A Portable Telerehabilitation System for Remote Evaluations of Impaired Elbows in Neurological Disorders

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***Abstract*—A portable teleassessment system was designed for remote evaluation of elbow impairments in patients with neurological disorders. A master device and a slave device were used to drive a mannequin arm and the patient's arm, respectively. The elbow flexion angle and torque were measured at both the master and slave devices, and sent to each other for teleoperation. To evaluate spasticity/contracture of the patient's elbow remotely, the clinician asked the patient to relax the elbow, moved the mannequin arm at a selected velocity, and haptically felt the resistance from the patient's elbow. In other tasks, the patient moved his/her elbow voluntarily and the clinician observed the corresponding mannequin arm movement and determined the active range of motion (ROM). The clinician could also remotely resist the patient's movement and evaluate the muscle strength. To minimize the effect of network latency, two different teleoperation schemes were used depending on the speed of the tasks. For slow movement tasks, real-time teleoperations were performed using control architectures that considered causality of the tasks, with performance similar to that during an in-person examination. For tasks involving fast movements, a teach-and-replay teleoperation scheme was used which provided the examiner with transparent and stable haptic feeling. Overall, the teleassessment system allowed the clinician to remotely evaluate the impaired elbow of stroke survivors, including assessment of the passive ROM, active ROM, muscle strength, velocity-dependent spasticity, and catch angle.**

***Index Terms*—Haptic feel, rehabilitation robot, remote assessment, stroke, teleoperation.**

I. Introduction

TELEREHABILITATION enables delivery of healthcare services to patients in remote locations using telecommunications technology. It provides the convenience and readiness of services to those living in rural areas and improves the quality of their lives [1], [2]. Telerehabilitation also brings economic benefits [3], [4] such as reduced medical cost, reduced travel-time, and increases the number of patients a clinician can treat in a single day. Telerehabilitation has an extremely promising future business potential considering the growing population of elderly people worldwide—people who will need easy access to healthcare services [5], and medical staff shortages, especially in rural areas [6], [7]. This paper aims at developing a telerehabilitation system for patients with neurological impairments including stroke, spinal cord injury, multiple sclerosis, and cerebral palsy. These conditions affect the life of millions of people worldwide.

Patients with neurological disorders develop impairments such as reduced range of motion (ROM), contracture, spasticity, and muscle weakness [8]–[10]. These impairments are usually assessed through physical exams by experienced clinicians. Furthermore, various surgical, drug, and physical therapy treatments of neurological disorders need to be followed by timely clinical assessment, and physical interaction between clinicians and patients are essential in these clinical assessments [11], [12]. For example, to evaluate spasticity and contracture, a clinician moves the patient's impaired joint at certain velocities and feels the corresponding muscle tone and catch. For the assessment of muscle strength, the patient is also asked to move his/her joint against the resistance of the clinician's hand. For many individuals with neurological impairments, access to expert clinical assessment is limited by financial resources and distance to a qualified medical center, resulting in suboptimal treatment. Teleassessment using the internet could overcome those difficulties [13].

Although telerehabilitation systems can be used to address the need for quantitative and timely assessment, few studies have been done on physical assessments of the patient's impaired limbs through the internet, with the clinician, physically located at a hospital, examining the patient, physically located at home or a local clinic. Several telerehabilitation systems have been developed to remotely monitor progression of motor dysfunctions using networking technology such as the internet-based database system [14], [15] and video conferencing [16]–[20] without providing "the feel" which is essential in clinical assessments. Unilateral telerehabilitation systems can provide patients with haptic "feeling" based on virtual reality [21], [22], but does not allow the clinicians to feel the patients. The telerehabilitation system developed in this study was aimed at implementing haptic "feeling" so that both the clinicians and the patients feel each other, enabling remote access to medical professionals for quantitative assessment of neurological impairments. Most importantly, the teleassessment system developed in this study provides clinicians with transparent haptic

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feeling, which is sometimes more meaningful than quantitative measures for experienced clinicians.

The underlying technology for the transparent haptic feeling has been developed in the area of telerobotics. Two manipulators interacting with shared virtual environments achieve cooperative control over the internet [23], [24] and the feeling of touch in shared virtual environments significantly improves task performance and the sense of togetherness when the time delay between the two manipulators is negligible [25].

A major difficulty in achieving remote physical examinations with transparent haptic feeling is that the transparent and stable teleoperation system will be precluded by the inherent time delay involved in communications between the central hospital and the remote location (e.g., a local clinic or the patient's home). In previous studies of teleoperation, it was well recognized that bilaterally controlled master and slave robots experienced instability due to the time delay (even though the delay was small) [26]. In addition to the stability issue, reliable implementation of transparent feeling without losing stability was another difficulty involved in telerobotics [26]. In previous literature, this instability problem has been solved by making the master–slave system passive [27]–[31]; however, the implementation of transparent haptic feeling is limited, especially for fast tasks, and results in a degradation of the quality of haptic feeling. The degraded haptic feeling of the patient's limb may result in inaccurate assessment since the clinician may feel differently compared to an in-person physical examination.

The purpose of this study was to develop a portable teleassessment system which would allow clinicians to reliably evaluate, through the internet, the neuromuscular properties of the patient's elbow including the passive and active ROMs, stiffness, muscle strength, spasticity with velocity dependence and catch angle. To address the critical issues related to the time delay involved in internet communication, different control strategies were developed to deal with tasks with different bandwidths (or speeds). For tasks involving slow movement (low bandwidth), a real-time teleassessment was achieved based on causality analysis of the teleassessment tasks to guarantee stability with transparent haptic feeling. For tasks involving fast movements (high bandwidth), a teach-and-replay control method was developed, which allowed a clinician to examine patients with reliable haptic feeling through repeated identical movements.

II. Telerehabilitation System and Tasks

A. Telerehabilitation System

A telerehabilitation system was developed to provide physical as well as audiovisual interaction between a clinician and a patient (Fig. 1). For teleassessment, the clinician and the patient could see and talk to each other using web-cameras and microphones connected through the internet. In the meantime, the clinician moved a mannequin arm mounted on the master device and the movement information was sent through the internet to control the remote slave device with the patient's arm attached to it. In this way, the patient's elbow was moved identically to the mannequin elbow. The resistance torque from the patient's elbow was measured and haptically displayed at the master device so that the clinician could *feel* the resistance from the patient's elbow. Joint torque and angular rotation were measured at both the master and the slave devices and sent to the other device for real-time control of both devices.

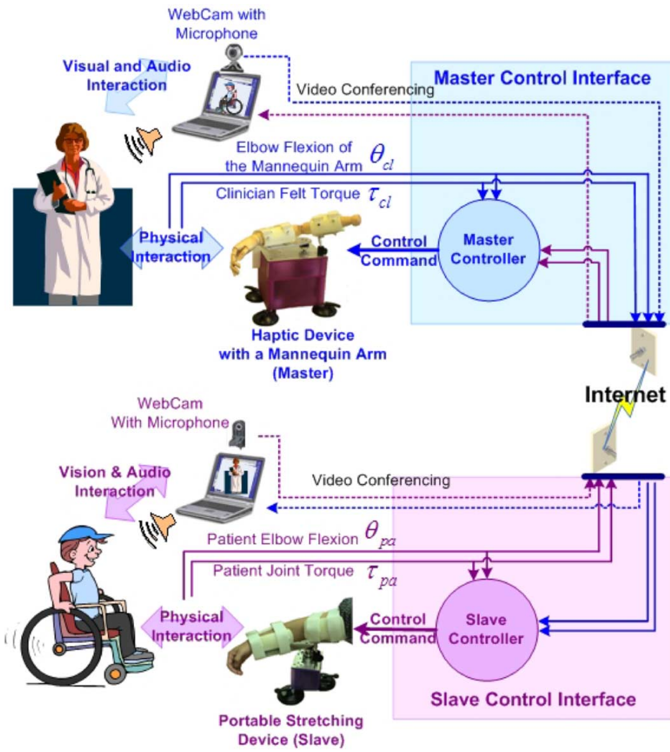

Fig. 1. Schematic diagram of the telerehabilitation system. The master and the slave devices provide physical interactions between the clinician and the patient with remote controls based on the position and torque measurements at both devices. In addition, the clinician and the patient can see and talk to each other using a pair of webcameras and microphones.

In the clinician's office, the haptic device (master) was connected to a desktop PC or laptop with data acquisition capability. The PC, connected to the internet, ran programs for video conferencing and haptic display. At the patient's home similar components were needed: webcamera, microphone, desktop or laptop PC, and the portable stretching device (slave).

The portable stretching device (slave) was designed for portability (Size: $14 \times 11 \times 19\ \mathrm{cm}^3$, Weight: 2.2 kg), while the haptic device (master) measured $16 \times 20 \times 25\ \mathrm{cm}^3$ and weighed 4 kg. Each device has a convenient design for surface mounting using suction cups (Fig. 2). The motor in the portable stretching device had low power requirements, enabling potential use of batteries. The dc servomotor (RE 35, Maxon Motor Inc., Fall River, MA) with a harmonic drive (80:1 in speed reduction, Harmonic Drive LLC, Peabody, MA) generated a maximum torque of 7 Nm. The motor with the gear combination directly rotated a forearm brace, and was mounted through a torque sensor. In the master haptic device, a larger dc servomotor (EC 60, Maxon Motor Inc.) with smaller speed reduction (15:1) by cable driven mechanism was used to enhance back-drivability. The output axis of the cable-driven gear box was aligned with the elbow joint of the mannequin arm and rotated the joint through a torque sensor. The prototype was designed for control and data acquisition using the PC for convenience in programming and data collection; however, a digital signal processor (DSP) can be used to

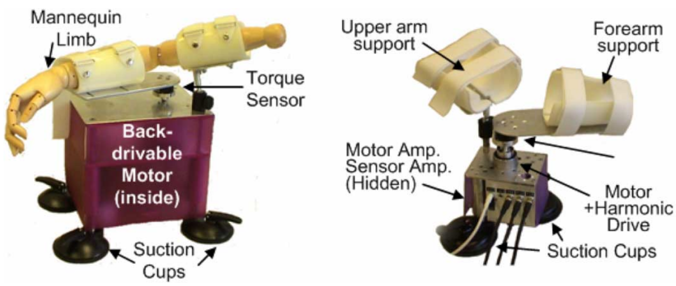

Fig. 2. Portable design of the haptic device (left) and the portable stretching device (right). A Mannequin arm with light weight (wood) was strapped to the haptic device. The portable stretching device was designed for portability by using small motor, harmonic gear, and suction cups.

enhance the portability. The advantage of portable design lies in the convenience of use (easy to move around and set up) and low cost.

The portable design with small components is naturally associated with lower cost. For example, a small motor generally costs less than a larger one. The prototyped master and slave devices used commonly available motors, gears, sensors, amplifiers, and other circuit boards, costing a few thousand dollars. Reimbursement through insurance coverage should make the end-user (patients) cost for these devices fall within a reasonable range. In addition, using a leasing option may potentially decrease the end-user cost.

Besides the teleassessment function which is the main focus of this paper, the telerehabilitation system was aimed at remote treatment in the patient's home. Even without the online connection, the portable limb stretching device located in the patient's home can be used independently for effective therapeutic treatment [32]. The stretching device will be able to measure biomechanical properties of the limb independently at the remote location and transfer the measured data to the clinician.

The haptic device, located at the clinician's office, can also be used for direct quantitative measurement of neuromuscular properties such as the passive/active ROM, passive/active stiffness, active strength, velocity dependence of resistance torque, and catch angle by placing the patient's arm in the haptic device instead of the mannequin arm.

B. Teleassessment Tasks

Teleassessments were classified and carried out as follows.

1) Passive ROM Test: At the beginning of an assessment session, the clinician moved the mannequin arm at the master device slowly (to minimize potential reflex responses). This commanded the slave device, through the internet, to move the patient's elbow in the same trajectory, and the resistance torque at the patient's elbow was recreated at the master device to provide real-time haptic feeling of the patient's elbow joint. With the slow movement, the haptic feeling could be recreated at the master device reliably in real-time and the clinician could remotely determine the position limits in both elbow flexion and extension under controlled peak resistance torque. The clinician flexed and extended the elbow with the haptic feel and the ROM during the motion was measured.

2) Spasticity Test With Catch Angle Determination: Spasticity involves velocity-dependent resistance to passive movement, which was evaluated remotely by moving the subject's elbow through the ROM determined above. The resulting "muscle tone" was felt by the clinician remotely, providing a measure of the spasticity. The passive movement was done in both flexion and extension and at several velocities, simulating those in clinical examinations. The spastic catch angle of the impaired limbs is defined as the angle above which the resistance to externally imposed movement rises rapidly [33]. The catch angle during the passive movement was determined as a clinical measure using a recently developed method [34].

3) Active ROM Test: The subjects were asked to voluntarily move their elbow and the back-drivable slave device throughout the elbow ROM. The clinician could place a hand on the mannequin arm with little resistance and feel as well as observe the patient's active movement. Elbow joint position during the movement was measured to determine the ROM.

4) Muscle Strength Test: The subjects were asked to flex/extend their elbow while the clinician remotely held the elbow at a selected position. The slave device simply held the patient's elbow according to the position of the master device and sent the measured torque generated by the subject to the master device. The clinician felt the torque generated by the subject during the voluntary strength test.

Among the several tasks, the passive/active ROM tests and muscle strength test did not involve high-speed motions, so real-time and transparent teleassessment control was designed based on causality analysis of the tasks. The spasticity test, however, required fast movement with fast changes in force and its real-time implementation was limited considerably by network latency. Therefore, for the tasks involving fast movement, a teach-and-replay teleassessment method was used, which insured patient safety as well as system transparency and reliability.

III. Real-Time Teleassessment for Slow Tasks

A. Modeling the Assessment Tasks

Before developing teleassessment control architectures, the assessment tasks were modeled with the task causality identified. Appropriate modeling of the assessment tasks lead to proper teleassessment control architectures. Here, causality referred to the causal (cause and effect) relationship between the force (or torque) and position (or angle) variables characterizing the dynamic system. Designing controllers based on proper causality analysis has improved stability and transparency of teleoperation systems [30], [35]–[37].

There were two types of causality among the four teleassessment tasks. For the passive ROM and spasticity tests, the clinician determined the position variable independently and felt resistance torque accordingly. This type of task causality was called the clinician control task (CCT). On the other hand, for active ROM and muscle strength tests, the power was transferred from the patient to the clinician. This represented another type of causality, called the patient control task (PCT). For CCT, the clinician determined the independent angular position and the patient's elbow generates the resultant resistance torque. In contrast, for PCT, the patient determined the independent angular position and felt the resistance torque generated by the clinician.

Understanding and analysis of the teleassessment tasks through the causality-identified model helped to design appropriate control architectures. With the dependency relationship among the angle and torque variables identified, the communication structure between the master and slave devices could be designed accordingly.

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

As mentioned previously, real-time teleassessment was implemented for *slow* tasks such as the passive and active ROM tests, and the active muscle strength test. For the passive ROM test, the clinician moved the mannequin arm strapped to the master haptic device, felt the resistance torque from the patient in real-time, and determined the position/torque limits of the elbow joint based on the haptic feeling and/or real-time torque feedback. The position and torque limits set in the passive ROM test insured safety throughout the whole teleassessment session.[1] The slave device never moved beyond the preset position/torque limits. The use of torque limits ensured safety when misalignment of the elbow joint or movement of the arm in the device might have introduced position measurement error. This acted as a failsafe for the position limits; the device did not stretch the joint above the torque limits even when the position limits were not working properly due to measurement errors.

In order to set the limits properly, the clinician needed to have reliable haptic feeling of the patient's elbow through the teleassessment system. In previous research on teleoperation, the stability issue has been investigated thoroughly [26]–[31], [35]. Among several methods that guaranteed stability, we selected a causality-based method [35], [37] since it allowed the clinician to feel the patient's elbow with minimal distortion.

Two control architectures were chosen for the two types of task causality. For the CCT, the master device sent the position command to the slave device and the slave device sent the resistance torque from the patient's elbow back to the master device so that the control scheme conforms to the causality of CCT. Accordingly, a torque tracking controller was implemented in the master device and a position tracking controller in the slave device. On the other hand, for the PCT, we reversed the control architecture; the slave device sent the position signal to the master device and the master device sent back the torque signal. The control architecture for PCT was applied to the active ROM test and the muscle strength test since, in those tasks, the patient independently created the movement while the clinician resisted. The task causality and corresponding controllers for each task are summarized in Table I.

The control laws of the master device are as follows:

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

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_* represents the gains of the controller of the master device. Similarly, the control law at the slave device is as follows:

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

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, a solution to the time-varying network latency was needed. By nature, network latency is time-varying and unpredictable; therefore, the time course of the position and torque data might be distorted after they were transferred through the network. As a remedy to the problem, we added time tags to the position and torque data so that the time course of the data could be reconstructed without distortion.

[1]For measurement of passive ROM, 3 Nm of resistance torque was used; however, higher values were used for torque limits in the spasticity test to allow observation of the hypertonic reflex when it was stretched with fast speeds.

TABLE I
TASK CAUSALITY AND CORRESPONDING CONTROLLERS FOR EACH TASK

	Passive ROM	Active ROM	Muscle Strength	Spasticity
Task causality	CCT*	PCT**	PCT	CCT
Control mode	Real-time	Real-time	Real-time	Teach & Replay
Master controller	Torque tracking	Position tracking	Position tracking	Torque tracking
Slave controller	Position tracking	Torque tracking	Torque tracking	Position tracking

* CCT stands for Clinician Control Task
** PCT stands for Patient Control Task

IV. TEACH-AND-REPLAY TELEASSESSMENT FOR THE SPASTICITY TEST

A teach-and-replay method was developed for fast tasks such as the spasticity test where the angular speed during the test ranged from a slow movement of approximately 30°/s to a fast movement of approximately 210°/s [38]. The real-time implementation of these tasks was limited by network latency. A recent investigation on three wide-area internet paths over a period of two to three days showed that the typical latency varied from around 0.11–0.210 s in an intercontinental application [39]. For an intercity application, the round trip time delay was 0.086 ± 0.032 s between our institution and another city in the country.[2] The real-time teleassessment could not achieve transparent and reliable haptic feeling during the spasticity test with this magnitude time delay. As a remedy, we developed a teach-and-replay strategy to address this limitation.

Spasticity is characterized by a velocity-dependent increase in tonic stretch reflexes, considered to be associated with exaggerated stretch reflexes with a velocity-dependent increase in the resistance to passive movement [40]. Furthermore, a "catch" (sudden appearance of increased muscle tone) can often be felt during passive movement of the spastic limb, and the catch angle is a commonly used clinical measure (e.g., Tardieu and Modified Tardieu Scales) [41], [42]. Therefore, the spasticity test

[2]The round trip time delay was measured at http://www.speedtest.net in July 2007.

through the teleassessment system needed to characterize the velocity-dependent increase in resistance torque and the presence of a "catch," as would be done in an in-person assessment.

The teach-and-replay teleassessment was composed of the "teaching mode" and the subsequent "replay mode." In the teaching mode, the clinician generated the position command trajectory by moving the mannequin arm with a desired speed within the patient's elbow ROM, and the patient's elbow was stretched passively following the same movement within the preset torque and position limits. Although the motion at the slave device was delayed, the position and torque measured at the slave device were synchronized, and they could be used to determine the relationship between the position and resistance torque. When the clinician repeated the same movement immediately in the next trial in "replay mode," the clinician could *feel* the joint resistance and stiffness recreated based on the torque-angle relationship. In the replay mode, the clinician was asked to repeat the task with the same movement pattern as that he/she generated in the "teaching mode." The replay trial was done immediately after the teaching trial so that the clinician could repeat the movement closely.

In the teaching mode, there were two important issues for the safety and the reliability of the test. First, due to the lack of haptic feeling of the resistance torque, the clinician might move the elbow beyond the patient's ROM. Second, the motion that the clinician created in the teaching mode may not be the same as the motion that the clinician would have created during an in-person test, including the clinician's reaction (slowing down) to the high resistance torque. For the first issue, the slave device was programmed so that it could override the command from the master device if the command was either beyond the patient's ROM (which was measured during previous passive ROM testing), or the resistance torque at the patient's elbow was greater than the torque limits. For the second issue, the clinician's reaction to the high resistance torque was recorded during an in-person test and the following velocity adjustment was active after the peak $d\tau/dt$ was reached, as shown in the equation at the bottom of the page.

The command for the stretching velocity of the patient's elbow ($\dot{\theta}_{\rm cmd}$) was equal to the commanded velocity ($\dot{\theta}_{cl}$) when the magnitude of the resistance torque at the patient's elbow (τ_{pa}) was smaller than a threshold value, $\tau_{t\_{\rm hold}}$. When $|\tau_{pa}| > \tau_{t\_{\rm hold}}$, $\dot{\theta}_{\rm cmd}$ was inversely proportional to the magnitude of the resistance torque. This slowed the stretching speed with the increasing resistance torque [43]. The speed adjustment based on resistance torque insured safety and imitated clinician behavior at increased resistance.

The teaching mode and the subsequent replay mode could be used multiple times with different motion profiles. For example, the clinician could feel the stiffness of the joint at low, medium, and high speeds by teaching at a certain speed and replaying the motion profile in the trial that immediately followed.

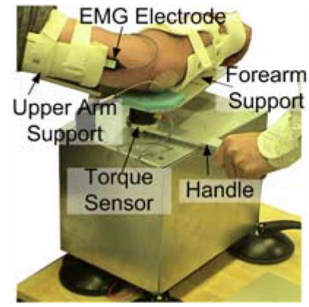

Fig. 3. Setup for the in-person assessment, using a modified version of the master device. The arm of the subject was strapped to the master device with the motor turned off. The clinician held the handle and rotated the elbow passively to measure the passive ROM and spasticity. The clinician held the handle in place or let it move to measure active muscle strength or active ROM, respectively. The torque sensor and encoder (hidden) measured the joint torque and the elbow flexion angle, respectively. EMG signals were measured at the elbow flexor and extensor muscles to monitor the muscle contractions.

V. Experimental Validation

Four patients poststroke (60 $\pm$ 12.9 years old, 7.8 $\pm$ 3.8 years poststroke, 2.25 $\pm$ 0.95 in Modified Ashworth Scale, and 3 $\pm$ 0 in reflex scale) were recruited and evaluated using the teleassessment device. All subjects gave informed consent before the study, which was approved by the Institutional Review Board of Northwestern University.

The controller for the master device was implemented in a PC using a data acquisition card (PCI-6229, National Instruments Inc., Austin, TX) to interface between the PC and the master device. For the slave device, the same data acquisition board interfaced between the PC and the slave device. Real-time communication between the master and the slave devices was implemented using the UDP (User Datagram Protocol) since it showed better performance than did the TCP/IP (Transmission Control Protocol) in real-time teleoperation [44].

During the teleassessment sessions, the clinician and the patient could see and talk to each other using a video conferencing tool (Microsoft Messenger 7.0) with a web-camera and microphone installed on each PC. The delay in the video conferencing was not negligible; however, the clinician and patient could successfully communicate with each other.

The haptic device and the stretching device were located in different rooms in the same building. The closed network within the same building did not show significant network latency or congestion.

The round trip time-delay between the two devices was intentionally added with randomly chosen delays between 0.06 and 0.12 s based on our measurements of the network latency from

$$\begin{cases} \dot{\theta}_{\rm cmd} = \dot{\theta}_{cl}, & \text{when } \theta_{\rm cmd} \text{ is within the ROM, and } |\tau_{pa}| \leq \tau_{t\_{\rm hold}} \\ \dot{\theta}_{\rm cmd} = \dot{\theta}_{cl}\frac{\tau_{t\_{\rm hold}}}{|\tau_{pa}|}, & \text{when } \theta_{\rm cmd} \text{ is within the ROM, and } |\tau_{pa}| > \tau_{t\_{\rm hold}} \\ \dot{\theta}_{\rm cmd} = 0, & \text{when } \theta_{\rm cmd} \text{ is out of the ROM} \end{cases}$$

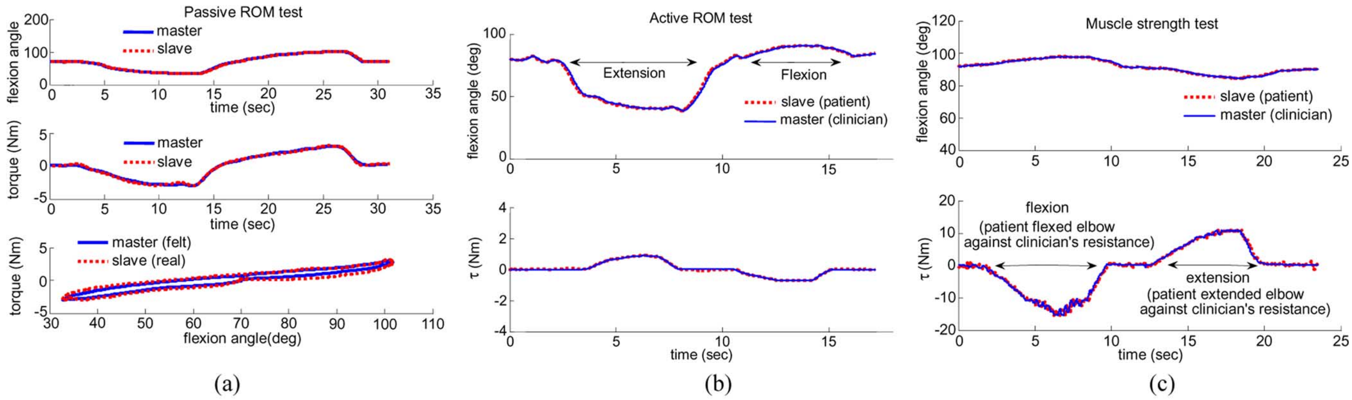

Fig. 4. Results from real-time teleassessment (one representative case). (a) Passive ROM test: the position of the subject's elbow (dotted red line in the top figure) tracked the position of the haptic device (solid blue in the top figure) while the clinician felt torque (solid blue in the middle figure) tracks the torque measured at the subject's joint (dotted red in the middle figure). As a result, stiffness felt by the clinician (solid blue line in the bottom figure) was the same as the stiffness at the subject's elbow joint (dotted red in the bottom figure). (b) Active ROM test: the subject flexed and extended the elbow as much as he could. The elbow movement at the slave device was followed by the same movement of the master device. (c) Muscle strength test: the patient was asked to flex and extend his elbow maximally while the clinician resisted the movement by holding the manikin arm in place. The slight motion created at the slave device was transferred to the master device so that the master device could follow the command and the clinician felt the push from the patient and his muscle strength. Meanwhile, the resistance torque at the master was measured and transferred to the slave so that the patient experienced the resisting torque from the clinician. The three task could be performed with close haptic feeling during the slow tasks at the presence of $0.03 \sim 0.06$ s of network latency.

TABLE II
MEASURES OF THE IN-PERSON AND TELE ASSESSMENT TESTS FROM FOUR SUBJECTS

		Passive ROM (deg)*		Active ROM (deg)*		Muscle Strength (Nm)		Catch Angle (when elbow was extended)
		Extension	Flexion	Extension	Flexion	Extension	Flexion	
Subj. 1	In-person	26.6	109.3	35.4	105.4	11.8	14.7	Not observed
	Tele	29.1	108.1	38.0	104.9	11.3	15.8	Not observed
Subj. 2	In-person	31.8	103.9	73.2	95.3	6.2	7.8	58.8 deg
	Tele	33.2	101.5	75.8	96.7	4.9	6.2	58.4 deg
Subj. 3	In-person	50.1	105.2	78.6	101.0	3.0	4.5	Not observed
	Tele	49.4	102.1	77.0	99.8	3.2	4.9	Not observed
Subj. 4	In-person	56.2	102.6	75.3	98.5	4.8	5.4	50.3 deg
	Tele	53.8	100.0	72.2	97.3	4.0	5.1	49.8 deg
Mean±	In-person	41.2±14.2	105.3±2.9	65.6±20.3	100.1±4.3	6.5±3.8	8.1±4.6	
STD	Tele	41.4±12.1	102.9±3.6	65.8±18.6	99.7±3.7	5.9±3.7	8.0±5.2	
MPD**		9.4%	2.9%	7.3%	1.5%	6.7%	20.1%	1%
Pearson's Correlation		1.000	0.990	0.992	0.961	0.986	0.980	
Significance (P value)		0.000##	0.010##	0.008##	0.039#	0.014#	0.020#	

*: 0 deg corresponding to elbow full extension.
**: Maximum Percentage Difference (MPD) between the in-person and teleassessment measurements.
#: Correlation was significant at the 0.05 level (2-tailed).
##: Correlation was significant at the 0.01 level (2-tailed).

our institution, and the report that the maximum allowable delay in haptic feedback is less than 0.1 s [45], [46].

For monitoring muscle activation at the elbow joint, EMG signals were measured from the biceps and triceps muscles using surface electrodes (Bagnoli-8, Delsys Inc., Boston, MA). The overall amplification was 1000. EMG signals were sampled at 1000 Hz with a 16-bit resolution. The EMG electrodes were placed on the main elbow flexor (biceps brachii) and extensor (triceps brachii), and the reference electrode was placed on the lateral epicondyle. In order to determine the onset time for verifying the catch angle, the raw EMG was full wave rectified.

For each of four tests, both an in-person assessment and a teleassessment were performed and compared to each other.

A. Passive ROM

For the in-person assessment, the passive ROM was measured manually. The subject's limb was affixed to the master device for quantitative measurement of the passive ROM (Fig. 3). The clinician held the handle and rotated the subject's elbow until a certain level of resistance torque (3 Nm) was reached. The torque curve was displayed on a monitor with visual feedback so that the clinician could perform the task accurately. Meanwhile, the elbow flexion angle and torque were recorded using the device.

The real-time teleassessment of the passive ROM was implemented by using the control architecture for CCT. The clinician rotated the mannequin arm in flexion and extension slowly until the resistance torque reached 3 Nm, based on real-time visual feedback and haptic feel.

The real-time teleassessment control, performed at a slow speed of $< 10°/\mathrm{s}$, matched the in-person passive ROM test closely [Fig. 4(a)]. The passive ROM results from the teleassessment were similar to those from the in-person assessment and were highly correlated (Table II).

Practically, for the data shown in Table II, the examiner was more cautious during the teleassessment than during the in-person test since teleassessment was new to the examiner. As a result, the examiner extended/flexed the elbow to the level of slightly less than 3 Nm (stopped near the displayed 3.0 Nm target). This made the passive ROM determined in the teleassessment mode slightly smaller than that obtained in the in-person test.

B. Active ROM

First, for the in-person assessment, the active ROM was measured with the subject's limb affixed to the master device (Fig. 3). Second, the active ROM was measured through real-time teleassessment with the control architecture for PCT implemented. The task was performed at a slow speed so that the time delay did not influence the performance of teleassessment system [Fig. 4(b)]. The active ROMs measured during teleassessment were similar to those from the in-person assessment with high correlations between them (Table II).

C. Muscle Strength Test

The flexion and extension strengths were measured by the torque sensor when the subjects strongly flexed/extended their elbow. Teleassessment was then performed with the PCT control architecture implemented. The task was done in a quasi-static condition and no high-speed movement was involved. The patient's strength was haptically felt by the clinician with negligible distortion [Fig. 4(c)].

The results from the three teleassessment tasks were highly correlated with the results from the in-person assessment (Table II), indicating a highly linear transfer function of the telerehabilitation system. The real-time teleassessment provided not only the transparent haptic feeling of the subject's elbow, but also the quantitative measures obtained during the tests.

The maximum percentage difference (MPD) of the in-person and teleassessment measurements ranged from 1% to 20.1% (Table II). Although the clinician felt very similar torque measured at the patient's elbow during teleassessment, the MPD was not negligible. This might be due to the extra caution the examiner (or the subject) took and pushed the elbow slightly less during the teleassessment. For example, Subject 2 flexed/extended the elbow with lower torque in the teleassessment setup than in the in-person setup.

D. Spasticity Test

1) Velocity-Dependence of the Resistance Torque: The examiner manually rotated the subject's elbow joint in the extension direction at slow (about 30°/s), medium (about 90°/s), and fast (about 180°/s) speeds. For the in-person spasticity test, the master device was used to measure the position and torque (Fig. 3). The arm of the subject was affixed to the master device and the clinician held the handle and rotated the elbow at slow, medium, and fast speeds to evaluate velocity-dependence of the resistance torque. For teleassessment, the arm of the subject was affixed to the slave device, and the clinician rotated the mannequin arm in the master device. Teaching and replay modes were performed repeatedly at slow, medium, and fast speeds. The angle-torque curves at the three speeds showed the velocity-dependence of the joint. Higher joint stiffness was

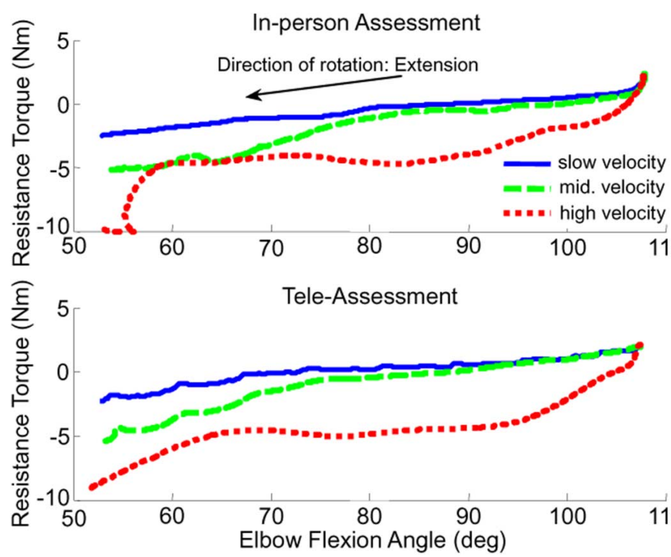

Fig. 5. Velocity dependence of resistance torque. The subject's elbow was rotated externally with three different speeds: slow ($\sim 30°/s$), medium (90°/s), and high (180°/s) speeds. The amount of resistance torque (positive when the subject resisted elbow extension) increased with the elbow extension, and the rate of increase was higher for higher velocity. The examiner felt higher resistance at higher velocity both in the in-person (upper plot) and the teleassessment (lower plot) tests.

measured for higher extension speeds both in the in-person assessment and during the teleassessment (Fig. 5). Throughout the test, the patient's elbow did not go beyond the position/torque limits (preset during the passive ROM test). In teaching mode, the velocity adjustment at the slave device was implemented with 4 Nm assigned for τ_{t_hold} according to measurements made during the in-person test.

For testing of the velocity-dependence of the resistance torque, beep sounds, and a visual display at certain velocity levels were used as references to assist the examiner in generating a consistent speed for two consecutive teaching and replay trials. The clinician heard a beep and saw a lit LED on the monitor screen when the target speed was reached. With those aids, clinicians could generate the target speed within 5%. For example, a single clinician generated a speed of $183.9 \pm 5.4°/s$ when the target speed was 180°/s.

2) Catch Angle Measurement: There are two events associated with the "catch angle" commonly measured in clinical practice.

1) The angle where the derivative of the resistance torque ($d\tau/dt$) reached its peak is related to the rapid increase in the resistance torque due to the stretch reflex. The peak of $d\tau/dt$ was used to determine the catch angle [34], [37].
2) The angle where the clinician slowed the movement speed to a local minimum after he/she felt the rapid increase in resistance. This angle with the local minimum speed was reached shortly after the instant corresponding to the peak $d\tau/dt$ and catch angle. It was used as a landmark to help determine the location of the peak of $d\tau/dt$.

For the in-person assessment, a sequence of events occurred in the "catch" process, as shown in a representative case of a poststroke patient with elbow spasticity [Fig. 6(a)].

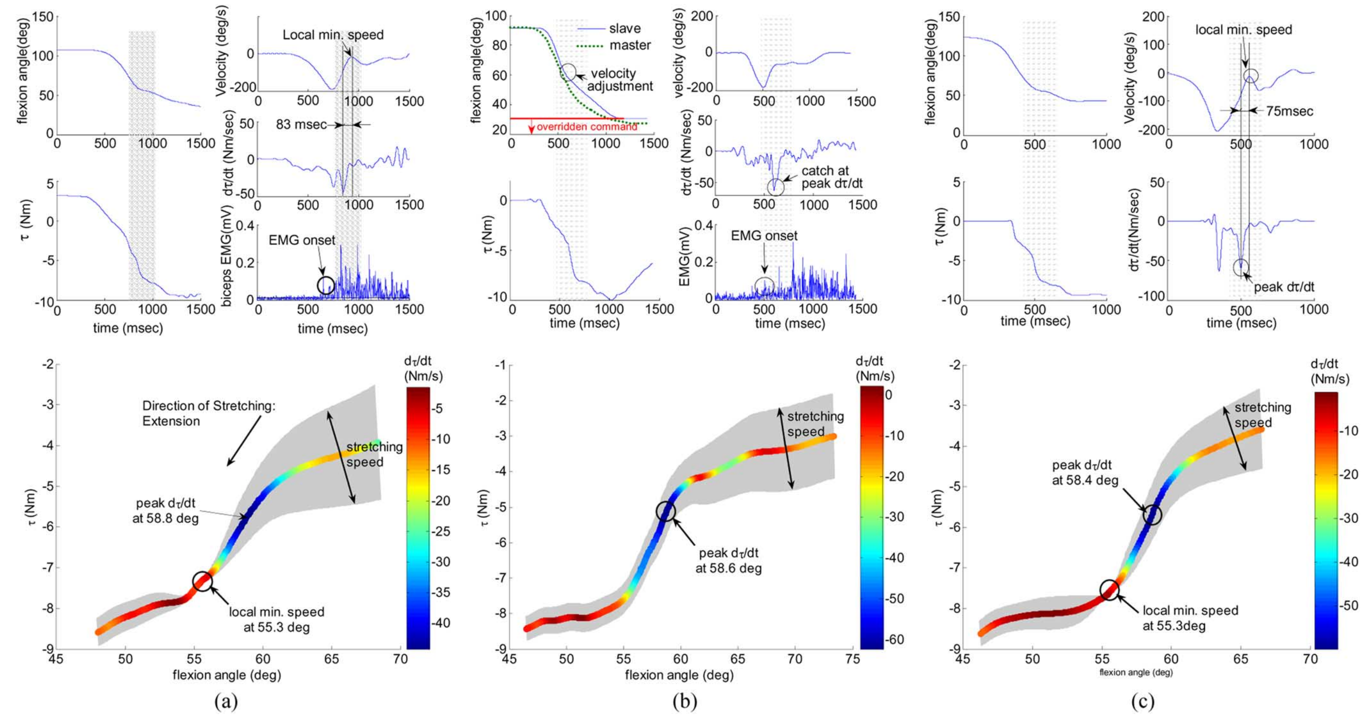

Fig. 6. Catch angle determination. (a) In-person spasticity test (left column). The clinician extended the elbow joint with the peak speed of 180°/s. The reflex-mediated biceps EMG started at ~ 0.7 s, $d\tau/dt$ peaked at 0.9 s, and the speed reduced to a local minimum at 0.983 s due to the reaction of the clinician to the rapid torque increase. In the lower figure, four variables were used in determining "catch" angle in spasticity test (zoomed figure of the shaded period in the upper figure. In the lower figure of the torque-angle curve, the color represented $d\tau/dt$ and the width of the shaded area showed the speed. In this way, four factors related to the "catch" in spasticity test could be displayed in the same plot. The stretch started from the top-right corner and proceeded to the bottom-left corner. The two events related to the catch could be found by the point where $d\tau/dt$ had the darkest blue and the narrowest shade. The four-in-one graph showed that the catch angles measured by $d\tau/dt$ (at 58.8°) occurred shortly before the speed dropped to a local minimum (at 55.3°). (b) Teleassessment spasticity test in the teaching mode (middle column). The clinician rotated the manikin arm in the master device to extend the elbow and the patient's elbow strapped in the slave followed the movement. The commands below 27° were overridden because they were out of the predetermined ROM. The stretching speed at the slave slowed down when $\tau_{t\_\mathrm{hold}} \geq 4$ Nm. The stretch reflex action occurred around 0.5 s (biceps EMG was onset), the peak value of $d\tau/dt$ was observed at 0.6 s with the flexion angle at 58.6°. (c) Teleassessment spasticity test in the replay mode (right column). The clinician stretched the manikin arm at the master device to extend the elbow and felt the replayed resistance from the data obtained in the teaching mode. The clinician showed similar behavior as that in the in-person assessment shown in (a). The peak $d\tau/dt$ was observed at 0.51 s with the flexion angle of 58.4° and a local speed minimum was reached 0.075 s later at 55.3° elbow flexion.

For teleassessment, in the teaching mode, the catch angle defined by the peak $d\tau/dt$ was observed at 58.6°. The $d\tau/dt$ and EMG were used to verify the catch related responses [Fig. 6(b)].

In the replay mode, the clinician felt the catch from the torque-angle relationship at the patient's elbow through the master device. The clinician showed a similar behavior of slowing the movement after feeling the rapid increase in resistance torque. In order to show the similarity between the teleassessment and the in-person assessment, the catch angles defined by the two methods were measured in the replay mode [Fig. 6(c)], and the results matched closely with those from the in-person assessment. Most importantly, the clinician in the teleassessment setting reported similar haptic feeling as during the in-person assessment.

VI. Discussion

A portable teleassessment system for the elbow joint of neurologically impaired patients was developed including physical assessment as well as video conferencing. For the four teleassessment tasks, two control strategies were used to deal with network latency. For relatively slow tasks, such as the passive/active ROM tests, and active muscle strength test, real-time control architectures were proposed using causality models of the tasks. For fast tasks, such as the spasticity test, a teach-and-replay control was proposed by implementing teach and replay modes in two consecutive trials.

The sequence of the tasks was organized to insure patient safety. The passive ROM test was performed at slow speeds at the beginning of the teleassessment session to set position/torque limits of the patient's elbow. The limit values were then used in other tasks to insure that the joint was moved within the safe range.

For real-time teleassessment in slow tasks, causality- consistent control architectures were designed after analyzing the causality of each task. Two control architectures were designed for causality-consistency with two types of task causality. Slow tasks such as the passive/active ROM tests and active muscle strength test could be performed successfully in real-time when the network latency (round trip delay) was smaller than 0.12 s.

For tasks with high bandwidth, such as the spasticity test, the clinician first moved the patient's limb at the desired speed without any resistance torque feeling. Safety was guaranteed by preset limits. After building the position-torque relationship and transferring it to the master device, the clinician could replay and experience the resistance torque feeling in the next trial. The stability and transparency of this teach-and-replay method were not affected by the amount of network latency—the clinician could always experience the true feeling regardless of the amount of network latency.

Evaluations at both slow and fast velocities were validated experimentally on four patients poststroke. The passive/active ROM test, the active muscle strength test, and the spasticity test including catch angle determination were conducted successfully. The clinician and the patient could see and talk to each other, and the clinician haptically *felt and evaluated* the patient's elbow joint in real-time.

The performance of the teleassessment system was evaluated by measuring how closely the teleassessment system could simulate an in-person assessment. Quantitative measures were defined for each test and obtained from both the in-person and the teleassessment tests. For the passive/active ROM test, the maximum and minimum flexion angles were measured. The maximum flexion/extension torque values measured during the active muscle strength test. For the spasticity test, we defined a novel quantitative measure, the catch angle. The results from the teleassessment were similar to those from the in-person assessment and the statistical analysis showed that the correlations (Pearson correlation coefficients ≥ 0.961) between the in-person assessment and teleassessment were significant $(p < 0.05)$.

Although the teleassessment system simulated the in-person assessment quite well, there were still limitations. First, the real-time control did not implement transparent haptic feeling when the tasks were performed at high speeds. Although the examiner could feel and evaluate the passive/active ROM and active muscle strength at slower speeds, some clinicians may want to evaluate them at high speeds. The bandwidth of real-time teleassessment is intrinsically limited by network latency. The latency caused by network traffic may potentially drop dramatically with the development of high-speed internet technologies and the improvement of the network infrastructure in the future.

Second, the spasticity test was constrained in that the clinician had to rotate the master device with a similar speed between the teaching and replay modes. Visual displays and beeping sounds at certain speeds were used to guide the clinician and the clinician could repeat the same speed within a 5% error bound. For more advanced operation, incorporating the velocity-dependent model of the patient's elbow joint into the angle-torque relationship would virtually present the haptic feeling without this constraint.

Third, the experiments were performed under short network latency $(0.03 \sim 0.06\ \mathrm{s})$ assuming an intercity application within the same country and broadband internet connections between the patient's home and the hospital. However, the network latency could be larger for intercontinental applications. For those applications, all tasks can be executed using the teach-and-replay method and can still provide safe and reliable teleassessment.

The teleassessment control methods developed in this study enable the remote monitoring of the progression of physical treatment with the physical feel which is an essential part of a physical examination. After remote treatment by rehabilitative robots [48]–[52], the progression of physical treatment could be monitored remotely through audio-visual media using videoconferencing techniques [16]–[20]. In addition to the audio-visual information, this study could add haptic feeling, making remote physical examination more accurate and closer to an in-person physical examination.

This study focused mainly on the technical feasibility of the proposed teleassessment system. The intra- and interrater reliability tests will be performed in the future to prove the reliability and the repeatability of the proposed system.

Telerehabilitation has attracted much attention due to its economic benefits [3], [4], [53]—saving both time and money associated with rehabilitation. The teleassessment system in this study is attractive since it was designed to be *low-cost* and *portable*. Furthermore, in addition to the assessments shown above, the slave device could also be used as an independent tool to treat spasticity/contracture. Finally, similar setups can be developed for other joints such as the wrist, ankle, and knee in the future.

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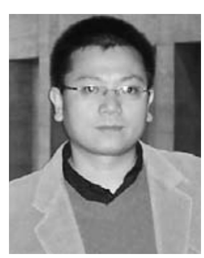

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