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Virtual-Environment-Based Telerehabilitation in Patients with Stroke

Abstract

We describe a telerehabilitation system that has been developed in our laboratory, and initial results following use of the system on 2 patients with stroke. The system allows a therapist in a remote location to conduct treatment sessions, using a virtual-environment-based motor-training system, with a patient who is located at home. The system consists of a patient computer with motion-capture equipment and video camera, a therapist computer with video camera, and virtual-environment software that is synchronized over a high-speed Internet connection. The patient's movements are animated within the context of a virtual scene as she attempts to imitate a prerecorded movement, while the therapist can direct and monitor the activity in real time, as displayed in the animated virtual scene and via videoconference. The design, technical testing, and clinical feasibility testing of the system are reported. Results from the first 2 stroke patients to use the system indicate that patients made significant gains in upper-extremity function as measured by standard clinical tests and by their subjective report. As well, both patients demonstrated gains on quantitative kinematic measures of upper-extremity trajectories performed in the real world, indicating transfer of training from VE to real-world performance.

1 Introduction

The health care delivery system in the United States has been undergoing significant change in recent years. Due to the shortening of hospital stays, patients are returning to their homes following disabling events, such as stroke, sooner than in the past. Often they do so at lower functional levels, and with significant need for continued rehabilitation (Dobkin, 1995). This need is typically met through home care or outpatient therapy services, but often these services are limited in duration. Many patients also encounter transportation problems in accessing outpatient therapy, especially if dependent on others to drive them to appointments. Others experience extreme fatigue from long commutes in tandem with therapy sessions. These patient populations could benefit greatly from a system that allows a therapist to provide rehabilitation services from a remote location, while the patient remains in their home setting.

In addition to this need for new health care delivery models in rehabilitation, the need for new methods in stroke rehabilitation is pressing (National Center for Medical Rehabilitation Research, 1993). The sharp decline in stroke mortality, due to improved medical care, has resulted in a larger number of survivors in recent years. Many of these survivors are left with residual disability. In fact, stroke is the leading cause of disability in the United States, resulting in an estimated annual cost of $30 billion dollars (Dobkin, 1995). To address this need for new treatment approaches, we have developed a novel motor-training system that makes use of a virtual environment (VE) to assist rehabilitation (Holden, 2001; Holden & Dyar, 2002). Recently we have expanded the functionality of the VE system to include home-based telerehabilitation capability (Holden, Dyar, Schwamm, & Bizzi, 2003). Our hope is that we can enable more stroke patients to make use of their latent potential for motor recovery through the use of both a novel treatment approach (VE) and a novel delivery system (telerehabilitation).

A few other groups have reported on the development of telerehabilitation systems. Burdea and colleagues have developed a VE-based telerehabilitation system that focuses on hand rehabilitation using force feedback, and tested this system on orthopedic patients (Burdea, Popescu, Hentz, & Colbert, 2000; Popescu, Burdea, Bouzit, & Hentz, 2000). Reinkensmeyer, Pang, Nessler, and Painter (2002) have developed a Web-based telerehabilitation system that the patient can access independently, and with which he/she can practice simple movements using an adapted computer joystick with force feedback. These systems appear to be designed mainly for independent work by the patient, with the networking component being used to send data to the therapist for later evaluation. Although a videoconferencing link is included in one of these systems (Popescu et al., 2000), it was too slow to support real-time interactive therapy. As presently configured, only highly constrained movements in a very small workspace can be practiced using these systems. Both systems have proven feasible in pilot testing on a single patient. However, neither of the patients was reported to have significant improvement on standard clinical tests of upper-extremity (UE) function following training, though some changes in force production (Burdea et al. 2000; Popescu et al., 2000), movement, and speed (Reinkensmeyer et al., 2002) on selected test items were seen. Piron, Tonin, Atzori, Trivello, and Dam (2003), working in Italy, have reported greater success with home-based telerehabilitation, finding a significant improvement in the mean values for clinical and VE trajectory measures for the first 5 subjects tested, following 4 weeks of daily therapy via telerehabilitation. Their VE software was developed in our laboratory at MIT, and is a precursor to our system, having a similar architecture with synchronized VE at both the patient and therapist locations. Their Internet connection consisted of multiple Integrated Services Digital Network (ISDN) lines providing bidirectional bandwidth of 512 kbps, obtained through a special arrangement with the local Italian phone company. A Web-based telemonitoring system for ankle rehabilitation has also been reported (Deutsch, Boian, Lewis, & Burdea, 2003; Lewis, Boian, Burdea, & Deutsch, 2003). This work has shown the feasibility of using Web-based telerehabilitation for a clinic-to-clinic (vs. a home-to-clinic) setup.

In contrast to the systems described by others (Burdea et al., 2000; Popescu et al., 2000; Reinkensmeyer et al., 2002), our telerehabilitation system (Holden et al., 2003; Dyar & Holden, 2004; Piron et al., 2003) can provide real-time home-based interactive treatment sessions with simultaneous VE and videoconferencing, and can be used to train a wide variety of movements in any part of the UE workspace. In this paper we describe initial results from an ongoing study designed to develop and test the clinical feasibility of the system. We describe the system design and challenges encountered during deployment of the system for home-based use. As well, we describe the details of the VE treatments used, and the results obtained with our first 2 patients. Both have demonstrated clinically meaningful gains on a variety of outcome measures.

2 System Description

2.1 Telerehabilitation Component

Our telerehabilitation system is an enhancement and expansion of a virtual environment (VE) motor-training system previously developed for use with patients with stroke and acquired brain injury (Holden &

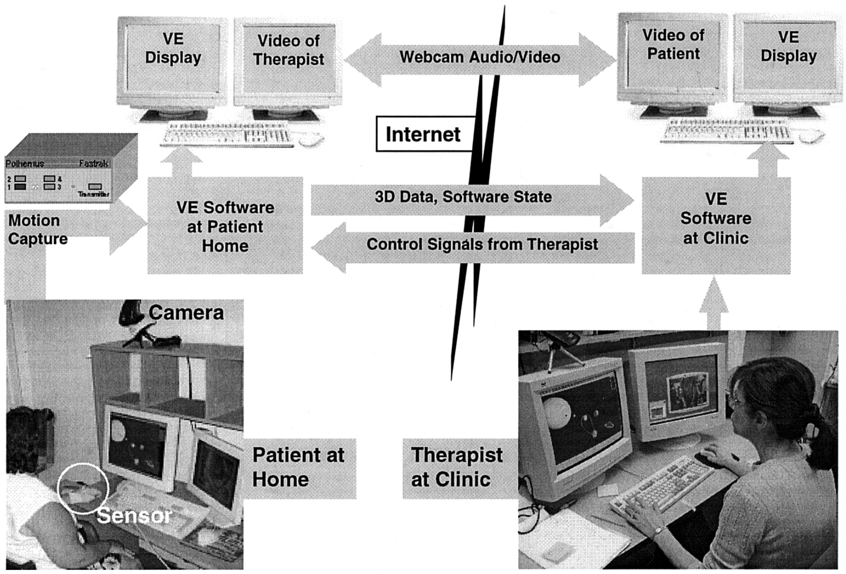

Figure 1. *Schematic of the home-based VE telerehabilitation system. The patient and therapist can see and hear each other via a videoconferencing link on one monitor. Motion-capture equipment transmits information about patient's arm movements to the VE display. The therapist in the clinic controls the software and views the same virtual-environment scene as that displayed to the patient in her home (second monitor). The video camera can be remotely pointed to any part of the patient's workspace.*

Dyar, 2002; Holden, 2001; Holden, Dettwiler, Dyar, Niemann, & Bizzi, 2001; Holden & Todorov, 2002). A diagram of the telerehabilitation system and its various components is shown in Figure 1. The system allows a therapist in a remote location to conduct treatment sessions with a patient who is located at home. The patient's and therapist's computers are connected in real time over the Internet. A videoconferencing link (VC) allows the patient and therapist to see and hear each other in real time during the session; thus the therapist can monitor and guide the patient during treatment. A special feature of the system is the use of a virtual environment (VE) to provide augmented feedback to the patient during the sessions. (Augmented feedback is feedback that is not present during normal environmental conditions.) During training, the patient's movements and error-related feedback are displayed on a computer screen in the patient's home. Simultaneously, the same information is transmitted to and displayed on the therapist's computer at the treatment center. The therapist can view patient's movements and remotely control the VE software and video camera at the patient's home, all in real time.

2.2 VE Training Component

The concept for the VE motor-training component of the telerehabilitation system was initially developed by Bizzi, Mussa-Ivaldi, and Shadmehr (1996), then later adapted for use with patients (Holden, Todorov, Callahan, & Bizzi, 1999; Holden, 2001; Holden & Todorov, 2002). The system uses an electromagnetic motion-tracking device, custom VE software, and a desktop computer monitor. Other visual display devices such as stereo headsets, flicker glasses, or wall-size display using a computer projector may also be used. A central feature of our VE training system is the simultaneous display on the computer screen of the prerecorded arm movements of a "virtual teacher" and of the arm movements made by a patient using the device.

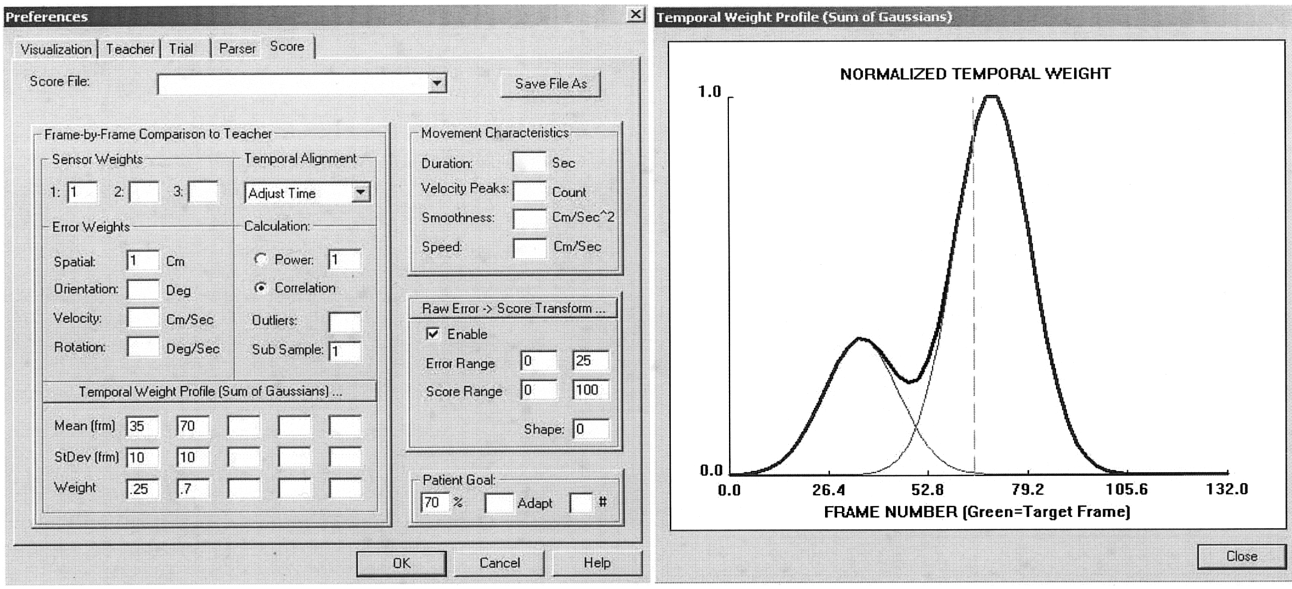

Figure 2. *Left panel: Score-preferences panel in which all score settings are accessed. Right panel: Temporal weighting profile showing two out of a possible five user-defined gaussian curves that differentially weight segments of the movement.*

The movements of the teacher (usually a physical therapist) and those of the patient are monitored with electromagnetic sensors and displayed on the screen as movements of the limb's endpoint (or, if desired, as movement of the entire limb). During an experimental session, the patient is asked to imitate the virtual teacher's trajectory, as it is displayed. We term this process "learning by imitation" (Holden, 2001). The difference between the teacher's trajectory and that of the patient provides augmented feedback in a visual context, which is concurrent with performance. Enhanced knowledge of results feedback (Bilodeau & Bilodeau, 1962) can be provided following each trial by showing a score, representing the "match" with the teacher's trajectory. The score is calculated using a flexible algorithm, which allows the therapist to shape aspects of the patient's performance, (e.g., spatial elements, speed, timing, velocity profile) by adjusting parameters (see Figure 2 for example). The score display shown to the patient is based on a 0–100 scale; a horizontal line indicates the goal level set for that trial (e.g., see Figure 3, middle panel, and Figure 4, bottom left). The virtual teacher and/or score may be hidden from the patient if practice in the virtual environment without enhanced feedback is desired.

Since the score provides a salient indicator for patients to gauge their performance, it is useful to highlight the important features of how we compute it. Since the movements that can be trained with the system are rather general, and a goal of the system was to allow many different methods of training and rehabilitation, the scoring system was made very flexible. In all, there are 40 parameters that determine how a score is computed. At a high level, the score consists of 2 steps: compare teacher and patient movements in various ways to compute a *raw error*. Then transform this error into a score, high errors corresponding to low scores. The raw error is composed of a frame-by-frame error and an intrinsic error. The frame-by-frame error calculation consists of 3 steps: temporal alignment, error weighting, and combination.

Temporally aligning the teacher and patient movements can be done exactly, or the patient movement can be shortened or lengthened to match the teacher. Additionally, the software has alignment options to ignore excursions away from the teacher trajectory, or to

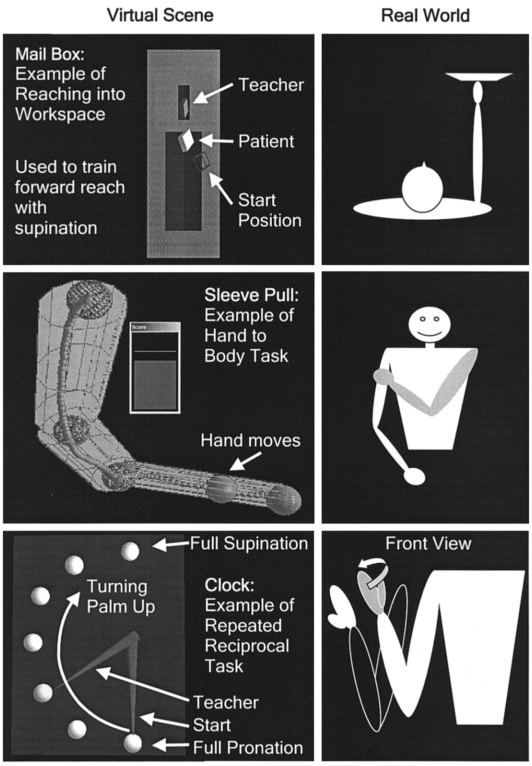

Figure 3. *Examples of the three standard training scenes used by all subjects. The left column shows the VE scene; the right column shows a schematic of the subject's movement in the real world that the scene is designed to train. Top panel: Mailbox scene, training reach into the workspace; middle panel: SleevePull, training a hand-to-body movement, showing score indicator for previous movement as below target performance level; bottom panel: Clock, training repeated reciprocal movement (here, supination/ pronation).*

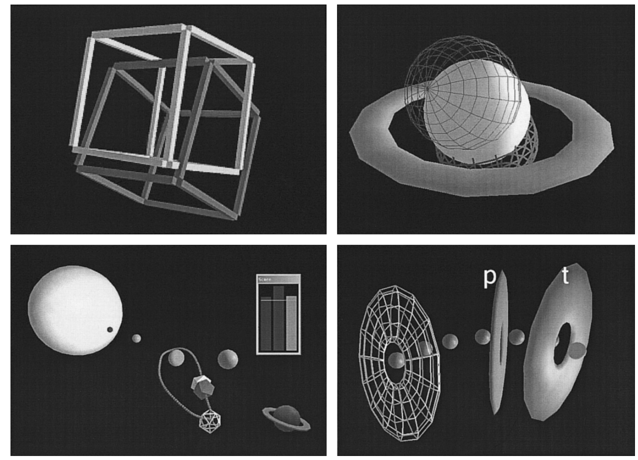

Figure 4. *Examples of additional scenes used by subjects, designed for their individual needs. Top panel, scenes used for S1 to enhance control of wrist extension, with and without grasp. The scene shown on the left allowed practice of wrist extension without grasp; subject's hand was the virtual cube; alignment of the patient and teacher cubes was achieved by wrist extension with slight ulnar deviation to help counteract patient's tendency to excessive radial deviation during the extension. The scene shown on the right required wrist extension against gravity, while grasping a ball (move white ball to upper wire-frame ball). Bottom panel, customized scenes used by S2. Left, scene allowed practice of elbow extension with shoulder flexion and adduction (take spaceship around Earth). Score box shows results of previous three trials, all above target performance level. Right, practice of isolated shoulder external rotation in neutral flexion/abduction with elbow flexion (patient rotated hand-held ring (p) around balls in semicircular trajectory, following teacher (t) ring.*

ignore portions of the teacher trajectory the patient does not perform.

Once aligned, the errors for each frame are computed from individually weighted teacher-to-patient differences, including translation, orientation, velocity, and angular velocity. The therapist can choose higher weights for those measures that are most important for the particular task. The frame-by-frame errors can also be weighted by a temporal profile (Figure 2), which is the sum of up to 5 Gaussian curves of variable height and width, normalized to a maximum weight of 1.0. This provides a method to focus the score on a particular segment of a movement, such as the beginning of the movement or the part near the target. Data from all three tracker sensors (one each at the endpoint or held object, the back of the hand, and on the upper arm) can be weighted and included in the final score, to reflect joint position and orientation error of the entire arm. For endpoint trajectory error alone, only the endpoint sensor is scored.

There are two options by which the frame-by-frame errors are calculated, P-Average, or Correlation. P-Average, or Mean Absolute Standard Deviation, can be set to return the root mean squared error (RMS) or an approximate maximum deviation, depending on the power setting. *Spatial* error is computed as the Euclidean distance, and *Velocity* compares the instantaneous velocity at each time sample. *Orientation* is computed using quaternions that yield the minimum angle that would align the patient and teacher orientations. *Rotation* is the instantaneous angular velocity at each frame. The error weights are used to give relative importance to different measures, and also to scale the values that have different ranges (e.g., position in cm, and orientation in degrees). This calculation can be summarized by the following equations:

$$ERR_{power} = \left[\frac{1}{N} \sum_{t=1}^{N} e(t)^p \right]^{1/p}, \qquad (1)$$

where

$$e(t) = \sum_{s=1}^{3} \varepsilon_s g(t) [w_{tpos} d(\mathbf{x}_T, \mathbf{x}_P) + w_{rpos} \Theta(\mathbf{q}_T, \mathbf{q}_P) + w_{tvel} d(\dot{\mathbf{x}}_T, \dot{\mathbf{x}}_P) + w_{rvel} \Theta(\dot{\mathbf{q}}_T, \dot{\mathbf{q}}_P)]$$

$$d(a,b) = \sqrt{\sum_{i=1}^{3} (a_i - b_i)^2},$$

$$\Theta(\mathbf{j},\mathbf{k}) = 2\cos^{-1}(\mathbf{j} \cdot \mathbf{k}),$$

$g(t)$ is the sum of 5 Gaussian temporal weighting profiles, p is the power (2 corresponds to root mean squared error (RMSE), 10 for maximum deviation), N is the number of samples of movement, s are the sensors, ε_s are the sensor weights, w_{tpos}, w_{rpos}, w_{tvel}, w_{rvel} are error weights (position, orientation, velocity, angular velocity, respectively), $\mathbf{x}_T$, $\mathbf{x}_P$ are the teacher and patient position vectors at sample t, $\mathbf{q}_T$, $\mathbf{q}_P$ are quaternions at sample t, $\dot{\mathbf{x}}_T$, $\dot{\mathbf{x}}_P$, $\dot{\mathbf{q}}_T$, $\dot{\mathbf{q}}_P$ are the derivatives with respect to time, at sample t.

Vector Correlation (Shadmehr & Mussa-Ivaldi, 1994) uses the dot product to compare multidimensional vector series. The magnitude of each error type (expressed as $1 - r^2$, or the percent variance of the teacher trajectory "not explained" by the patient trajectory), for each sensor is computed separately, incorporating the temporal weighting. The correlations are combined using the sensor and error weights, which are normalized so the combined error ranges from 0 to 1 are:

$$ERR_{correlation} = 1 - \sum_{s=1}^{3} \alpha_s [\rho_{tpos} c(\mathbf{x}_T, \mathbf{x}_P)^2 + \rho_{rpos} c(\mathbf{q}_T, \mathbf{q}_P)^2 + \rho_{tvel} c(\dot{\mathbf{x}}_T, \dot{\mathbf{x}}_P)^2 + \rho_{rvel} c(\dot{\mathbf{q}}_T, \dot{\mathbf{q}}_P)^2] \qquad (2)$$

where

$$c(\mathbf{a},\mathbf{b}) = \frac{\operatorname{cov}(\mathbf{a},\mathbf{b})}{\sqrt{\operatorname{cov}(\mathbf{a},\mathbf{a}) \operatorname{cov}(\mathbf{b},\mathbf{b})}},$$

$$\operatorname{cov}(\mathbf{a},\mathbf{b}) = \sum_{t=1}^{N} \frac{g(t)}{N} (\mathbf{a}_t - \bar{\mathbf{a}}_t) \cdot (\mathbf{b}_t - \bar{\mathbf{b}}_t),$$

α_s are the normalized sensor weights, ρ_{tpos}, ρ_{rpos}, ρ_{tvel}, ρ_{rvel} are the normalized error type weights.

Movement characteristics such as duration, number of velocity peaks, smoothness, and average speed can be individually weighted and added as the intrinsic error. The error is then transformed to a score that increases with performance, by user-specified minimum and maximum error, so a meaningful range can be displayed to the patient. Although the number of parameter settings and complexity for the score is high, the benefit is that a very general class of comparisons can be devised for a wide variety of training goals.

2.3 Training Scenes, Scripts, and Data Recording

The motor training occurs by practicing movements, along with the virtual teacher, in a virtual "scene" (for examples, see Figures 3, 4, and 5). Each scene is a 3D picture in the virtual environment, designed to suggest a functional task or goal. The scenes provide a way to adjust task difficulty for the patient, and to customize a practice sequence during training. The training session can be semiautomated by using a "script" consisting of a sequence of scenes and related training options. This feature allows the therapist to specify in advance a series of scenes that will play automatically one after the other, in effect simulating a typical rehabilitative therapy session, where different exercises are performed one after another. The scripts can "skip" exercises if the patient exceeds a target performance level, automatically advancing to the next scene. Training data, including information about the patient, session dates and times, feature settings, and scores for each trial are recorded in a Microsoft Access database. Reporting software provides summary reports of the database contents, as well as data analysis and graphing capability. Raw sensor data are also recorded to flat files, which may be imported into other software, such as Matlab, for additional user-developed analyses.

3 System Development and Testing

Our goal in this project was to develop a system for VE motor training that would be simple enough for patients to use in their homes over a broadband Internet connection, be relatively low in cost, yet provide the opportunity for a high-quality interactive experience with a therapist, who would be located remotely. Development and testing of our home-based telerehabilitation system is briefly described here for three main phases: (1) development and testing of hardware/software configurations and compatibilities; (2) testing of Internet connection options; and (3) clinical feasibility testing. A more extensive description of the technical development and test results may be found in a forthcoming paper (Dyar & Holden, 2004).

3.1 Phase I: Equipment Selection and Configuration

In Phase I, different types of off-the-shelf hardware and software components were selected and tested to assess their compatibility with each other and their usefulness for therapy. We began with the lowest cost components, and increased the cost and quality until we arrived at a usable system. Some of the criteria for usability included: video quality (freeze, jump, pixelation; adequate camera field of view and ease of remote operation to see the patient from different angles and distances; delay and synchronization with VE); sound quality (distortion and delay); compatibility (software and hardware working with each other [e.g., VC and VE software needed to be adequately supported by video accelerator card on two monitors]); software (ease of use for patient and therapist, size of menus, control buttons, complexity of menu controls, remote operation, accessible with one-handed operation).

Components tested included: Video cards, Web cameras and associated software, networking software, dual- versus single-processor computers, dual versus single monitors, and Internet carrier options (DSL and cable broadband). The final prototype system, which was used for the first clinical experiments reported here, consisted of a PC w/ 1.2 GHz dual processors, ATI FireGL 8800 video accelerator, dual LCD monitors, Polycom Via-Video Web cameras, and software. The source code is written in Open GL and C++, designed to work on a Windows 2000 platform.

3.2 Phase II: Testing of Internet Connections

To test the quality and reliability of Internet connections, a series of automated scripts were developed and run every 30 minutes over a range of transmission rates (64 to 1024 kbps). Using *iperf* software (Tirumala & Ferguson, 2001), the scripts computed and recorded (1) packet loss (reliability) and (2) jitter (variation in interpacket delay) (Schulzrinne, Casner, Frederick, & Jacobson, 1996; Tirumala & Ferguson). These measures correlate with the level of degradation in a data stream such as motion capture and video due to network congestion, resulting in "freezing" and "jumping."

These data were used to evaluate how the connection quality was affected by the following factors: type of carrier (cable vs. DSL), direction of transmission, location of town and distance from our research center, time of day, and transmission delay. Finally, simulated treatment sessions were conducted by the experimenters, in multiple towns, to subjectively assess the effects of these factors (i.e., type of carrier, direction of transmission, etc.), at different bandwidths, on the quality of VE and videoconferencing (VC) data displays, and on the quality of recorded data.

Testing revealed an asymmetry of connection speed and quality. Connection quality was worse for the patient-to-MIT (upstream) connection direction, even when sending small amounts of data. Though upstream speed was offered at 256 kbps for cable, for DSL it could be as low as 128 kbps. In general, though we found DSL to have better performance characteristics (lower jitter and less packet loss), cable was more reliable in that dropped connections were rare. We also found that although longer distance did degrade quality, there was a significant interaction with town location, so that the effect was not linear. For example, towns at 5 and 100 mi distance had low packet loss (<10%) at transmission speeds up to 256 kbps, but a town at 10 mi distance began a steep rise in packet loss at speeds above 128 kbps. This discrepancy was likely due to service-provider equipment configuration. In another case we found excessive packet delay was due to packets being routed through Washington, DC in order to travel 15 miles.

We determined that the VE and VC software combined would need to use < ~120 kbps, and be resistant to varying amounts of jitter and packet loss, especially when used over the poorer quality connections. Since the video-capture software required at least 64 kbps to be usable for therapy, modifications were made to the VE software to meet these challenges. The software was improved to better synchronize the internal states of both machines under adverse network conditions, that is, when network traffic caused high packet loss, delay, and jitter, ensuring the therapist and the patient would see identical views of the training sessions, and the sampling rate of the 3D transmitted data was reduced by half to 20 Hz. Full-resolution data were recorded on the patient's computer and transferred after the session. Following these changes, we found that transmission delays were for the most part <50 msec.

To verify that the raw network quality measures reported by our *iperf* scripts corresponded to actual experience, we measured network delay while performing and transmitting motion-capture data, while also running a videoconference at various speeds. We used functionality provided by Microsoft DirectPlay that allowed monitoring of network traffic statistics. Round-trip delay, the time necessary for a packet to travel to the patient and back to the therapist's computer, was recorded for different locations. Data were recorded when different video speeds were used for the videoconferencing. Reinforcing our previous observations of higher connection quality for DSL versus cable, the delay for DSL was lower at all video speeds (28 ms round-trip at 256 kbps video speed, vs. 40 and 80 ms for cable locations at a distance of 5 and 100 miles, respectively). Overall, the delay data suggested that at a reasonably high-quality video speed of 128 kbps, delays will be approximately 25 ms in each direction for cable, a level that caused no difficulties for synchronization or user perception.

3.3 Phase III: Clinical Feasibility Testing

3.3.1 Subjects. Two subjects with stroke were recruited who were familiar with the VE training system from participation in a prior study in our laboratory. We felt that this prior experience would minimize frustrations that might be involved for the first few subjects in our feasibility study. Both subjects had a neurological exam by the study physician as part of the screening protocol. Neither was receiving therapy for their arm.

Subject 1 (S1) was a right-handed female, age 42 years, who had sustained a large right middle cerebral artery stroke, 3.5 years earlier, felt to be due to essential thrombocythemia. The infarct was confirmed by computed tomography (CT) and magnetic resonance imaging (MRI). Following several months in rehabilitation, she partially regained strength, sensation, and awareness of the left hemispace. She eventually arrived at a stable recovery. She had more weakness in the left arm than leg, and diminished sensation in the left arm; her weakness in the hand was greater than in the shoulder. Her initial upper-extremity (UE) Fugl-Meyer (FM) motor score was 30; total UE score was 72 (Fugl-Meyer, Jaasko, Leyman, Olsson, & Steglind, 1975). The FM is an established clinical test of recovery poststroke, consisting of upper-extremity, lower-extremity, and trunk components. The total UE test has 4 subscales—motor function, sensory function, range of motion, and pain. The maximum score is 66 for the motor subscale; 126 for total test. Brain MRI was consistent with prior infarction involving both inferior and superior divisions of the right middle cerebral artery. The infarction included basal ganglia, temporal, parietal, and frontal lobes. The lesion volume, calculated from the MRI, was large, at 160 cc. (For reference, volume range for a typical human brain is 1350–1450 cc.)

Subject 2 (S2) was a right-handed (prestroke) male, age 69 years, who had sustained a left pontine infarct 8 years prior to the study, felt to be due to intrinsic atherosclerosis and stenosis of the basilar artery. His past history was remarkable for syncope with prolonged hypotension (1 year prior to stroke), coronary artery disease with exertional angina, status postcoronary artery bypass grafting, hypertension with exacerbation, hyperlipidemia, diabetes mellitus, macular degeneration, asthma, and gout. MR imaging at the time of the stroke showed evidence of basilar artery stenosis with left midpontine infarction in the penetrating artery territory. He had a chronic stable right hemiparetic deficit, and stable coronary disease confirmed by recent cardiac catheterization.

S2 had a normal level of arousal and attention, with fluent speech and no dysarthria or aphasia. He had decreased passive range of motion in the right shoulder (90° flexion), elbow (minus 30° extension), and forearm (minus 45° from neutral). His initial Fugl-Meyer UE motor score was 32; total UE score was 81. In contrast to S1, S2 had more weakness in the shoulder than the hand, despite having a similar FM motor score. S2's MRI films were not available for review, so his lesion could not be quantified in terms of volume.

3.3.2 Evaluation Tests. The evaluation consisted of three tests, all performed in the real world. Since all training was in the virtual world, these tests served as a measure of transfer of virtual training to real-world function. Two were standard clinical tests used for stroke patients, the Fugl-Meyer Test of Motor Recovery (FM) (Fugl-Meyer et al., 1975), and the Wolf Motor Test (Wolf et al., 2001). The UE-FM (see also Section 3.3.1) tests motor abilities of the upper extremity, particularly in terms of intralimb joint coordination patterns, strength, reflexes, hand function, range of movement, pain, and sensory function. The Wolf Motor Test is a timed test of 15 upper-extremity functional tasks and two strength tests. Strength was assessed for shoulder flexion by attaching Velcro weights to the arm, and recording the maximum weight lifted during movement of the hand from the lap to a table located in front of the patient; hand grip was measured using a handheld dynamometer, best of three attempts. The third test was a Behavioral Kinematic Test (BKT). In the BKT, subjects performed 5 upper-extremity movement tasks in the real world, while the kinematics of their arm and trunk were recorded using an electromagnetic tracking device. Sensors were placed on the trunk, upper arm, forearm, hand or held object, and on the target. The tasks were (1) forward reach to put a card in a slot, forearm in full supination; (2) forward reach to put a card in a slot, forearm in neutral position; (3) simulated motion of pulling on a sleeve; (4) supination, from a start position of full pronation, with arm supported on the table; (5) repeated supination/pronation, at fastest possible speed, for 5 s duration. Tasks 1–4 were performed for 5 trials; Task 5 was performed for only 1 trial.

Subjects were tested with this evaluation battery four times: pretraining, post 15 sessions, post 30 sessions, and at the 4-month follow-up. At follow-up, only the 3 clinical tests were administered. Follow-up testing for S2 had to be delayed until 7 months posttraining, secondary to intervening medical problems at the 4-month mark. Tests were administered once at each time point. For S2 the FM clinical test was given twice (3 weeks apart) prior to the study, so the mean of these two tests was used in the analysis (scores were 31 and 33, respectively). The sequence of tests, and of the individual test items for the BKT, were randomized across subjects, but remained the same at each time point for a particular subject.

3.3.3 Rehabilitation Training. The VE training was given in two 3-week blocks, with 1-hr sessions delivered 5 times per week, for a total of 30 sessions. Treatments were interactive in real time with a therapist who was located at the MIT Clinical Research Center.

To design the VE exercise program, we first defined four categories of movement control that present difficulty for patients with stroke, but are key to functional use of the upper extremity. Then, training tasks were developed to suit each category. The categories were: (1) Reaching movements to transport the hand away from the body into the workspace; (2) hand-to-body movements, such as are needed for grooming and dressing; (3) repeated reciprocal movements, and (4) control of hand grasp/release and wrist orientation. To work on these movement-control categories, subjects trained with three standard scenes (used by all subjects), plus several additional scenes designed specifically for individual subjects.

The three standard scenes, named “Mailbox,” “SleevePull,” and “Clock,” are shown in Figure 3. The Mailbox scene (Reach-to-Workspace category) trained shoulder flexion and elbow extension with lateral grasp and supination; the SleevePull scene (Hand-to-Body category) trained shoulder flexion/adduction with trunk rotation and elbow flexion with lateral grasp, as in pulling on the sleeve of a jacket; the Clock scene (Repeated, Reciprocal Movement category) trained forearm supination-pronation, with slight wrist extension, initially in shoulder neutral with elbow flexion; later with more shoulder flexion and/or elbow extension. The fourth control component, hand grasp/release and wrist control, was incorporated into the standard scenes as a variation. This could be done by attaching a sensor to a lightweight real object, which the subject held in their hand during practice. If the subject was unable to grasp an object, a sensor could be attached directly to the subject’s hand via a glove. The hand or held object was then displayed as the virtual object in the scene, allowing the subject to practice grasp control (or hand-orientation control if unable to grasp) in combination with a variety of arm and trunk movements.

The scenes could be adjusted to the subject’s ability by choosing different reach and hand-orientation excursions (Mailbox) or setting target goals at different points along the teacher trajectory (SleevePull and Clock). As well, the teacher speed, delay time between movement attempts, and the precision of match with the teacher on a variety of movement parameters (e.g., linear and angular displacement and velocities) could be adjusted to suit the patients’ abilities. Each subject also practiced with several other scenes that were designed and created for their particular motor-control deficits. Examples of these scenes are shown in Figure 4.

For each subject, a treatment script was then developed, consisting of eight scenes, with 25 repetitions per scene. Feedback settings and score parameters were adjusted to fit each subject’s needs. The goal was to have the task be at a difficulty level that kept the subject interested, but avoided boredom or frustration. As the subject improved, the settings were readjusted to keep the patient adequately challenged. Neither subject was able to complete all the scenes in a script during a session. Typically, subjects worked with ~2–4 scenes, and performed ~75–100 movement repetitions total in each session. Then, in the following session, the scenes that were not completed in the prior session were practiced. Feedback from the virtual teacher, a histogram score reflecting the degree of match with the teacher trajectory, and a goal level was provided on most trials (~80–100% of trials). Patients often began practice with a goal of 30–50% match; later they progressed to 75–90% match. The replay feature was frequently used immediately following the completion of a trial. This feature allowed the therapist to play a recording of the patient movement just performed in a continuous loop, with or without the teacher trajectory. The animations could be paused, or the viewing angle manipulated to help the patients understand the nature of their errors and how to correct them. S2 found this feature especially useful, often making immediate dramatic corrections following observation of his replayed trajectory.

3.3.4 Data Analysis. Since there were only 2 subjects, inferential statistics were not used. Data for the clinical tests were evaluated based on raw scores and per cent changes from pretest to post 30 Rx values. The significance of the clinical measures was judged in two ways: (1) by comparing the magnitude of changes we found with the percent changes reported by others using similar measures and doing similar work; (2) clinical judgment of the investigators. For the Behavioral Kinematic Test, several quantitative measures were derived, using the 3D position and orientation data recorded by the 4 Polhemus sensors that were attached to the subject during the real-world movement tests. The measures were designed to capture whether the task goal was achieved, and to assess the quality of movement used to attempt the task. For example, in the Mailbox task, simple achievement of the goal could be assessed by measuring the distance of the "envelope" sensor to the sensor located at the target slot. Quality was assessed by change in pertinent trunk-limb or intralimb coordination patterns. For example, leaning forward was a typical compensation for poor shoulder control that both subjects displayed and had to "unlearn" during initial training in the Mailbox task. Thus, a decrease in the amount of trunk movement during the reach served as one useful index of improvement.

Eight measures were calculated, and defined as follows: *Trunk Control Measure:* (1) Path Length Trunk (PLT)—The length of the trajectory (in 3D) traced by the sensor located on the patient's trunk (at level of T6) during the entire movement. *Target Acquisition Measures:* (2) Spatial Error (SE)—The minimum distance from the sensor located at the endpoint of the patient's limb (or held object) to the sensor located on the target in the real world. Errors were corrected for compensatory trunk movements such as leaning forward or to the side used by some patients to improve their reach; (3) Maximal Supination (SUP)—the sensor was positioned on the subject's forearm such that supination coincided with the roll axis of the sensor. These values were used to detect the maximal supination for each supination/pronation attempt. Corrections for compensatory external rotation movements of the shoulder were made using an arm model and data from a second sensor. *Speed Measures:* (4) Response Time (RT)—duration recorded from the computer generated "Go" signal to the end of the movement trial. The trial was ended manually by the tester when the subject returned to the start position, or, if unable to return to the start, when the subject had stopped moving; (5) Average Velocity (AV)—average of the instantaneous velocity of the hand or held object over the course of the movement; (6) Peak Velocity (PV)—the highest velocity of the hand or held object over the course of the movement. *Skill Measures:* (7) # Velocity Peaks (VP)—Instantaneous velocities were computed from raw data, then smoothed using a quadratic least squares polynomial filter (Press, 1993). Velocity peaks were defined as samples for which the two preceding and two succeeding smoothed samples were monotonically rising and falling, respectively. Peaks were then summed over individual movements as an index of motor learning. While normal subjects show 1–2 peaks/movement, the stroke subjects often showed a large number of peaks, indicating movement decomposition, frequent correction attempts midmovement, or other abnormalities; (8) # of supination/pronation movement cycles completed in 5 s during the attempted repeated reciprocal movements, and the mean of the maximum amplitudes of the supination cycles (Measure 3, above) during these attempts.

The mean values over five trials for each measure, for each test movement, were used in the analysis. Values at the pretest were compared to values at post 30 Rx. Differences greater than two standard deviations and/or >25% were considered to be clinically significant.

4 Results

4.1 System Performance

Most of the challenges encountered with the system operation occurred with S1. Technical difficulties occurred almost daily, and four times were severe enough that the treatment session could not be conducted. Early in S1's treatment we switched the service provider from DSL to cable due to Internet-connection quality, causing disruptions. Additionally, failure of a main computer board, with subsequent deployment of a backup, and software bugs caused delays. The second block went much more smoothly, with no sessions lost to technical difficulties. For S2, technical difficulties occurred only sporadically, and no treatment sessions were lost due to technical difficulties, despite the fact that the distance of this subject's home to MIT was greater (100 mi vs. 5 mi).

4.2 Subjective Reports by Subjects

Both subjects reported that they enjoyed using the system, and that it was motivating, particularly as they observed their scores improving. S1 reported that following a session she often experienced fatigue, not of the arm, but more of a "mental fatigue" secondary to the high level of concentration required. S2 did not report this effect. Neither subject had difficulty with soreness or pain in the arm due to the exercises. Both subjects were very pleased with the convenience of performing the guided therapy at home.

4.3 Virtual Training Performance

Qualitatively, we were able to see improvements in the performance of both subjects during their daily VE training sessions. Figure 5 shows an example of the Clock training scene with both subjects' performance at three time points during training period (top panel, S1, bottom panel, S2). The magnitudes of the supination excursions are increasing in both cases, with S2 showing more gain than S1.

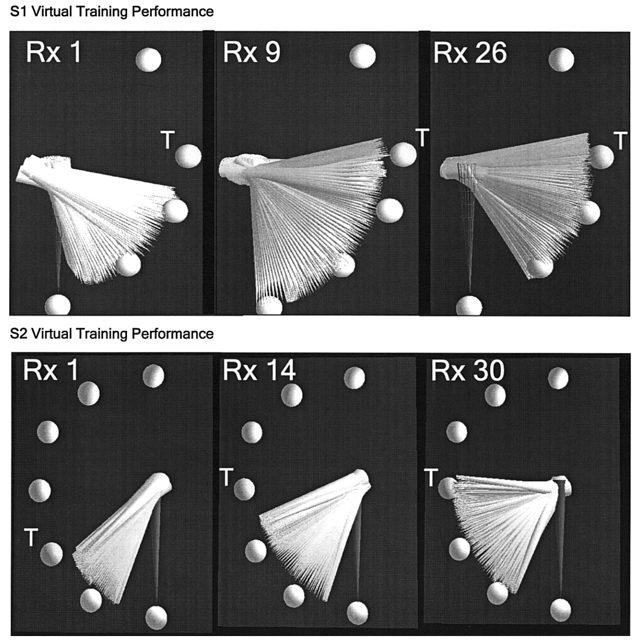

Figure 5. *Examples of improved performance during VE training. Panels, from left to right, show attempted supination during early, middle, and late VE training sessions for each subject. Top, S1, bottom, S2. Thin gray needle indicates 0°, or full pronation. White needle rotation around the "clock" coincides with supination of patient's hand, as if the top of the needle were attached to patient's palm. Balls are spaced at 30° intervals, from 0° (lowermost ball, full pronation) to 180° (uppermost ball, full supination). Yellow ball (here, labeled "T") identifies the target goal for that session.*

4.4 Evaluation Tests

Clinical Tests. Both subjects improved their scores on all three clinical measures. The scores for the Fugl-Meyer, Wolf, and strength tests are shown in Figure 6, a–d. After 30 Rx, S1 had improved by 17% on the FM (5 pt.), 12% on the Wolf Motor (8 s decrease in mean time/task), 900% on grip strength (+18 lb), and 100% on shoulder flexion strength (+4 lb). At the same time point S2 had improved 41% on the FM (13 pt.), 62% on the Wolf Motor (30 s decrease in mean time/task), 33% on grip strength (+5 lb), and 100% on shoulder flexion strength (+3 lb). Both subjects reported that the improvements were large enough to be meaningful to them, that is, to improve daily functional use of the affected arm.

At follow-up testing (S1 at 4 months, S2 at 7 months; Figure 6), both subjects showed some continued improvement on the Fugl-Meyer Test, as compared to the test immediately following the 30 VE sessions. S1 increased by 6% (2 pt.), S2 increased by 18% (10 pt.). On the Wolf Motor Test, S1 was able to maintain her gains, with the same score at 4 months as at the end of treatment. S2 had lost some of the gains made (+9.3 s), but still was 43% faster than at his initial pretest. This was impressive, considering his intervening medical problems. In terms of the strength test, only S1 was measured at follow-up. While she had lost most of the grip strength gains made during treatment (but still at +4 lb relative to pretest value), she maintained the shoulder strength gains (see Figure 6).

Behavioral Kinematic Tests (BKT). Examples of raw data from the BKT for S1 are shown in Figure 7. The figure shows examples of (real-world) reach trajectories and velocity profiles for the Mailbox task, pre- and post-treatment. The trajectory represents the path of the held "envelope" during attempts to place it in the slot. The dot at the top of the boxes (left panel) represents slot location. Note straighter upward trajectory (left panel), and changes in the *Y* and *Z* trajectories (right panel,

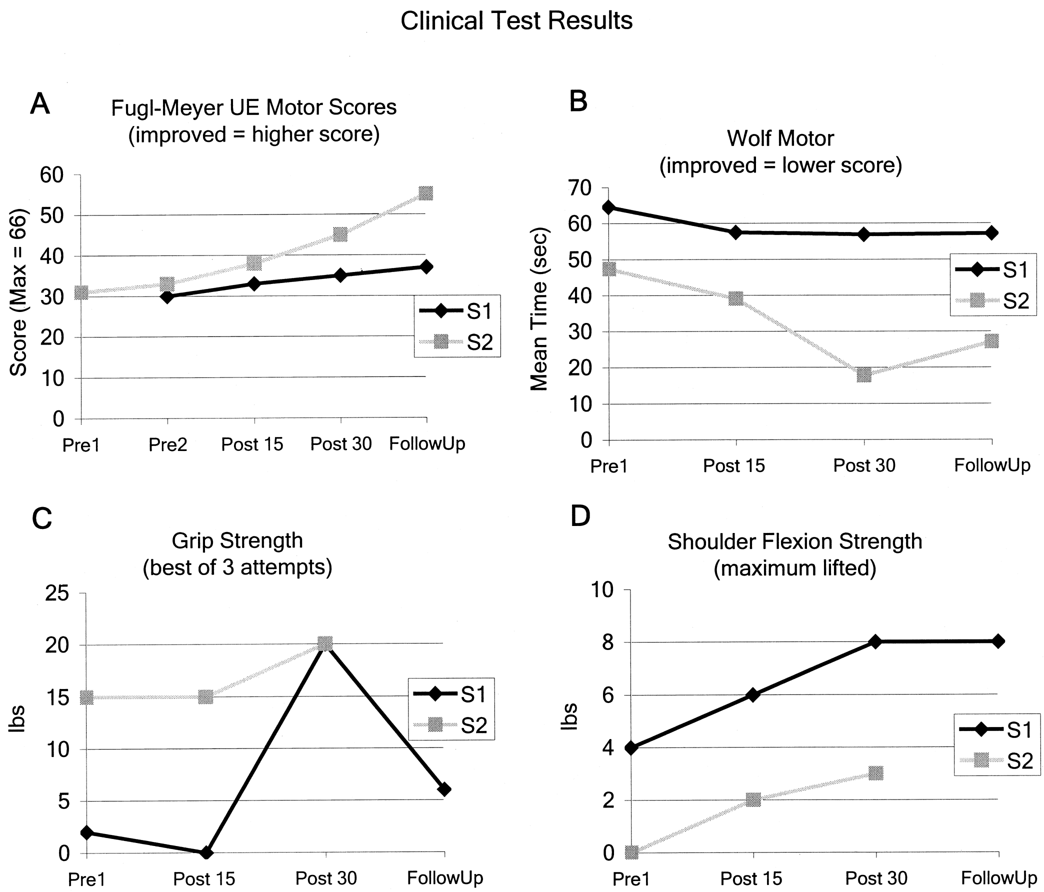

Figure 6. *Results of clinical tests before and after VE treatment via telerehabilitation. Improvements can be seen for both subjects for: (a) FM Test of Motor Recovery, UE motor scores; (b) Wolf Motor Test, mean time for 15 functional tasks; (c) grip strength, measured with a hand-held dynamometer; (d) shoulder flexion strength measured with cuff weights. Follow-up was at 4 months for S1; for S2 it was necessary to delay follow-up until 7 months due to an intervening medical problem.*

2nd and 4th graph) indicating improved shoulder-elbow coordination during the forward (Y) and upward (Z) movement posttraining. Increased speed (~100% gain) and smoother velocity profiles posttraining can also be seen (right panel, 1st and 3rd graphs).

Figures 8 and 9 summarize the quantitative analysis of the BKT results for S1 and S2, respectively. Only data with a difference of >2 standard deviations or >25% as compared to the pretest are shown. S1 showed changes on almost all measures, but mostly for the two Mailbox tasks (Figure 8, a–e). A significant improvement in target acquisition ability was seen for the SleevePull task (Figure 8b), but only small changes were seen($<2SD$) in other measures for that task. Little to no change was seen after 30 Rx. in the supination/pronation task, although a moderate gain (~10°) in active supination was seen following the first block of treatment (Figure 8f). For the repeated reciprocal task of supination/pronation, a similar pattern was seen, that is, a small change after the first block, with regression after the second block of treatment (1.25 complete cycles in 5 s pretest; 2.0 cycles at post 15 Rx, and 1.5 cycles post 30 Rx; maximum amplitude/cycle was 35°, 37°, and 35°, respectively, at pre-, mid-, and posttraining).

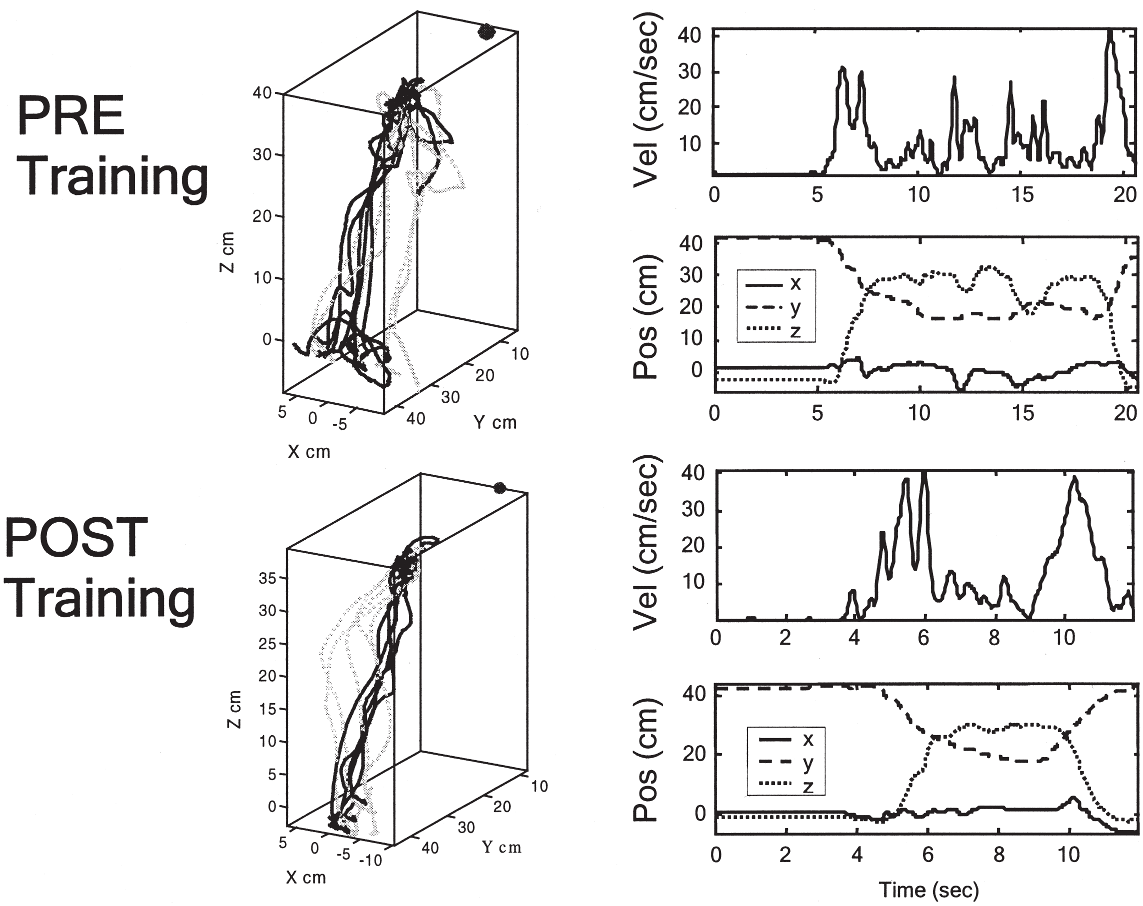

Figure 7. *Example of Behavioral Kinematic Test. Real-world performance before (top panel) and after (bottom panel) 30 sessions of VE training, conducted via telerehabilitation for S1. Left, 3D plots for 5 hand trajectories during reaching toward a slot. Black is upward trajectory, gray is the return movement, dot is target location. Right, velocity and position profiles for one sample trajectory from each plot shown on left. Note smoother trajectories, smoother velocity profiles, and faster speed posttraining.*

S2 showed changes on all measures, but mostly for the SleevePull and Supination/Pronation tasks (Figure 9a–g). The SleevePull task showed the greatest number of changes (Figure 9), but the supination/pronation task improved significantly in maximum amplitude of supination, # of velocity peaks (fewer), and decrease of compensatory trunk movements (following Block 1 only) (see Figures 9a, 9d, and 9g). Also, for the repeated reciprocal task of supination/pronation, although S2 showed little change in the number of cycles he could perform (1.75 complete cycles in 5 s pretest; 1.5 at post 15 Rx, and 1.75 cycles post 30 Rx), the mean maximum supination amplitude/cycle did show significant change, going from 28° on pretest, to 36° at post 15 Rx, to 45° at post 30 Rx. Only small or no changes were seen(<2SD) in measures for the two Mailbox tasks (e.g., Figure 9h), due mainly to persistent shoulder weakness.

5 Discussion

We have found that our telerehabilitation system is not only feasible for use with patients, but that we have

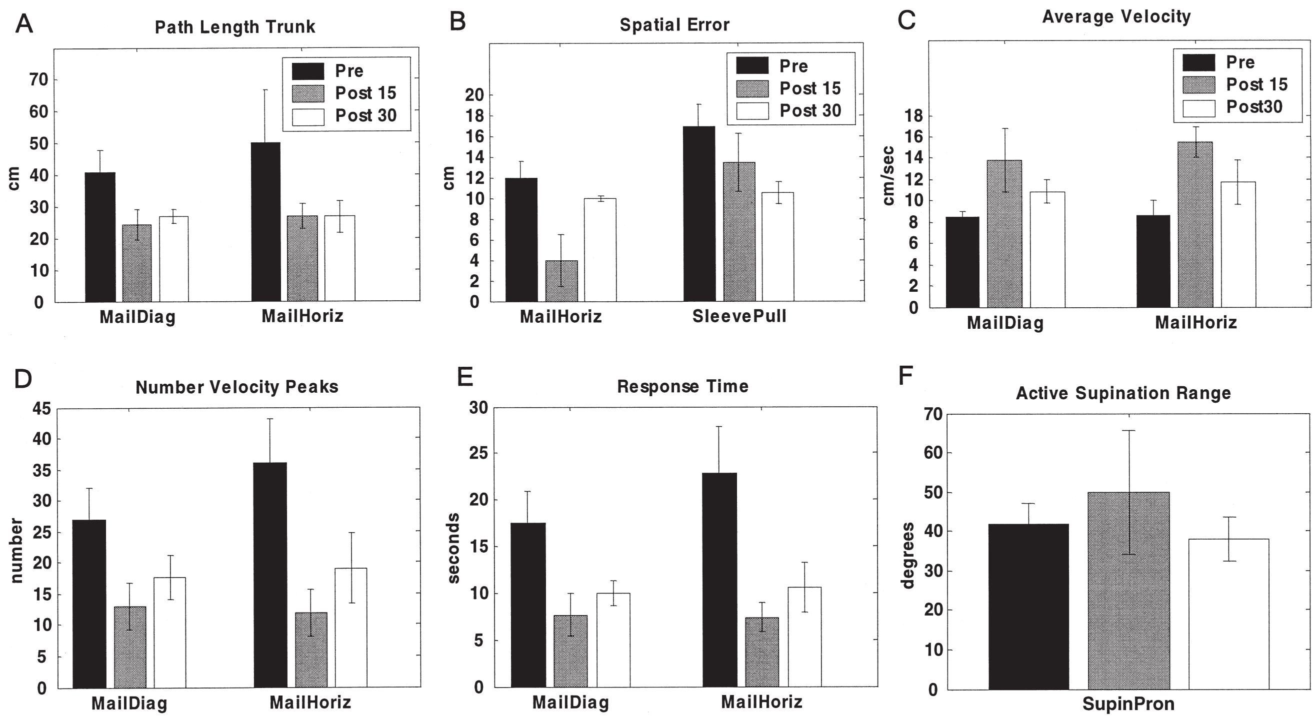

Figure 8. *Behavioral Kinematic Test, S1. Results are shown for all conditions where the pre-post measure changed by >2 standard deviations or >25% (a–e), and one example of change considered to be nonsignificant (f). (a) Path length of trunk; (b) spatial error; (c) average velocity; (d) # velocity peaks; (e) response time; (f) maximal supination in supination/pronation task. Note that most improvements for S1 were in the Mailbox and SleevePull Tasks. Only small changes were noted in the supination/ pronation tasks (e.g., f). Bar legend: Black = >pretraining, Gray = >post 15 Rx, White = >post 30 Rx.*

been able to see clinically significant improvement in our first 2 subjects following 30 sessions of VE therapy delivered over the Internet (see Results). Of particular importance are the findings of improvement on both the Behavioral Kinematic and clinical tests, indicating that subjects can generalize skills learned in the virtual environment to real-world performance of similar tasks and to untrained tasks. Although generalization (also called *transfer*) of training from virtual environments to the real world has been reported for spatial skills (Regian, Shebilske, & Monk, 1992; Brooks, McNeil, et al., 1999), for procedural learning (Kenyon & Afenya, 1995; Brooks, Attree, Rose, Clifford, & Leadbetter, 1999), and for sensorimotor learning in normal subjects (Todorov, Shadmehr, & Bizzi, 1997, Rose et al., 2000), few data on this point exist for subjects with stroke. We have previously reported evidence for transfer of upper-extremity movements trained in VE to both trained and untrained real-world tasks, (Holden et al., 1999; Holden, Dyar, Callahan, Schwamm, & Bizzi, 2001; Holden, Dettwiler, et al., 2001; Holden & Dyar, 2002). Others have reported evidence for transfer of VE hand-movement training to grasp of a real-world object (Adamovich et al., 2003), and transfer to improved stair-climbing ability following VE training of ankle torque and range of motion (Deutsch, Latonio, Burdea, & Boian, 2001). The results reported here allow us to extend our prior finding of generalization of training to transfer following VE conducted via telerehabilitation.

The relatively large improvements in the two strength measures were somewhat surprising, although we have seen a similar pattern in a prior study (Holden & Dyar, 2002). Subjects in this study trained using only active movements. However, because they were so weak initially

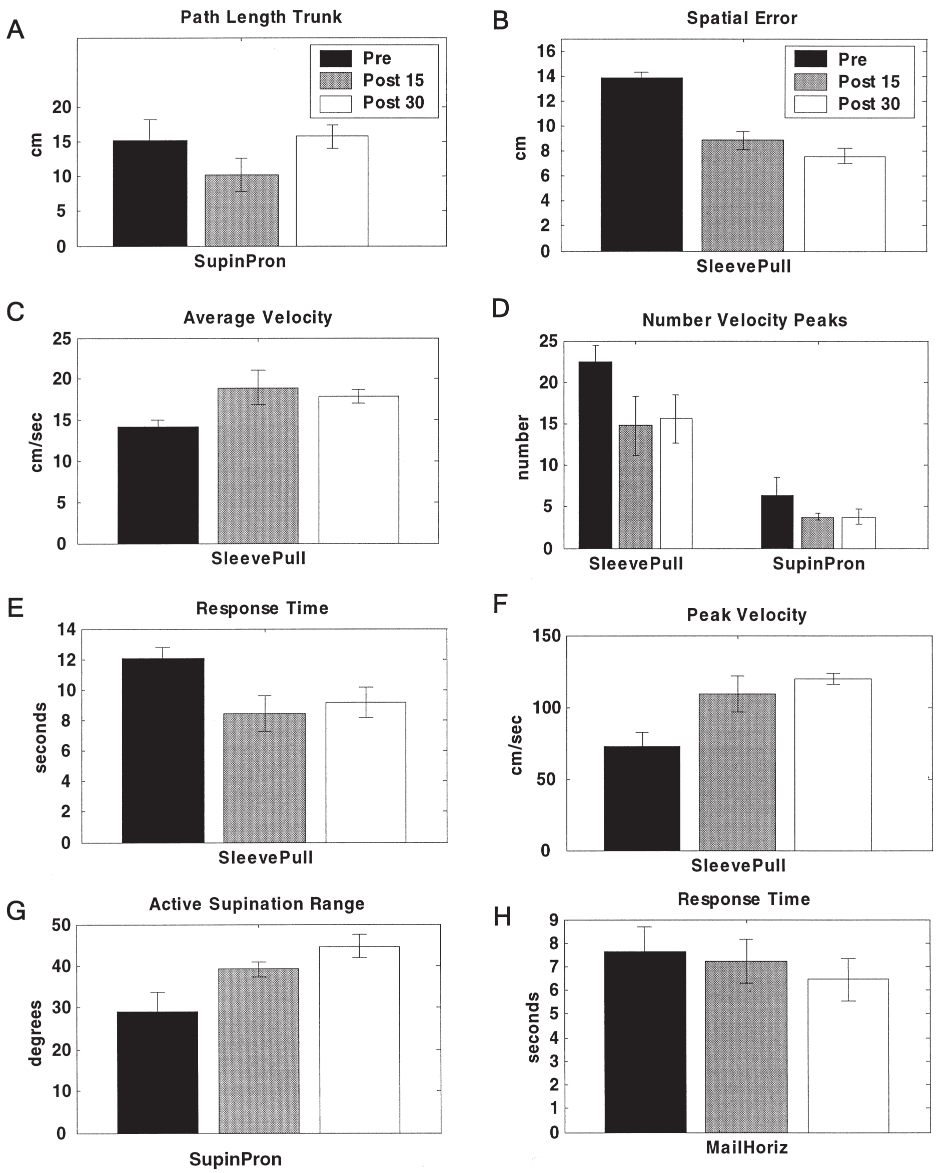

Figure 9. *Behavioral Kinematic Test, S2. Results are shown for all conditions where the pre-post measure changed by >2 standard deviations or >25% (a–g), and one example of change considered to be nonsignificant (h). (a) Path length of trunk; (b) spatial error; (c) average velocity; (d) # velocity peaks; (e) response time; (f) peak velocity; (g) maximal supination in supination/pronation task. Note that most improvements for S2 were in the SleevePull and Supination/Pronation Tasks. Only small changes (e.g., h) were noted in the Mailbox tasks. Bar legend: Black = >pretraining, Gray = >post 15 Rx, White = >post 30 Rx.*

this practice may have served as a sort of "progressive resistance" training. During practice, subjects held lightweight objects during many of the practice trials (e.g., plastic cup, Styrofoam "envelope"), and were encouraged to use their impaired arm in everyday functional activities when possible. This repetitive practice may have contributed to the strengthening effect. The physiological etiology of the strength changes could be improved neural recruitment patterns (more likely) or muscle fiber hypertrophy (less likely, due to short time frame). That the percent changes in both the FM and WMT were smaller than those seen for strength may be explained by the fact that many other factors besides increased strength are necessary to produce change in the functional performance measured by these tests. Some examples of such factors include improved control of intralimb joint coordination, perceptual-motor changes, faster reaction times, and ability to inhibit unwanted muscle activity. Another explanation for the improvements seen may be the reversal of learned nonuse, such as is seen following Constraint-Induced therapy methods in stroke patients (Taub, Uswatte, & Pidikiti, 1999; Liepert, Bauder, Miltner, Taub, & Weiller, 2000).

Although both subjects improved, S2 showed more gains than S1, despite being much longer poststroke, being much older, and having multiple significant comorbidities, all factors thought to contribute to less potential for recovery. Several factors may account for this difference. The most likely one is the difference in the size and location of the lesion between the two subjects. S1 had a much larger lesion, involving multiple areas of the cortex concerned with motor control, motor learning, and motor planning. Although we were not able to quantify S2's lesion from his MRI, we know a priori that it had a smaller volume because it was a pontine lesion. However, this area of the brain stem does contain the neural fiber connections to a broad array of cortical areas involved with motor control. Although it is difficult to say for sure, his clinical findings, together with the MRI report, imply that the connections to cortical areas controlling hand function were spared to some extent for S2. Because he had the ability to open and close the hand (although imperfectly) prior to training, as soon as he began to gain some active control of supination, elbow extension, and shoulder external rotation, he began to be able to use the arm in daily tasks, thus solidifying his newly learned motor control. In contrast, because S1 had such a weak grasp at the start of training, even when she improved her ability to control the shoulder and elbow, she had less ability to make use of this function in everyday tasks. While our setup allowed for some practice of hand grasp through use of held "instrumented" objects, we could not provide specific feedback about hand and finger motions. This setup may have been insufficient for S1 to learn enough hand control to have improvements equivalent to those seen for S2. However, the fact that S1 did increase her hand grip on the strength test implies that she does have the potential to improve, and that our method had a small amount of success. We are presently working to add hand- and finger-training capability to our system, to enhance its effectiveness. A third factor that potentially affected the outcome difference between subjects was the greater number of technical problems experienced during S1's telerehabilitation sessions.

We chose a relatively high standard to define "improvement" in our BKT test, that is, >2 *SD* or $>25\%$ more than the pretest mean value. This is because the amount of change that is needed to achieve clinically significant improvement in subjects is often greater than change that simply reflects a statistical difference. The magnitude of the improvements we have found for these two subjects is greater than the levels of change reported by others working with VE rehabilitation in stroke upper extremity (Merians et al., 2002; Adamovich et al., 2003; Piron et al., 2003). The larger improvements we have found could simply be a spurious effect due to the limited number of subjects, or a result of our subjects being at a lower level of recovery at the start of training compared to subjects in other studies. An alternative explanation is that our training is more customized to the subject's needs, and allows for practice of whole arm movements, providing increased ecological validity of training. However, our method does not provide haptic feedback or detailed feedback about hand posture, as do the methods reported by other researchers in the field. At the least our findings imply that haptic feedback may not be as critical to achieving functional carryover from virtual- to real-world upper-extremity tasks as has been previously thought (Deutsch et al., 2002).

Another intriguing finding is that subjects so long poststroke were able to show these changes following relatively brief treatment exposure (30 sessions) and relatively few total number of repetitions (typically

75–100 repetitions total/session). Although 30 sessions are probably more than a typical chronic stroke patient would be allowed for motor retraining in today's health care system, in terms of motor-skill learning, this is not a great amount of practice (e.g., see Crossman, 1959). We think that the customization of the movements trained and the customized augmented feedback most likely played a role in the enhancement of learning seen in our subjects. However, whether these effects will hold up in a larger sample of subjects, or whether similar effects could be achieved by simple real-world practice of the movements for similar amounts of time, is an open question, and awaits further study. In normal subjects though, there is evidence that virtual practice is superior to real-world practice for some aspects of motor learning (Todorov et al., 1997; Rose et al., 2000).

We found in our follow-up evaluations that subjects had, for the most part, maintained their gains or even continued to improve in the absence of continued VE training (Figure 6). This may represent evidence for consolidation of motor learning. Similar findings have been reported by others using VE in stroke rehabilitation (Adamovich et al., 2003; Merians et al., 2002).

In terms of practicality, the system is still too costly for mass use, and the system could benefit from further automatization. Cost reductions could be achieved by using lower cost tracking systems. Home-based "off-line" training could be feasible for patients with less impairment, if the software were simplified somewhat, and preset practice routines were used. Eventually, we would like to make the system "smarter" so that the virtual teacher could recognize exactly what the patient is doing wrong when a score is low, and provide hints for correction automatically during practice.

6 Conclusions

We have developed a workable VE training system for the delivery of home-based telerehabilitation utilizing VE. The system is operated remotely, and has worked successfully at distances ranging from 5 to 100 miles. Results from our first 2 subjects indicate that the system can be useful in enhancing motor recovery in chronic stroke patients (>3 yr. poststroke).

Acknowledgments

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References

Adamovich, S. V., Merians, A. S., Boian, R., Tremaine, M., Burdea, G. S., Recce, M., et al. (2003). A virtual reality based exercise system for hand rehabilitation post-stroke. *Proceedings of the Second International Workshop on Virtual Rehabilitation,* 74–81.

Bilodeau, E. A., & Bilodeau, I. (1962). Motor skills learning. *Annual Reviews of Psychology, 13,* 243–280.

Bizzi, E., Mussa-Ivaldi, F. A., & Shadmehr, R. (1996). System for Human Trajectory Learning in Virtual Environments. *U.S. Patent No. 5,554,033. Massachusetts Institute of Technology.*

Brooks, B. M., Attree, E. A., Rose, F. D., Clifford, B. R., & Leadbetter, A. G. (1999). The specificity of memory enhancement during interaction with a virtual environment. *Memory, 7,* 65–78.

Brooks, B. M., McNeil, J. E., Rose, F. D., Greenwood, R. J., Attree, E. A., & Leadbetter, A. G. (1999). Route learning in a case of amnesia: The efficacy of training in a virtual environment. *Neuropsychological Rehabilitation, 9,* 63–76.

Burdea, G., Popescu, V., Hentz, V., & Colbert, K. (2000). Virtual reality-based orthopedic telerehabilitation. *IEEE Transactions on Rehabilitation Engineering, 8*(3), 430–432.

Crossman, E. R. F. W. (1959). A theory of the acquisition of speed-skill. *Ergonomics, 2,* 153–166.

Deutsch, J. E., Boian, R., Lewis, J., & Burdea, G. (2003).

Virtual reality-based gait rehabilitation of individuals post-stroke using real-time web-based telerehabilitation monitoring. *Proceedings of the XIV International World Congress of Physical Therapy,* Barcelona. SI-PL-2025.

Deutsch, J. E., Latonio, J., Burdea, G. C., & Boian, R. (2001). Post-stroke rehabilitation with the Rutgers ankle system: A case study. *Presence: Teleoperators and Virtual Environments, 10*(4), 416–430.

Deutsch, J. E., Merians, A. S., Burdea, G. C., Boian, R., Adamovich, S. V., & Poizner, H. (2002). Haptics and virtual reality used to increase strength and improve function in chronic individuals post-stroke: Two case reports. *Neurology Report 26*(2), 79–86.

Dobkin, B. (1995). The economic impact of stroke. *Neurology, 45* (Suppl. 1), s6–s9.

Dyar, T. A., & Holden, M. K. (2004). Telerehabilitation system for motor training: Design and development. Manuscript submitted for publication.

Fugl-Meyer, A. R., Jaasko, L., Leyman, I., Olsson, S., & Steglind, S. (1975). The post-stroke hemiplegic patient: A method for evaluation of physical performance. *Scandanavian Journal of Rehabilitation Medicine, 7,* 13–31.

Holden, M. K. (2001). Neurorehabilitation using "learning by imitation" in virtual environments. In J. Smith, G. Salvendy, D. Harris, & R. J. Koubek (Eds.), *Usability evaluation and interface design: Cognitive engineering, intelligent agents and virtual reality,* Vol. 1 (pp. 624–628). London: Erlbaum.

Holden, M., Dettwiler, A., Dyar, T., Niemann, G., & Bizzi, E. (2001). Retraining movement in patients with acquired brain injury using a virtual environment. In J. D. Westwood, H. M. Hoffman, G. T. Mogel, D. Stredney, & R. A. Robb (Eds.), *Proceedings of Medicine Meets Virtual Reality* (pp. 192–198). Amsterdam: IOS.

Holden, M. K. & Dyar, T. (2002). Virtual environment training: A new tool for neurorehabilitation. *Neurology Report, 26*(2), 62–71.

Holden, M. K., Dyar, T., Callahan, J, Schwamm, L, & Bizzi, E. (2001). Quantitative assessment of motor generalization in the real world following training in a virtual environment in patients with stroke. *Neurology Report, 25*(4), 129–130.

Holden, M. K., Dyar, T., Schwamm, L., & Bizzi, E. (2003). Telerehabilitation: Development and initial testing of a remotely operated computerized motor training system to provide patients with home-based therapy via the Internet. *Neurology Report, 26*(4), 198.

Holden, M., & Todorov, E. (2002). Use of virtual environments in motor learning and rehabilitation. In K. Stanney (Ed.): *Handbook of virtual environment technology* (pp. 999–1026). Mahwah, NJ: Erlbaum.

Holden, M., Todorov, E., Callahan, J., & Bizzi, E. (1999). Virtual environment training improves motor performance in two patients with stroke: Case report. *Neurology Report 23*(2), 57–67.

Kenyon, R. V., & Afenya, M. B. (1995). Training in virtual and real environments. *Annals of Biomedical Engineering, 23,* 445–455.

Lewis, J., Boian, R., Burdea, G., & Deutsch, J. (2003). Real-time web-based telerehabilitation monitoring. *Proceedings of Medicine Meets Virtual Reality* (pp. 190–192). Amsterdam: IOS.

Liepert, J., Bauder, H., Miltner, H. R., Taub, E., & Weiller, C. (2000). Treatment-induced cortical reorganization after stroke in humans. *Stroke, 31,* 1,210–1,216.

Merians, A. S., Jack, D., Boian, R., Tremaine, M., Burdea, G. C., Adamovich, S. V., et al. (2002). Virtual reality-augmented rehabilitation for patients following stroke. *Physical Therapy, 82*(9), 898–915.

National Center for Medical Rehabilitation Research, (1993). *Research plan for the national center for medical rehabilitation research.* NICHD-NIH Publication No. 93-3509.

Piron, L., Tonin, P., Atzori, A., Trivello, E., & Dam, M. (2003). A virtual-reality based motor tele-rehabilitation system. *Proceedings of the Second International Workshop on Virtual Rehabiliation,* 21–26.

Popescu, V., Burdea, G., Bouzit, M., & Hentz, V. (2000). A Virtual-reality based telerehabilitation system with force feedback. *IEEE Transactions on Information Technology in Biomedicine, 4*(1), 45–51.

Press, W. H. (1993). Numerical recipes in C: The art of scientific computing (2d ed). Cambridge, UK: Cambridge University Press, 650–655.

Regian, J. W., Shebilske, W. L., & Monk, J. M. (1992). Virtual reality: An instructional medium for visual-spatial tasks. *Journal of Communication, 42,* 136–149.

Reinkensmeyer, D. J., Pang, G. T., Nessler, J. A., & Painter, C. C. (2002). Web-based telerehabilitation for the upper extremity after stroke. *IEEE Transactions on Neural Systems and Rehabitation Engineering 10*(2), 102–108.

Rose, F. D., Attree, E. A., Brooks, B. M., Parslow, D. M., Penn, P. R., & Ambihaipahan, N. (2000). Training in virtual environments: Transfer to real world tasks and equivalence to real task training. *Ergonomics, 43*(4), 494–511.

Schulzrinne, H., Casner, S., Frederick, R., & Jacobson, V.

(1996). ORFC 1889: RTP: A transport protocol for real-time applications. Retrieved May 27, 2004; From: *http://www.faqs.org/rfcs/rfc1889.html.*

Shadmehr, R., & Mussa-Ivaldi, F. A. (1994). Adaptive representation of dynamics during learning of a motor task. *Journal of Neuroscience, 14,* 3,208–3,224.

Taub, E., Uswatte, G., & Pidikiti, R. (1999). Constraint-induced movement therapy—A new family of techniques with broad application to physical rehabilitation: A clinical review. *Journal of Rehabilitation Research and Development, 36,* 237–251.

Tirumala, A., & Ferguson, J. (2001). Iperf 1.2—The TCP/UDP bandwidth measurement tool. Retrieved May 27, 2004, from: *http://dast.nlanr.net/Projects/Iperf/.*

Todorov, E., Shadmehr, R., & Bizzi, E. (1997). Augmented feedback presented in a virtual environment accelerates learning of a difficult motor task. *Journal of Motor Behavior, 29,* 147–158.

Wolf, S. L., Catlin, P. A., Ellis, M., Archer, A. L., Morgan, B., & Piacentino, A. (2001). Assessing Wolf Motor Function test as an outcome measure for research in patients after stroke. *Stroke, 32,* 1635–1639.