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Path Control of a Rehabilitation Robot Using Virtual Tunnel and Adaptive Impedance Controller

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***Abstract*—Interactive control strategies have been widely used in many rehabilitation robotic devices. The distinctive feature of these strategies is that the patient can be encouraged to actively participant in the therapy program. In this paper, a novel adaptive impedance control method, which allows the patient to actively influence the robot movement trajectory, is presented. The control algorithm developed in this paper is capable of regulating the desired impedance according to the patient's actual deviation from the desired path and the dynamic relationship between patients' motion intention and the reference trajectory. A virtual tunnel surrounding the reference trajectory is designed to ensure the patient's range of motion is always physiologically meaningful. The proposed rehabilitation strategy encourages participants to make contributions to rehabilitation training task as much as possible, which may facilitate provoking motor plasticity and motor recovery. Preliminary experiments with several healthy subjects were conducted to evaluate the feasibility and effectiveness of this strategy. Experimental results demonstrated that subjects could successfully finish the tracking task assisted by robot with the proposed control algorithm.**

Keywords—path control; rehabilitation robot; virtual tunnel; adaptive impedance controller

I. INTRODUCTION

As the number of aged people who are always vulnerable to neurologic impairments such as stroke has been increasing, there is an increasing interest in using robotic devices to provide rehabilitation therapy to these people[1]. A systematic review of control strategies for robotic movement training has been presented by Marchal-Crespo et al.[2]. A detailed review of the treadmill based robotic devices aided to gait training was presented by Hussain et al.[3].

With the previous rehabilitation robotic devices, such as the Lokomat and Gait Trainer, patients often followed the predefined trajectories and without personal voluntary participation[4]. Researchers have showed that patient's efforts were essential to improve rehabilitation outcomes[2]. Riener et al. developed a patient-cooperative method by taking into account patient's intention and voluntary efforts to assist orthopedic rehabilitation[5]. A human-centered approach was implemented on the gait trainer Lokomat in order to provide patients with a more comfortable and more efficient therapy[6]. However, many researches have shown that providing too much assistance may have negative consequences for rehabilitation training [2]. Solutions proposed to figure out the problem were to use the assist-as-needed (ANN) strategy[7, 8]. For example, an impedance-based ANN gait training scheme was developed to provide interactive gait training[7].

Since electromyography (EMG) signals contain much important information such as muscle force and intention of participants[9], they were widely employed as control signals for robot-aided rehabilitation systems. In recent years, many EMG-based control strategies have been proposed. On the one hand, EMG signals were simply used to detect patients' intended motion[10].On the other hand, robotic assistance can be triggered[11] and the amount of assistance can be adaptively adjusted according to EMG signals[12]. However, EMG signals are sensitive to many environmental factors such as electrode placement[2], and it is not easy to achieve the real-time and high accuracy motion prediction[10].

Impedance-based controllers are widely applied to meet the requirements of active rehabilitation training. However, if the robot is too stiff, the patient may feel passively controlled. If it is too soft, the patient may deviate from the reference physiological trajectory too much[4]. A solution to this problem was proposed by L. Cai et al. in [13]. During their experiments, within the tunnel, the subjects received a small constant guidance and could move freely. Outside the tunnel, the robotic device would drive the subjects back. The main limitation of these methods is that participants might inadvertently move out of the tunnel frequently, which might have bad effects. Moreover, if participants could correct their motion deviation, the robot would not need to create a restoring force to drive participants back into the tunnel. In this study, a novel path control method combining virtual tunnel and adaptive impedance controller is presented. The virtual tunnel is designed to prevent participants moving out of the physiological range. And the adaptive impedance controller is designed to make robot's compliance adjust according to actual deviation and relationship between motion intention and desired trajectory.

II. PATH CONTROL METHODS

A. Virtual-tunnel

In order to keep the patient closing to the reference physiological trajectory, virtual tunnel was proposed by

Keller[8]. In this paper, a virtual tunnel is also designed according to the reference trajectory (started from position T_a to the target position T_b) shown in Fig.1. Different from [8], the control algorithm in this paper ensures that patients always move within the tunnel. The radius of the tunnel is set to a constant R. And the increased R will lead to a larger movement range. Within the tunnel, to a certain degree, the operators can move freely. That means if the interaction force implemented on the robot is in the same direction of the desired path, patients can move easily.

As shown in Fig.1, since the interactive force is composed of F_x, F_y, F_z, we use α , β , γ to denote the angle between F_x, F_y, F_z and the tangent of reference trajectory, respectively. Obviously, the smaller angles will result in the more compliant robot. Another key factor that affects robot's compliance is the distance between the actual position P_a and the reference point P_b. In this paper, the distance is denoted by Δd . Specially, if the P_a is in front of the target point T_b, Δd will be set to $|P_a - T_b|$ (the distance between these two points). Similarly, if the P_a is rearward to the starting point T_a, Δd will be set to $|P_a - T_a|$, as shown in Fig.1. Detailed quantitative analysis of robot's compliance will be presented in the next section.

Two main rationales can be given for this rehabilitation strategy. One rationale is that active efforts are thought to be essential for rehabilitation training, while the patient's inappropriate efforts should be distinguished from the right efforts. We assume that the deviation from desired path caused by inappropriate efforts should be reduced compared with the correct one. Another motivation is that in order to ensure the patient's safety, the allowed deviation should not beyond the physiological range of motion.

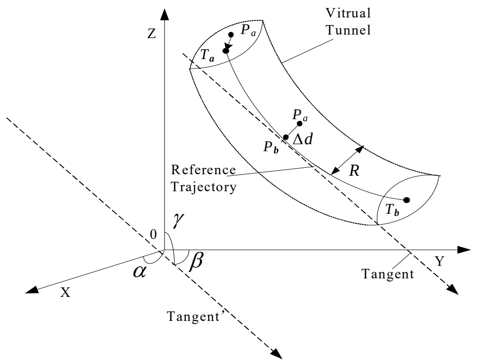


Fig.1. Proposed virtual tunnel model in Cartesian coordinate

B. *Adaptive Impedance control algorithm*

Impedance control algorithm was first proposed by Hogan[5, 6], and recently it has been widely used in robotic rehabilitation devices. In this paper, a novel adaptive impedance controller is proposed. Generally, the desired impedance model between robot and the injured limb can be described as:

$$M_d(\ddot{x} - \ddot{x}_d) + B_d(\dot{x} - \dot{x}_d) + K_d(x - x_d) = -F_e \tag{1}$$

where M_d , B_d , K_d are the desired inertia, damping and stiffness matrix, respectively. $\dot{x}_d$, $\dot{x}$, x_d , x are desired and actual velocity and position of rehabilitation robot, respectively. F_e is the interaction force[14]. Since acceleration of the parallel robot changes very slowly, (1) can be simplified as:

$$B_d(\dot{x} - \dot{x}_d) + K_d(x - x_d) = -F_e \tag{2}$$

As aforementioned if the direction of the interaction force is parallel to the tangent of the desired path, the impedance should be very low, so the robot's behavior will be very flexible and then the patient can move along the path freely. For convenience, we use the angle θ to denote the three angles (α , β , γ). In order to allow patients' deviation from reference trajectory and keep them moving within the tunnel, the compliance of robot should be also adjusted according to Δd . It is reasonable that a larger Δd will result in a higher impedance of robot to prevent patients' further deviation from reference trajectory. At last, the impedance parameters B_d and K_d are on-line adjusted according to the following equations:

$$B_d = B_0 - C_1 \cos\theta + C_2 \Delta d \tag{3}$$

$$K_d = K_0 - C_1 \cos\theta + C_2 \Delta d \tag{4}$$

where B_0 and K_0 are initial viscous damping and spring coefficient diagonal matrices, C_1 and C_2 are the coefficients. Therefore, the value of impedance parameters B_d and K_d increase when Δd and θ simultaneously increase.

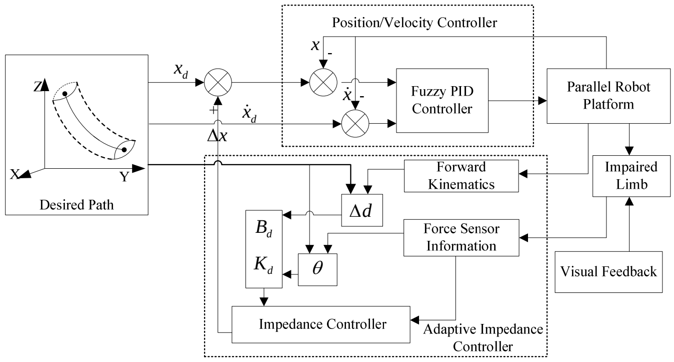


Fig.2. Block diagram of adaptive impedance control system

The block diagram of this proposed controller system is shown in Fig.2. And it is mainly composed of a position/velocity controller and an adaptive impedance controller. A fuzzy PID (Proportion-Integration-Differential) control algorithm is employed for position and velocity tracking. The compliant control of robot is realized by an impedance controller. A visual feedback block is provided to instruct patients in training process.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. *Experimental protocol*

In order to evaluate the feasibility and effectiveness of the parallel robot system and the adaptive impedance control algorithm, preliminary experiments were conducted. As shown in Fig.3, experiments were conducted on a parallel robotic system mainly consists of a robot platform, a force sensor, a

DSP controller cabinet and a PC. The parallel robot platform has six degrees of freedom (DOFs), namely, three transitional DOFs (x, y, z) and three rotational DOFs (Alpha, Beta, Gamma). The interaction force (F_x, F_y, F_z,) can be measured by a tri-axial force sensor (Futek, Advanced Sensor Technology, INC. USA) mounted between the moving platform and the footplate.

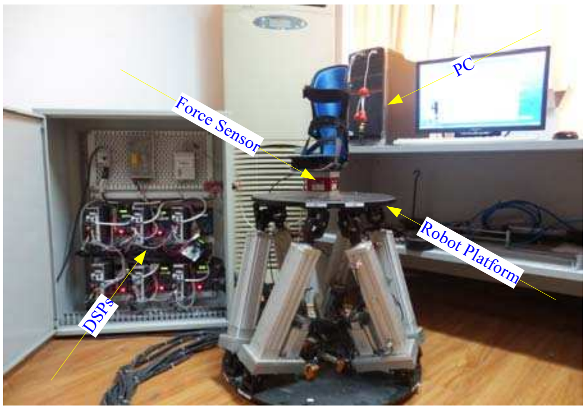


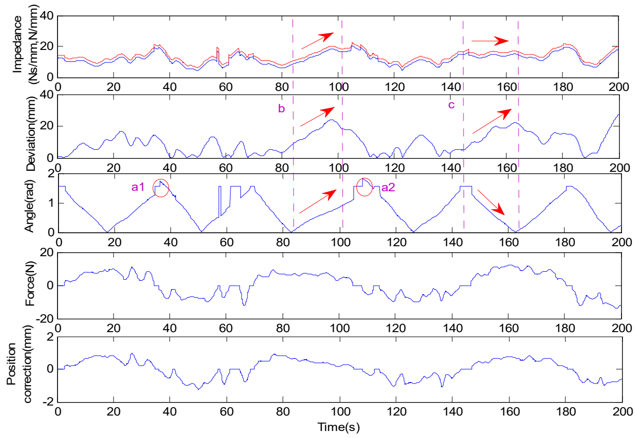
Fig.3. Parallel robotic system for lower limb rehabilitation

Several healthy subjects were selected to undergo a trajectory tracking experiment assisted by the rehabilitation robot. And all of them were informed of how to operate the robot. For convenience, the reference trajectory was set to be a circle (plane z = 90 mm) and its radius was 80 mm. And the radius of the tunnel was 40 mm. Since the desired movement range was in a plane, without loss of generality, the compliance of robot could be affected by operators' efforts only in x and y directions. The interactive force measured by force sensor was used to indicate the subject's voluntary efforts. During evaluation experiments, participants will find it hard to move against the path and easy to move toward the desired path. In each experiment, the subject could obtain the corresponding information in real-time including the actual position, the desired path and the value of interactive force through a monitor. And some important data such as adjusted impedance parameters, force value and actual/reference trajectories were recorded for off-line analysis.

B. Results

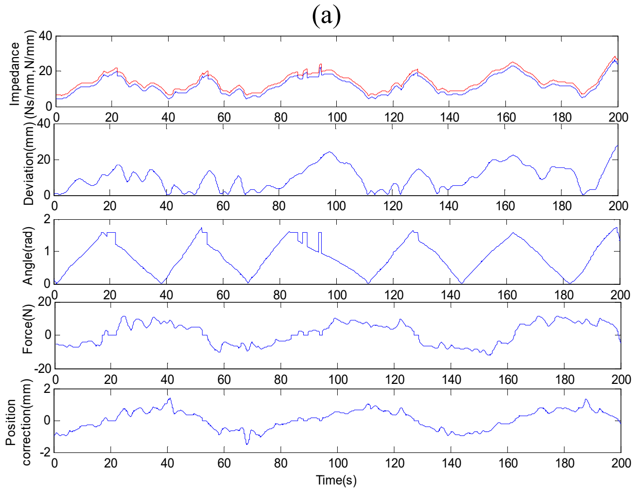
In this section, the preliminary experimental results of the proposed control scheme are presented. The process of the adaptive impedance control algorithm designed in this paper can be divided into two parts: adjustment process in x direction and that in y direction. Since the adjustment principle in each direction is similar, we take the x direction as an example to evaluate the proposed method. Fig.4 shows the impedance adjusting process in x direction and y direction and Fig.5 shows the actual trajectory tracking results.

As shown in Fig.4 (a), the deviation Δd and the angle α changed significantly over time, and as a result, the impedance parameters were adjusted simultaneously. It demonstrates that the subjects had actively participant in the experiments by applying their efforts to track the reference trajectory. The peak of the deviation curve was below 30 mm which was less than the radius of virtual tunnel. That means the robot always moved within the tunnel, and the designed virtual tunnel worked well in preventing operators moving out of the physiological movement range. In addition, the part a1 and part a2 (circled by red line) shows that when operators inadvertently applied a force against the direction of desired path, the angle α would increase to more than π /2 rad, which would result in the increase of impedance. Part b and part c (between the two purple dashed lines) clearly reveal the



dynamic adjustment process of impedance parameters.

(a)



(b)

Fig.4. A djustment process in x direction (a) and in y direction (b). From top to bottom of both graphs, the first one indicates the change of impedance parameters during movement, in which the blue line is the damping and the red line is the stiffness parameter. The second one indicates the limb's actual deviation Δd from desired path. The third one indicates the angle α between the force vector and the tangent vector of the desired path. The fourth one indicates the force signal in x direction. And the last one is the output of adaptive impedance controller. In this paper, the output is the position correction of reference trajectory.

As shown in Fig.5, although the actual trajectory was not a standard circle, the curve always surrounded the reference circle. As the above mentioned, a virtual tunnel based path control method was also employed in [8]. Their experimental results demonstrated that in order to bring the arm trajectories closer to the reference trajectories, the radius of tunnel should be decreased and the impedance of robot should be increased. In this way, the participants' were limited to a smaller movement range (since the radius of tunnel was decreased) and their ability to drive robot was also weakened (since the impedance of robot was increased) instead of encouraging participants to actively correct their motion deviation in real time. It is hypothesized that the latter may facilitate to motor recovery. As for our study, the proposed adaptive impedance control scheme can help participants complete the task of trajectory tracking successfully.

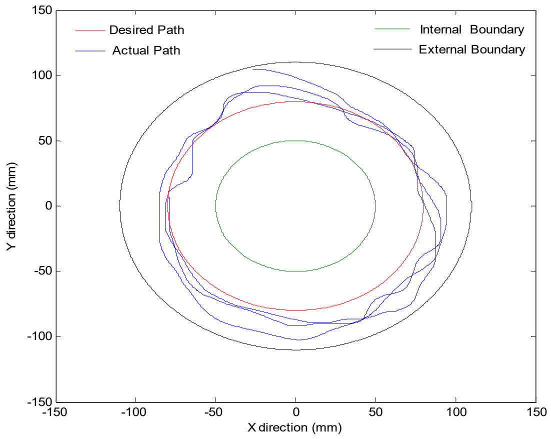


Fig.5. Actual trajectory tracking results compared to reference trajectory. The red line indicates the desired path, which is a circle and its radius is 80 mm. The blue line indicates the actual trajectory of limb. The green line indicates the internal boundary of virtual tunnel and its radius is 50 mm. The black line is the external boundary of tunnel and its radius is 110 mm.

C. Discussion

The main purpose of rehabilitation training for patients who suffered from neurologic impairments such as stroke and spinal cord injury is to provoke motor plasticity. Repeated motor-learning task assisted by robot was proposed by Krishnan to induce brain plasticity and motor recovery[15]. In this study, a novel scheme was proposed for the same reason. We did not provide a restoring force to help subjects move toward the target. We just informed subjects when they tried to deviate from the desired path by increasing the impedance of robot. Subjects were encouraged to correct their motion deviation by their own efforts. We assume that after repeating this task, the participants will gradually learn how to complete the task in a fast and accurate way, and as a result, the proposed control scheme will improve the outcomes of rehabilitation training.

IV. Conclusion and Future Work

This study presented a novel adaptive impedance control scheme for rehabilitation robot. This control strategy is capable of adjusting the desired impedance between robot and impaired limb in real time. The distinctive feature of this strategy is to encourage the patient to complete training exercise using their own efforts as much as possible and limit their inappropriate motion intention. Furthermore, the control scheme is capable of providing a virtual tunnel to prevent the patient moving out of the physiologically meaningful range of motion. Preliminary experimental results with several healthy subjects on a parallel robotic system demonstrated that subjects could successfully finish the tracking task assisted by robot with the proposed adaptive impedance control algorithm. Future work should be invested in experiments on patients to test whether the proposed strategy can actually enhance the rehabilitation outcomes.

Acknowledgment

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