Telerehabilitation Using a Virtual Environment Improves Upper Extremity Function in Patients With Stroke

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***Abstract*—In this paper, we describe our experience in designing a virtual environment-based (VE) telerehabilitation system, and the results of a clinical study of the first 11 subjects with stroke to use the system. Our telerehabilitation system allows a therapist to conduct interactive VE treatment sessions remotely with a patient who is located at home. The system, software architecture, and development experience are described. Results of the clinical study on subjects with stroke showed significant improvements in upper extremity function following 30 1-h VE treatment sessions as measured by three standard clinical tests: Fugl–Meyer test of motor recovery (FM) ($p < 0.0001$), Wolf motor test (WMT) ($p = 0.0097$, and shoulder strength (ShS) ($p = 0.0027$). Grip strength (GS) showed a trend toward improvement ($p = 0.025$). These changes were maintained, for the most part, at four-months follow-up (FM $+7.6$, WMT -18.4 s, ShS, $+169\%$, GS, $+53\%$).**

***Index Terms*—Motor learning, stroke, virtual reality.**

I. INTRODUCTION

DUE to changes in the health care delivery system in recent years, many patients in the United States are returning to their homes following disabling events, such as stroke, sooner than in the past. Often they do so with significant functional deficits and a continuing need for rehabilitation [1]. This need is typically met through home care or outpatient therapy services. However, many patients can suffer reduced access to care for a variety of reasons. Home care services may be short in duration, and once patients are physically able to leave their home independently, they are expected to utilize outpatient services. For those who cannot drive because of their disability, logistical issues involved in obtaining transportation to a clinic, such as lack of public transportation, high cost of taxi service, or family members who are unavailable to help due to work schedules, can present major barriers to obtaining needed care. Other patients may find it too tiring to go to the clinic on a frequent basis, even if transportation is available. Still others have completed their standard course of rehabilitation, but would like to do more.

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, i.e. "telerehabilitation." Most telerehabilitation applications have utilized a basic teleconferencing setup, where participants see and hear each other on computer monitors. Such systems have been used most often to provide access to rehabilitation services in rural communities or to provide expertise in locales where little exists, such as underserved urban communities [2]. Teleassessment has also been investigated [3].

A different approach to telerehabilitation, which we believe greatly enhances its therapeutic potential, involves the addition of different types of virtual environment training systems to this basic teleconferencing setup. We have developed such a VE-based (virtual environment) telerehabilitation system as an extension of a stand-alone virtual environment motor training system previously developed in our laboratory [4]–[8].

Several other groups have also reported on the development of VE-based telerehabilitation systems [9]–[13]. The system designed by Burdea *et al.* [9]–[11] is designed for clinic to clinic (versus clinic to home) operation. In a pilot study of one patient with stroke, the Rutgers Arm was used to train arm movements in 12 local sessions, followed by three telerehabilitation sessions with good success, as indicated by improvements in arm motor control and range of motion [9]. A second study used the system to train ankle control in six patients with stroke [10]. Sessions were conducted in local mode for the first three weeks, followed by one week of training using telerehabilitation in a clinic to clinic format. Patients in this study showed improvements in five performance measures, but mostly in the first two weeks of training. Reinkensmeyer *et al.* [12] adapted a computer joystick with force feedback to allow patients to independently practice simple movements using web-based telerehabilitation. The system proved feasible in pilot testing of one patient with stroke. Piron *et al.* [13] used a home based VE telerehabilitation system to conduct a randomized trial of VE therapy versus home-based conventional rehabilitation in 24 patients with stroke. Subjects in both groups showed significant improvement on clinical measures of arm function, and both treatments were reported as comparably effective. The VE software used in the Piron study was initially developed in our

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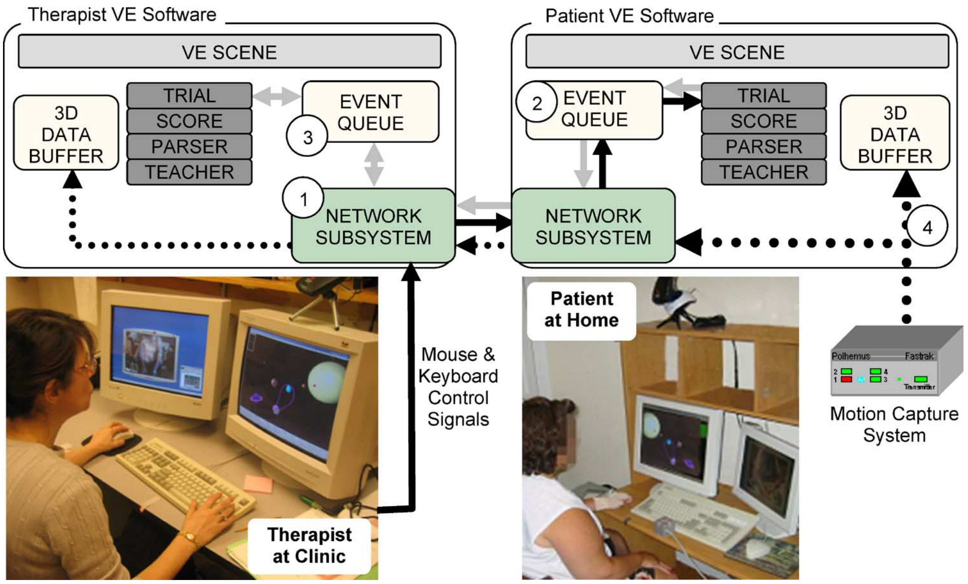

Fig. 1. Schematic of the home-based VE telerehabilitation system. Patient and therapist can see and hear each other via a teleconferencing link on one monitor. Motion capture equipment transmits information about patient's arm movements to the VE display. Therapist in the clinic controls the software and views the same VE scene as that displayed to the patient in her home (second monitor). Video camera allows the therapist to remotely view any part of the patient's workspace [14], [15]. Software architecture depicting main modules and data flow during training sessions shown at top. The major software modules (TRIAL, SCORE, PARSER, TEACHER, EVENT QUEUE, 3-D DATA BUFFER) interact to produce the VE SCENE. The NETWORK SUBSYSTEM passes data between the patient and therapist Computers. Solid black arrows show the flow of a keyboard control signal before it effects change on the patient computer. Gray arrows show subsequent flow of that control signal to synchronize the therapist VE scene. Dotted arrows show the flow of 3-D data that is transmitted in a continuous stream (smaller dots indicate reduced temporal resolution for the transmitted data). See text for details.

laboratory at Massachusetts Institute of Technology (MIT), although the networking components used for the telerehabilitation were developed separately in Italy.

The purpose of this paper is twofold: 1) to discuss our experience with the development of the telerehabilitation system, and 2) to report the results of clinical efficacy testing on the first 11 subjects with stroke to use the system. Subjects were tested after 15 and 30 sessions and at four month follow-up. Group means on standard clinical measures of motor control, function and strength all showed significant change after 15 and 30 sessions, which were maintained at four month follow-up.

II. DESCRIPTION OF TELEREHABILITATION SYSTEM

The overall system we have developed to help regain upper extremity function is shown in Fig. 1, and has been described in detail elsewhere [14], [15]. Briefly, to use the system, the patient sits in front of a computer with two monitors—one for the VE scene and one for the videoconference image of the therapist. The patient wears 2–3 Polhemus sensors—one on the back of the hand, one on the upper arm, and an optional sensor attached to an instrumented, held object—that capture the motion of the upper extremity. The VE software produces a real-time "virtual upper extremity" from an algorithmic model of the arm that infers shoulder, elbow and wrist locations and orientations. The model is constrained by parameters that can be customized for each patient such as arm segment lengths, the sensor positions relative to the elbow and wrist joints, and the assumption that the trunk is oriented vertically. The motion data is simultaneously transmitted to the VE software at the clinic where a synchronized VE scene is viewed and controlled by the therapist.

The primary training philosophy is that of learning by imitation [7], in which the patient attempts to copy the motion of a prerecorded teacher movement being performed in the VE scene. The therapist controls the speed of the teacher, can pause the teacher, and also controls whether real-time mismatch feedback, sounds, and text are displayed. Multiple VE scenes can be saved that focus on different skills and training techniques. Further detail on this aspect of training may be found in two prior reports [8], [15].

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, including patient and therapist computers, with most of this amount due to the motion tracking device (∼$8500).

III. DESCRIPTION OF SYSTEM—SOFTWARE ARCHITECTURE

The rehabilitation software is internally comprised of a number of semi-independent software modules, each responsible for a specific function. The SCORE module calculates a score based on the patient movement (collected in the 3-D DATA BUFFER that holds a history of tracker *xyz* and orientation data) and the TEACHER data. The score algorithm can analyze both intrinsic properties of the patient movement such as speed and smoothness, as well as how closely it matches the TEACHER movement [8], [15]. The PARSER monitors patient 3-D data, and detects when the patient starts and stops moving, as well as when the patient's hand reaches a target location. The TRIAL module manages writing data to raw data files and the database, and displaying trial-related information to the patient. The TEACHER manages displaying a prerecorded "virtual teacher" movement.

The EVENT QUEUE provides a means for the objects to interact flexibly by posting and reacting to messages. If the system is configured in "manual trial" mode, a trial starts/stops when the therapist presses the spacebar at the beginning/end of the patient's movement. The keyboard event is posted to the EVENT QUEUE and the TRIAL module reacts by initiating 3-D data recording, and posting in turn a "Trial-Start" message. The TEACHER then initiates playback of the recorded movement. Stopping a trial entails a similar process, and additionally the SCORE module calculates a quantitative match between the patient's and the prerecorded teacher's data in response to the "Trial-End" message. The software can alternatively be configured to start/stop trials automatically when the patient starts/stops moving, and the PARSER will emit a "Movement-Start" signal when it detects the movement has started, to which the TRIAL module will react. These events will subsequently signal the TEACHER to start/stop animating, just as in manual trial operation.

Both the therapist's and patient's computers contain identical scene and virtual teacher information and they have to be synchronized to each other for networked operation. Fig. 1 illustrates how this is accomplished. ①Keyboard and mouse commands, such as to start/stop a movement trial, are issued by the therapist. Instead of instantly changing the VE state, the command is sent to the Patient computer via the network subsystem (black arrows). ② Once at the patient's computer, the command is placed on the event queue, and when processed by the VE, the network subsystem sends notification back to the therapist computer (gray arrows). ③ The event is now processed on the therapist computer, where changes to the VE state are integrated into the VE scene, and will mimic what happened in the Patient's VE. This scheme ensures synchronized activity on both computers even when delays are highly variable. ④ Also depicted in the figure is the transmission of the 3-D motion capture data. It is displayed and stored in full-resolution on the Patient computer, but down-sampled before being sent to the therapist computer.

IV. DEVELOPMENT EXPERIENCE

In a prior paper, we described solutions for the constraint of limited upstream bandwidth (128–256 kilobits/s maximum) for the home to clinic direction, and for other technical issues [16]. Here, we report how well these solutions worked in practice. During each session, the therapist recorded any technical problems that occurred. These data were then analyzed, assigned to a category, and summarized as follows: 1) internet problems (poor quality signal, or intermittent loss of connectivity) were the most frequent, affecting 60 or 18.2% of the total 330 sessions; 2) software defects ("bugs") that caused a software crash, or network de-synchronization of the software between patient and therapist occurred in 45 sessions, or 13.63%; 3) hardware issues such as computer main board failure, or malfunction of the internet router component, disrupted 20 sessions or 6.1%. Overall, however, most problems were minor and did not delay training more than 10 min before resolution. Some problems were more serious, and a total of 22 sessions (6.7%) had to be rescheduled.

In creating a system suitable for independent home use by patients with stroke, various practical problems were encountered, such as space issues for housing the equipment and safety considerations [17] for patients with poor balance and and/or functional use of only one arm. In a prior paper, we described our solutions for these problems [16].

V. CLINICAL STUDY—METHOD

The purpose of our clinical study was to test the feasibility of deploying our system in a home-based environment and to evaluate the clinical efficacy of the VE training in a group of subjects with stroke.

Subjects: Twelve subjects with prior stroke (>6 months post) were admitted to the study: one dropped out after baseline testing but prior to any VE training; 11 completed the protocol. Mean age for these 11 was 56.7 ± 15.6 year; time poststroke was 3.8 ± 3.1 year; initial Fugl–Meyer motor [18] score was 38.4 ± 13.9; 5 subjects had right hemiparesis, six had left, six were male, five were female; one had aphasia.

Subjects were included if they met the following criteria: 1) unilateral cerebral or brain stem lesion of vascular etiology, with resultant hemiparesis; 2) six months or $>$ poststroke; 3) discharged from rehabilitation therapy for upper extremity (UE) with stabilized motor recovery; 4) some motor and sensory recovery in the involved UE, i.e., >20 out of 66 on the motor subscore of the Fugl–Meyer test of motor recovery (FM) and >4 out of 12 on FM Sensory subscore [18]; 5) able to maintain a seated posture without back support for >5 min., and to transfer with $\leq 25\%$ assistance of one person; 6) the ability to pass a laboratory-developed computerized VE screening test, which was designed to eliminate subjects whose cognitive, perceptual or visual problems might interfere with VE motor training. The test was performed using the noninvolved UE, and required patients to execute reaching movements to all parts of the virtual and real world UE workspace, read instructions on the screen, interpret visual stimuli in all four quadrants of the virtual workspace, and make judgments about both their own performance and that of a therapist performing movements in the virtual environment.

Subjects were excluded if they had 1) implanted electronic devices such as pacemakers, defibrillators, or medication pumps (a precaution due to our use of an electromagnetic motion tracking device); 2) poorly controlled seizure activity or any other unstable medical problems as judged by the examining neurologist; 3) pain or contractures in the involved UE severe enough to interfere with therapy as judged by the examining physical therapist; or 4) bilateral cerebral injury or cerebellar infarct.

All subjects signed an informed consent form, which was approved by our Institutional Review Board (IRB). One subject (S10) completed the protocol, but did not return for the 4 month follow-up test. Detailed individual subject characteristics may be found in Table 1 of an earlier report [16].

VE Training Protocol: The VE training was given in two three-week blocks, with 1-h sessions delivered 5x/week, for a total of 30 1-h 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 home (Fig. 1). If subjects had been following a home exercise program prior to the study, they were allowed to continue that, but were asked

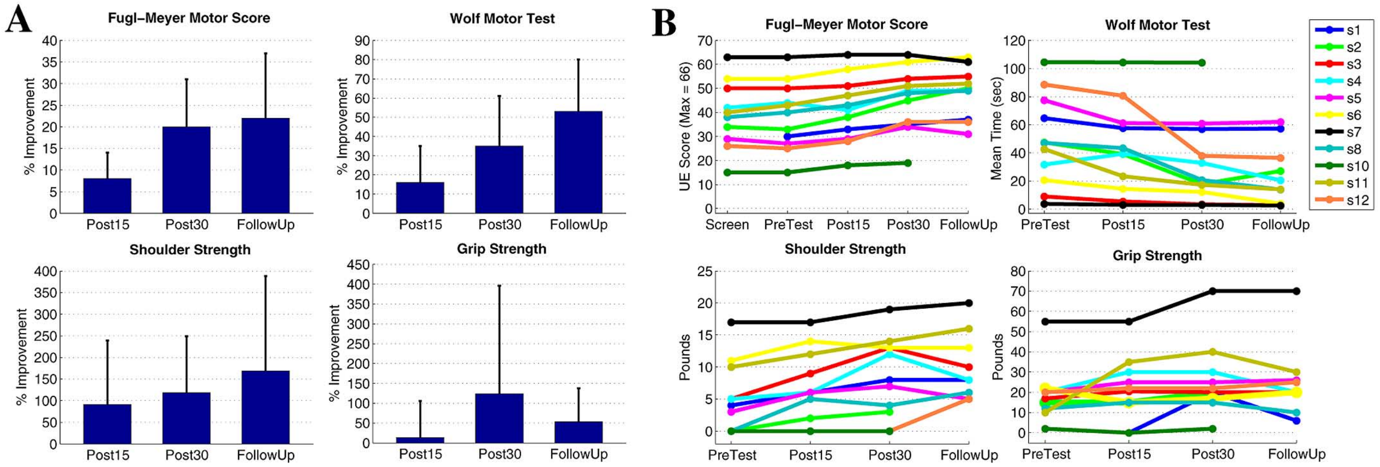

Fig. 2. Improvements in upper extremity function for subjects with stroke $(n = 11)$ following 15 and 30 sessions of VE Telerehabilitation and at four months follow-up testing. (A) Left panel shows percent changes versus pretest values $(\mathrm{mean} \pm \mathrm{sd})$ for the group as a whole for UE Fugl–Meyer (FM) test; and Wolf motor (WMT) test (upper graphs); shoulder flexion strength; and grip strength (lower graphs). (B) Right panel shows raw data values for each measure by individual subjects, at each time point. Upper graphs: Fugl–Meyer test (score range 0–66) and Wolf Motor test (seconds). Lower graphs: shoulder flexion strength (pounds) and grip strength (pounds). ANOVA results were significant for all four measures $(p < 0.0001)$. Pairwise comparisons for FM were significant at all three time points; for WMT were significant at post-30 and at follow-up; for shoulder flexion strength were significant at all three time points; but for grip strength, changes were nonsignificant, likely due to the high variability for that measure. See text for further detail and p values for each comparison. (A) Group averages. (B) Individual subjects—raw scores.

not to change it during the study period (including the four month follow-up period). Subjects kept a weekly "exercise activity log" which was monitored and recorded by study therapist. A review of the logs showed that subjects, in general, complied with the request to keep their home programs unchanged during the study.

A detailed description of the VE training method may be found in two prior reports [15], [16], 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 (see [15], Figs. 3 and 5), 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 was addressed by additional scenes (see [16, Figs. 2 and 3]).

Details 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 [15]. 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 (see [15], Fig. 4; [16], Figs. 2–3 for examples). A description of how we attempted to overcome some of the inherent limitations of our system in training skilled hand functions by using scene design and simple adaptations to the clinical setup may be found in [16]. 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).

Evaluation Tests: Following referral and an initial phone screening, subjects came to the MIT Clinical Research Center where they were evaluated by a nurse, neurologist and physical therapist to ensure that they met the study entry criteria. They were then scheduled to return for a pretest evaluation and begin the study. The stability of motor recovery prior to training was assessed by comparing scores on two Fugl–Meyer UE tests (FM) [18], the first administered during the screening evaluation, and the second during the pretest session, 1–12 weeks later.

The pretraining/posttraining evaluation battery consisted of four standard clinical tests: 1) the FM, 2) the Wolf Motor test (WMT) (a timed test of 15 upper extremity functional tasks) [19], 3) strength test for shoulder flexion, and 4) hand grip. Shoulder flexion strength was measured by attaching weights to the wrist and recording the maximum amount the subject could lift without compensatory trunk movements; grip strength was measured with a standard Jamar hand dynamometer. Best of three attempts was recorded. A fifth test was also performed. The Behavioral Kinematic test (BKT) consisted of UE movements which were performed in the real world, while 3-D arm and upper trunk kinematics were recorded. These results will be presented in a subsequent paper.

Note that all the evaluation tests were performed in the real world, while all training occurred in the virtual world. Thus, the clinical tests served to measure transfer of virtual training to real world function. Subjects were tested at four time points: pretraining, post-15 sessions, post-30 sessions, and at four months follow-up. The sequence of tests (FM, WMT, strength tests) was randomized across subjects, but remained the same at each time point for a particular subject.

Data Analysis: Stability of motor recovery pre-training was assessed using a paired t-test to compare the screening and PreTest FM scores. To assess the effectiveness of the VE treatment, a 1-way ANOVA for repeated measures was performed for each dependent variable, followed by four pairwise comparisons (pretest versus post-15, versus post-30, versus follow-up, and post-30 versus follow-up) using a paired t-test [20]. A Bonferroni adjustment was then performed to control for Type I error [21].

VI. CLINICAL STUDY—RESULTS

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 training. The mean of these two tests was used as the PreTest FM score for the ANOVA analysis.

Fig. 2 (left panel) shows the percent improvement in each of the four clinical measures (FM, WMT, strength of shoulder flexion and grip) for the group as a whole after 15 sessions, 30 sessions, and at four months follow-up. Raw scores for each subject at each time point for each outcome measure are shown in the right panel. ANOVA results were significant ($p < 0.0001$) for all four measures. Pairwise comparisons indicated the following: 1) mean FM scores improved significantly relative to pretest after 15rx (+2.5, $p = 0.003$), after 30rx (+6.7, $p < 0.0001$), and at four months follow-up (+7.6, $p = 0.001$); 2) mean WMT scores improved somewhat after 15rx (−6 s, $p = 0.0235$), significantly after 30rx (−15.5 s, $p = 0.0097$), and at four months follow-up (−18.4 s, $p = 0.0032$); 3) shoulder flexion strength improved after 15rx (91%, $p = 0.0027$), 30rx (118%, $p = 0.0010$) and at follow-up (169%, $p < 0.0001$); and 4) grip strength improved somewhat after 15 Rx (14%, $p = .207$) and 30 Rx (124%, $p = 0.0253$) and was partially maintained at follow-up (53%, $p = 0.0897$). Pairwise comparisons for post-30 Rx versus follow-up were all nonsignificant, indicating maintenance of gains made during therapy, but not increased gains. Note that the Bonferroni adjustment requires $p < 0.0125$ for the above t-tests to be to be considered significant [21].

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' significant gains on 3 out of 4 clinical measures (FM, WMT, shoulder 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 four months. Our results concur with those of others that subjects with chronic stroke are capable of significant motor improvements even many years after stroke [22].

The elimination of commuting time and effort secondary to the home-based nature of the treatment 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. Enhanced neural plasticity might also be an explanation for the improvements we found in our subjects. Carey *et al.* [23] recently reported significantly greater activation of cortical area M1 during precision-demanding tracking movements than during simple repetitive movements. Since our system incorporates a type of "tracking" through the use of the virtual teacher [7], it is conceivable that this feature of our VE system could serve to enhance motor reorganization in M1 (primary motor area, a cortial area commonly affected by stroke) during practice, relative to other types of practice.

The gains seen after 30 Rx were maintained at four months follow-up for all measures except grip strength. Even so, grip strength at follow up was still 53% higher than its pretest value. These finding imply that patients were now using their UE in new ways, practicing in everyday life the gains made during VE treatment—exactly as we had hoped they would. The finding of smaller improvements and decreased retention of grip strength relative to the other outcome measures has several possible explanations. The motor control of the hand is typically the most severely involved in the most common type of strokes [24] and thus fewer cortical cells might be available to produce and retain changes to grip strength. That the improvements in FM and WMT tests were retained during follow-up, despite a relative decline in grip strength could be explained by the functional tasks in both tests that required grip control, i.e., for the most part these tasks required only mild to moderate grip strength to accomplish. In addition, grip strength *per se* was not emphasized in our training except in the context of function, i.e., just enough grip to hold, transport and manipulate lightweight objects. We did not have any force feedback available to subjects, nor a sophisticated hand model available for VE display to enhance the feedback on this aspect of performance for our subjects. In future versions of the system, we hope to improve this aspect of the system. It is also important to note that although the group results for grip strength were not statistically significant, this was due in part to high variability among subjects. As Fig. 2 (b) shows, some individual subjects had large improvements in grip strength and partially maintained of these gains through the four months follow-up. Future studies should begin to examine which combinations of subject characteristics and training parameters will predict the best functional response to VE training.

We think it is also important to consider the issue of statistically versus clinically significant change in outcomes following VE or other treatments of UE motor recovery following stroke. Although our results showed statistically significant change after both 15 and 30 session, in our opinion, only the changes following 30 sessions were of sufficient magnitude to really be clinically significant. If we compare our results on level of improvement on the FM to those of another group using a similar VE telerehabilitation system [13], we find that for a group of 12 subjects with stroke, who had a mean FM on entry to study of 48.8, improved following 20 sessions of VE training by 4.5 points, a gain of 9%. At one month follow-up, their subjects had maintained this gain for the most part (4 points, 8%). Our subjects had an entry level mean FM motor score of 38.4, and improved by +2.5 points (7%) after 15; +6.7 points after 30 (17%), and +7.6 points (20%) at follow-up, relative to baseline values. These results seem roughly comparable, with perhaps a slight advantage for subjects in our study. No other studies using VE telerehabilitation that reported clinical outcomes were found, but several studies report the effects of clinic based VE therapy on FM score. A report of a pilot study on one patient with stroke whose entry FM motor score was 22, reported a gain of seven points following 12 sessions of VE training [9]. While these authors performed three additional sessions of VE training via a clinic to clinic telerehabilitation setup, they did not report the FM findings following this training. Two prior studies by this group focused VE training on the hand [25], [26]. The first study $(n = 3)$ reported an 11% gain on the Jebson test of hand function following 45 hour of combined constraint-induced (CI) and VE therapy [25]. The second study $(n = 8)$ reported a 15% gain for the Jebson test following 26 h of VE therapy [26]. Although it is difficult to compare across tests, these results seem comparable to our FM improvements (17% gain after 30 sessions), but less robust than our WMT results (36% improvement after 30 sessions). The WMT is more comparable to the Jebson as both are time-based tests of functional task performance. Grip strength was reported for one of these studies [25] as a range of 13%–59% across the three subjects after 45 h of therapy. In contrast, our subjects $(n = 11)$ had a mean increase of 124% in grip strength after 30 sessions. Another group has reported on the results of VE training in two subjects with stroke following 12 sessions of training (1–2 h each, so 12–24 h total) [27]. Entry level FM's were 21 and 41; subjects gained 1 point and 2 points, respectively, on the FM, significantly less than what we have found for our subjects (+7.6 points).

Another popular technique in stroke rehabilitation is constraint-induced movement therapy (CI) [22]. Recently, a telerehabilitation system (AutoCITE) has been developed by this group with the eventual goal of allowing home-based CI therapy [28]. The system was pilot tested in a study using two rooms in the same building. The authors tested seven subjects with stroke, who had a mean entry level WMT score of 2.8 s (versus 43.3 s for our subjects). Following 30 h of training (3 h/day for 10 days in their study versus 1 h/day for 30 days in our study), subjects decreased their WMT score (indicating improvement) by −0.9 s $(p < 0.05)$ in the AutoCITE study, versus by −15.5 s $(p < 0.01)$ in our study. In terms of percent change, these improvements are comparable, i.e., for the CI study, 32%, for our VE study, 36% after 30 h of training.

In a large national randomized controlled trial of CI therapy recently reported, subjects in the CI group $(n = 106)$ had mean WMT entry scores of 19.3 s with reductions of −10 s (52%) at 1 year following 2 week (∼60 h) of CI therapy [29], while subjects in our VE study had decreases of −18.4 s (53%) at four months posttraining. Thus, improvements found in our VE study are comparable in terms of percent change to those in the large CI study, but the CI subjects received twice as much therapy as those in our VE study. It is possible that the changes we observed might not be retained at 1 year follow-up as was the case for those receiving the CI therapy. However, considering that this was the first group of subjects to use our system, and in light of the technical challenges we encountered during training, we consider our findings fairly robust and supportive of VE motor training as a viable treatment options for patients with stroke.

Taken together, the findings of this and other studies seem to suggest that we may simply not be treating our patients with stroke long enough. In much of the literature reviewed here, and in the present study, one can see a definite trend toward greater improvement with longer times in therapy [13], [28], [29]. However, caution must be used with this interpretation due to the very real differences in the clinical status of subjects at entry, time poststroke, and age, as well as differences in the treatment protocols applied.

Limitations: This was a small study with only 11 subjects and no control group. Variability in subject clinical characteristics and in the technical quality available in each subject's home setup may have contributed to noise in our results. We were also limited in our ability to train skilled hand and finger control and by the lack of haptic feedback.

VIII. CONCLUSION

This novel VE motor retraining via telerehabilitation appears effective in improving UE motor control and functional performance in subjects with chronic stroke.

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Maureen K. Holden, photograph and biography not available at the time of publication.

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