reality scene helps to improve the patient's engagement in rehabilitation training.

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