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A Virtual Reality–Based Exercise System for Hand Rehabilitation Post-Stroke

Abstract

This paper presents preliminary results from a virtual reality (VR)-based system for hand rehabilitation that uses a CyberGlove and a Rutgers Master II-ND haptic glove. This computerized system trains finger range of motion, finger flexion speed, independence of finger motion, and finger strength using specific VR simulation exercises. A remote Web-based monitoring station was developed to allow telerehabilitation interventions. The remote therapist observes simplified versions of the patient exercises that are updated in real time. Patient data is stored transparently in an Oracle database, which is also Web accessible through a portal GUI. Thus the remote therapist or attending physician can graph exercise outcomes and thus evaluate patient outcomes at a distance. Data from the VR simulations is complemented by clinical measurements of hand function and strength. Eight chronic post-stroke subjects participated in a pilot study of the above system. In keeping with variability in both their lesion size and site and in their initial upper extremity function, each subject showed improvement on a unique combination of movement parameters in VR training. Importantly, these improvements transferred to gains on clinical tests, as well as to significant reductions in task-completion times for the prehension of real objects. These results are indicative of the potential feasibility of this exercise system for rehabilitation in patients with hand dysfunction resulting from neurological impairment.

1 Introduction

Recent experimental evidence suggests that intensive training that entails new motor-skill acquisition is required for inducing long-term brain plasticity (Plautz, Milliken, & Nudo, 2000). A critical variable needed to induce this plasticity is sensorimotor stimulation that is intensive, highly repetitive, and rewarded. Existing HMO-defined rehabilitation settings clearly cannot provide for such massed supervised training. Computerized robot-assisted therapy systems have been shown to be suitable for providing clinical training of the required intensity (Volpe, Krebs, & Hogan, 2001). The systems currently under development are focusing on the rehabilitation of elbow-shoulder function (Krebs, Hogan, Aisen, & Volpe, 1998; Burgar, Lum, Shor, & Van der Loos, 2000; Reikensmayer et al., 2000; Volpe et al., 2000; Krebs et al., 2003) and wrist (Reinkensmayer, Pang, Nessler, & Painter, 2002) function.

Another equally important, but technically challenging, aspect is the recovery of hand function. Even a fully recovered arm of a hemiparetic patient will not substantially improve quality of life if it is not accompanied by recovery in the manipulative abilities of the hand. We have recently developed a unique fully computerized system for the rehabilitation of hand function. The description of the earlier versions of the VR-based system hardware and software can be found elsewhere (Jack et al., 2001; Boian et al., 2002; Merians et al., 2002). The system uses two types of instrumented gloves, one of them with force feedback. A unique aspect of the system is the use of virtual-reality-based therapy. Virtual reality, as opposed to simple 2D graphics, has been shown to be an engaging, motivating, adaptable tool (Burdea & Coiffet, 2003). It is currently under development in various medical areas, including investigations to determine its suitability for rehabilitation in patients post-stroke. VR provides an interactive environment where a subject can practice repetitively, but it is also a tool through which new motor skills can be acquired. This technology enables the clinician to gather precise kinematic and kinetic outcome measures on the patient's current performance and learning histories, and to use these data to efficiently and precisely adapt the levels of difficulty of the sensorimotor tasks to be practiced. It thereby provides the ability to create a challenging and motivating environment through which the needed intensive, repetitive, and rewarded practice of new motor skills can be delivered. Both repetitive practice and new-skill acquisition have been shown to be prerequisites for inducing long-term functional plasticity.

Telerehabilitation is the remote provision of rehabilitation interventions as well as the remote evaluation (or reevaluation) of patients' function by a therapist or physician (Rosen 1999). In a telerehabilitation setting the patient and therapist are geographically separated, usually the patient being at a rural clinic, and the therapist at an urban clinic. This represents a great benefit for rural patients because it reduces extensive travel. Other benefits are a potential reduction in health care costs (Buckley, Prandoni, & Tran, 2001) and possible improved compliance when exercising at home (Dhurjaty, 2001; Reinkensmeyer et al., 2002). Reinkensmeyer et al. demonstrated the feasibility of a Web-based library of status tests, therapy games, and progress charts in conjunction with a force-feedback joystick for telerehabilitation of post-stroke patients. Holden and colleagues (Holden, Dyar, Schwamm, & Bizzi, 2003) recently reported on two case studies of chronic post-stroke patients trained in arm reaching tasks using a VR-based telerehabilitation system. The arm motion was sampled using a 3D tracker, while graphics provided 8 to 10 scenes customized for each patient. The two patients made significant gains in upper-extremity function, while bidirectional video/audio data was exchanged over the Internet. Importantly, the therapists had the ability to intervene and change the VR exercise parameters remotely.

This paper presents a VR-based system for retraining hand function in patients in the chronic phase post-stroke. Section 2 describes the software exercise modules, as well as the remote monitoring station and database portal. Sections 3 and 4 give experimental procedure and results of a pilot study of eight subjects in the chronic phase post-stroke. Section 5 discusses these results, while concluding remarks and future research directions are given in Section 6.

2 The Virtual Reality Hand-Rehabilitation System

2.1 The Hardware Setup

The system developed by our group uses a CyberGlove from Immersion Co. and the Rutgers Master II-ND (RMII) force-feedback glove prototype developed in the Human-Machine Interface Laboratory at Rutgers University (Bouzit, Burdea, Popescu, & Boian, 2002). The two gloves are connected to a multiplexing box wired to the serial port of a host PC running the VR simulation. The RMII glove has a dedicated electropneumatic control interface, which receives compressed air from a small compressor. This controller sets the air pressure in the glove's small pneumatic actuators to provide force feedback to the patient's fingers. Neither glove is tracked, since the focus here is on finger training, rather than wrist or arm movement. The PC is connected over a Local Area Network (LAN) to a second PC serving as remote monitoring station for the thera-

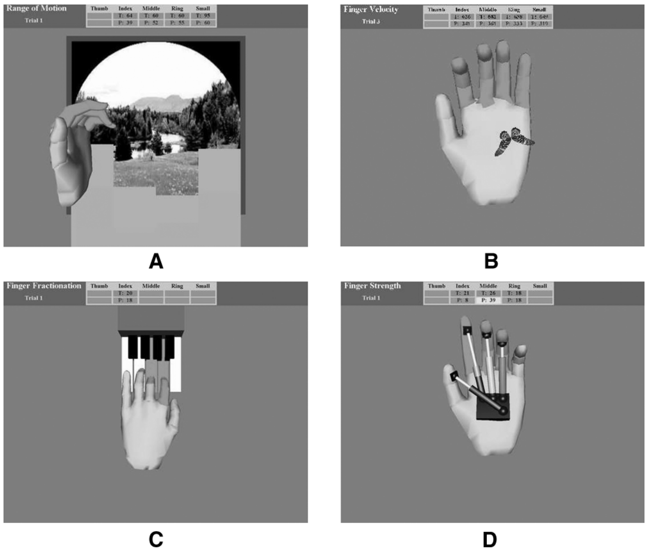


Figure 1. *Screen snapshots for the four VR exercises (A) range of motion, (B) speed of movement, (C) finger fractionation, and (D) finger strength (adapted from Boian et al., 2002). © Rutgers University 2001.*

pist. A Web-capable Pan-Tilt-Zoom (PTZ) camera and a microphone provide additional video and audio information to the remote therapist.

2.2 The VR Exercises

Four hand-exercise simulations were developed using the commercially available WorldToolKit (Sense8) graphics library. The exercises are in the form of simple video games that provide frequent feedback about the success of the action as well as the quality of the performance to encourage participation and concentration (see Figure 1). Each game is designed to exercise one parameter of finger movement: either range, speed of movement, or fractionation (using the CyberGlove), or strengthening of the fingers (using the Rutgers Master glove). An Oracle database transparently stores all exercise data for later retrieval and analysis (as will be described in Section 2.5).

The patients, wearing one of the gloves previously described, are seated in front of the computer. The amount of movement in the virtual hand they see on the screen is an exact representation of the movement of the patient's hand in real space. In each set of trials, the patients have to move either their thumb or their fingers, as prompted by a green color in the appropriate virtual fingers. For the range-of-motion exercise, the patients have to flex their fingers to remove "dirty pixels" covering various pleasing images. The higher the range of motion, the larger the portion of the image that is revealed. Each finger movement clears a part of the image proportional to the angular range achieved. For the speed exercise, the patients have to quickly flex their fingers or thumbs to "chase away" a virtual butterfly. The butterfly flies away when the finger velocity exceeds a target goal. For the fractionation exercise, the patients have to play a virtual piano keyboard, one finger at a time. The piano key turns green and makes a sound when the patient moves the intended finger. If the patient is also moving other fingers, then that key turns from pink to red, indicating the amount of ancillary (unwanted) movement. For the strengthening exercise, the patient has to push down a piston with the thumb, index, middle, and ring fingers against a constant force. The more the patient pushes, the more mechanical work is done by the hand being trained. The virtual pistons displayed on the screen fill with a yellow color proportional to the displacement of the real pistons. Before each trial begins the patients must extend their fingers to match a ghostlike hand image on the screen. The extension in the ghost image is set to a predetermined target, allowing patients to exercise their hand-extension motion.

The patients receive auditory, visual, and numerical feedback about their target goal and their current performance. During each trial, "performance meters" on the computer screen, both numerical and graphical, indicate the level of success in relation to the target goal (Boian et al., 2002). A red bar at the top of the computer screen indicates numerically the movement goal for each finger and a green bar displays the patients' real-time performance as they are doing the activity. When they exceed their target goal the green number turns yellow and flashes. Pictorial displays of fireworks accompanied by pleasing musical sounds indicate a series of successful trials, as a way to further motivate the patient.

2.3 The Target-Setting Algorithm

The target goals of the VR exercises are calculated automatically by the system, based on the patient's previous results. The exercises are executed in blocks, each block containing a number of trials. Each block is assigned an average target. The targets for each trial are chosen from a normal distribution around the assigned average target. The average block target is computed by first averaging the performances of the patient in the previous block. Then the algorithm computes a new target by adding or subtracting a fraction to or from the current target. Thus, as patients improve their performance they are pushed by higher target levels to perform even better. The fraction change is positive if the current target was achieved and negative if it was not.

The algorithm for calculating the next targets was refined over a number of revisions (Jack et al., 2001; Boian et al., 2002; Merians et al., 2002) to adapt to the patient's performance while raising the difficulty levels and keeping the patient motivated. Initial algorithms relied solely on the performance measures of each exercise. Because the patient's ability to exercise changed from one day to another, the algorithm sometimes adapted slower to the patient's performance, which resulted in either a series of difficult or a series of very easy exercises. In both cases, the motivation of the patient decreased. To address this issue, an alternative algorithm takes into account the success history of the patient. The goal was to set the targets so that the patient would have a 70% to 90% success rate in each block of trials (Boian et al.).

For each exercise and each finger, a change gain was calculated from the history of success rates of that finger over all the blocks of the exercise within the same day. Success rates below 70% were assigned negative coefficients. Values over 90% were assigned a positive gain. The target change gain was calculated by summing up the products of each value in the success history and the gain assigned to it. To avoid fluctuations caused by accidental low-performance blocks, negative change gains were applied only when there were two consecutive blocks with success rates below 70%.

$$\text{Gain} = K_{>90\%} \cdot \sum_{\text{Day success history}}^{>90\%} \text{SuccessRate}_{\text{block}} - K_{<70\%} \cdot \sum_{\text{Day success history}}^{<70\%} (1 - \text{SuccessRate}_{\text{block}}) \quad (1)$$

2.4 The Remote Monitoring Graphical User Interface

The upper-extremity VR exercises are integrated with a real-time Web-based telerehabilitation monitoring system previously developed for the lower extremity (Lewis, Boian, Burdea, & Deutsch, 2003). The local (patient) side consists of the upper-extremity hand-exercise system described above. The remote therapist is able to oversee multiple patients exercising simultaneously using a monitoring applet and the PTZ camera Web client. The applet, created in Java 3D (SUN Microsystems), extends the virtual hand representation presented previously (Popescu, Burdea, & Boian, 2002). The software used to monitor the patient trials provides additional exercise and performance information, while demonstrating several views of the patient's active hand in a simple graphics model. A 3D mock-up of the exercise being performed is at the core of the monitoring screen, while performance measures are represented numerically along the bottom and graphically along the right side of the screen (see Figure 2). When a target is met, it is indicated by a change in color on the remote therapist's numerical bar. A patient-selection menu, as well as the current exercise information, is displayed on the left. Since each VR application separately sends real-time data to the remote server, multiple monitoring clients can be opened simultaneously from various locations, each retrieving its own information. This represents a multiplexed telerehabilitation approach that is, to our knowledge, a first. While a therapist has the ability to switch between active patients using the menu, in this application, two windows can be opened on the same screen in order to view both patients working si-

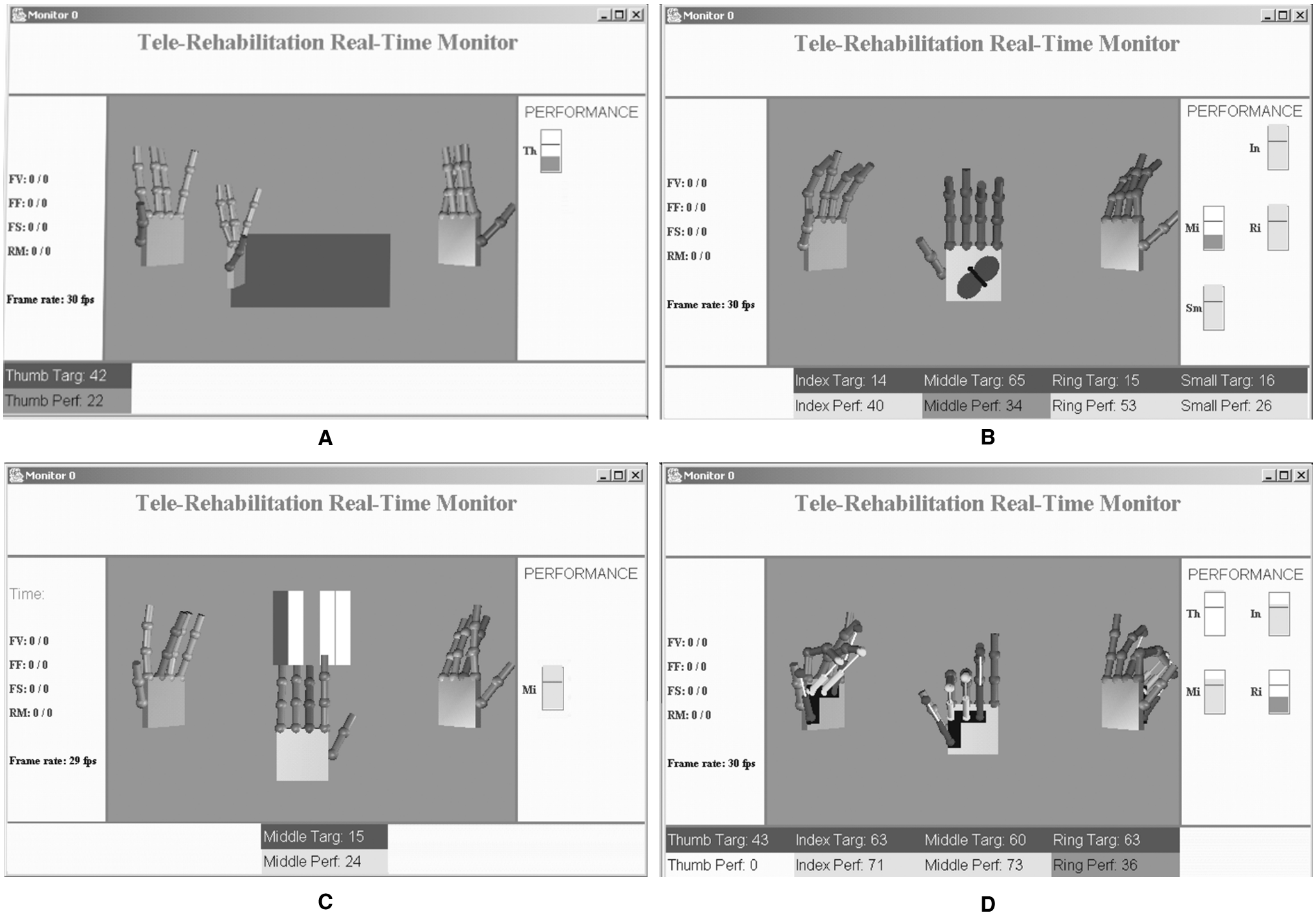


Figure 2. *Screen snapshots for the four monitored exercises; (A) range of motion, (B) finger velocity, (C) finger fractionation, and (D) finger strength. The three virtual hands represent three views of the same patient's hand at a given moment in time. © 2003 Rutgers University and UMDNJ.*

multaneously. In addition, the therapist can manipulate the local PTZ camera using Web movement controls to switch between patients and their active hands. Figure 3 shows screen snapshots of three different views of the hand during remote monitoring of the four VR exercises.

2.5 Web Data Access Portal

The data stored by the system can provide the therapist or the physician with an objective view of the patient's progress and the effect of the therapy. Direct access to the database is impractical unless it is done through an intuitive interface that allows the user to focus on the data and not on how to retrieve it. Ideally, the therapist would just have to ask for a report of the patient's activity, which will include all the relevant information and data graphs. The creation of such a report is very simple provided that there exists a set of measures agreed upon as relevant and broad enough to properly describe the patient's status. Such a set of measures can be found only by exploring the data in all its complexity and viewing it from different perspectives.

The first version of the Web data portal was intended for research use, and was designed to be easy to use and powerful enough to provide the user enough flexibility.

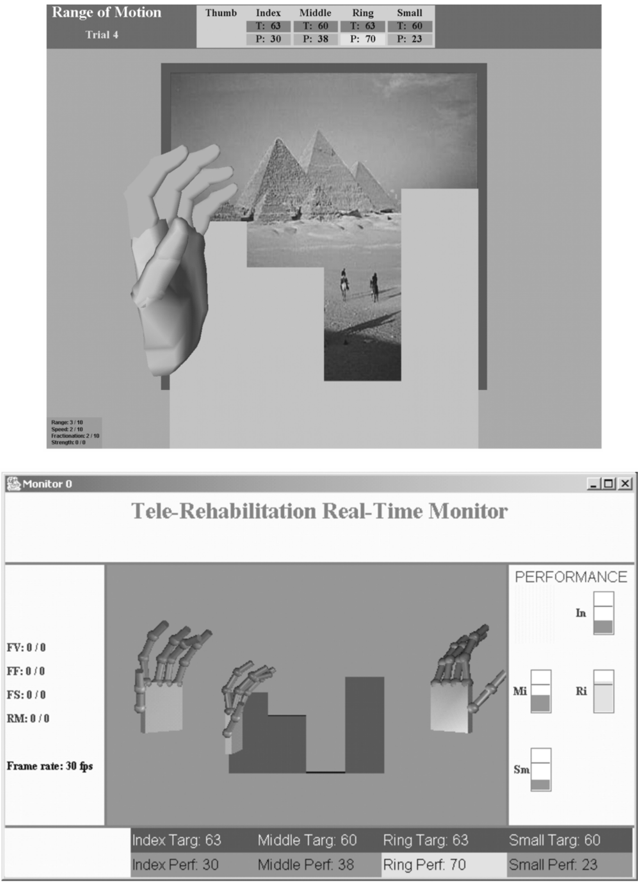
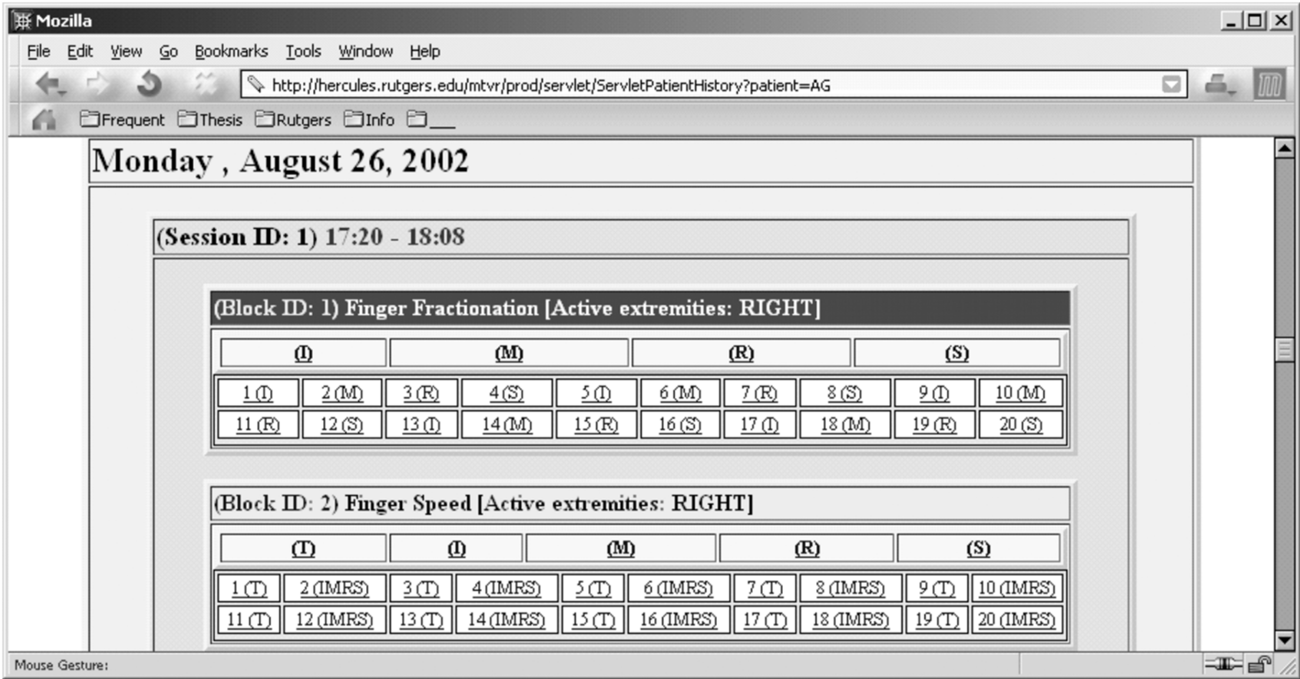


Figure 3. *VR-based remote monitoring of hand therapy: top* panel represents the patient's view of the VR Exercise, while the *bottom* panel shows the corresponding remote monitoring view of the same exercise, being updated in real time. © 2003 Rutgers University and UMDNJ.

The data portal is best presented by an example. Considering the finger range-of-motion exercise, the system stores at 50 Hz for approximately 30 min each session the metacarpophalangial (MCP) and proximal interphalangial (PIP) joint angles of each finger and thumb, totaling a set of 10 angles. In practice, per-finger measures are preferred over per-joint ones, so the mean of the MCP and PIP joint angles is taken as the "angle" of the respective finger. These 15 joint and finger angles (called "raw data") can be directly used during a trial to plot the activity of each finger against a preset target. The difficult aspects of accessing these graphs are the large number of trials (about 100 per day) and the large number of data points in one graph. Two interfaces were developed for this. The first one (Figure 4, top) provides a color-coded history of the patient's activity, grouped by blocks and days. By clicking on a trial entry, the user can see the raw-data graph of that trial. Also, per-finger links are provided for each block, which generate a list of graphs of the activity of the finger over the entire block. As mentioned before, not all fingers are active during each trial. To make this visible, after each trial number a list of the active fingers is presented in parentheses. The fingers are coded with the first letter of their names (i.e., T, I, M, R, S). Although this interface is easy to use, it does not allow the user to select the data plotted on each graph. This may be necessary when trying to visualize data that does not match the default settings.

Besides raw-data graphs, the system provides the therapist with history graphs that present the patient's performance in each trial compiled across trials, blocks, or days. Basically, these are the graphs that show whether or not the patient is improving. Trial performances are computed after each trial is finished and stored in the database. Although redundant, having the performances calculated and stored, speeds up significantly the graph-creation process. The window in Figure 4, bottom, presents the user with a series of choices: patient, data aspect to be plotted, interval over which the data will be grouped (day, block, or trial), function to be applied over the grouping interval (minimum, maximum, average, or summation) and the first and last date to be shown. These choices completely identify the data to be plotted. In addition, there are two more aspects to be selected: the filter to be used over the data and the additional aspects to be plotted (e.g., high/low standard deviation, linear regression, or the unfiltered data). The filters are selected from a drop-down list of existing entries in the database. This stems from the need to apply the filters off-line due to the long time necessary to execute them. Multiple filters are supported over the same data to allow for experimentation as to which one is the best in eliminating outliers. Additional choices for graph formatting and output are given to the user in the lower left part of the window.



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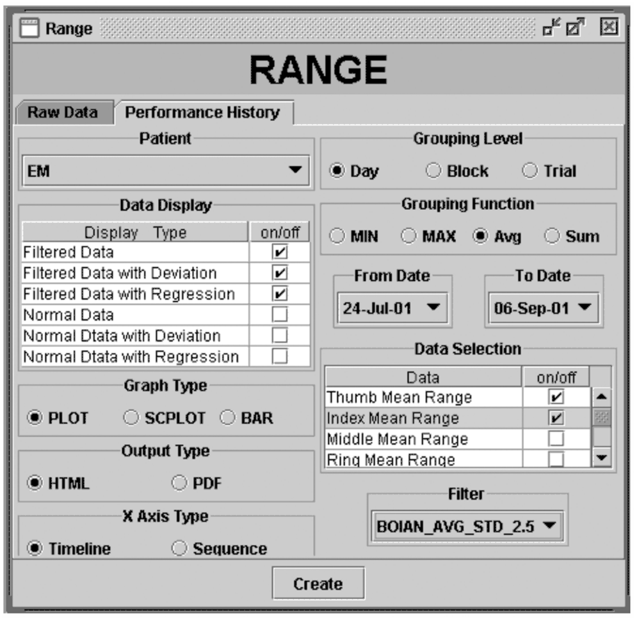

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Figure 4. *Web portal for patient-database remote access: (A) Raw data interface; (B) Performance history interface allowing clinician to graph patient-performance data across the duration of the therapy. © Rutgers University. Reprinted by permission.*

3 Methods

In the current study, subjects in the chronic phase post-stroke were trained exclusively in the VR environment, for about 2–2.5 hours/day, 5 days/week, for a total of nearly 3 weeks. Each VR exercise session consisted of four training blocks: range of motion, speed of movement, fractionation of individual finger motion, and strengthening of the fingers. The remote monitoring graphical user interface was designed and tested twice from a remote location without disturbing the exercise process. However, it was not used during the training. Eight subjects (6 male, 2 female; age range 50–81) were selected to participate in this study. Seven of the subjects sustained a right-hemisphere lesion and 1 had a left-hemisphere lesion, all occurring at least one year prior to the training regimen described here. The subjects were selected according to the following criteria: they were able to actively extend the wrist of the hemiplegic limb at least 20° and extend the metacarpophalangeal joints at least 10° (Taub & Wolf, 1997). None of the subjects was receiving therapy at the time of the study.

To determine whether the skills gained in the VR environment transferred to real-world movements, two generalization tests were utilized, a clinical evaluation using the Jebsen Test of Hand Function and kinematic analysis of prehension movements. The Jebsen Test of Hand Function (Jebsen, Taylor, Trieschmann, Trotter, & Howard, 1969) consists of seven subtests that provide a broad sampling of functional tasks. These subtests consist of writing, turning index cards, picking up small common objects, simulated feeding, stacking checkers, picking up large light objects, and picking up large heavy objects. In addition, we analyzed the kinematics of the finger and arm motion during a real-world prehension task. Specifically, we looked at the hand and finger kinematics of five-finger precision prehension when patients picked up two small objects, a roll of tape and a rectangular box, from a table. The data were collected before and after VR rehabilitation therapy. The 3D coordinates of the arm joints and the trunk were tracked by electromagnetic position sensors (Flock of Birds, Ascension Technologies Inc.). Finger-joint flexion and extension were obtained via the CyberGlove. Both the Flock of Birds and the CyberGlove were connected to an SGI Octane/SSE workstation. All experimental sessions were videotaped for off-line analysis of error patterns. During the experiment, objects were presented in a pseudorandomized fashion. Subjects were instructed to maintain a preset initial position until they heard a tone signaling the start of the trial. Once the tone sounded, subjects reached to and grasped the object, lifted the object vertically, and placed it on a platform. Each subject made a total of 40 reaches per experiment. If the subject did not grasp an object successfully (e.g., was not able to lift the object and release it on the platform), another trial was run in its place. Subjects practiced before the experiment for 5 to 10 trials. One subject (LD) was not able to grasp the objects, and had to use smaller objects of the same shape, both before and after the therapy. Interestingly, after the therapy he was able to grasp and lift regular-size objects.

4 Results

4.1 VR Measures

As a representative example of the raw-data graphs available through the Web portal, Figure 5 presents for one subject (EM) the changes in fractionation of index-finger motion between Day 1 (left) and Day 13 (right) of training. The graphs depict the mean of the angles of the MCP and the PIP joints for four fingers of the affected hand. The measure is the maximum difference between the value for the active finger (upper curve on both graphs) and the values for the inactive fingers. On Day 1 of the training, based upon pretest measures, the target goal was set for 11°. The subject was not able to reach the target (left panel). Although by Day 13 the target was elevated to 18°, the right panel shows that after training, EM was able to surpass the target by 3°. This increase in the subject's performance indicates an improved ability to extend the index finger without extending the other three fingers.

Figure 5 presents data collected during practice while wearing the Cyberglove, whereas Figure 6 presents data collected during practice using the Rutgers Master II

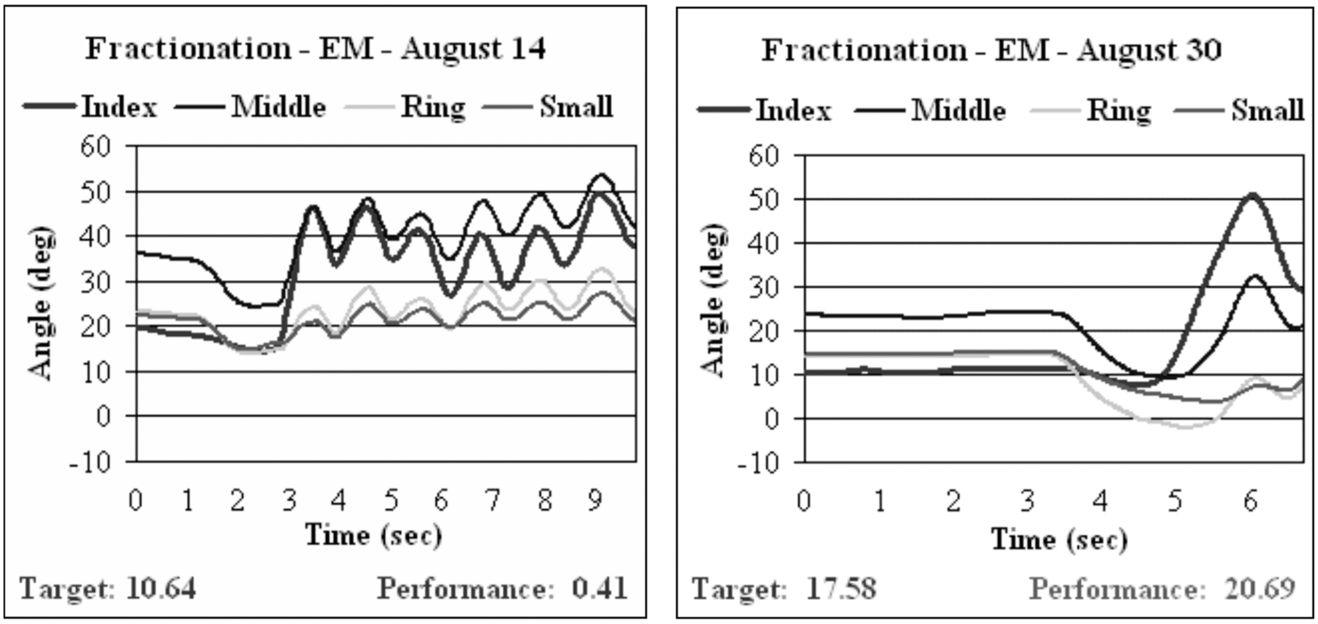

Figure 5. *Changes in fractionation of index finger on Day 1 (left) and Day 13 (right) of VR training for subject EM.*

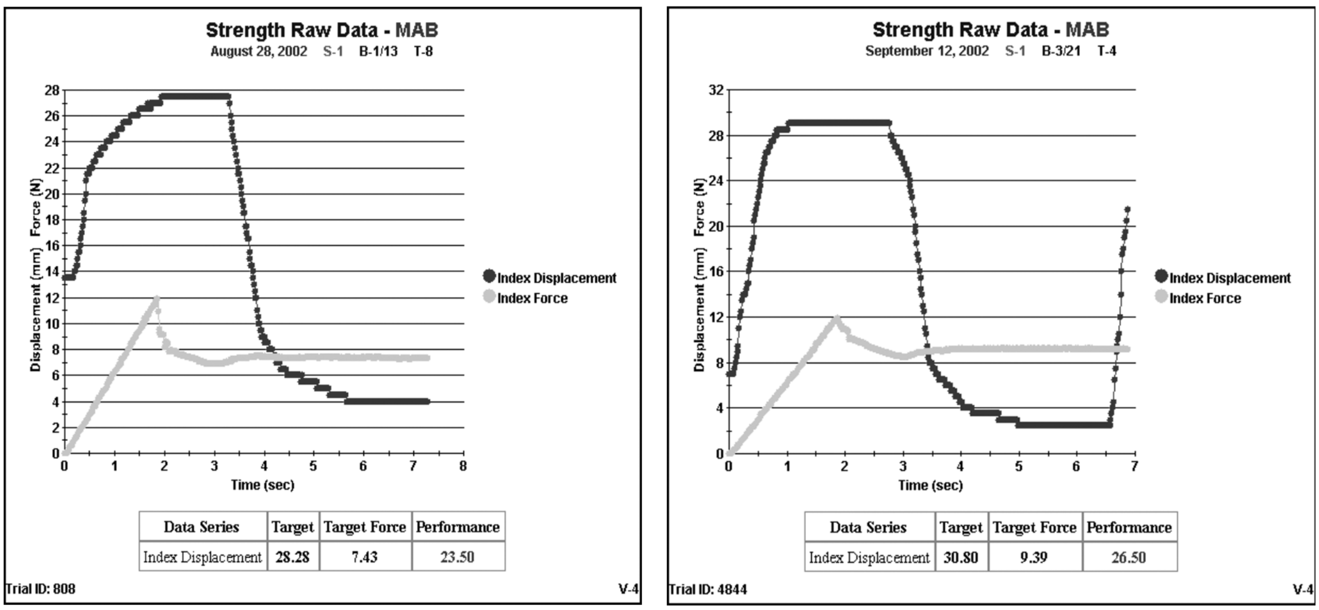

Figure 6. *Changes in force and finger displacement for subject MAB at the beginning (left) and end (right) of VR training.*

force-feedback glove. This graph shows the change in the amount of work (force × actuator displacement) produced by MAB. These data are collected from one trial, with the light gray line indicating the force produced by the RMII glove and the dark line showing the displacement (in mm) in the position of the index finger

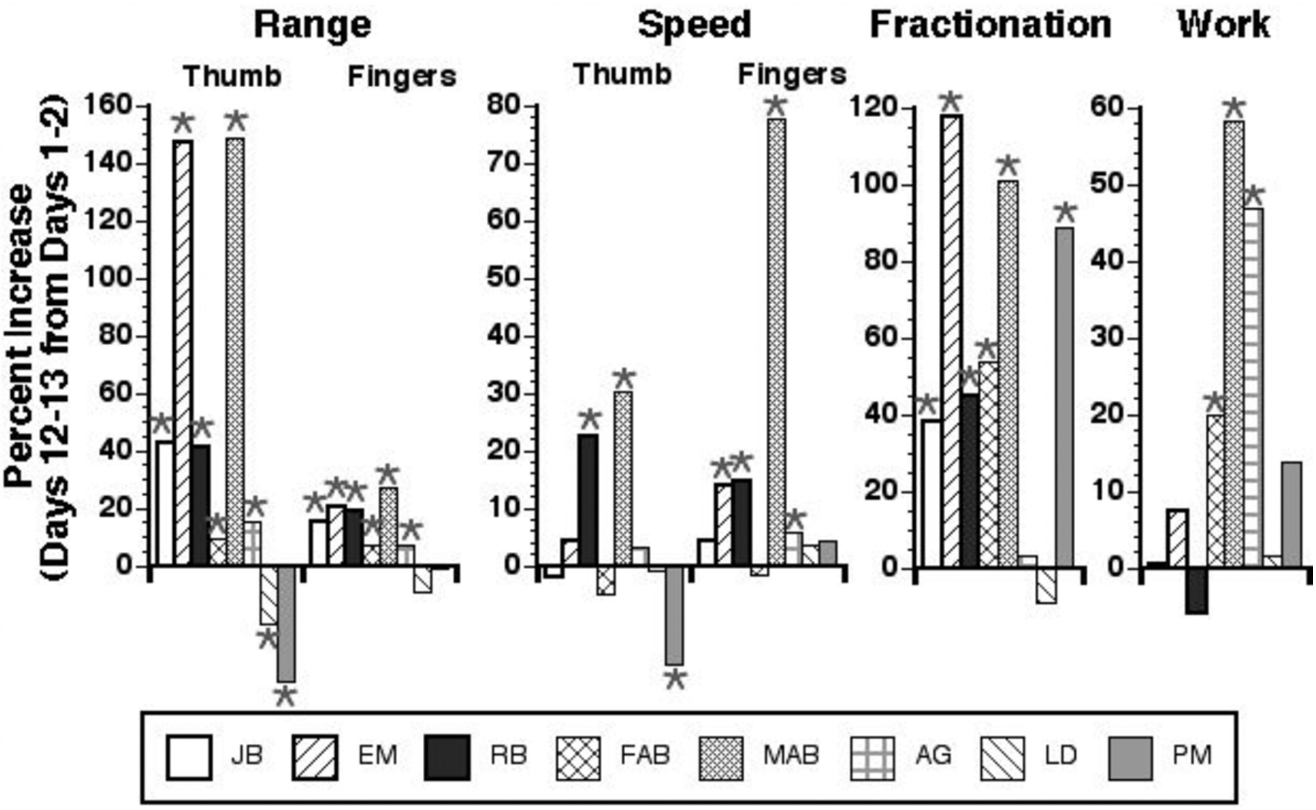

Figure 7. *Percentage increase between the first two days and the last two days of the therapy for four exercises: range of motion, flexion speed, fractionation, and mechanical power. Significant changes are marked by asterisks (two-tailed unpaired t-test, $p < .05$).*

against this force. Position sensors inside the pressurized actuators measure the fingertip position in relation to the palm. Before the subject is prompted to close the virtual pistons against the targeted resistance, a force is generated to help the subjects extend their fingers. The initial curved part of the dark displacement line shows the change in position of the fingertip as a result of the force generated to assist extension of the index finger. The vertical portion shows the amount of piston displacement the subject could produce against a constant force. On Day 1 (left), the target was set to 28 mm of piston displacement (again based upon pretest measures) and MAB was able to move her index finger 24 mm against a force of 7 N, whereas on Day 13 she was able to move a similar distance but against a force of 9 N.

To test whether subjects as a group improved in the VR exercises, we compared the first two days with the last two days of the therapy. Overall, subjects as a group showed a tendency for improvement in the range of motion ($F(1, 7) = 4.53$, p = .07). Individually, 6 out of 8 subjects significantly increased their finger and thumb range of motion, while 2 subjects significantly decreased their thumb range of motion (unpaired two-tailed *t*-test for each subject, $p < .05$; see Figure 7). There was no significant group improvement in finger and thumb speed. Individually, 4 subjects significantly improved in finger speed and 2 in thumb speed. In fractionation, 6 out of the 8 subjects showed significant improvement, with an overall group effect ($F(1, 7) = 34.8$, $p = .0006$). Finally, 3 subjects improved in strength, with no significant group effect. Of note, 2 subjects showed a significant decrease in their performance over the course of the therapy in several parame-

Table 1. *Jebsen Test of Hand Function. Mean scores in seconds for the affected hand of each subject before and after training*

Affected Hand		
Subject	Pretest (seconds)	Posttest (seconds)
EM	223	206
FAB	134	128
AG	142	128
JB	152	124
LD	264	218
MAB	151	140
RB	300	217
PM	208	217

ters of their thumb movement (see Figure 7). These subjects used inappropriate movement patterns at the beginning of the course of training, which artificially inflated their thumb scores. In addition, 1 of these 2 subjects (LD) did not improve on any of the movement parameters. He was substantially older than the other subjects and found the daily travel to the lab fatiguing.

4.2 Generalization Test

The Jebsen Test of Hand Function showed an overall reduction in task-completion time for the affected hand after the therapy (group mean (SD) decreased from 196 (62) s to 172 (45) s; paired t-test, $t = 2.4$, $p < .05$). In contrast, no changes were observed for the unaffected hand ($t = .59$, $p = .54$). Completion times for all of the subjects were averaged across all the subtests. Individual pre- and posttest completion times are shown in Table 1.

When the five-finger precision prehension was tested before the beginning of the therapy, each subject showed various severe deficits in both the transport and grasping components (slowness, excessive trunk involvement, intersegmental discoordination). After the therapy, subjects showed some improvement in various aspects of the hand kinematics during grasping. Time to peak velocity of the affected hand did not change after the therapy ($F(1, 7) = .55$, $p = .48$). This result could be expected since elbow and shoulder were not trained during the VR therapy. However, time from peak velocity to the moment when the object was lifted from the table did decrease significantly after the therapy ($F(1, 7) = 5.78$, $p = .04$), indicating an improvement in the subjects' ability to appropriately match their finger positions to the shape of the object. On average, the task was performed 22% faster after the intervention, illustrating transfer of their improvement in VR to a functional task.

5 Discussion

This preliminary study demonstrates the feasibility of our recently developed exercise system for hand rehabilitation in patients with chronic hand dysfunction resulting from neurological impairment. Several technology-assisted therapies have been developed by other research groups to retrain upper-extremity function in patients post-stroke (Burgar et al., 2000; Reinkensmeyer et al., 2000; Holden, 2001; Holden & Dyar, 2002; Krebs et al., 2003). However, no system has been developed to improve hand coordination by retraining individual finger dexterity and velocity. The ability of patients to utilize their hands effectively for everyday tasks is extremely important to improving the quality of life and level of independence post-stroke. To our knowledge, this is the first fully integrated, computerized system to train hand function in virtual reality. The system includes VR-based interfaces, objective evaluation of finger motion through the use of instrumented gloves, online adaptation of exercise targets to the current status of the patient, remote monitoring capabilities, and storage/retrieval of the data in an online database. This is a unique VR-based rehabilitation system that allows for objective measures of the current status of the subject's hand function, as well as progress during the therapy. The exercises for range of motion and fractionation induced improvement in the majority of patients. Gains in finger-strength parameters were modest, due in part to low levels of force feedback in the Rutgers Master glove, which in turn was due to an unexpected hardware malfunction during the therapy for the first 4 subjects. In keeping with clinical outcomes of patients who have variability in both the lesion site and in initial upper-extremity function, each subject showed improvement on a unique constellation of movement parameters (range of motion, speed, fractionation, and strength) and clinical tests (Jebsen test). We have noticed this trend previously (Merians et al., 2002). It is interesting to speculate whether this might be due to the particular lesion location, lesion volume, or initial severity of paresis.

We believe that functional plasticity will likely underlie many of the effects that we are getting in VR-based rehabilitation. Recent animal studies demonstrated the importance of motor learning as opposed to unskilled repetitive movements in producing changes in motor maps (Plautz et al., 2000). It has recently been shown that in addition to the importance of repetition in inducing synaptic reorganization it is critical that the repetitive motor activity involves the learning of a motor skill (Plautz et al.). It has been demonstrated in animal studies that only repetitive training in a sufficiently challenging environment (retrieval of food pellets by the monkey from a small versus wide well, Plautz et al.) drives representational plasticity and perhaps engenders improved motor control (Nudo, Plautz, & Frost, 2001). It is clear from these studies that rehabilitation paradigms must be based upon our understanding that the nervous system has the potential for neural modification and that attention, repetition, reward, progression of complexity, and skill acquisition are critical conditions of practice for driving this change in neural structure and function. Results obtained in this feasibility study indicate that VR has the potential to serve as an appropriate environmental tool to apply these conditions of practice.

In terms of patients with neurological impairment, it has not been well elucidated whether skills acquired through practice in a VR environment transfer to real-world activities (see Holden, Todorov, Callahan, & Bizzi, 1999; Merians et al., 2002). One of the outcome measures used in this study to test generalizability of the VR practice was the Jebsen Test of Hand Function (Jebsen et al., 1969). An important finding was that there was a significant improvement in the time scores of this functional clinical measure as a result of the VR training, indicating that the changes evident in the VR measures appear to transfer to real-world function. Moreover, this generalization was also evident in several of the kinematic measures of grasping. Subjects with abnormal finger flexion-extension synergies or abnormal desynchronization of the finger motion reduced the intertrial variability after the therapy. Moreover, subjects with severe spasticity increased the range of finger motion.

The combination of VR with a computerized therapy system can provide new tools for creating treatments, by extending the role of the therapist in the clinic. Desktop VR has significantly fewer of the side effects (e.g., dizziness) seen in fully immersive VR environments using head-mounted displays. It provides precise kinematic and kinetic data on subjects' baseline performance and learning history, and provides updating of motor task difficulty, affording great precision in individualizing treatment programs. This combination constantly challenges patients to learn new motor skills. The usability of this computerized environment will further increase in the near future when the "MTV generation" will become, in part, the target population of these video-game-based therapies. Finally, fully computerized systems will make telerehabilitation possible in the future, with potential cost savings and increased patient access (Burdea, 2003).

6 Conclusions and Future Work

Our pilot study demonstrates that technology-assisted intensive therapies that utilize virtual-reality (VR) interfaces may improve hand function in chronic hemiplegic patients. Our fully computerized system allows for quantitative measures of patients' finger motion during the therapy. Functional improvements observed after the technology-assisted therapies, although significant, are small. Studies are needed to evaluate possible strategies that could improve the efficiency of these therapies, for example, pharmacological interventions (see Goldstein, 2003, for a review), or deafferentation of the arm during hand rehabilitation (Muellbacher et al., 2002). In the current version of the system, the therapy is focused exclusively on the hand, without any training for the wrist, elbow, and shoulder of the affected arm. Future studies should address integrated hand and arm training. Virtual-reality-based training should test whether intensive training in VR that involves integration of both hand and arm in a functional task will improve the effectiveness of the therapy when compared to training of the hand in isolation. Bilateral exercises in VR, utilizing both the affected and unaffected hands, is another area of future research. They may also prove to be more effective than exercising only one hand of the patient. This extension of the system could mark a significant advance in the development of an effective technology-assisted therapy for rehabilitation of manipulative function.

Moreover, an important aspect of functional rehabilitation is the role of attention. We believe that functional plasticity will likely underlie many of the effects that are evident as a result of the rehabilitation protocols based on intensive training. It is reasonable to assume that attention and motivation may play a major role in plasticity. Novel movements that we attend to while repeating them during a skill acquisition process may induce greater plastic changes than movements performed unattended.

For two patients in this study, we tested the ability of a remote therapist to monitor ongoing exercises in two patients in a *multiplexed* telerehabilitation environment. The software we have developed enabled the therapist to accurately visualize the patients' ongoing movement sequences and outcomes. Finally, since telerehabilitation is a newer form of therapy delivery, it is unclear at this time how psychological factors will influence recovery. Certain patients may exercise less without direct therapist intervention, since they feel they get less attention than they deserve. Others will prefer less human contact; thus studies are needed to elucidate questions such as: "Is training in a remote virtual-reality telerehabilitation environment as efficacious as training in a virtual-reality environment at a clinic?" However, an increasing body of evidence (Burdea, Popescu, Hentz, & Colbert, 2002; Dhurjaty, 2001; Holden et al., 2003) seems to indicate telerehabilitation is beneficial, at least in some cases.

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