Home-Based Telerehabilitation Using a Virtual Environment System

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Abstract

We describe a Telerehabilitation system that has been developed in our laboratory. 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 design, technical testing and clinical feasibility testing of the system are reported. Results from the first two 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.

Keywords

telerehabilitation, virtual environments, stroke rehabilitation

INTRODUCTION

The health care delivery system in the United States has been undergoing significant change in recent years. One consistent trend has been the shortening of inpatient length of stay in both the acute hospital and the rehabilitation setting. Thus, 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[1]. 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 if they must depend on family or friends to drive them to appointments. 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 particularly pressing[2]. The sharp decline in stroke mortality, due to improved medical care in recent years, has resulted in a larger numbers of survivors. And 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[1]. Recent studies on Constraint-Induced (CI) therapy have demonstrated the ability of selected stroke patients to recover functional use of their arms, even many years following the stroke,[3,4]and have demonstrated that the improvements were associated with treatment-induced cortical changes[5]. Stroke patients with such untapped potential may benefit from a variety of new approaches to retrain their movement control. One such novel approach is the use of virtual environments (VE) to assist rehabilitation[6,7]. We have developed our current Telerehabilitation system with the hope 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). The system is described in detail in the next section below.

Two 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, which has been tested on orthopedic patients[8,9]. Reinkensmeyer and coworkers[10] have developed a web-based Telerehabilitation system which 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,[9] it appears to be too slow at present (2-10 frames/sec) to support real time interactive therapy. As presently configured, only highly constrained movements within a very small workspace can be practiced using these systems. Both of these Telerehabilitation systems have proven feasible in pilot testing on a single patient. However, neither of these patients were reported to have significant improvement on standard clinical tests of upper extremity (UE) function following training, though changes in force production,[8,9] movement and speed[10] on selected test items were seen.

In contrast, the Telerehabilitation system we have developed[11] can provide real time interactive treatment sessions with simultaneous VE and videoconferencing, and can be used to train any kind of movement in any part of the UE workspace.

SYSTEM DESCRIPTION

Telerehabilitation Component

Our Telerehabilitation system was developed to provide motor retraining for patients with stroke. However, we have built a great deal of flexibility into the system, so that with appropriate adjustments, the system could potentially be used to treat a wide variety of clinical populations. The system is an enhancement and expansion of the virtual environment (VE) motor training system we have previously developed for use with patients stroke and acquired brain injury [6,7,12,13].

A diagram of the Telerehabilitation system and its various components is shown below 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. 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 movements and remotely control the VE software and video camera at the patient’s home, all in real-time.

VE Training Component

The VE motor training component of the Telerehabilitation system was developed in our laboratory at MIT[14], and uses an electromagnetic motion tracking device, laboratory developed 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. 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, a prerecorded movement of the teacher is displayed to the patient, and the patient is asked to imitate the trajectory, as it is displayed. We term this process “learning by imitation”. The same teacher movement can be displayed over and over, or different teacher’s movements may be displayed in turn. The difference between the teacher’s trajectory and that of the patient’s provides the augmented feedback in a visual context, which is concurrent with performance.

The difference between the patient's and teacher's trajectories may be quantified using a flexible algorithm. A score representing the 'match' with the teacher trajectory can then be presented immediately following each trial (enhanced knowledge of results feedback). By adjusting parameters in the score algorithm, the therapist can use the score to shape different aspects of the patient's performance, e.g., spatial elements, speed, timing, velocity profile, etc. The virtual teacher, and or score may be hidden from the patient if practice in the virtual environment without enhanced feedback is desired.

Training Scenes and Scripts

The motor training occurs by practicing movements, along with the virtual teacher, in a virtual 'scene'. Each scene is a 3-D 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 semi-automated by using a 'script'. This feature allows the therapist to specify in advance a sequence 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. Training options control the number of repetitions per scene, the type of feedback, scoring criteria and other features. Once composed, a script can be replayed many times, or modified to emphasize selected scenes or training options, depending on the needs of an individual patient.

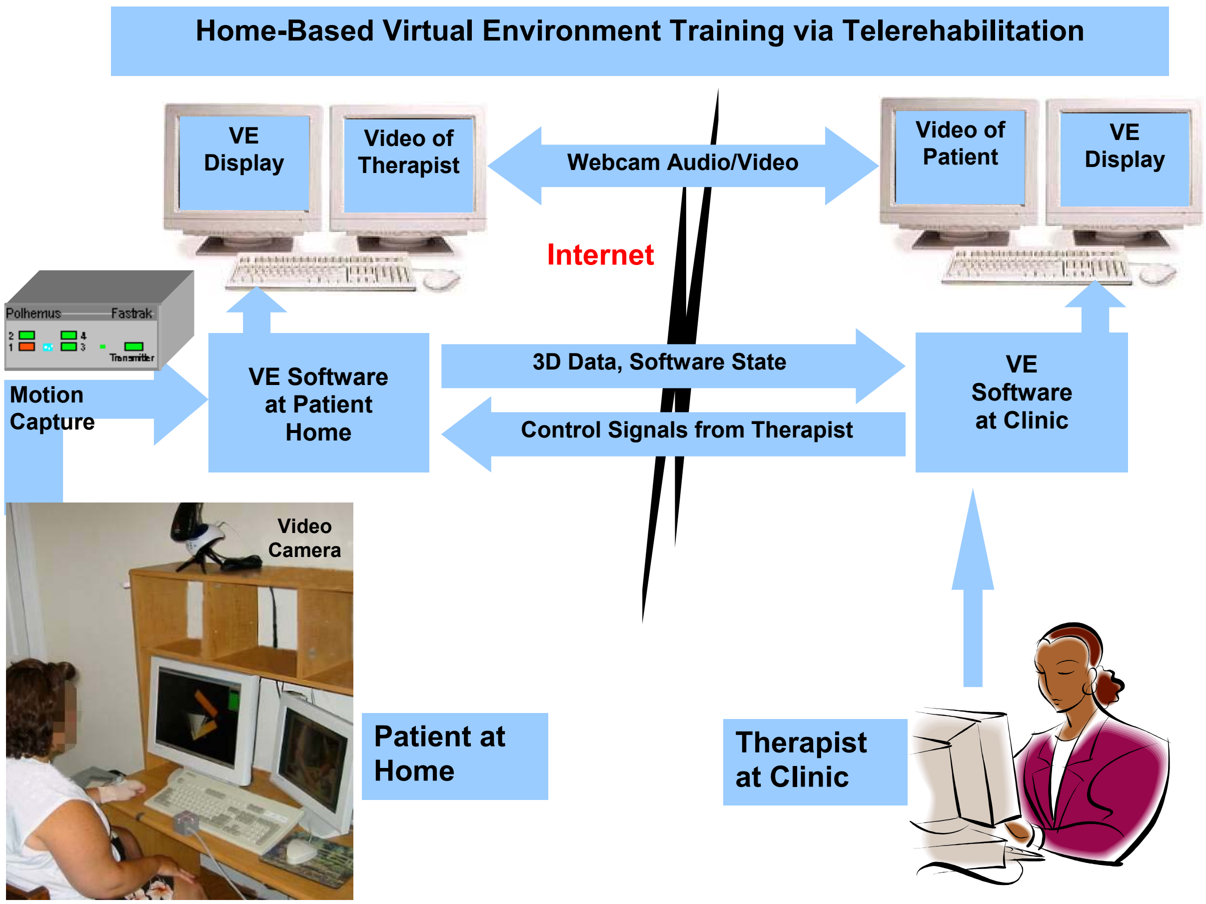


Figure 1. Schematic of the VE Telerehabilitation System

DataBase and Recording Capability

The system has extensive data recording capability. A Microsoft Access database is used to store information about the patient, sessions, and the specifics of the training that occurred in each session. For example, the names of scenes, number of repetitions, performance score and all the feature settings (currently, ~130 settings) that were used during each session are recorded. These data can be used to monitor treatment response to determine how the different training parameters affect learning. The system also saves the sensor data into raw data files, so that the trajectories can be displayed and reviewed post training. Reporting software, interfaced with the database, allows the generation of a variety of report summaries, and the viewing of graphs of patient performance over time, as scores or as raw trajectories. Trajectory data may also be imported into other software, such as Matlab, for additional user-developed analyses.

SYSTEM DEVELOMENT 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. Here we provide a brief overview of the development and testing of our Telerehabilitation system. The work occurred in three main Phases: 1) development and testing of hardware/software configurations and compatibilities; 2) testing of internet connection options; and 3) clinical feasibility testing. Although the Phases are described separately, in actual practice there was overlap among the different Phases as the development of the system progressed.

In this paper we provide a short summary of the development and testing. A future paper will provide a more extensive description of the technical aspects of development, tests preformed and the results obtained.

Phase I: Equipment Selection and Configuration

In Phase I, different types of off the shelf Hardware and Software components were selected and tested in a variety of configurations to assess compatibility with each other and their usefulness for therapy. We always began with the lowest cost components, then continued to higher cost components, until feasibility could be achieved, i.e., the integration of hardware and software into a working and useable system. Components tested included: Video cards, web cameras and associated software, networking software, dual vs. single processor, dual vs. single monitor configuration, and internet carrier options (ISDN, 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 Radeon 7500/FireGL 8800 video accelerator, dual LCD monitors, Polycom ViaVideo web cameras and software, Microsoft DirectPlay networking software, and ability to interface with either Cable or DSL broadband connections. ISDN was rejected due to higher cost, longer time to install, spotty availability and hardware incompatibilities. The VE motor training component of the system was developed in our laboratory at MIT. The source code is written in Open GL and C++, designed to work on a WinNT or Win2000 Platform.

Phase II: Testing of Internet Connections

To test the quality of internet connections, a series of automated scripts were first developed. These scripts were then used to test transmission quality and reliability every 30 minutes over a range of transmission rates (64 to 1024 kbs). Quality was measured by quantifying 1) Packet Loss and 2) Jitter ($J=J+(|D(i-1,i)|-J)/16$, roughly, the average variation in delay between packets)[15]. Highly variable delays (Jitter) and low reliability (Packet Loss) are undesirable because they degrade data streams such as motion capture and video, making them “freeze” and “jump”.

Using the automated test scripts, the following factors were evaluated: type of carrier (Cable vs. DSL), direction of transmission, location of town and distance from MIT, 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.

One of the first problems the testing revealed was an asymmetry of connection speed and quality. Connection quality was worse for the Patient to MIT connection direction, even at low speeds. Asymmetry of connection speed was worse for cable (~200 kbps) than for DSL (~384 kbps) in this direction. Since the speed requirements for the video capture software were essentially fixed (as we were using a commercial video capture system), we had to make changes at this point to the VE software to reduce overall usage to ~190 kbps. These changes then made the Telerehabilitation system suitable for use with both Cable and DSL providers. In general, we found DSL to have better performance characteristics (lower jitter and less packet loss) than Cable, especially at higher transmission speeds. However, Cable was more reliable in that dropped connections were rare. In contrast, dropped connections occurred with much higher frequency with DSL.

We found that although longer distance did degrade quality, there was a significant interaction with town location, so that the effect was not linear. We tested towns at 5, 10 and 100 mi. from MIT, and found that the towns at 5 and 100 mi. distance had low packet loss (<10%) at transmission speeds up to 256 kbps, but the town at 10 mi. distance began a steep rise in packet loss at speeds above 128 kbps.

Transmission delays were first approached by making further optimization changes in the VE software. Following these changes, we found that transmission delays were for the most part < 50 msec. These delays were dealt with in two ways: 1) the sampling rate of the 3-D data transmitted over the internet was reduced by half; 2) a new function was added to the VE software to better synchronize the internal states of both machines so that the therapist and the patient would see identical views of the training sessions. Full resolution data were then recorded locally on the patient's computer during the session, and transferred off-line following completion of the session. Only the full resolution data were used for analyses.

Phase III: Clinical Feasibility Testing

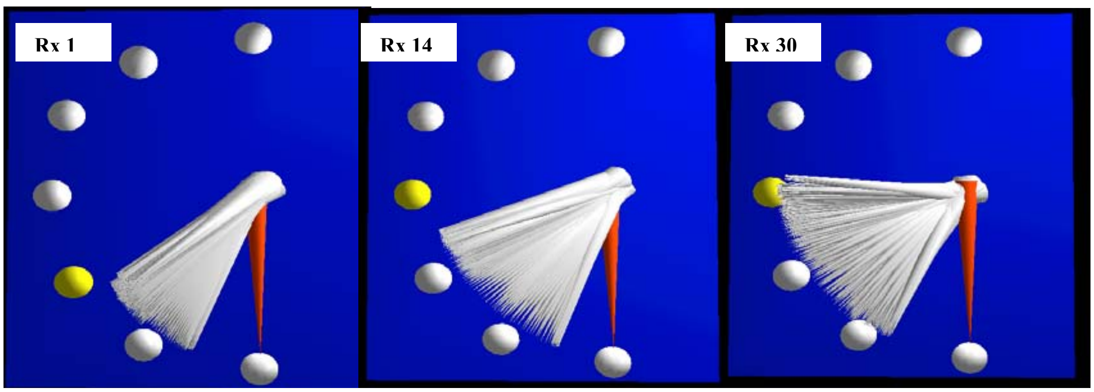


Figure 2. Examples of Improved Performance during VE training. Panels, from left to right, show attempted supination during 1st , 14th and 30th VE training sessions for S2. Red needle indicates 0°, or full pronation. White needle rotation around the 'clock' coincides with supination of patient's hand. Balls are spaced at 30° intervals, from 0° (lowermost ball, full pronation) to 180° (uppermost ball, full supination). Yellow ball identifies target goal for that session.

Subjects

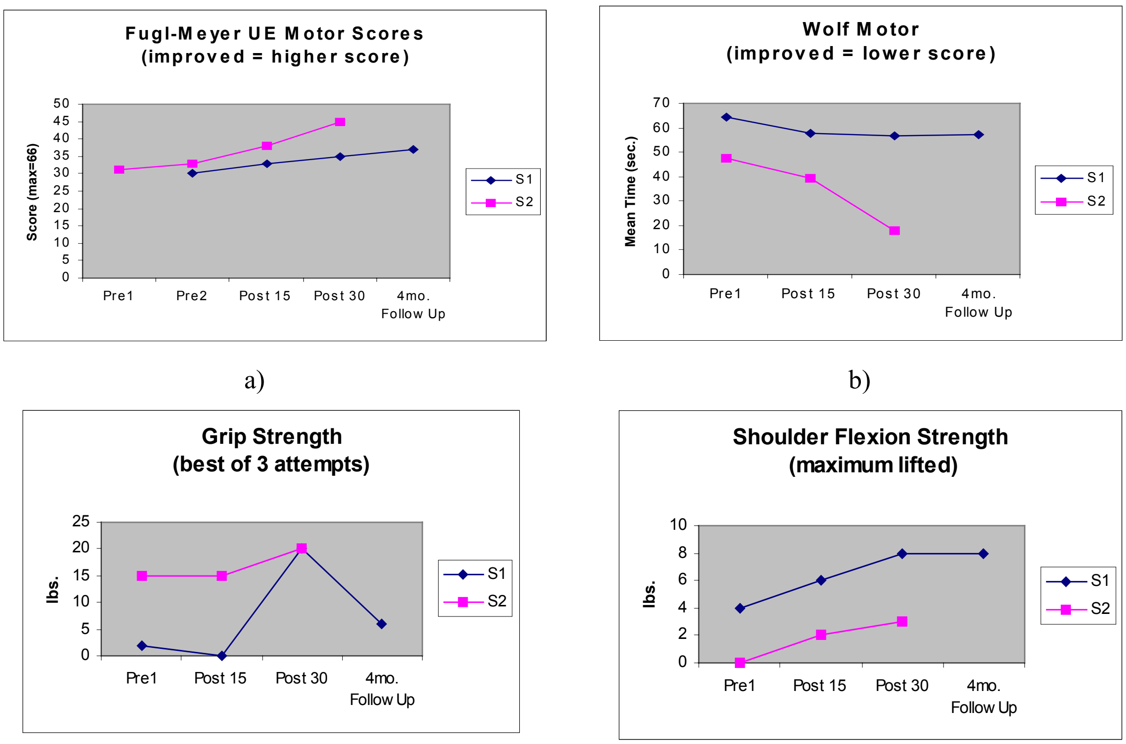
Two subjects with stroke were recruited who were familiar with the VE training system from participation in a prior study in our laboratory. Our purpose was to assess the workability of the Telerehabilitation system and the feasibility of the protocol. We felt that this prior experience would minimize frustrations that might be involved for the first few subjects.

Subject 1 (S1) was a female, age 42 yr., with L hemiparesis, 3.5 yr. post stroke, not currently receiving rehabilitation. Her initial UE Fugl-Meyer (FM) Motor score was 30; Total UE score was 72. (Maximum score is 66 for Motor, 126 for Total UE-FM.) S1 had more weakness in the hand than the shoulder. Subject 2 (S2) was a male, age 69 yr., with R hemiparesis, 7.5 yr. post stroke, not currently receiving rehabilitation. His initial Fugl-Meyer UE Motor score was 32 ; Total UE score was 81. S2 had more weakness in the shoulder than the hand.

Evaluation Tests

The evaluation consisted of three tests, all performed in the real world. Note that all training was in *virtual* world, thus 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 [16], and the Wolf Motor Test [17] (a timed test of 15 upper extremity functional tasks, and Strength tests for shoulder flexion and hand grip). The third test was a laboratory-designed Behavioral Kinematic Test (BKT). In the BKT subjects performed five upper extremity movement tasks in the real world, while the kinematics of their arm and trunk were recorded. 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 sec. duration.

Subjects were tested with this evaluation battery four times: PRE-training, POST 15 sessions, POST 30 sessions, and at 4 mo. follow-up. In general, tests were administered once at each time point. However, S2 had two PRE-tests (given 3 weeks apart) for the F-M clinical test, to ensure that his motor status was stable. Only S1 has had the follow-up test, as S2 is not yet 4 mo. post training. 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.



a) b)

c) d)

Figure 3. 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.

Rehabilitation Training

The VE training was given in two 3-week blocks, with 1 hr. sessions delivered 5x/week, for a total of 30 sessions. Treatments were interactive in real time with a therapist who was located at MIT.

The training was designed to improve three categories of movement control which present difficulty for patients with stroke, but are key to functional use of the upper extremity. These categories were: 1) Reaching movements to transport the hand away from the body into the workspace; 2) Hand to body movements, such as is needed for grooming and dressing; and 3) Repeated Reciprocal movements. To work on these control categories subjects trained with three standard scenes: Mailbox, SleevePull, and Clock. Specifically, these three scenes trained the following movement combinations: 1) Forward reach into shoulder flexion and elbow extension with lateral grasp and supination (Mailbox); 2) Shoulder flexion/adduction with trunk rotation and elbow flexion with lateral grasp (SleevePull); and 3) Forearm supination from full pronation, with slight wrist extension, and return to full pronation; arm supported in neutral shoulder flexion/abduction and elbow flexed to 70-90^{o} (Clock). 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 in the scene, along the teacher trajectory (SleevePull and Clock). Figure 2 shows an example of the Clock training scene with one subject's performance at three time points during training.

In addition to the standard scenes, each subject practiced with several other scenes that were designed and created for their particular motor control deficits. For each subject, a treatment script was developed, consisting of 8 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 not so easy that the subject got bored, nor so difficult that the subject was unduly frustrated. 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. Feedback from the virtual teacher was provided on most trials (~80-100% of trials).

RESULTS

System Performance

Most of the challenges we encountered with the system operation occurred with S1, our first subject. Technical difficulties occurred almost daily, and four times were severe enough that the treatment session could not be conducted. 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.

Subjective Reports by Subjects

Both subjects reported that they enjoyed using the system, and that it was motivating, particularly as they observed their score 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. Neither subject had difficulty with soreness or pain in the arm due to the exercises.

Evaluation 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 3, a-d. After 30 Rx, S1 had improved by 17% on the FM, 12% on the Wolf Motor, 900% on Grip strength, and 100% on Shoulder Flexion Strength. At the same time point S2 had improved 41% on the FM, 62% on the Wolf Motor, 33% on Grip Strength and 100% on Shoulder Flexion Strength. Both subjects reported that the improvements were large enough to be meaningful to them; i.e., to improve daily functional use of the affected arm.

Qualitative review of data from the Real World BKT also suggests that improvements occurred. Figure 4a-b shows examples of Real World trajectories and velocity profiles for the Mailbox task for S1, pre and post treatment. Note straighter upward trajectory, indicating improved shoulder elbow coordination post training (left panel), and increased speed and smoother velocity profiles post training (right panel).

Review of Virtual World trajectories collected during training indicate progressive improvement as well. An example of data for S2 for the Supination /Pronation task during early, middle and late training sessions is shown in Figure 2.

DISCUSSION AND CONCLUSIONS

We have found that our Telerehabilitation system is not only feasible for use with patients, but that we have been able to see clinically significant improvement in our first two subjects following 30 sessions of VE therapy delivered over the internet (See Results). Of particular importance is the finding of improvement on the clinical tests, indicating that subjects can transfer skills learned in the virtual environment to real world performance of similar tasks and to untrained tasks. The relatively large improvements in the two strength measures were somewhat surprising, although we have seen a similar pattern in a prior study[7]. Subjects in this study trained using only active movements. However, because they were so weak initially 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 the result of two factors: 1) improved neural recruitment patterns (most likely ; 2) muscle fiber hypertrophy (less likely, perhaps possible for changes at post 30 sessions). That the per cent 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 intriguing finding is that subjects so long post stroke 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). In terms of motor skill learning, this is not a great amount of practice. 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 a similar effect could be achieved by simple practice of the movements for similar amounts of time is an open question, and awaits further study.

In terms of practicality, the system is still too costly for mass use, and the system could benefit from further automatization. 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, as a therapist does during treatment

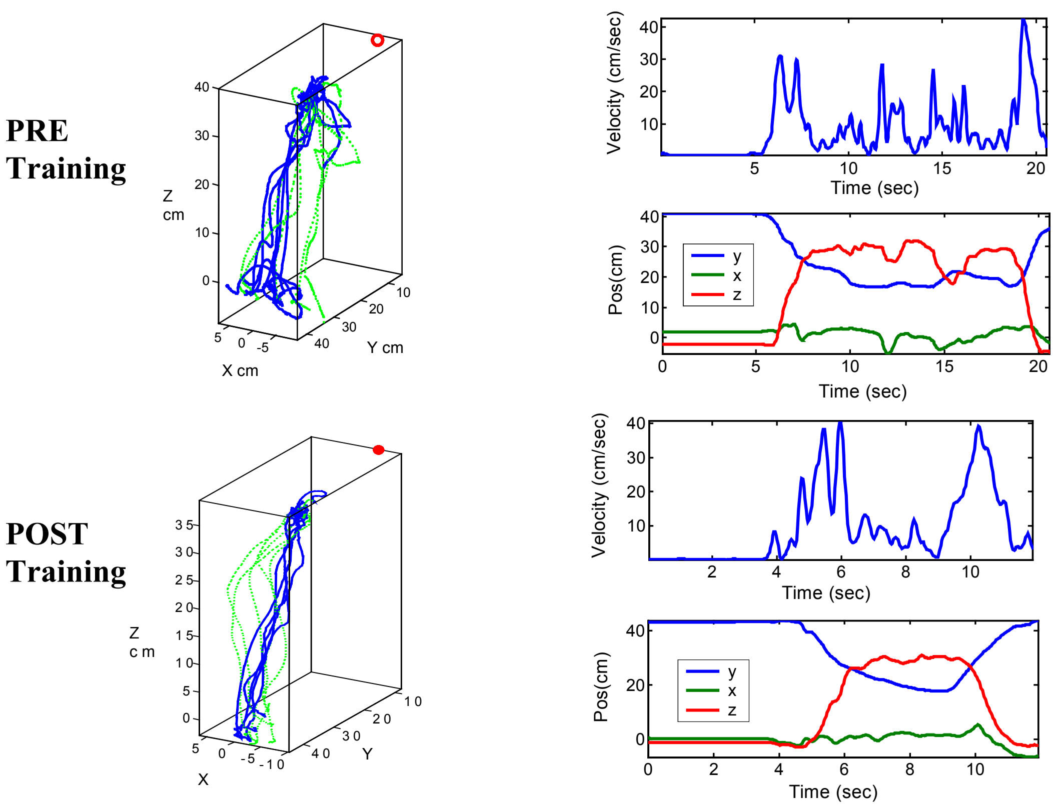


Figure 4. Example of Behavioral Kinematic Test. Real World performance before (top panel) and after (bottom panel) 30 sessions of VE training, conducted via Telerehabilitation for S1. Left, 3-D plots for 5 hand trajectories during reaching toward a slot. Blue is upward trajectory, green is the return movement; red dot is target location. Right, Velocity and Position profiles for one sample trajectory from each plot shown on left.

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