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Development of a Tele-Rehabilitation System for Outcome Evaluation of Physical Therapy

Hyung-Soon Park[1], Jeong Wan Lee[2]

[1]Sensory Motor Performance Program, Rehabilitation Institute of Chicago,
[2]Associate professor, Division of Mechanical Mechatronics Engineering

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Abstract

This paper presents a portable tele-assessment system designed for remote evaluation of the hypertonic elbow joint of neurologically impaired patients. A patient's upper limb was securely strapped to a portable limb-stretching device which is connected through Internet to a portable haptic device by which a clinician remotely moved the patient's elbow joint and felt the resistance from the patient. Elbow flexion angle and joint torques were measured from both master and slave devices and bilaterally fed back to their counterparts. In order to overcome problems associated with the network latency, two different tele-operation schemes were proposed depending on relative speed of tasks compared to the amount of time delay. For slow movement tasks, the bilateral tele-operation was achieved in real-time by designing control architectures after causality analysis. For fast movement tasks, we used a semi-real-time tele-operation scheme which provided the clinicians with stable and transparent feeling. The tele-assessment system was verified experimentally on patients with stroke. The devices were made portable and low cost, which makes it potentially more accessible to patients in remote areas.

Key words : Telerehabilitation, remote assessment, task causality, passive/active ROM (range of motion), active muscle strength test, spasticity test

I. INTRODUCTION

Tele-rehabilitation has been considered as a solution to support remote delivery of rehabilitation and home care services for individuals with limited access to comprehensive medical and rehabilitation outpatient services. For the patients with motor impairment such as stoke, spinal cord injury, and cerebral palsy, effective treatments and the monitoring of the progression of motor dysfunction typically relies upon a physical exam by an experienced clinician. For example, spasticity is often assessed by physical manipulation of the joints to determine the resistance to motion. However, for many individuals with motor impairment, routine access to expert clinical assessment is severely limited by financial resources and distance to a qualified medical center, resulting in suboptimal treatment therapies or dosages. The tele-assessment system developed in this study can reduce the barrier, and provide patient access to medical professionals for the assessment of motor disorders.

A number of devices have been developed to exercise human joints and reduce spasticity and contracture. Serial casting which fixes the limb at a corrected position has been used to correct and prevent ankle plantar-or dorsi-flexion contracture. Combining serial casting with manual stretching is usually a more effective treatment for correcting ankle plantar-or dorsi-flexion contracture[1]. Dynamic splinting and traction apply a continuous stretch to the joint involved through an adjustable spring mechanism[2]. The continuous passive motion (CPM) device is widely used in clinics and in patients' homes to move the joint within a pre-specified movement range, to prevent postoperative adhesion and to reduce joint stiffness[3]. Advanced robot-aided devices have also been developed to evaluate arm impairment quantitatively, and to assist and guide patient's hand to reach a target in the arm workspace to enhance neuro-rehabilitation following brain injury[4,5].

The therapeutic treatment must be followed by timely assessment and evaluation by expert clinicians; however, few works on tele-rehabilitation focused on achieving the real-time remote assessment function. Many tele-rehabilitation systems were developed using networking technology such as the video conferencing[6,7] yet without implementing physical interaction between the clinicians and the patients which is an

Corresponding Author : Jeong Wan Lee
Division of mechanical and Mechatronics Engineering, 192-1, Hyoja2-dong, Chunchon, Kangwon-do, 200-701, Korea
Tel : +82-33-250-6377 / Fax : +82-22-257-4190
E-mail : jwlee@kangwon.ac.kr

essential function to achieve realistic assessment. One of the difficulties that might be involved in real-time tele-assessment function is the instability problem of bilateral tele-operation. For example, bilaterally controlled master and slave robots were known to experience instability due to the time delay in the data transmission line even though the delay is small[8]. In addition to the stability issue, reliable implementation of transparent feeling without losing stability was a major difficulty involved in tele-robotics[8]. In the literature, the instability problem was solved by making the master-slave system passive[9-13]; however, the transparency of the system degraded instead. The distorted feel of the patient's limb may result in the inaccurate assessment different from the in-person assessment. In this paper, we developed a tele-assessment system that is capable of simulating in-person assessment: the clinicians could move and feel the true stiffness of the patient's limb remotely. To resolve the issues related to the time delay involved in the internet connection, two control strategies were developed for different types of tasks regarding the bandwidth (or speed) of the tasks. For tasks with lower bandwidth (slow movement), a real-time tele-assessment could be achieved based on the causality analysis of the tele-assessment tasks to guarantee stability with maximum transparency. For tasks with higher bandwidth (fast movement), a quasi real-time control method was proposed to overcome the problems coming from the time delay. In quasi real-time tele-assessment, the clinician could examine the patients with true feeling as he/she repeated the same tasks.

II. OVERVIEW: THE TELE-ASSESSMENT SYSTEM AND TASKS

A. Tele-assessment System

The tele-assessment system consists of devices for physical interaction as well as the video conferencing equipment (Fig. 1). The clinician and patient can see and talk to each other by using web-cameras and microphones connected through internet. Meanwhile, the clinician can make physical interaction with the patient using the master device which is connected through internet to the slave device at patient's home or local clinics. Both angular rotations and joint torques are measured at the master and the slave devices and sent to their counterparts. The clinician holds and moves a manikin arm mounted on the master device and the movement information is sent through the internet to a remote slave device where the patient's arm is securely strapped to. In this way, the patient's elbow undergoes identical movement as that of the manikin

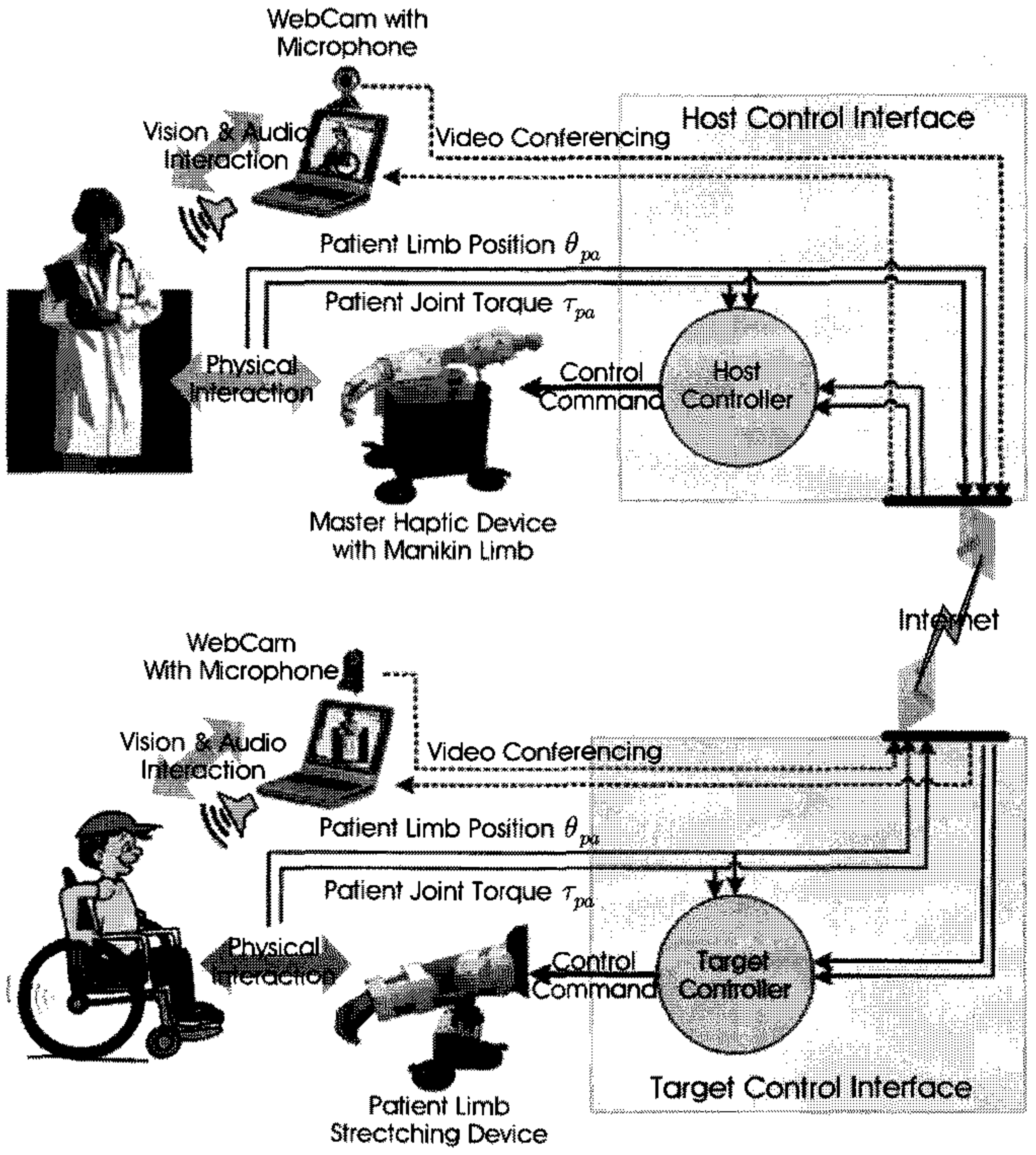

Fig. 1. Schematic Diagram of Tele-Assessment System: The clinician sees the patient and talks with him using web-camera and microphone. Meanwhile, the master and the slave devices enable physical interaction between them based on the position and torque measurements and corresponding control.

elbow. Meanwhile, the resisting torque from the patient's elbow is measured and recreated at the master device so that the clinician can *feel* the resistance from the patient's elbow.

The tele-assessment system was designed to be low-cost and portable, which would make it more widely available to the patients. Furthermore, in addition to the assessment tasks, the slave device can also be used independently for treatment functions.

B. Tele-Assessment Tasks

1) Passive ROM (Range of Motion) Test

At the beginning of an assessment session, the clinician slowly moves a subject's limb to find the ROM. The clinician will move the spastic elbow joint using the master haptic device with the feel of the resisting torque measured at the subject's elbow joint. Through this real-time and slow passive ROM test, the clinician can determine the position and torque limits at both flexion and extension.

2) Spasticity Test

Spasticity is the velocity-dependent resistance to passive movement. The subject's arm will be positioned at various points within the ROM and then rapidly displaced. The resulting "stiffness" will be felt by the clinician, providing an indicator of the subject's spasticity severity.

3) Active ROM Test

The subjects are asked to make free and slow movement. In this test, the clinician does not need to feel any torque from the subject therefore, this task can be performed without bilateral torque display. The position during the movement will be measured at the slave device locally to evaluate the active ROM.

4) Active muscle strength

The subjects are asked to flex/extend similarly with active ROM test, but this time they move against the clinician resisting his/her movement. The clinician does not necessarily need to feel the torque actively generated by the subject because the active muscle strength can be evaluated locally by locking the slave device at pre-specified flexion angles and asking the subjects to flex/extend their limb as strong as they can.

Among the four tasks, the first two tasks require the real-time assessment function in which the clinician needs to see and feel the patient's limb while the other two tasks do not necessarily require the real-time interaction. In this study, we focused on implementing the real-time assessment when the clinician is performing the first two tasks. The passive ROM tests do not need high-speed motions, so we could achieve the real-time and transparent tele-assessment based on the causality analysis of the tasks. The spasticity tests, however, require fast movement and the reliability of its real-time implementation will be limited by network latency. For those tasks with fast movement, we propose a semi-real-time tele-assessment method which guarantees the transparency, reliability, and safety.

Ⅲ. REAL-TIME TELE-ASSESSMENT FOR PASSIVE ROM TEST

A. Modeling the Assessment Tasks

Before developing tele-assessment control architectures, the assessment tasks were modeled with the task causality identified. Appropriate modeling of the assessment tasks leads to designing correct tele-assessment control architectures. By causality, we mean dependency (cause and effect) relationship among force (or torque) and position (or angle) variables that describe the behavior of the dynamic system. It has been reported that designing controllers after causality analysis brought benefits in stability and transparency of tele-operation systems[14,15].

Bond-graph modeling[16], a very good modeling tool for assigning causality, was adopted for modeling the assessment tasks. For example, when the clinician examines the passive ROM of the joint, the task was modeled by two inertia-spring-damper systems transferring power from the clinician to the patients (Fig. 2 (b)). After applying the sequential causality assignment procedures[16], the causality was assigned to describe the clinician determining independent position and feeling resistance torque (Fig. 2 (c)). This type of task causality is named as position commanded tasks (PCT). When the clinician examines the active strength of the patient, the power is transferred from the patient to the clinician and the model shows another type of causality (Fig. 3). This type of task causality was named as force commanded tasks (FCT) since the force was independently determined from the clinician's side[1].

The novel causality-identified model helped understanding and analyzing the tele-assessment tasks so as to design appropriate control architectures. With the dependency relationship among the position and torque variables identified, the

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[1] The task causality was named by following the independent variable determined by the clinician.

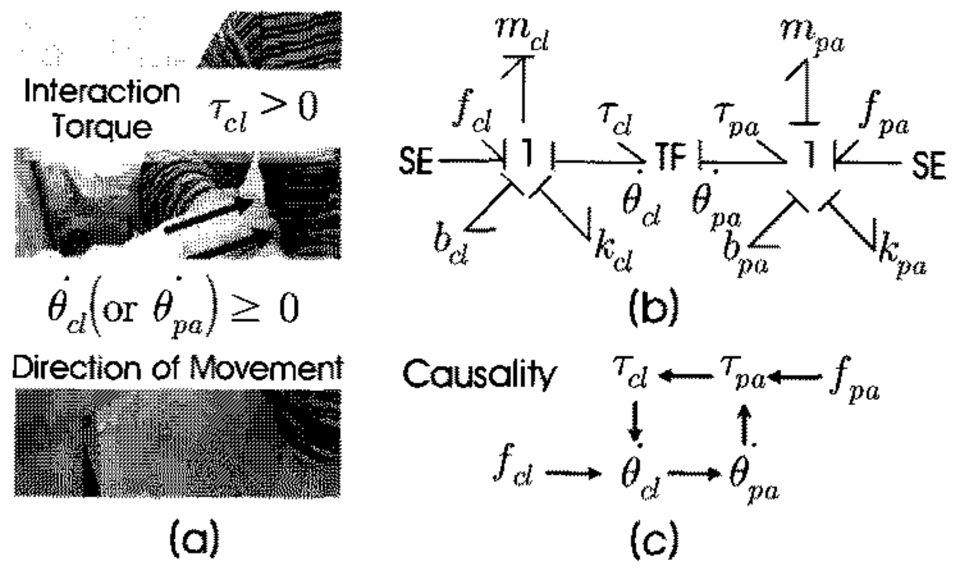

Fig. 2. Model of Passive ROM Test: (a) The direction of τ_{cl}(interaction torque) and $\dot{\theta}_{cl}$(angular velocity) coincide. (b) bond-graph model with causality assignment where m_{cl}, b_{cl}, and k_{cl} denote inertia, damper, and spring model of the clinician arm. f_{cl} denotes force from the clinician's muscle. Similarly, $^{*}_{pd}$ denotes parameters of the patient. (c) From the bond-graph model the causality is identified. The clinician determines position independently and feels dependent torque coming from the patient.

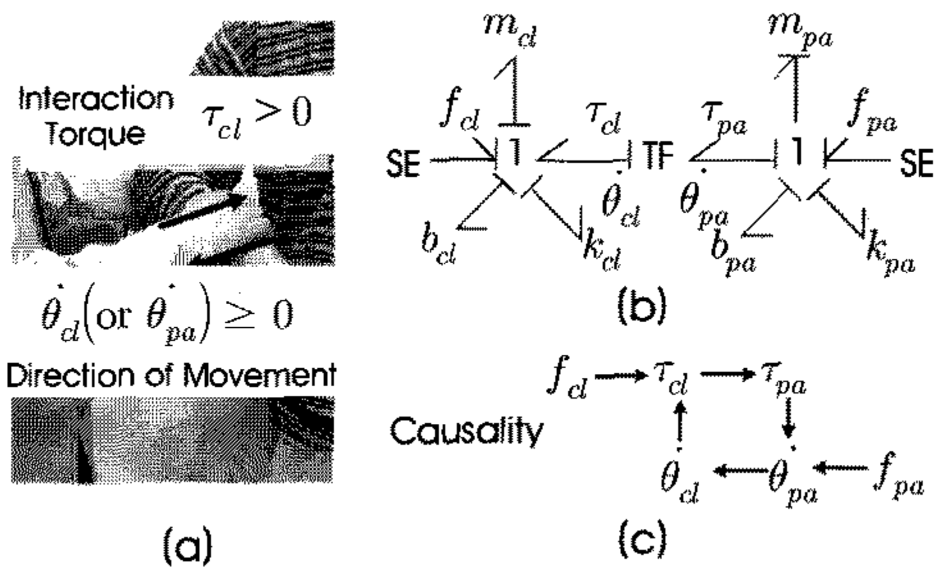

Fig. 3. Model of Active Strength Test: (a) τ_{cl} and $\dot{\theta}_{cl}$are in opposite direction. (b) Bond-graph model with causality assignment. (c) Causality drawn from the bond-graph. The patient makes independent movement and the clinician resists the movement. As a result, the clinician determines independent resistance torque rather than the position.

communication structure between the master and the slave could properly designed, and the controllers at the master and the slave could be designed accordingly.

B. Designing Real-Time Control Architectures According to the Task Causality

As aforementioned, the real-time tele-assessment was implemented for *slow* tasks such as the passive ROM test. While the clinician moved the manikin arm strapped to the master device, he/she felt the resistance torque from the patient in real-time and set the position/torque limits of the elbow joint based on the feel. The position/torque limits set by the real-time passive ROM test guaranteed safety throughout the whole tele-assessment session; the slave arm was never operated out of the position/torque limits.

In order to set the limits correctly, the clinician needs to experience true feel through the remotely operated tele-assessment system. In the bilateral teleoperation which in principle is exactly the same as our real-time tele-assessment, the stability issue has been considered intensively. Among several stability guaranteeing methods, we will adopt a causality-based method[14,15] since it can provide the clinician with the feeling of the patient's elbow minimally distorted; no additional distortion is induced except for the distortion due to time delay which is inevitable in teleoperation.

Two control architectures were chosen to be consistent with the two types of task causality. For PCT, the master device sends position command to the slave device and the slave device sends the torque back to the master. Accordingly, a torque tracking controller was implemented in master and position tracking controller in the slave (Fig 4 (a)). For FCT, we can reverse the control architecture to be consistent with the causality (Fig 4 (b)) the master sends the force to the slave and the slave returns back the position. The selection of causality-consistent control architectures enabled stable tele-assessment with maximum transparency[15].

The control laws of the tracking controllers of the master device (Fig. 4) are given as follows

$$u_m = \begin{cases} K_{\tau m} e_{\tau m} & , \quad when \ \ \tau_{cl}\dot{\theta}_{cl} \geq 0 \ \ (PCT) \\ K_{Dm} \dot{e}_{\theta m} + K_{Pm} e_{\theta m} & , \quad when \ \ \tau_{cl}\dot{\theta}_{cl} < 0 \ \ (FCT) \end{cases} \tag{1}$$

where $e_{\tau m} = \tau_{pa} - \tau_{cl}$, and $e_{\theta m} = \theta_{pa} - \theta_{cl}$ denote the torque tracking error and position tracking error, respectively. K_{*} denotes the gains of the controller at the master device. Similarly, the control law at the slave device will be expressed as follows;

$$u_s = \begin{cases} K_{Ds} \dot{e}_{\theta s} + K_{Ps} + e_{\theta s} + K_{Is} \int e_{\theta s} dt & , \ when \ \tau_{cl}\dot{\theta}_{cl} \geq 0 \ (PCT) \\ K_{\tau s} e_{\tau s} + K_{pm} e_{\theta m} & , \ when \ \tau_{cl}\dot{\theta}_{cl} < 0 \ (FCT) \end{cases} \tag{2}$$

where $e_{\tau s} = \tau_{cl} - \tau_{pa}$, and $e_{\theta s} = \theta_{cl} - \theta_{pa}$ represent the torque tracking error and position tracking error, respectively.

For successful application of the causality-consistent control architectures, two practical problems were addressed. First, the solution to time-varying network latency will be considered. By nature the network latency is time-variant and unpredictable; therefore, the time course of the position and

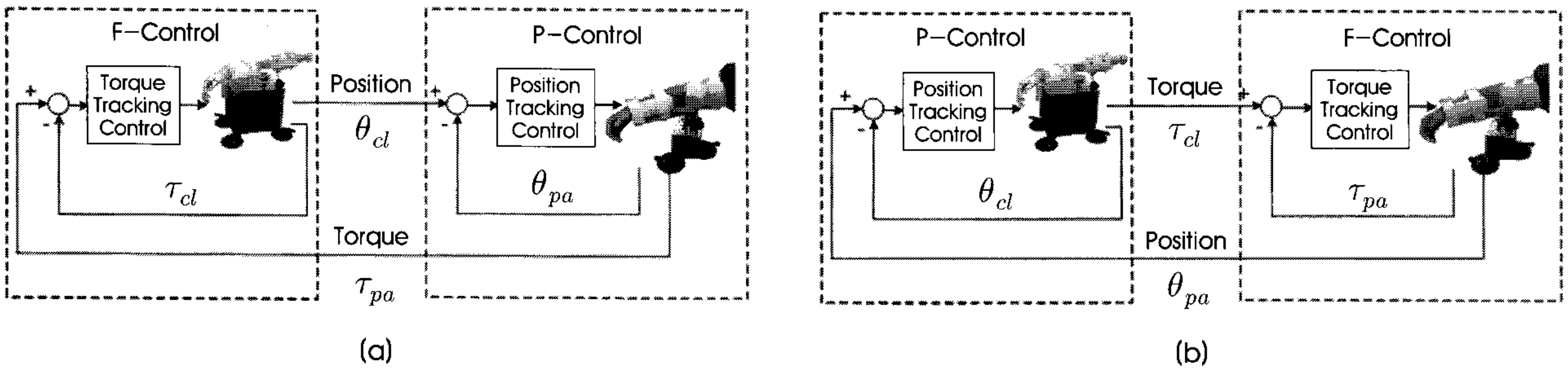

Fig. 4. Control architectures for the two types of task causality

torque data may be distorted after they are transferred through network. As a remedy to this problem, we added time tag to the position and torque data so as to reconstruct the time course of the data without any distortion.

Second, a chattering problem that occurred due to the switching between the two control architectures was solved by implementing smooth transition between the two control architectures. According to the modeling of the assessment tasks, task causality does not change throughout a single task. For example, the power flows from the clinician to the patient throughout the passive ROM test. However, the direction of the power flow may change during the passive ROM test due to the time delay. In addition, the sign of $\tau_{cl}\dot{\theta}_{cl}$ which determines the causality may switch due to the sensor noise. To resolve this, the boundary layer used in the sliding mode control[17] was used since it has solved similar chattering problems. With the gain scheduling of K_{sat}(Fig. 5), the control laws are rewritten as follows. The control input switches between PCT and FCT gradually by defining the transition region where $h_{\min} < \tau_{cl}\dot{\theta}_{cl} < h_{\max}$.

$$u_m = K_{sat}K_{\tau m}e_{\tau m} + (1 - K_{sat})[K_{Dm}\dot{e}_{\theta m} + K_{Pm}e_{\theta m}] \tag{3}$$

$$u_s = K_{sat}[K_{Ds}\dot{e}_{\theta s} + K_{Ps}e_{\theta s} + K_{Is}\int e_{\theta s}\,dt] + (1 - K_{sat})K_{\tau s}e_{\tau s} \tag{4}$$

IV. SEMI-REAL-TIME TELE-ASSESSMENT FOR SPASTICITY TESTS

A semi-real-time method was developed for fast tasks such as the spasticity test where the angular speed during the test ranges from 30 deg/sec to 210 deg/sec[18]. The real-time implementation of these tasks is limited by the network latency. For inter-city application within US, the amount of network latency may go up to 200 msec[19] with which any real-time tele-assessment can never achieve the *true feel*. As a remedy, we developed a semi-real-time strategy to overcome the limitation (Fig. 6).

First, the clinician moves the manikin limb without feeling any reaction torque. Meanwhile, the patient's limb undergoes the same but delayed motion while the position and the reaction torque at the patient's limb are measured. This first task is called as 'teaching mode' where the clinician generates the motion profile from which he/she wants to feel the reaction torque of the spastic joint. Since the position and torque measured at the slave limb-stretching device are synchronized, the received data can be used to make a look-up table that contains the relationship between the position and the resistance torque during the above task. From the look-up table, we can provide the clinician with the *true feel* of the joint stiffness if he/she repeats the same task at the next trial.

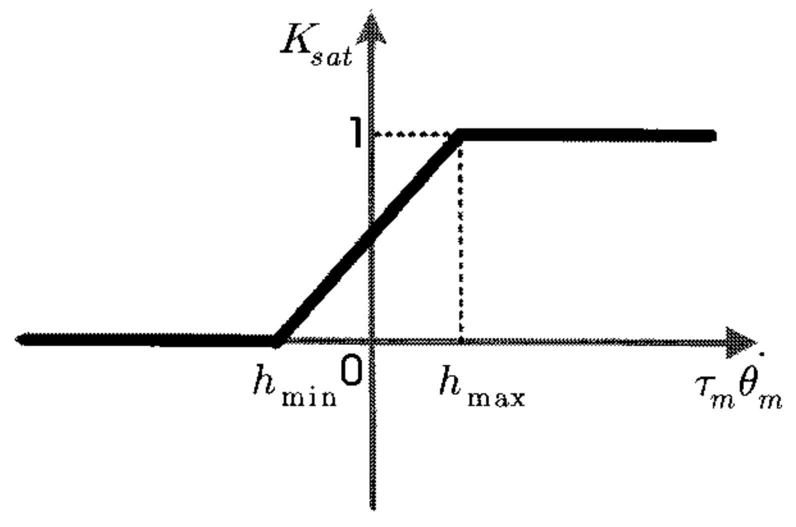

Fig. 5. Gain scheduling of K_{sat}. $h_{\max}$ and $h_{\min}$ are free parameters to be tuned.

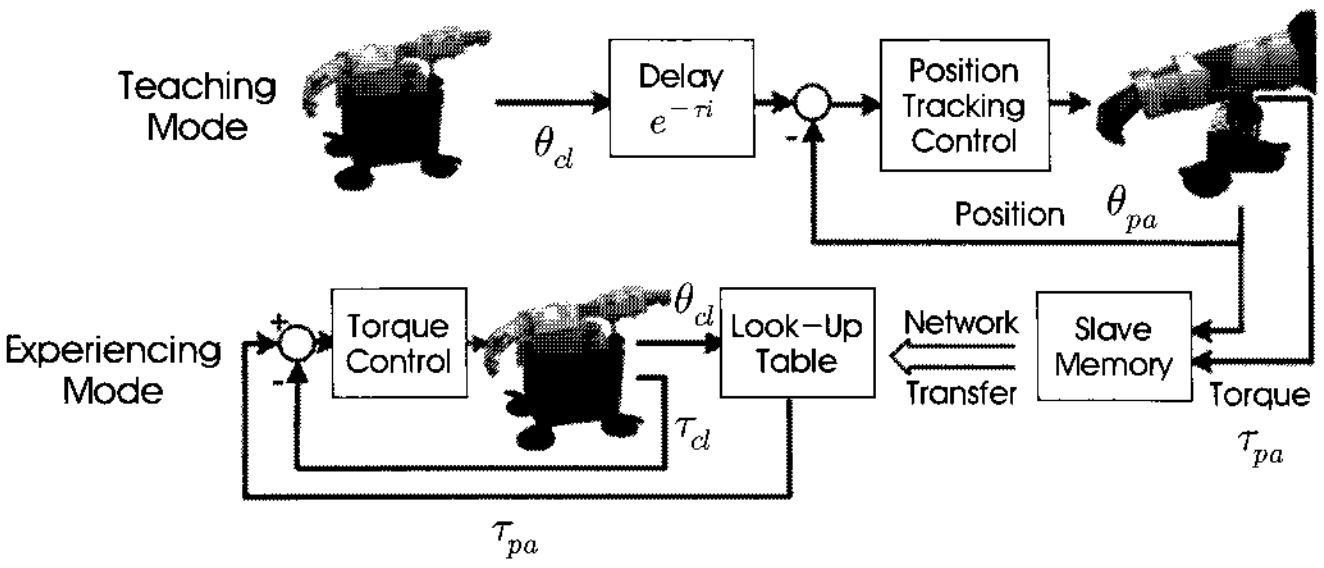

Fig. 6. Semi-real-time control mode using memory-based torque display

The trial after the teaching mode is called as 'experiencing mode'. In the 'experiencing mode', the clinician was asked to repeat the task with the similar velocity that he/she used in the last trial done in 'teaching mode'. With the trial of 'experience mode' and that of 'teaching mode' done right next to each other, variation of the resistance torque associated with movement velocity can be minimized. Further, the difference between velocity profiles of the 'teaching mode' and 'experiencing mode trials will be displayed in real-time so that the clinician can make more consistent movement.

The teaching mode and the experiencing mode could be performed multiple times with different motion profiles for different pairs of teaching-experiencing modes for example, the clinician could feel the stiffness of the joint at low, medium, and high speed by teaching the three different motion profiles and experiencing the torque display from each of the three look-up tables. The clinician experienced true stiffness without any delayed feel since the position and the torque saved in the look-up table were synchronized.

In both the teaching and the experiencing modes, the position and torque limits set previously from the real-time passive ROM test were always valid to insure the safety of the patients. The patient's elbow joint never went out of the position limits even though the clinician gave motion commands over the limits. Since the clinician did not feel any resistance in the 'teaching mode', the clinician was notified by beep sounds and warning signals when he/she went over the limits.

V. EXPERIMENTS

The proposed control method was verified through experiments with a stroke patient. With the IRB approval, the subject was recruited and signed the consent form before the experiment.

The controller for the master was implemented on a laptop platform. A data acquisition card (NIDAQ 6036E, National Instrument Inc.) interfaced the signals between the laptop and the master device. For the slavedevice, another data acquisition board (NIDAQ PCI-6031, National Instrument Inc.) interfaced between the PC and the slave. The real-time communication between the master and the slave was implemented using the TCP/IP protocol.

First, the passive ROM test was performed using the real-time tele-assessment. The time delay between the master and the slave varied from 30 to 60 msec and the real-time tele-assessment control could simulate the in-person assessment. The resistance torque (and joint stiffness) felt by the clinician was close to the real resistance torque (stiffness) at the spastic joint while the rotation angle of the spastic joint underwent same angle that the clinician commanded (Fig. 7). The passive ROM test could be performed with slow speed; therefore, the delayed feeling due to the network latency was negligible so that the clinician could make correct evaluation.

Second, the spasticity test was performed using the semi-real-time tele-assessment function. The clinician operated in

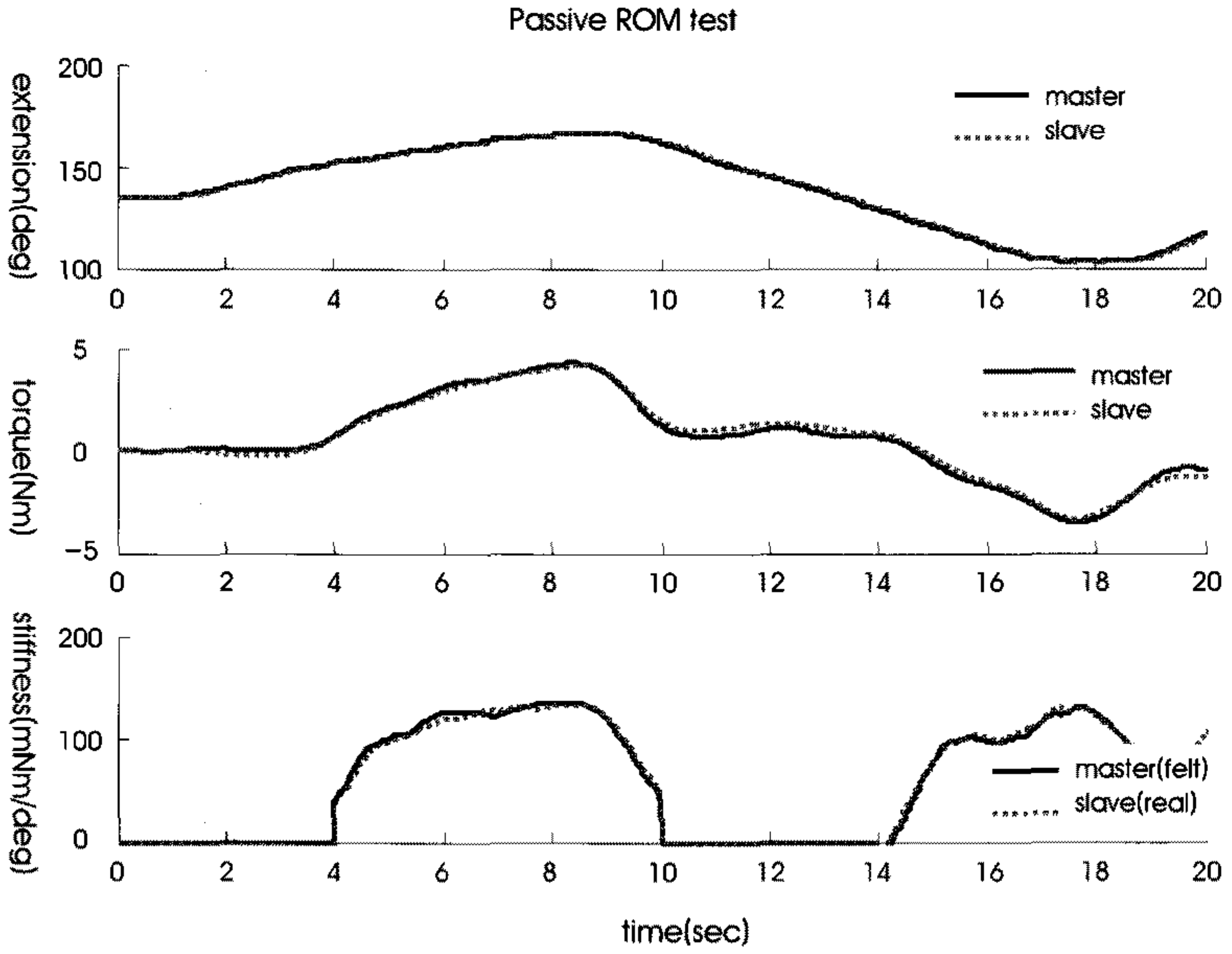

Fig. 7. Passive ROM test by real-time tele-assessment. The position of the subject's limb (dotted red) tracked the position of the haptic device (solid blue) while the clinician felt torque (solid blue) tracks the torque measured at the subject's joint (dotted red). As a result, the stiffness felt by the clinician (solid blue) was same with the stiffness at the subject's joint (dotted red). Throughout the task, the position and torque limits were measured.

two control modes teaching mode and experiencing mode. In teaching mode, the position and torque data were collected at the slave to construct the position-torque relationship of the spastic joint. Then in experiencing mode, the clinician felt the torque from the look-up table which has the position-torque relationship. The clinician was asked to make movement similar to the movement he made in the teaching mode and he could feel the true stiffness of the spastic joint (Fig. 8). The patient's joint did not go out of the position/torque limits which were set from the passive ROM test previously done.

Duringthe two tasks, the clinician and the patient saw and talked each other using the video conferencing tool, Microsoft Messenger 7.0 with the web-camera and microphone installed on the PC. The delay in the video conferencing was not negligible; however, the clinician could successfully communicate with the patient.

Ⅵ. CONCLUDING REMARKS

A tele-assessment system for hypertonic elbow joints of neurologically impaired patients was developed with the video conferencing and physical assessment functions. Two control strategies were proposed to deal with the network latency. For relatively slow tasks such as the passive ROM test, real-time control architectures were proposed based on the causality models of the tasks. For relatively fast tasks such as the spasticity test, a semi-real-time control method was proposed by implementing 'teaching and experiencing' modes.

The sequence of the tasks was organized in order to guarantee the safety. The passive ROM test was performed at the very beginning of the tele-assessment session to set the position/torque limits for safety. The limit values were used later for the other tasks so the patient's elbow joint could be operated in the safe region.

For the real-time tele-assessment for relatively slow tasks (the passive ROM test), causality-consistent control architectures were designed after analyzing the causality of each task. Two control architectures were designed for causality-consistency with the two types of task causality; PCT and FCT. To cope with the chattering problem caused by the switching between two control architectures, smooth transition between the two control architectures was achieved by adopting the boundary layer. The Passive ROM test could be performed successfully in real-time under the network latency up to 60 msec.

For relatively fast tasks such as the spasticity test, a semi-real-time control was achieved using a 'teaching and experiencing' method. The clinician firstly moved the patient's limb with the desired speed without feeling any resistance torque. After recording the position-torque relationship to a look-up table at the slave and transferring it to the master, the clinician could experience the feel in the next trial. The

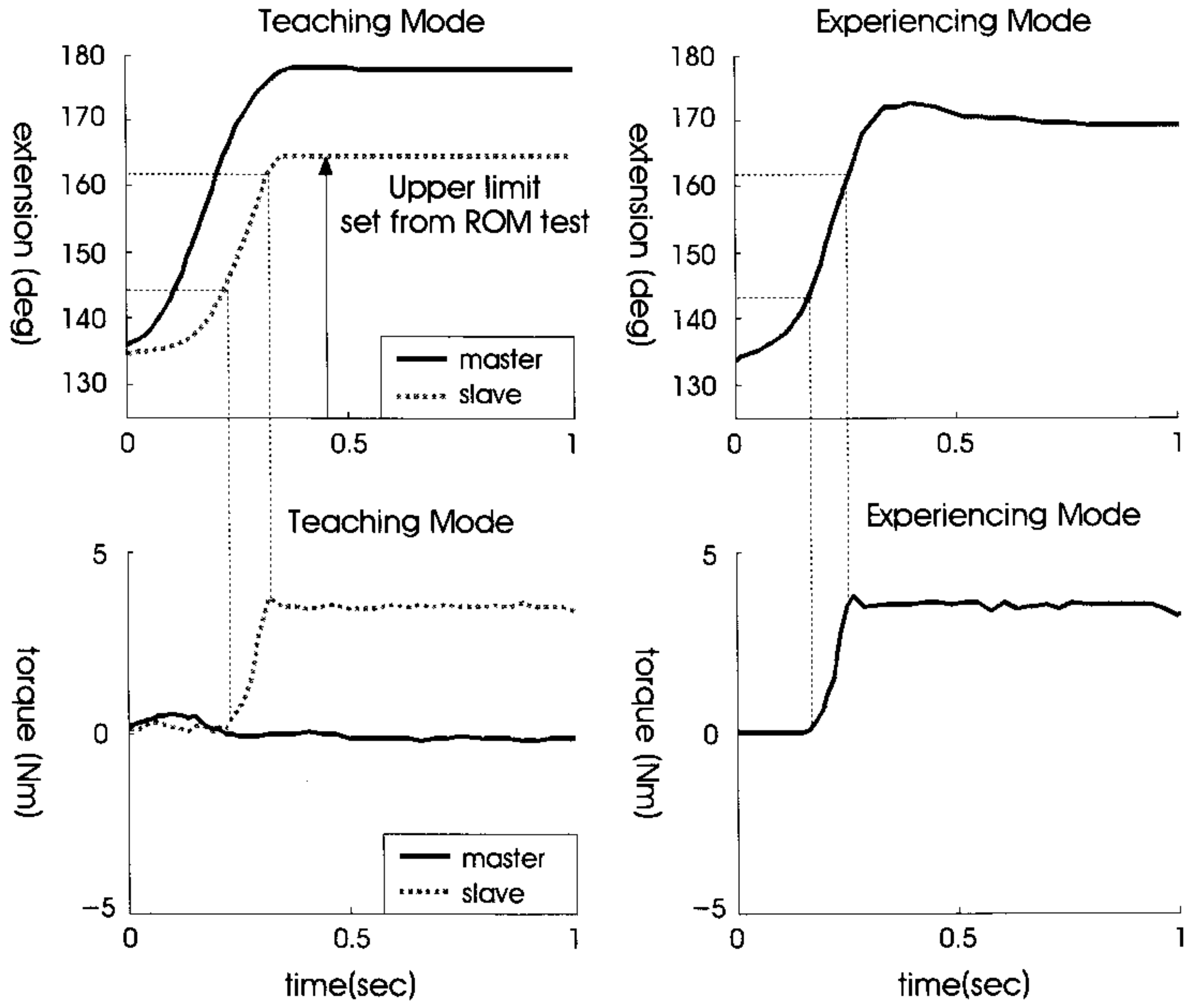

Fig. 8. Spasticity test by semi-realtime tele-assessment. In teaching mode, the clinician made position command (solid blue of left upper plot) and the subject's limb position (dotted red of left upper plot) underwent the command. Although the position command from the clinician went over the upper position limit (164 deg), the slave did not go over the limit. Meanwhile the torque at the suject's joint (dotted red of left bottem plot) was measured while the clinician felt no resistance. In the experiencing mode, the clinician felt same torque saved in the teaching mode when he repeated the task.

stability and transparency of this semi-real-time method were not affected by the amount of the network latency - the clinician could always experience *true feel* regardless of the amount of network latency.

The two methods were verified experimentally on a patient with stroke. The passive ROM test and the spasticity test were conducted successfully. The clinician could not only see and talk to the patient, but also feel the patient's elbow joint in real-time.

The tele-assessment system was designed with low cost and portability for a potential commercialization issue. In addition, the device can potentially be modified for other joints such as wrist, ankle, and knee.

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