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Force assistant master-slave telerehabilitation robotic system

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Abstract: A prototype of the master slave telerehabilitation robotic system with force feedback is developed. This system contains a pair of robots with the master being operated by the therapist and the slave following the master to guide the patients to exercise. A slave device with a slave controller is designed to stretch and mobilize the impaired elbow joints accurately and safely. A master device with a master controller is designed to control/monitor the procedure of treatment and assess the outcome of treatment remotely and accurately. By using the two-port network theory and the circuit equivalent impedance models, the position-force control scheme is designed to generate force feedback for the therapist who is to be informed of the interaction force between the subject and the robot arm during exercise. Experiments were conducted with a healthy male. Results show that the therapist can guide the patient to exercise by the master arm and can feel the interaction forces between the impaired arm and the robot. Compared with the traditional therapy, this system is more cost-efficient, more convenient and safer for both the stroke patients and the clinicians.

Key words: telerehabilitation; force feedback; robot; position-force control scheme

Due to the limits of conventional physical and occupational therapy, robotics was introduced into the field of rehabilitation of stroke patients, such as MIT-MANUS[1], MIME[2] and ARMin[3]. With the increasing number and costs of healthcare of stroke victims, the idea of telerehabilitation is gaining popularity[4]. Lum et al. [5] developed AutoCITE to deliver constraint-induced movement therapy. During training, the therapist supervised the training remotely with teleconferencing equipment and intermittent interaction was done using remote control. Peng et al. [6] developed a portable telerehabilitation system for home-based therapy of the elbow deformities of stroke patients. This is in fact a master-slave telerehabilitation system, but the force feedback is not described in detail. Another telerehabilitation system concept is TheraDrive, presented by researchers at the Medical College of Wisconsin and Marquette University[7]. It was built on the concept of embedding therapy within a "fun therapy" environment. In these telerehabilitation robotic systems, the therapists monitor the training process mainly by videos, that is, visual feedback.

Other telerehabilitation systems commented on force feedback. However, the force feedback referred to is the force exerted on the patients through joysticks, gloves or some other haptic display devices. Generally, this force is generated by movement in a virtual environment. One prototype of such systems was developed by Rutgers University and Stanford[8]. Reinkensmeyer et al. [9] adopted a computer joystick with force feedback to allow patients to independently practice simple movements using web-based telerehabilitation. Several other groups have also reported on the development of telerehabilitation systems[10–13].

Currently, most systems rely on visual feedback alone to guide the user, providing no force/haptic cues to the therapist. However, while the therapist guides the patient to exercise with the telerehabilitation system by video only, the therapist cannot be well informed about the exact status of the patients, and the security and reliability of the system cannot be ensured. Force feedback would be helpful for the therapist to adopt an appropriate therapy scheme. For this purpose, the master-slave structure is a feasible choice. In this paper, we describe a master-slave telerehabilitation system with force feedback that contains a pair of networked PCs and a pair of robots.

1 System Description

We begin with a brief description of the mater-slave telerehabilitation system(see Fig. 1). The system consists of an operator, a master arm, a slave arm, a communication block, and the subject. Unlike most of the existing telerehabilitation systems, the therapist is considered as an important unit in this system. A master robot and a slave robot are connected through the Internet. The role of the master arm is to provide position commands for the slave arm as well as to provide the operator with force feedback from the slave site. The main function of the slave device is to assist and guide the patients to stretch and mobilize the impaired arm through a number of repetitive movements in different modes.

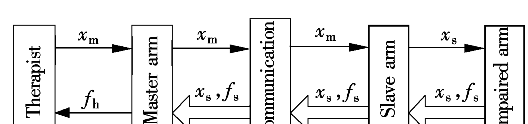

Fig. 1 Diagram of the master-slave telerehabilitation system

At the clinic site, the therapist operates the master arm. The position command x_m is measured and sent to the slave controller. At the slave site, the patient puts his/her arm on the slave arm and holds the handle attached to the tip of the slave arm. While receiving commands from the master, the slave arm is controlled to follow the master arm's movements to guide the impaired upper-limb in the remote therapy environment. Displacement x_s and interaction force f_s of the slave arm are reflected at the master site. The master motor exerts the force feedback f_s on the therapist through the master arm. Then he can feel and assess the patient's arm during a training process, further optimizing the therapy

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scheme according to the status of each patient.

2 Realization of Force Feedback

Because the patient's status goes through changes and the program control cannot handle unexpected situations, it is necessary for the therapist to feel and intervene in the exercise process at the right time. We think that a telerehabilitation system should be first equipped with an effective support system for monitoring the interaction forces between the patient and the rehabilitation robot and then the program controller of the training should be replaced by the interactive control of the therapist. The telerehabilitation can be dramatically improved by providing the therapist with real-time force feedback from the client stations through the Internet.

In this context, the position-force control scheme was developed to generate force feedback as shown in Fig. 2. x_m and x_s are the displacements of the master arm and the slave arm, respectively; f_s is the interaction force between the impaired-limb and the robotic arm; f_m is the force generated by the therapist; f_d is the output of the motor performing the command; $G_m(s)$ and $G_s(s)$ refer to open-loop transfer functions at the master site and the slave site, respectively; $G_t(s)$ is a force-adjustor transfer function.

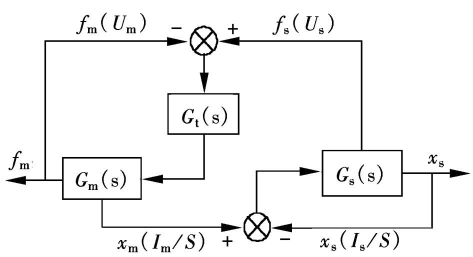

Fig. 2 Diagram of the position-force control scheme

During the telerehabilitation procedure, the therapist controls and experiences the impaired arm. The fact is that the impedance of the impaired arm is fed back to the therapist. So it is feasible to evaluate the performance of the force feedback by the veracity of impedance transfer.

Based on the equivalence principle between the mechanical and circuit systems, the relationship between force feedback and movement of the telerehabilitation system can be modeled by a two-port hybrid matrix $\boldsymbol{H}(s)$:

$$\begin{Bmatrix} F_m \\ \dot{x}_s \end{Bmatrix} = \boldsymbol{H}(s) \begin{Bmatrix} \dot{x}_m \\ F_s \end{Bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{Bmatrix} \dot{x}_m \\ F_s \end{Bmatrix} \tag{1}$$

For convenience of analysis, the virtual impedance and the impaired-arm impedance are defined as

$$Z_v(s) = \frac{F_m(s)}{\dot{x}_m(s)} \tag{2}$$

$$Z_s(s) = \frac{F_s(s)}{\dot{x}_s(s)} \tag{3}$$

From Eqs. (1) to (3), the relationship between the virtual impedance and the impaired arm can be deduced:

$$Z_v(s) = h_{11} + \frac{h_{12}h_{21}Z_s(s)}{1 - h_{22}Z_s(s)} \tag{4}$$

In the telerehabilitation robotic system, it is desirable that the slave can follow the master and the therapist can feel the interaction force at the right time. That means the system is transparent:

$$Z_v(s) = Z_s(s) \tag{5}$$

From Eqs. (4) and (5), the hybrid matrix of $\boldsymbol{H}(s)$ is

$$h_{11} = \frac{U_m}{I_m}\bigg|_{U_s=0} = 0, \quad h_{12} = \frac{U_m}{U_s}\bigg|_{I_m=0} = \frac{G_t(s)G_m(s)}{1+G_t(s)G_m(s)}$$
$$h_{21} = \frac{I_s}{I_m}\bigg|_{U_s=0} = \frac{G_s(s)}{1+G_s(s)}, \quad h_{22} = \frac{I_s}{U_s}\bigg|_{I_m=0} = 0 \tag{6}$$

Generally, $G_m(s) = 1$, then

$$Z_v(s) = \frac{G_t(s)G_s(s)}{[1+G_t(s)][1+G_s(s)]} Z_s(s) \tag{7}$$

Eq. (7) shows that the impaired-arm impedance $Z_s(s)$ is expressed in virtual impedance $Z_v(s)$. In an ideal situation, the transparency realization should satisfy

$$G_t(s) = -[1 + G_s(s)] \tag{8}$$

If Eq. (8) is satisfied, $Z_s(s)$ is transferred to the master arm without distortion. For the force feedback scheme shown in Fig. 2, $G_s(s)$ is a typical double-order unit, then $G_t(s)$ is convenient to realize by either hardware or software and does not affect the stability of the system. It means that the slave can follow the master and the therapist can experience the interaction forces between the subject and the slave arm.

3 Experiments

In order to experimentally demonstrate the above approach, we built a prototype of the master-slave telerehabilitation system for experiments. The purpose of this preliminary experiment is to investigate the performance of the force feedback in the telerehabilitation system.

3.1 Hardware configurations

Master and slave arms are both one DOF (degree of freedom) planar manipulators with force/haptic transducers (BK-5) at the endpoints and angular displacement sensors (WDD30) at the axes of rotation. Both the arms are connected through the Internet. The force/torque transducer at the slave site is to measure the interaction force between the subject and the slave arm, and that at the master site is to measure the force feedback exerted on the therapist. Angular displacement sensors are attached to sample the joints' positions. DC servo motors are used to drive the slave arm to track the master arm's movement and also to present the force feedback at the master site. Configurations of master and slave arms are physically equivalent on the whole and the frame structure is adopted to reduce the moment of inertia for accurate position tracking. The difference between the master arm and the slave arm lies in that the slave arm is symmetric itself for the reason that it can also be controlled by the therapist directly at the other side. Fig. 3 shows the master-slave telerehabilitation system.

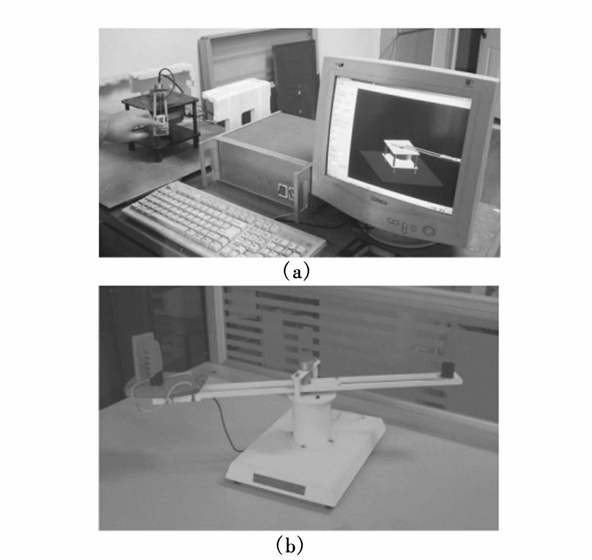

Fig. 3 Prototypes. (a) The master device; (b) The slave device

3.2 Software configurations

The master and the slave have different softwares. At the master site, a visual C++ program is developed to provide several services which include the ability to acquire the position and torque signals of the master arm, to communicate with the slave arm through the Internet, to receive data during the rehabilitation progress, and to display and save data from both the master and the slave arms. The therapists remotely control/monitor the program of the treatment and assess the rehabilitation effects by the master arm and the information feedback. At the slave site, a module is designed to control the movement of the slave motor, sample the position and force signals of the slave arm, acquire video images, and communicate with the master through the Internet.

The Internet protocol for communication is TCP/UDP. The torque and position signals are sampled and exchanged between the master site and the slave site by the TCP. In the meantime, the video images at the slave site are acquired at a rate of 15 frame/s and are buffered and transmitted to the master site by the UDP.

3.3 Security

Security is implemented both in hardware and software levels. Two bars are fixed around the rotation axis to restrict the movement range of the slave arm to avoid hurting the impaired upper-limb. A pressure sensor is employed to detect if the impaired upper-limb is on the tray. The robotic device does not work without an upper-limb on the tray, avoiding colliding with the patients in its workspace. On the other hand, the software detects and analyzes the movement of the arm. When the position or velocity exceeds the predefined limits, the slave controller gives commands to stop the robot. The slave arm can also be stopped by shutting down the power supply with an emergency button by the subject, or by a stop command from the therapist. In addition, warning messages through sound occur when an unexpected situation occurs at any time.

3.4 Experimental setup

A healthy right-handed male subject participated in this study. We conduct circular arc movements guided remotely by the therapist through the Internet. The subject is seated in front of the rehabilitation robot system and the wrist is held with a strap to the grip of the slave robotic arm. The range of the slave arm movement is from 10° to 110°. The therapist controls the master arm to drive the slave arm by the PI-scheduling force controller. To provide the clinician with the "true" feeling of the patient's arm, the master device should produce the same resistance torque as is produced by the stroke patient's limb at the salve arm. Therefore, the master device works in the torque control mode (TCM) to exert an appropriate resistant torque to the clinician. The slave motor works in the position control mode (PCM) to allow the movement of the patient's elbow following the movement of the clinician. During the rehabilitation procedure, forces and positions at the slave site and the master site are sampled at the frequency of 100 Hz. The data is also recorded for performance assessments.

4 Results and Discussion

Fig. 4(a) and Fig. 4(b) show the positions and interaction forces at the master site and the slave site, respectively. It is clear from Fig. 4(a) that the slave arm attached with the impaired arm can follow the master arm while the movement is within the set range. But when the slave arm moves toward the predefined maximum, the slave controller does not follow the master. Instead, the slave motor generates an interaction force. Then the force is reflected to the master site and exerted on the therapist through the master arm. So the therapist can guide the patient and feel the resistant force at a certain position. Fig. 4(b) shows that the force feedback exerted on the therapist at the master arm is consistent with the interaction of the force at the slave site.

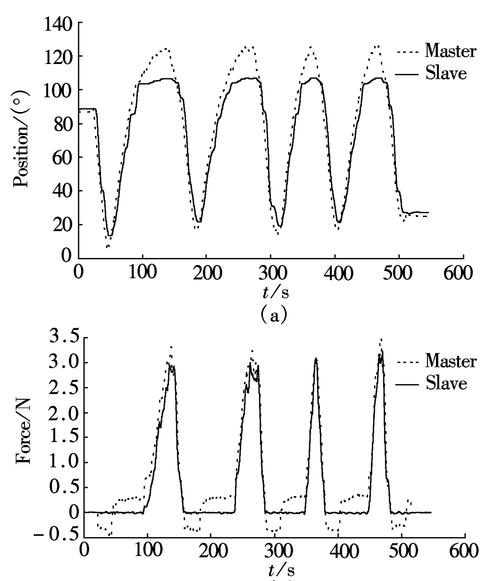

Fig. 4 Experimental data during telerehabilitation. (a) Position curves; (b) Force curves

For reasons of security, the force feedback increases with the slave arm reaching a maximum. In this way, the therapist is well informed if he/she is guiding the impaired arm to the insecure area. In that situation, the therapist may keep moving toward, but the force at the slave site will prevent the subject from moving to the insecure region. Combined Fig. 4 (a) and Fig. 4(b), it is obvious that the interaction force increases with the error distance between the master and the slave arm. When the force is great enough that the therapist notices he is approaching to the insecure area, he will turn and guide the slave arm to move in the opposite direction. The experimental results show that the position-force control scheme is effective in the telerehabilitation robotic system.

It should be noticed that the objective is to investigate the efficiency of the force feedback, so the healthy subject in this study can control the slave arm. For real patients without muscle motor functions, the error distance is expressed in the form of a virtual force. That is, this virtual force is calculated and reflected to the master but is not exerted on the impaired arm.

Limited by the experimental environment, mechanical structure, sensor technology and other reasons, there exists measurement noise in these figures. Optimizing the mechanical structure, experimental setup and filter design may reduce the measurement noise. Due to inertial forces and friction forces introduced by mechanical impedance of the master arm, there are differences between forces detected at the master site and forces generated at the slave site.

5 Conclusion

A telerehabilitation robotic system is developed. The position-force control scheme is introduced to provide the therapist with force feedback. Experimental results show that the slave arm can follow the master arm and the therapist can feel the interaction force between the upper-limb and the robotic arm. The robot will be safer compared with the robots implemented with a pure position control. Further work would involve experimentation with real patients to determine the efficacy of this system in rehabilitation.

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主从式远程康复机器人系统中力反馈的实现

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摘要：设计了一种力觉辅助主从式远程康复训练机器人系统，该系统由主机械臂和从机械臂构成，二者通过 Internet 网络相连. 治疗师在医院操纵主机械臂，远地从机械臂跟踪治疗师的运动，可以使患者在家或社区康复中心进行康复训练. 从机械臂及其控制器用于引导患肢关节进行安全准确地伸展和运动. 主机械臂及其控制器用于远程控制和监测患者的训练过程，并对输出数据进行分析，评估训练效果. 基于二端口理论和电路等小阻抗模型，设计了力反馈-位置型的控制结构来实现力反馈，使治疗师可以及时感知到患者训练过程中与机械臂的交互力. 在此基础上，建立了一套单自由度远程康复训练机器人系统，对一名健康男性进行了实验研究，结果表明治疗师可以通过操纵主机械臂引导实验对象训练并感受到实验对象与从机器人的交互力信息. 与传统的康复方法相比，该方式无论对于医生和患者都更为经济方便.

关键词：远程康复；力反馈；机器人；位置-力控制

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