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Premilitary Performance Evaluation of Model-mediated Telerehabilitation System with Task Stiffness Estimation

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***Abstract* –For the telerehabilitation robotic system, the stable and transparent remote therapist-patient interaction under the internet communication latency remains an open challenge. In this paper, we proposed a model-mediated telerehabilitation system to avoid the delayed force feedback on the therapist side. Moreover, a variable stiffness robot is employed in the proposed telerehabilitation system to improve the patient-robot interaction on the slave side. On the slave side, a performance-based variable stiffness interactive assistance control law was utilized and the task stiffness estimation method is designed for master-side interaction model updating. On the master side, the master subsystem was implemented by a haptic device with visual and force feedback. The overall telerehabilitation was realized by the TCP/IP internet communication method. From the premilitary experimental results, the therapist subject could conduct the therapy with the aid of visual and force feedback, and the patient subject could complete the training task with their active efforts.**

Index Terms – Telerehabilitation, model-mediated teleoperation, variable stiffness, variable stiffness actuator (VSA), and physical human robot interaction (pHRI)

I. INTRODUCTION

Along with the elder society processing, there will be almost 800000 patients who are suffering from stroke, which will lead to a huge shortage of traditional manual-aided medical sources [1]. Moreover, post-stroke patients usually are disabled to hardly access the hospital by themselves. Considering the access convenience of the patients, the home-based haptic-enabled robotic telerehabilitation systems were developed for providing rehabilitation training services for patients from the hospital to the patient's home over a distance [2] [3] [4] [5] [6] [7]. With internet technology, video, and audio information can be transferred within low time delay and stable communication to realize the telepresence of remote conferences. However, for the telerehabilitation scenarios, not only the video/audio information necessary but also the motion/force are indispensable for enabling the remote therapist-patient interaction (RTPI) which can enable the therapists to interventional assist the patients by operating the master-slave robotic system during the physical recovery training tasks [8]. However, the physical interaction method under time delay is disturbed by instability issues [9]. The delayed force/position information may cause the undesired dangerous control commands of the master-slave robotic system. To solve this problem, the teleoperation theory and technology catch the eye of researchers and a lot of research works have been proposed to guarantee the stability or passivity of the teleoperation system [10] [11] [12]. Teleoperation technology is also widely applied to medical scenarios, such as the telesurgery robotic system [13] [14] [15] and the telerehabilitation robotic system [16] [17] [18] [19]. For the medical teleoperation application, the position of the operators on the master side and the actual force of the environment on the slave side are important. Because the position generated by the operators represents the desired control commands to complete the teleoperation task and the actual force reflects the contact condition between the slave robot and the environment. The actual force of the slave side should be sent back to the master side for the operator's perception as the actual force information includes the interactions of the soft tissues or the affected limb of the patient. Thus, the position-force (P-F) teleoperation control frameworks are common for telemedical applications.

To ensure the stability of the P-F teleoperation system, there are two main solutions, the wave transformation (WV) method [20] [21] [22] [23] and the time domain passivity approach (TDPA) [12] [24]. The WV-based teleoperation system transfers the position/force information to the wave variables for internet communications, which can avoid the non-passivity problems of internet communication under time delay. On the other hand, the TDPA calculates the passivity power of each side subsystem by the passivity observer (PO) and regulates the obtained position/force from the contralateral side by the passivity controller (PC) to satisfy the passivity requirements. However, as the regulatory actions for passivity considerations, the position/force information will be not extremely same as the real information which lead to distortion issues. The distortion issues may lead to incomplete tasks for low working efficiency and the unreal haptic feelings of the therapists for low transparency. Regarding the transparency metric, the ideal transparency of the teleoperation is referring to the perfect match between the master and slave position/force profiles or the impedance matching between the real impedance of the

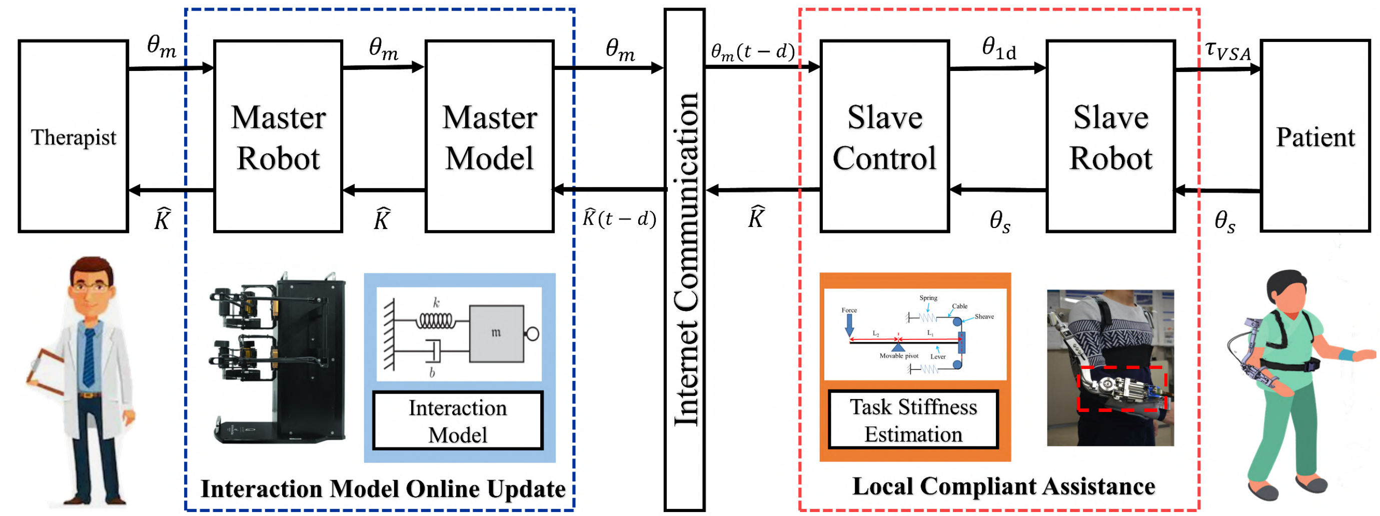

Fig. 1. Conception of the model-mediated telerehabilitation system control framework.

environment and the interaction impedance precepted by the operators. Obviously, stability and transparency are conflicted so that the some of trade-offs should be considered.

Nowadays, a novel teleoperation control framework, model-mediated teleoperation (MMT), is proposed to address both stability and transparency metrics in teleoperation under communication delays [25] [26]. In the novel MMT framework, a local interaction model on the master side is implemented to simulate the environment characteristics of the slave side. To this purpose, the slave robotic subsystem is supposed to complete the teleoperation task while estimating the slave environment characteristic parameters such as stiffness or damping in real-time. The information transferred from the slave side to the master side is not the force information but the environmental parameters. On the master side, the master local interaction model should be updated by the obtained environmental parameter so that the operators can feel the haptic feedback on slave environments by the local model without delayed force. In our previous work, a home-based telerehabilitation system with enhanced RTPI was proposed which includes two training modes, patient-in-charge and therapist-in-the-loop mode [27]. And the patient's active effort can be felt by the therapists by the surface electromyography (sEMG) signals-driven intention prediction methods [28] [29] [30] [31]. However, the separated operation and perception modes do not intrinsically solve the simultaneous stability and transparency trade-off issues.

In this study, we present a model-mediated telerehabilitation system with the patient's task stiffness estimation for realizing the stable and transparent RPTI. On the slave side, a flexible variable stiffness robot is utilized for compliant physical human-robot interaction (pHRI). Moreover, the performance-based variable stiffness modulation is used and the patient's task stiffness estimation is designed for representing the interaction characteristics. On the master side, a stiffness-damping impedance interaction model is implemented which can be updated by the obtained task stiffness from the slave side. To our best knowledge, this is the first work of a telerehabilitation robotic system using MMT. The conception and premilitary experimental validation is presented in this paper. The rest is organized as follows: In Section II, the technical details are introduced from the system configuration, and control method of the master and slave side. The demonstration experimental results are given in Section III. Finally, the conclusion is drawn in Section IV.

II. METHODS

A. System Overall

In this study, the proposed telerehabilitation system includes three parts, the master subsystem, the slave subsystem, and the internet communication port shown in Fig. 2. The master subsystem is aiming to provide a vivid patient interaction model for the therapists. To this end, a 6-degree of freedom (DOF) haptic-enabled manipulator HD2 is utilized as the master robot on the master side. To implement the high-fidelity haptic interface for the therapists, the Hardware-in-the-loop control board (Q8-USB Controller, Quanser Inc., Canada) is selected into the master subsystem which is connected to the HD2 by a SCSI communication cable. In the slave subsystem, a powered variable stiffness exoskeleton device (PVSED) is employed for patient assistance. The PVSED has one DOF on the elbow joint flexion/extension and one DOF for independent stiffness variations. There are other 5 passive DOFs for natural range of motion. The patients can wear the PVSED and carry out the elbow joint flexion/extension motion with the compliant variable stiffness assistance from the PVSED [32].

The master and slave robotic dynamic can be expressed as a set of nonlinear differential equations:

$$M_m\ddot{\theta}_m + B_m\dot{\theta}_m = \tau_m + \tau_{Th} \tag{1}$$

$$M_s\ddot{\theta}_s + B_s\dot{\theta}_s = \tau_{VSA} + \tau_{Pa} \tag{2}$$

$$\tau_{VSA} = K_r \cdot (\theta_s - \theta_1) \tag{3}$$

where M_m and M_s are the mass coefficient of the master and slave robot. And B_m and B_s are the friction coefficient of the master and slave robot. The τ_{VSA} and K stand for the output force and stiffness of the PVSED.

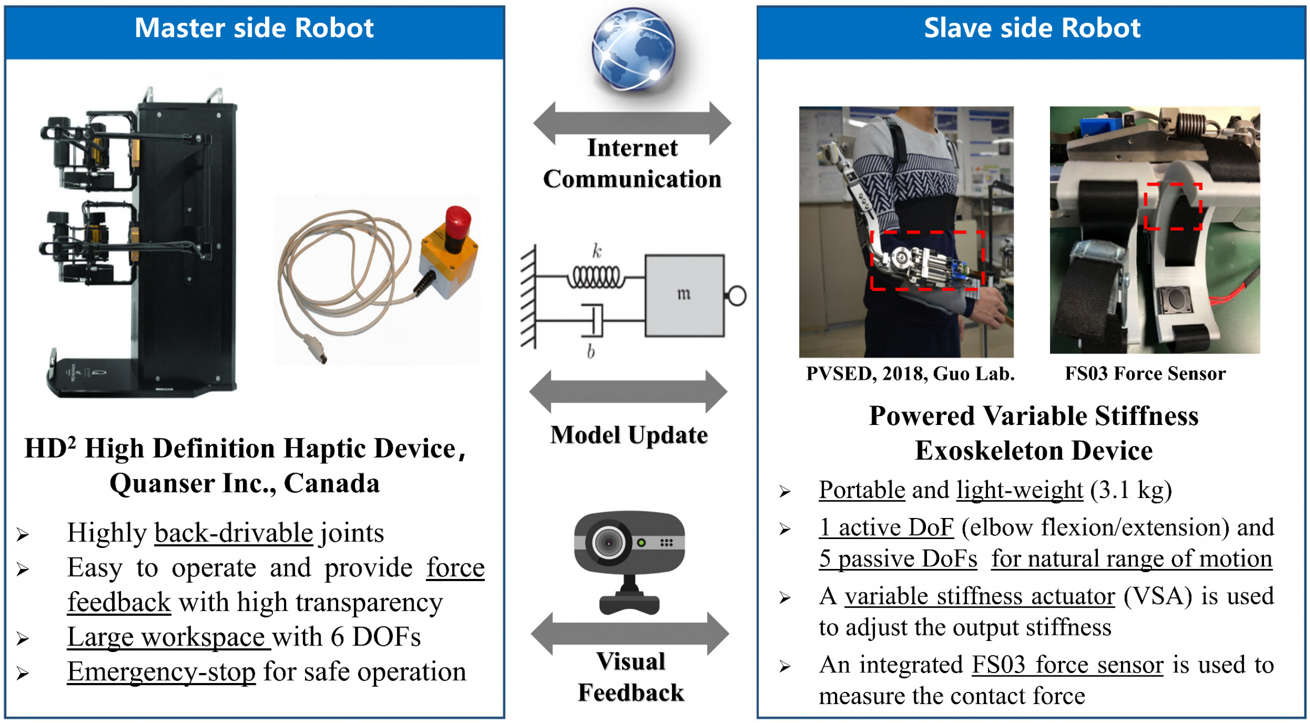

Fig. 2. Configuration of the model-mediated telerehabilitation system.

To communicate the master and slave subsystems, the internet communication port is built by the TCP/IP method for a high-fidelity stable internet communication. Due the inevitable communication delay, the transmit variable will be written as (t-d) for representing the delay d s.

B. Model-mediated Teleoperation

The conception of the proposed model-mediated telerehabilitation is to avoid the direct transmissions of a pair of power variables which will lead to non-passive of the communication port and further cause the instability due to the internet communication latency. By transmitting the interaction model parameters to the master side, the operator interactions can be guaranteed with local no-delay control loop. Thus, the proposed model-mediated telerehabilitation system is supposed to provide dynamic remote therapist-patient interaction for the therapists through the real-time interaction model update. To realize this concept, the task interaction dynamic characteristics of the patients should be estimated and sent to the master side during the telerehabilitation training task. Therefore, the forward information (master to slave) is the therapist's therapy motions and the backward information (slave to master) is the estimated task stiffness information of the patients during the telerehabilitation training task for the therapist's interaction model update.

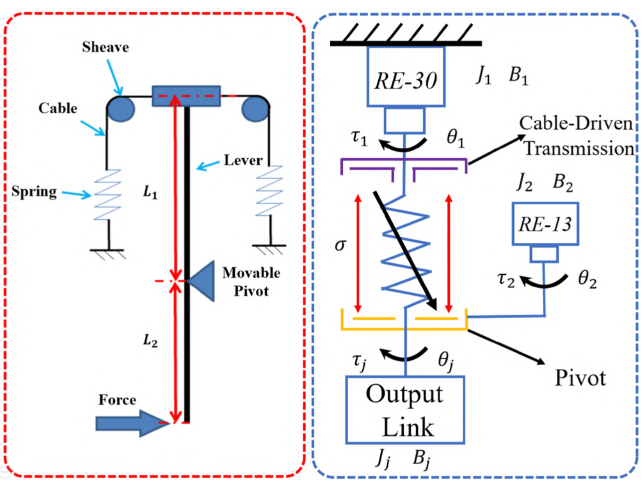

Fig. 3. The working principle of the VSA

C. Task Stiffness Estimation on the Slave side

The patients on the slave side is expected to track the obtained therapy motion trajectory with the aid of the PVSED. As the flexible structure of the PVSED, the assistance torque will be generated only if there is the deviation angle between the output link θ_s and the mainframe link θ_1 shown in Fig. 3. Based on this characteristic of the PVSED, the assistive interaction torque τ_{VSA} generated by the PVSED can be calculated as (3). In order to provide the compliant interaction for patient, the assist-as-needed strategy should be considered [33] [34] [35]. In this study, a position-error-based variable stiffness control law is utilized to get the desired input stiffness K_d of the PVSED as follows:

$$K_d = 16.95 + \varepsilon \cdot |\theta_m - \theta_s| \tag{4}$$

Where are the obtained therapist position and the actual patient position, respectively. And ε is the positive constant which is set as 3.418 in this paper.

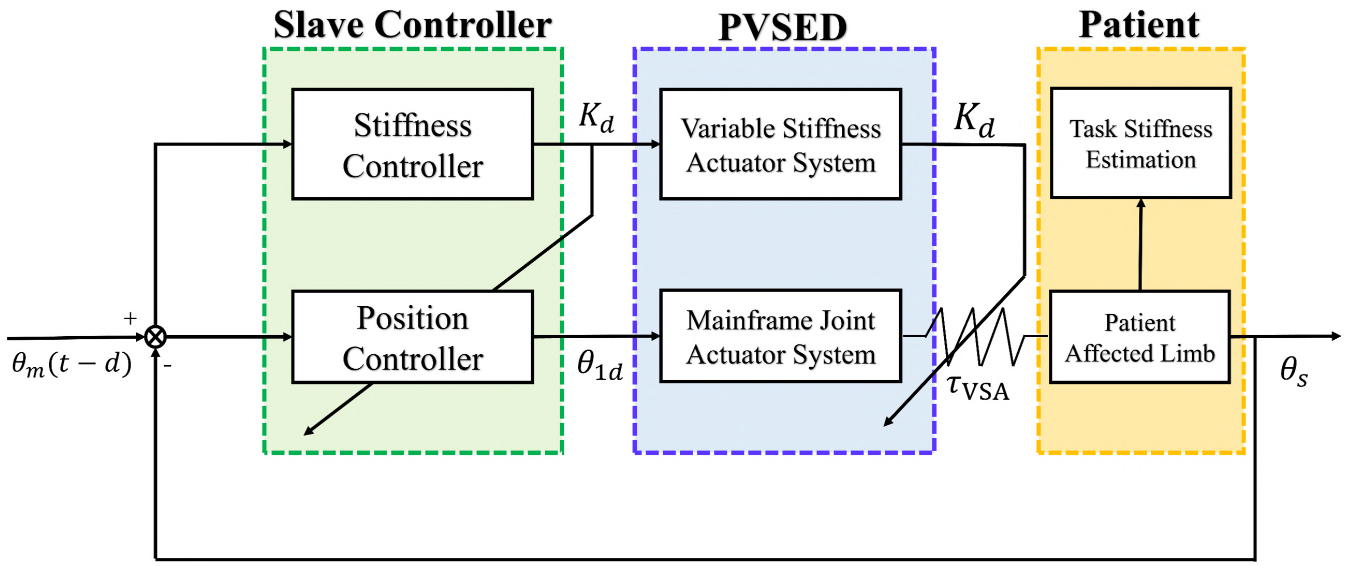

Fig. 4. The performance-based variable stiffness control framework of the slave subsystem with variable stiffness robot

After obtaining the desired stiffness of the PVSED, the tracking controller of the PVSED is aiming to control the mainframe position to tracking the desired position θ_{1d} to provide the desired assistance. In our pervious study, the tracking controller of the PVSED under the variable stiffness was proposed with proved stability performance, which is utilized in this study shown in Fig. 4.

Due to the patient active training efforts, the position error could reflect the patient's training task dynamic information. For this consideration, the estimated task stiffness $\widehat{K}$ of the patient can be calculated as follows:

$$\widehat{K} = \begin{cases} 16.95, & \theta_m - \theta_s < 3° \\ 16.95 + \varepsilon \cdot |\theta_m - \theta_s|, & 3° \leq \theta_m - \theta_s \leq 30° \\ 119.5, & 30° \leq \theta_m - \theta_s \end{cases} \quad (5)$$

As the above equation, the task stiffness of patients can be calculated in real-time and will be transmit to the master side. Moreover, the task stiffness of the patients will equal to the minimal stiffness level if the patient can track the desired position with predefined performance requirements. And the task stiffness will increase along with the position errors become larger, which means that the patient limb is too stiff to be moved.

D. Interaction Model Update on the Master Side

The interaction model on master side is the impedance model containing the spring and the damping terms [36]. Compared with the interaction model only including the stiffness term, the damping term will contribute to the interaction stability and further ensure the telerehabilitation safety. The interaction model is given as:

$$\widehat{D}(\dot{\theta}_0 - \dot{\theta}_m) + \widehat{K}(\theta_0 - \theta_m) = \tau_m \quad (6)$$

$$\widehat{D} = 2 \cdot \xi \cdot \sqrt{\widehat{K}} \quad (7)$$

Where θ_0 and $\dot{\theta}_0$ stand for the initial angle and angular velocity of the master robot. θ_m and $\dot{\theta}_m$ represent the task angle and angular velocity generated by the therapists. $\widehat{K}$ and $\widehat{D}$ are the estimated task stiffness and damping of the patients obtained from the slave side, respectively. And ξ is the damping coefficient which is 0.7. Therefore, the dynamic interaction can be implemented by the time-vary impedance information update, which can reflect the patient training task state. According to the above equation, the therapist will receive the interaction torques against to the motion direction of the motion and the interaction characteristics is determined by the task position and the patient's task impedance information. Moreover, if the patient can track the therapy motions so that the estimated task stiffness becomes to minimal level, the therapists will percept the softest impedance interaction characteristics corresponding to the minimal stiffness of the PVSED. Conversely, if the patient's tracking errors are huge so that the estimated task stiffness is large, the therapist will feel the harder level impedance interaction characteristics by which the therapists can be aware of the poor performance of the patients and adjust the training task difficulty easier for ensure the remote interaction safety.

III. Experiments and Results

A. Experimental Setup

The premilitary performance of the proposed model-mediated telerehabilitation system was evaluated in this study. An experimental demonstration trial was carried out at Kagawa University. Two subjects were employed in this experiment. One subject was asked to carry out the elbow joint flexion/extension motion by holding the HD2 device, and the other subject was asked to wear the PVSED on the master side and to track the obtained therapist's motions on the slave side. The video information of the slave side was transmitted to the master side to enable the master subject to be aware of the slave side tracking performance. The experiment was approved by the Institutional Review Board (IRB) of the faculty of engineering under protocol number 01-110.

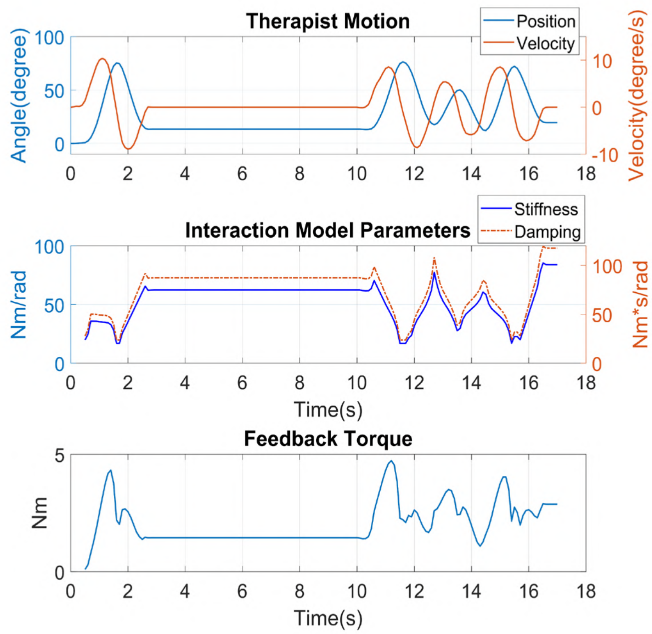

Fig. 5. Performance results of the master side. Top figure: Therapist kinematic motions, Middle figure: Interaction model parameters updated by the obtained patient's task stiffness from the slave side. Bottom figure: Feedback torque delivered to the therapist subject.

B. Experimental Results

During the demonstration trial, the master subject conducted free flexion/extension motions of the elbow joint while watching the slave subject's motion in the video. And the slave subject was asked to track the obtained kinematic position with his best efforts. The experimental results of the master and slave side were shown in Fig. 5 and Fig. 6. To simulate the patient's active efforts, the slave subject was asked to against the obtained position on purpose from 2.8s to 10.5s. Therefore, the deviation angle between the mainframe and output link became 13.3 degrees so that the PVSED generated the assistive torque at 13.87 Nm. In addition, the master subject also conducted three motion cycles of sine function like elbow joint motions, meanwhile the slave subject against the desired motions at the end of the motion cycle. The peak torques of each motion cycle are 20.45Nm, 12.40Nm, and 28.71Nm, respectively. Due to the patient's active efforts, the task stiffness is caused shown in Fig. 6. It is obvious that the estimated task stiffness is almost corresponding to the output stiffness of the PVSED. During the telerehabilitation training, the estimated task stiffness will be transferred to the master side to update the interaction model for therapist interaction perceptions. According to (6) and (7), the stiffness and damping terms of the impedance model were regulated in real-time to provide the dynamic task information. The interaction feedback torques are shown in Fig. Benefitting from the model-mediated telerehabilitation method, the therapist could feel the dynamic interaction force feedback and the visual feedback of the patient training task states.

IV. Conclusions

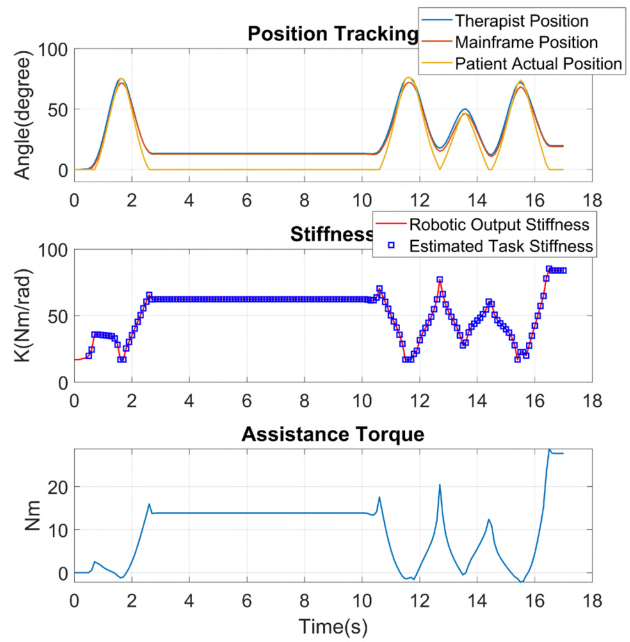

Fig. 6. Performance results of the slave side. Top figure: Patient tracking results, Middle figure: Comparison results between the output stiffness of the PVSED and estimated task stiffness. Bottom figure: Assistance torque delivered to the patient subject.

In this paper, we proposed a model-mediated telerehabilitation system with task stiffness estimation to felicitate telerehabilitation with remote therapist-patient interactions. The therapists could receive the visual and interaction force feedback of the telerehabilitation training task from the slave side and provide the therapy motions for patients. Moreover, a flexible robot was utilized to provide compliant interactive assistance to the patients for improving remote training safety. Based on the variable stiffness robot on the slave side, the performance-based variable stiffness control law and task stiffness task estimation method were presented. By transferring the estimated task stiffness from the slave side to the master side, the interaction model can be online updated in real-time to realize the dynamic task interaction feedback. To validate the performance of the proposed model-mediated telerehabilitation system with task stiffness estimation, a premilitary experiment was carried out. The experimental results show that the model-mediated telerehabilitation system can enable remote therapist-patient interaction with compliant assistance and interaction model updating. Future work will focus on adopting real post-stroke patients into the experimental validation.

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