# Design and Testing of a Telerehabilitation System for Motor Re-Training using a Virtual Environment

Maureen K. Holden, Thomas A. Dyar, and Lilian Dayan-Cimadoro

*Abstract*—**In this paper we describe our experience in designing and testing a virtual environment based (VE) Telerehabilitation system. The system allows a therapist to conduct interactive treatment sessions remotely with a patient who is located at home. Some of the technical and practical issues encountered during development and testing are described, as well as how we adapted the system to allow training of more skilled hand functions. Preliminary results of the first 12 subjects with stroke to use the system showed significant gains in upper extremity function following 30 one-hr treatment sessions (Fugl-Meyer, p<0.0001; Wolf Motor p=0.0097; shoulder (p=0.0027) and grip (p=0.025) strength. These changes were maintained, for the most part, at 4-month follow-up.**

## I. 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 out-patient therapy services. However, to qualify for home care (that is, the therapist comes to the patient's home to provide care), the patient must be classified as medically 'homebound'. This means that the patient is physically unable to leave the house independently. If a patient is not classified as 'homebound', then he/she is expected to travel to an out-patient clinic to receive care.

Many patients can suffer reduced access to care at this point due to transportation problems. For example, a patient who cannot drive because of their disability must depend on family or friends to drive them to appointments. This is often not feasible when family members are working. If the patient is located in a rural or even suburban area where public transportation is not readily available, the patient may be effectively cut off from receiving therapy services due to the logistical problems involved in obtaining transportation, despite qualifying for care in terms of their medical status. Others may be able to obtain transportation, but if they live some distance from the clinic, find it too tiring to go to the therapy sessions on a frequent basis.

Another group consists of patients who have completed their standard course of rehabilitation, but still would like to do more. They may find it too daunting to go to their local gym for exercise, where most equipment is not set up for easy use by someone with a disability. Or they may simply desire the extra motivation that guidance by a therapist or a novel approach to therapy, such as working in a virtual environment may provide.

All 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. We have developed a TeleRehabilitation system with such patients in mind. Our system was developed as an extension of the stand-alone virtual environment motor training system previously developed in our laboratory [2]−[6]. The system is depicted in Fig. 1. Prior reports have detailed some of the system features, and preliminary results on the first two patients to use the system [7], [8]. In this paper we discuss our experience with the development of the system from the perspective of both technical and practical/clinical issues encountered during our initial feasibility testing with 12 subjects with stroke who used the system in a home based environment. As well, we discuss further details of the VE treatment regimes used, and the significant improvements found for our subjects using standard clinical outcome measures.

## II. DESCRIPTION OF TELEREHABILITATION SYSTEM

The overall system is shown below in Fig.1, and has been described in detail elsewhere [7], [8]. Briefly, to use the system, the patient sits in front of a computer with 2 monitors – one for the VE scene and one for the videoconference image of the therapist. The patient flips one switch to turn on all the devices and activate the videoconferencing connection with the therapist. The patient wears 2-3 Polhemus sensors and his/her movement is captured and interpreted by the VE software to animate the VE scene. The motion data is also transmitted to the VE software at the clinic and where a synchronized VE scene is viewed by the therapist. The therapist can control the

Manuscript received April 1, 2006, and accepted May 31, 2006. This work was supported by NIH Grants No. HD40959, HD40959-01S2 and 3MO1RR01066-25S.

M. K. Holden is with the Department of Physical Therapy, Northeastern University, Boston, MA 02115 and the Department of Brain and Cognitive Sciences, the McGovern Institute for Brain Research, and the Clinical Research Center, Massachusetts Institute of Technology (MIT), Cambridge, MA 02139 USA (phone: 617-373-5274; fax: 617-373-3161; e-mail: m.holden@neu.edu ).

T. A. Dyar, was with the Department of Brain and Cognitive Sciences, the McGovern Institute for Brain Research, and the Clinical Research Center, Massachusetts Institute of Technology (MIT), Cambridge, MA 02139 USA (e-mail: tdyar@neuralcorrelate.com).

L. Dayan-Cimadoro was with the Clinical Research Center, MIT, Cambridge, MA 02139 USA, and Spaulding Rehabilitation Hospital, Boston, MA, 02115. She is now with the Department of Physical Therapy, Massachusetts General Hospital, Boston, MA 02114 USA (e-mail: ldayancimadoro@partners.org ).

VE scene via the keyboard and mouse, choosing the exercise-specific scene, the viewpoint in the virtual environment, and training parameters such as speed of the movement and different types of feedback.

The primary training philosophy is that of learning by imitation [5]. The VE scene contains a pre-recorded movement (Teacher movement) and the patient can see the movement being performed in the VE scene and then attempt to copy the motion in the same spatial frame of reference as the Teacher movement. The patient attempts to move so that their "virtual arm" or "hand" overlaps as closely as possible the Teacher's. The therapist controls the speed of the Teacher, can pause the Teacher, and also controls whether sounds and text are displayed to cue the movement start and whether to display real-time mismatch feedback. Multiple VE scenes can be saved that focus on different skills and training techniques, and the therapist can switch between them in a single training session to avoid overworking certain muscles and preventing the patient from becoming bored. The system also allows for real-time recording of new teacher movements by the therapist during the treatment session, if desired. These real-time Teacher recordings would best be used for simple on-line visual feedback during attempted movement by the patient. However, for quantitative feedback based on the degree of match between the patient and Teacher 3D trajectories, pre-recorded teacher trajectories should be used. This will allow time to set up and fine tune the parameters of the algorithm used to generate the score, and store the settings in a file. Further detail on this aspect of training may be found in Holden & Dyar, 2002 and Holden et al., 2005 [6], [8].

Combined with the videoconferencing, the real-time VE software provides a rich interactive training system. The cost of the system as developed was ~ $12,000, with most of this amount due to the motion tracking device (~$8,500).

## III. Development Experience – Technical Issues

We performed several tests prior to deployment in each patient's home, to determine the suitability of the Internet connection between the clinic and the home. We used *iperf* network utility [9] to test the quality of the connection using *iperf*'s measures of bandwidth and jitter (variability in timing

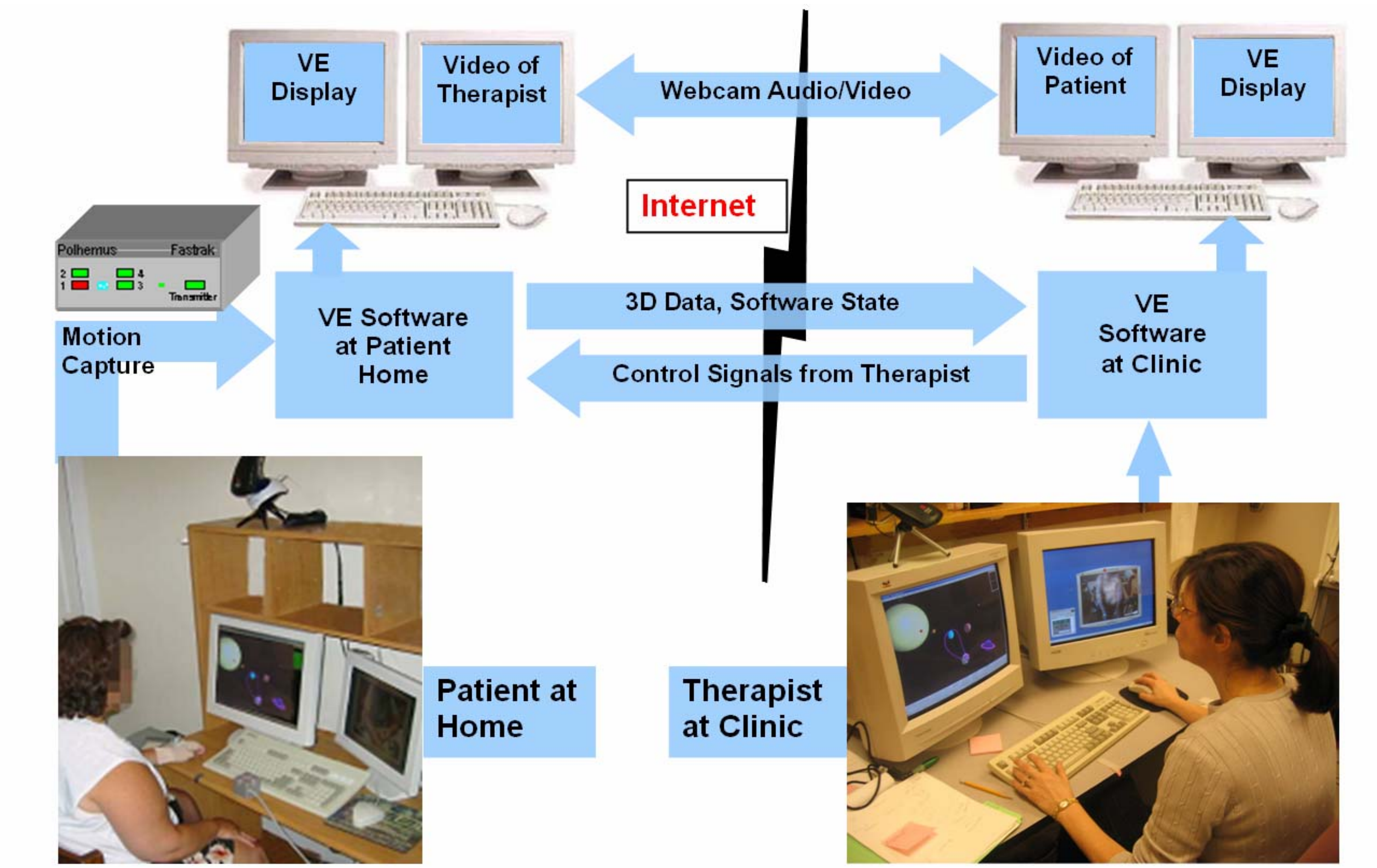


**Fig. 1**. Schematic of the Home-Based VE Telerehabilitation System. The patient and therapist can see and hear each other via a teleconferencing link on one monitor. Motion capture equipment transmits information about patient's arm movements to the VE display. The therapist in the clinic controls the software and views the same Virtual Environment scene as that displayed to the patient in her home (second monitor). The video camera allows the therapist to remotely view any part of the patient's workspace [7],[8].

of successive messages). With these data, we could retrospectively compare the various network carriers (Cable and DSL) for network quality and speed. Overall, we found that DSL provided a better-quality signal, but that the Cable carriers provided a better overall experience with less connection disruptions.

The primary technical constraint of our system is upstream bandwidth and quality. Commodity Internet service, until very recently, was limited to an upload speed of between 128 to 256 kilobits per second (kbps). This is very slow compared to the usual download speeds of over 1000 kbps. Thus, for a real-time patient training system both the audio-visual communication and motion capture information must be able to be transmitted within the 128-256 kbps "budget". Also, the quality of the connection was found to be variable between carriers, both DSL and Cable. The audio-visual system consumed the bulk of the budget, and was inflexible since intelligibility of speech and video resolution was not adequate when constrained to less than 128 kbps. Therefore, the only option was to reduce the bandwidth of the motion capture in most situations. In order to work over the worst links, we compacted our motion capture data using quaternion representation [10] for the rotational information of the sensors (using only 4 floating point numbers). We also allowed the therapist to configure the system to use less bandwidth by reducing the sampling rate of the motion capture data. We found that 20 Hz provided acceptable levels of motion information for the therapist to interact with the patient. Full resolution data (40 Hz) were recorded locally on the patient's computer, and then uploaded after the session to the MIT computer for use in data analysis.

Other performance issues such as network latency and timestamp accuracy were not found to be significant problems. Latency would only increase above a virtually unnoticeable 50 msec when the bandwidth budget was exceeded. Timestamps were not used to synchronize important aspects of system state between the therapist and patient VE systems. Instead, infrequent yet critical command messages (e.g. "Start Trial" or "Change VE Scene") were sent to the patient VE system over a "guaranteed in-order" network channel, and acknowledgement of the successful completion of the command was required before any other requests could be sent from the therapist computer.

## IV. Development Experience – Practical / Clinical Issues

Various practical problems had to be solved to create a usable system. For example, some patients' homes had little extra space for the desk and other equipment. We reduced the space requirements and increased portability by using LCD monitors. Because patients would be home alone during treatment (although in contact with the therapist via the computer), desktop monitors were chosen to avoid any potential problems with cybersickness secondary to the use of a stereo display headset. Our software was capable of 3D stereo display, but with the desktop display only 2D projection could be used. The 2D display was enhanced with various monocular depth cues [4], [6]. In addition, we utilized a replay feature that allowed us to replay patient performance in a repeating loop, and to change the viewpoint of the scene during the replay, so that depth could be easily visualized for movements originally performed in the frontal plane [6].

Software and hardware were configured so that the entire system could be turned on and off from a single switch. Also, since the patients had several sensors attached to their body, the wires from them had to be kept up and out of the way of movement. We eventually devised a wire harness that hung from the ceiling but was adjustable and removable with one hand so the patient could set up the wires before training, but after training they could be stored out of the way. We developed various "quick-release" sockets to hold the Polhemus receivers. They enable one-handed operation so that sensors could to be easily moved between objects and body parts depending on the task and VE scene. The socket was attached to the hand via a custom-designed "glove" that had adjustable loops for the fingers and a Velcro strap around the wrist. Through iterative design and testing, we arrived at a glove design that allowed most of the patients to don and remove the glove and sensors without assistance. The glove can be seen in Figs. 2-3. These adaptations allowed patients to get ready for treatment in ~ 5-10 min., which they typically did independently prior to 'connecting' to the therapist via the telerehabilitation system.

Although multiple cameras would provide a better view of the patient movement, it was not practical due to set-up and cost constraints. Instead, we attached a single ViaVideo camera (Polycom Inc., Pleasanton, CA) atop a Trackerpod (Eagletron, Inc., New York, NY) robotic device. The Trackerpod can point the camera left, right, up and down so the therapist can center the camera view over the relevant workspace area depending on the particular movement being trained. Microphones within the camera unit, which are mounted directly in front of and above the participants, provide adequate sound quality (i.e. speech of patient and therapist were mutually intelligible).

## V. Clinical Experience – Subjects and VE Training Protocol

**Subjects**. Twelve subjects with prior stroke (>6mo. post) were admitted to the study. All subjects signed an informed consent form, which was approved by our Institutional Review Board (IRB). One subject (S9) dropped out after baseline testing, but prior to the initiation of the VE training. The remaining eleven subjects completed the entire protocol and testing regime. Table I lists the pertinent subject characteristics.

**VE Training Protocol.** The VE training was given in two 3-week blocks, with 1 hr. sessions delivered 5x/week, for a total of 30 one-hour sessions. Treatments were interactive in real time with a therapist, who was located remotely at the MIT Clinical Research Center, while the patient remained at

TABLE I. TELEREHABILITATION STUDY SUBJECT CHARACTERISTICS

| | *S1* | *S2* | *S3* | *S4* | *S5* | *S6* | *S7* | *S8* | *S9** | *S10* | *S11* | *S12* | **Mean**** | **SD**** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ***Age (yr)*** | 42 | 69 | 73 | 58 | 64 | 30 | 47 | 56 | 70 | 80 | 39 | 66 | 56.7 yr. | 15.6 |
| ***Plegic Side (Left or Right)*** | L | R | L | L | R | L | R | L | R | L | R | R | 5R, 6L | |
| ***Gender (Male or Female)*** | F | M | F | M | M | F | M | F | M | F | M | M | 6M, 5F | |
| ***Duration Post (yr)*** | 3.6 | 7.3 | 0.8 | 7.5 | 1.5 | 5.3 | 3.7 | 9 | 1 | 0.6 | 1.3 | 0.7 | 3.8 yr. | 3.1 |
| ***Initial FM Total++*** | 72 | 82.5 | 99 | 89.5 | 80 | 107 | 121 | 92.5 | 76.5 | 68.5 | 100 | 81 | 90.3 | 15.7 |
| ***Initial FM Motor++*** | 30 | 33.5 | 50 | 43 | 28 | 54 | 63 | 39 | 23 | 15 | 41.5 | 25.5 | 38.4 | 13.9 |
| ***Aphasia*** | No | Yes+ | No | No | No | No | Yes | No | Yes | No | No | No | 1Yes, 10 No | |

*Subject 9 dropped out after Pretest, prior to start of VE training;
**Mean and SD for subjects who completed training (n=11);
+Resolved;
++ Initial FM-UE scores are mean of two pretests, 1-12 wk apart; higher FM score indicates greater recovery, with maximum Total score = 126 and maximum Motor subscore = 66

home.

A detailed description of the VE training method may be found in Holden et al. [8], so only a brief synopsis will be provided here. The training was designed to improve four 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; 3) repeated reciprocal movements, and 4) control of hand, grasp/ release and wrist orientation. To work on these control categories all subjects trained with three standard VE scenes: Mailbox, Sleeve Pull, and Clock, which addressed the reaching, hand to body, and repeated reciprocal movement control elements. The fourth category, control of hand, grasp/ release and wrist orientation was incorporated into the standard scenes as a variation, or addressed by additional scenes (see Figs. 2-3). Further detail on how these scenes were designed to retrain specific movements, and how the quantitative features of the trajectory matching score were implemented may be found in a prior report [8]. In addition to the standard scenes, each subject also practiced with several other scenes that were created and custom designed for their particular motor control deficits. 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).

In this paper, we describe how we attempted to overcome some of the inherent limitations of our system in training more skilled hand functions. Figs. 2-3 show scene designs and some simple adaptations in the clinical set-up that allowed us to train more skilled hand, finger and arm movements in our subjects. Fig. 2, left panel, illustrates how grasp with repeated reciprocal control of wrist flexion/ extension was achieved. If subjects had poor finger control, they could begin practice without using the ball at all. In this case the sensor was placed on the hand rather than inside the ball. This placement caused the hand movement to be mapped on to the virtual ball in the VE scene. Fig. 2, right panel, shows how we were able to train index finger extension in a subject who had difficulty with hand opening mainly due to poor index finger control. Fig. 3 shows how we trained a more complex skill of object grasp/ release combined with whole arm movement in a subject (S7) with a fairly high skill level.

**Evaluation Tests.** To assess stability of motor recovery pre-training, subjects received the upper extremity portion of Fugl-Meyer Test of Motor Recovery (FM) [11] twice, 1-12 wk apart. The Pre/Post training evaluation battery consisted of three standard clinical tests: 1) the FM; 2) the Wolf Motor Test (WMT) (a timed test of 15 upper extremity functional tasks) [12]; and 3) Strength test (shoulder flexion and hand grip). Note that all training was in the virtual world, but all the evaluation tests were performed in the real world. Thus, these tests served as a measure of transfer of virtual training to real world function. Subjects were tested with this evaluation battery four times: PRE-training, POST 15 sessions, POST 30 sessions, and at 4 mo. follow-up. The sequence of tests was randomized across subjects, but remained the same at each time point for a particular subject.

## VI. CLINICAL EXPERIENCE – RESULTS

Results were analyzed using paired t-tests [13]. **Baseline:** Mean values for the 2 baseline FM tests showed no significant difference (-0.3±1.6, p=0.56), indicating stable motor recovery prior to VE training via telerehabilitation. **FM:** Following

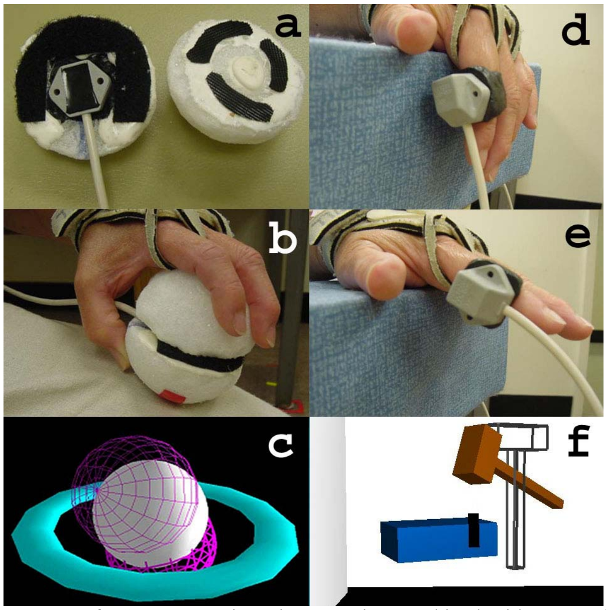


**Fig. 2**. Left: Set-up to train wrist extension combined with grasp. a) sensor was placed inside ball; b) patient grasped ball in hand; c) during training, held ball (solid) moved from start position of wrist flex (thick wire frame, below ring) into extension (thin wire frame, above ring). Right: Set-up designed to train individual finger control. d) start position; e) end position. f) VE scene in which the subject's index finger was displayed as the hammer, and the nail could be hit repeatedly by flexing and extending the index finger at the MCP joint, whilst maintaining the PIP and DIP joints in an extended posture. Grey outline of hammer corresponds to start position shown in d); solid hammer corresponds to halfway point, black 'nail' corresponds to the end position shown in e).

training, mean FM scores improved significantly after 15rx (+2.5, p=0.003), after 30rx (+6.7, p=<0.0001), and at 4 mo. follow-up (+7.6, p=0.001). **WMT:** Mean WMT scores improved significantly after 15rx (-6 sec, p=0.0235), after 30rx (-15.5sec., p=0.0097), and at 4 mo. follow-up (-18.4 sec., p=0.0032). **Strength:** Shoulder Strength improved after 15rx (40%, p=0.0027), 30rx (69%, p=0.0010) and at follow-up (66%, p=<0.0001).

Grip Strength improved significantly after 30rx (44%, p=0.0253) but was only partially maintained at follow-up (26%, p=0.0897).

## VII. Discussion

Subjects' improvements were both clinically and statistically significant. These findings indicate that VE training conducted remotely over the Internet is feasible and may be a viable new method for neurorehabilitation. Subjects gains on all 3 clinical measures (FM, WMT, Strength) show that they were able to generalize motor training received in VE to real world performance, even to tasks not specifically trained in VE, and to retain gains for 4 months. Our results concur with those of others that subjects with chronic stroke are capable of significant motor improvements even many years after stroke [14].

With the home-based treatment used in this study, the difficulty of obtaining transportation to/from the therapy clinic

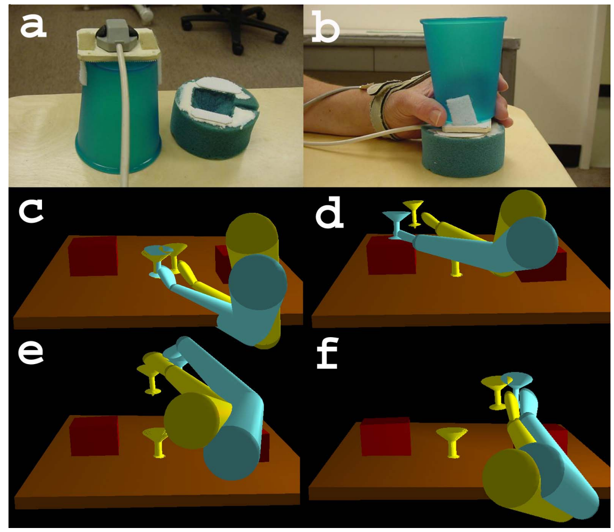


**Fig. 3**. Training more complex hand/arm movements. a-b) a cup was outfitted with a sensor in an attached base. *c)* the cup is displayed as martini glass, grasped and d) lifted to box at left. e) the glass was released, then re-grasped with different hand configuration (fingertip grasp from top), then moved to right box, where f) grasp was changed back to cylindrical grasp and glass was transported back to start position. Both teacher (yellow) and learner (blue) arms are shown.

was avoided. The elimination of commuting time and effort may have allowed our subjects to have more energy to devote to motor practice during sessions, and to tolerate the more intense frequency of treatment that was utilized in this study, thus facilitating their improvement.

## VIII. Conclusions

This novel VE motor retraining via telerehabilitation appears effective in improving UE motor control and functional performance in subjects with chronic stroke. In addition it provides a fun and motivating treatment alternative to standard therapy exercises.

## Acknowledgement

We would like to thank our patients who kindly gave of their time to participate in this experiment, the staff at the MIT-CRC who provided assistance with the study, and Dr. Emanuel Todorov for his earlier contributions to the development of the VE Training System.

## References

[1] B. Dobkin, "The economic impact of stroke," *Neurology*, vol. 45, Suppl 1, 1995, s6-s9.

[2] E. Bizzi, F. A. Mussa-Ivaldi, and R. Shadmehr, "System for human trajectory learning in virtual environments," US Patent No. 5 554 033, 1996.

[3] E. Bizzi, F. A. Mussa-Ivaldi, and R. Shadmehr, "System for human trajectory learning in virtual environments," US Patent No. 5 846 086, 1998.

[4] M. K. Holden and E. Todorov, "Use of virtual environments in motor learning and rehabilitation," in *Handbook of Virtual Environment Technology*, Vol. 1, K. Stanney, Ed., New Jersey: Lawrence Erlbaum Assoc, Inc.; 2002, pp. 999−1026.

[5] M. K. Holden, "NeuroRehabilitation using 'Learning by Imitation' in virtual environments," in *Usability Evaluation and Interface Design:*

*Cognitive Engineering, Intelligent Agents and Virtual Reality*, vol. 1, J. Smith, G. Salvendy, D. Harris, and R. J. Koubeck, Eds., London: Lawrence Erlbaum Assoc. London, 2001, pp.624-628.

[6] M. K. Holden and T. A. Dyar, "Virtual environment training: A new tool for rehabilitation," *Neurology Report*, vol 26 no 2, 2002, pp. 62-71.

[7] M. K. Holden, T. Dyar, L. Schwam, and E. Bizzi, "Home-based Telerehabilitation using a virtual environment system," in *Proc. 2nd International Workshop on Virtual Rehabilitation*, G. C. Burdea, D. Thalmann, and J. A. Lewis, Eds., 2003, pp. 4-12.

[8] M. K. Holden, T. Dyar, L. Schwamm, and E. Bizzi, "Virtual environment-based telerehabilitation in patients with stroke, *Presence: Teleoperators and Virtual Environments*, vol. 14, no. 2, 2005, pp. 214-233.

[9] A. Tirumala, J. Ferguson, "Iperf 1.2 -- The TCP/UDP Bandwidth Measurement Tool," http://dast.nlanr.net/Projects/Iperf/ 2001.

[10] K. Shoemaker, "Animating rotation with quaternion curves," *ACM SIGGRAPH*, vol. 19, no. 3, 1985, pp. 245-254.

[11] A. R. Fugl-Meyer, L. Jaasko, I. Leyman, S. Olsson, and S. Steglind, "The post-stroke hemiplegic patient: A method for evaluation of physical performance," *Scandanavian Journal of Rehabilitation Medicine*, vol. 7, 1975, pp. 13-31.

[12] S. L. Wolf, P. A. Catlin, M. Ellis, A. L. Archer, B. Morgan, and A. Piacentino, "Assessing Wolf Motor Function Test as an outcome measure for research in patients after stroke," *Stroke*, vol. 32, 2001, pp. 1635-1639.

[13] Analyze-It Software, Ltd. (1997-2006). *Analyze-it General statistics module, version 1.62*. Available at http://www.analyze-it.com.

[14] V. W. Mark, and E. Taub, "Constraint-induced movement therapy for chronic stroke, hemiparesis and other disabilities," *Restor Neurol Neurosci*, vol. 22, nos. 3-5, 2004, pp. 317-36.