Virtual Reality–Augmented Rehabilitation for Patients Following Stroke

Background and Purpose. Recent evidence indicates that intensive massed practice may be necessary to modify neural organization and effect recovery of motor skills in patients following stroke. Virtual reality (VR) technology has the capability of creating an interactive, motivating environment in which practice intensity and feedback can be manipulated to create individualized treatments to retrain movement. **Case Description.** Three patients (ML, LE, and DK), who were in the chronic phase following stroke, participated in a 2-week training program (3½ hours a day) including dexterity tasks on real objects and VR exercises. The VR simulations were targeted for range of motion, movement speed, fractionation, and force production. **Outcomes.** ML's function was the most impaired at the beginning of the intervention, but showed improvement in the thumb and fingers in range of motion and speed of movement. LE improved in fractionation and range of motion of his thumb and fingers. DK made the greatest gains, showing improvement in range of motion and strength of the thumb, velocity of the thumb and fingers, and fractionation. Two of the 3 patients improved on the Jebsen Test of Hand Function. **Discussion.** The outcomes suggest that VR may be useful to augment rehabilitation of the upper limb in patients in the chronic phase following stroke. [Merians AS, Jack D, Boian R, et al. Virtual reality–augmented rehabilitation for patients following stroke. *Phys Ther.* 2002;82:898–915.]

Key Words: *Motor learning, Recovery, Rehabilitation, Stroke, Virtual reality.*

Alma S Merians, David Jack, Rares Boian, Marilyn Tremaine, Grigore C Burdea, Sergei V Adamovich, Michael Recce, Howard Poizner

There are currently over 1 million people in the United States who have survived a stroke and are living with minor to severe functional limitations.[1] Impairments such as loss of range of motion, decreased reaction times, disordered movement organization, and impaired force generation create deficits in motor control that affect the person's capacity for independent living and economic self-sufficiency. Therapeutic interventions such as neurofacilitation techniques, progressive strengthening, biofeedback, and electrical stimulation have been used to promote functional recovery, but outcome studies have yielded inconsistent results.[2–4] The purpose of this case report is to

Adding computerized virtual reality capabilities to computerized motor learning activities provides three-dimensional visual feedback and guidance for the patient.

AS Merians, PT, PhD, is Professor and Chairperson, Department of Developmental and Rehabilitative Sciences, University of Medicine and Dentistry of New Jersey, 65 Bergen St, Newark, NJ 07103 (USA) (merians@umdnj.edu). Address all correspondence to Dr Merians.

D Jack was a doctoral student in the College of Computer Science, New Jersey Institute of Technology, Newark, NJ.

R Boian is a doctoral student in the School of Engineering, Rutgers University, Piscataway, NJ.

M Tremaine, PhD, is Professor of Information Systems and Director, Human-Computer Interaction Program, College of Computer Science, New Jersey Institute of Technology.

GC Burdea, PhD, is Associate Professor of Computer Engineering, School of Engineering, and Director, Human-Machine Interface Laboratory, Center for Advanced Information Processing, Rutgers University.

SV Adamovich, PhD, is Research Scientist, Center for Molecular and Behavioral Neuroscience, Rutgers University.

M Recce, PhD, is Director of the Life Sciences Program, Center for Computational Biology, and Associate Professor in Biomedical Engineering, Mathematical Sciences, Computer Sciences, and Biological Sciences, New Jersey Institute of Technology.

H Poizner, PhD, is Professor, Center for Molecular and Behavioral Neuroscience, Rutgers University.

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describe computerized training in a virtual reality (VR) environment as an enhancement to existing methods of retraining the hand in patients in the later phase of recovery after a stroke.

Although studies have demonstrated that physical therapy can improve the recovery rate of upper-extremity function,[3,5] the effectiveness of the interventions has generally been less pronounced for the upper extremity than for the lower extremity.[6–9] Although 75% of patients learn to walk again following a stroke, 55% to 75% have continuing problems with upper-extremity function.[3] This difference could reflect the focus of rehabilitation practice, in that the initial priority of rehabilitation is standing on both lower extremities and transferring.[10] In addition, more therapy time is generally spent on lower-extremity activities.[10] This disparity also could be due to the effects of secondary complications in the shoulder, such as pain and subluxation, which can hinder the patient's ability to move; to the pattern of arterial blood supply that would have a greater impact on the upper extremity than the lower extremity; or to the different types of voluntary movements required by the lower and upper limbs. Walking, for example, requires nearly automatic rhythmical movements, whereas functional use of the upper limbs requires complex, graded fine motor movements.[11] Walking also drives the integration of both the affected and unaffected limbs, whereas functional activities performed with the upper extremities may be completed with one limb or may demand 2 different responses when bilateral tasks are performed.[11]

Basic and clinical research provides evidence that for learning and relearning to drive measurable change in neural architecture, activities must be highly attended, repeated, rewarded, and carried out over time.[12–15] Nudo et al[13] demonstrated that, in primates, repetitive use of the digits in a retrieval task caused a use-dependent expansion of the motor cortex representation of the trained digits. Similar neural adaptation has been demonstrated in the sensory cortex of primates.[16] Monkeys that were trained for 1½ to 2 hours a day for 4-months and rewarded to repetitively place their fingertips on a rotating disk showed an increase in the sensory cortical representation of the fingertip area of that hand.[16] In monkeys that had been given focal ischemic lesions, similar to lesions occurring in stroke, Nudo et al[17] further demonstrated that 3 to 4 weeks of intensive, repetitive hand training prevented the usual loss of cortical tissue in the motor area adjacent to the infarcted region and in some instances led to an expansion of this cortical region.

Langhorne et al[18] reported that more intense physical therapy, specifically, a greater amount of therapy time per day, following stroke produced more improvement in activities of daily living (ADL) and impairments than less intense intervention. In a critical review of 11 studies, Kwakkel et al[19] found a small but statistically significant treatment effect related to the amount of daily therapy of patients who had a stroke. An effect of intensity of treatment also has been found for patients in the chronic phase following stroke. The treatment approach referred to as "constraint-induced movement therapy" uses intensive, repeated, massed practice of the affected arm for functional activities while constraining the use of the unaffected arm. This massed practice schedule, in which the amount of time between practice sessions or trials is very short, has resulted in improvement in the use of the affected arm.[14,15,20] Using constraint-induced movement therapy and transcranial magnetic stimulation to record cortical changes, Liepert et al[14] also found improvement in the use of the affected arm along with an enlargement of the cortical thumb area of the hand.

The research investigating repetitive, massed practice schedules and more frequent therapy has provided evidence that this method of intensive intervention can measurably affect neural reorganization and change in function.[14–18] This engenders a clinical challenge: how to deliver this type of intensive, concentrated therapy in today's clinical environment where a patient is usually seen for 30 to 45 minutes twice a day in a hospital or rehabilitation center or once or twice a week as an outpatient.

Computerized technology has the capability to create an exercise environment where the intensity of practice and positive feedback can be consistently and systematically manipulated and enhanced to create the most appropriate, individualized motor learning approach. Adding computerized VR capabilities to computerized motor learning activities provides a three-dimensional (3D) spatial correspondence between the degree of movement in the real world and the degree of movement seen on the computer screen. This exact representation allows for visual feedback and guidance for the patient. Exercising in a VR environment is in the nascent stage of exploration as a therapeutic intervention for retraining coordinated movement.[21–25] The akinesia of patients with Parkinson disease (PD) can be minimized by the use of visual cues in the gait path during ambulation.[26] Head-mounted VR displays are being investigated to determine the effect on akinetic episodes in patients with PD and the subsequent ability to facilitate a more normal gait pattern.[27] Two patients with chronic hemiplegia were trained in a VR environment on an upper-extremity reaching task in which the subject held a rectangular object and extended the arm in the real world. The trajectory of this movement was recreated on the computer screen and the virtual object was placed into a virtual mailbox. The task progressed sequentially through 6 levels of difficulty.[23] Both patients improved in performance of the task in the VR environment over the 16 sessions and were able to consistently progress to the fifth and sixth levels of difficulty. One of the patients showed improvement in the Fugl-Meyer Assessment of Sensorimotor Recovery After Stroke and reported that he was able to use his hemiplegic arm for several functional activities that he was not able to perform previously. The second patient did not show changes on the Fugl-Meyer Assessment of Sensorimotor Recovery After Stroke.

The literature reporting VR for rehabilitation training is inconclusive because of small sample sizes and mixed results, but suggests a potential benefit that should be more fully explored. This report describes a VR system that provides massed practice using target-based exercises, visual and force feedback during the exercises, quantitative outcome measures, adaptability to variation in patient function, transparent patient data storage, and an engaging and motivating user interface. These case reports illustrate the use of this VR system to augment rehabilitation training designed to improve motor function of the hand in 3 patients in the chronic phase after a stroke.

Case Descriptions

Patients

Three patients, 2 male and 1 female, participated in the intervention. All patients were right-hand dominant and had a left hemisphere stroke, which had occurred between 3 and 6 years previously. The patients were recruited through visits to local stroke support groups and met the criteria established by Taub et al.[15] The patients had to be able to actively extend the wrist of the hemiplegic limb at least 20 degrees and extend the metacarpophalangeal (MP) joints at least 10 degrees. None of the patients were receiving therapy at the time. They were evaluated and trained at the Center for Molecular and Behavioral Neuroscience, Rutgers University. Informed consent was received from all patients, and the rights of the patients were protected.

ML was an 83-year-old woman who had a past medical history of hypertension, diabetes mellitus, and hypothyroidism. She had a left posterior capsular infarct with resulting right hemiparesis 3 years previously. She received physical therapy and occupational therapy for 3 weeks as an inpatient and for 3 months as an outpatient. Before the stroke, ML lived alone and was independent in ambulation and all ADL tasks. Since the stroke, she had been living with her daughter, who worked full-time but provided meal preparation and assistance. At the time of her discharge from the rehabilitation center, ML was able to put on her clothes but needed assistance with fasteners and zippers. She was able to bathe herself but required contact guard using a tub transfer bench and assistance with lower-extremity washing. She required contact guarding for other transfers and was able to ambulate about 60 m (200 ft) with a small-based quad cane and close supervision. When she completed outpatient therapy, ML's passive range of motion was within normal limits and similar in all 4 extremities. She was able to transfer requiring only close supervision and to ambulate about 90 to 120 m (300–400 ft). The reliability of these measurements was not estimated. At the time of participation in this intervention, ML's grip strength was 7.3 kg in the right hand and 10 kg in the left hand, and she still required some assistance with dressing activities. Although she was able to use her right hand for putting on blouses and slacks, she needed assistance with hooks and buttons and was not able to use her right hand for activities such as eating, brushing her teeth, and combing her hair. ML required close supervision for transfers. She ambulated using a quad cane for short distances and used a rolling walker for longer distances, requiring close supervision for both.

LE was a 54-year-old man who had a past medical history of hypertension. He had an infarct of the left corona radiata of the posterior limb of the internal capsule that resulted in slurring of his speech and right hemiplegia 6 years previously. He received physical therapy, occupational therapy, and speech therapy for 3 months as an inpatient and occupational therapy and speech therapy for 1 month as an outpatient. LE lived alone both prior to and following the stroke. He was previously employed full-time, but after his stroke he worked as a volunteer. At the time of discharge from the rehabilitation center, he was able to ambulate 289 m (750 ft) independently with a narrow-based quad cane and a molded ankle-foot orthosis (MAFO). He required supervision for ascending and descending curbs and stairs. Strength in the right lower extremity was 4+/5 for hip and knee flexion, 5/5 for hip abduction, 4/5 for hip adduction and knee extension, and 3/5 for hip extension and ankle dorsiflexion.

Movement at the shoulder and elbow was hindered by increased postural tone, which was evident as a flexor pattern (combined shoulder and elbow flexion). LE was independent in all ADL tasks, including light meal preparation; however, he performed all ADL tasks with his left hand and used his right hand only to hold an object that he transferred into the left hand. At the time of the intervention, he continued to use his upper extremities in this manner. His grip strength was 11 kg in the right hand and 41 kg in the left hand. He had progressed to independent ambulation with the use of a

MAFO, and he no longer needed a cane for ambulation over level surfaces. He was also independent in ascending and descending curbs and stairs using a handrail.

DK was a 59-year-old man who had a hemorrhagic left frontal parietal infarct subsequent to bacterial endocarditis, which resulted in expressive aphasia and right hemiparesis 4 years previously. He received physical therapy and speech therapy as an inpatient for 3 weeks and as an outpatient for more than a year. Prior to the stroke, DK worked full time; however, he retired after the stroke. At the time of discharge from the rehabilitation center, DK was independent in all ADL tasks, including shopping and driving. He ambulated without any assistive devices. Active and passive range of motion and strength of the upper and lower extremities were normal, although he showed some slight influence of flexion synergy in his upper extremity during ambulation. At the time of this intervention, DK remained independent in ambulation. He exercised by walking briskly for a half-hour each morning. Although he initially was aphasic, he was able to speak with only slight hesitation in terms of the rate and precision of his conversational speech. His grip strength was 28 kg in the right hand and 37 kg in the left hand. DK initiated most activities with his left hand, ate solely with his left hand, and used only his left hand to steer the car; however, he used his right hand as an assist in dressing activities, opening doors, grooming, and kitchen activities.

Measurements

Three types of measures were used during the administration of the VR exercises: computer measures, clinical measures, and affective measures. Because the computer allowed us to obtain detailed measurements of the precise movements of the affected hand over time, we logged motor performance in a computer-based database. We also used clinical measures to assess hand function. Because massed practice requires the patient to be responsible for engaging in the exercises, we also used affective measures of the patient's motivation and interest in the tasks.

Computer measures. Computerized measurements of the changes in range of motion, speed, fractionation (isolated use of individual fingers), and strength were taken after each trial. The algorithms developed for each of these measures are described in Appendix 1.

Clinical measures. To measure improvement in hand function, each patient was evaluated before and after training using 2 clinical measures: the Jebsen Test of Hand Function[28] and 7 items from the hand portion of the Fugl-Meyer Assessment of Sensorimotor Recovery After Stroke.[29] The test-retest reliability determined for each subtest of the Jebsen Test of Hand Function using the Pearson product moment correlation coefficient ranges from .60 to .99.[28] Twenty-six patients with a variety of diagnoses contributing to hand disabilities were tested on 2 occasions.[28] This test has been reported to be able to discriminate various degrees of disability in patients with hemiplegia.[28] Intratester and intertester reliability as well as validity have been reported on the entire Fugl-Meyer Assessment of Sensorimotor Recovery After Stroke, but not on the hand portion alone.[29] This test was not responsive to the changes in the patients' movements. Grip strength was evaluated, using the mean of 3 measurements at each time period (before, during, and after training), using a Jamar dynamometer.* Using the Pearson product moment correlation coefficient, the highest values for test-retest reliability (r=.81–.93) are achieved when the mean of 3 trials is used.[30,31]

Affective measures. The affective measures included the patients' motivation to engage in the exercises and their perceptions of each of the games. We administered 2 short questionnaires. The first questionnaire was a brief survey instrument designed to assess the patients' perceptions of their current motor ability in the affected hand and their motivation to participate in the intervention. Answers to this questionnaire helped us assess the probability that the patients would fully participate in the VR therapy. This questionnaire was administered at the beginning of the study. The second questionnaire had 3 goals. First, patients were asked to assess the motor function in the affected hand. We then asked for an overall evaluation of the different exercises. The data from these questions will help us to design better and more engaging exercises in the future. We also asked patients several questions about their perceptions of various mechanisms we might use for introducing the therapy in the home. This third set of questions was designed to help us assess the potential for the continued use and perceived value of this type of exercise. The reliability and validity for the questions were not established; however, the questions were selected and modified from a published, validated and reliable (Cronbach alpha=.94) questionnaire commonly used for user interface evaluation by usability laboratories in industry.[32] A listing of the questions asked of the patients before and after the intervention is shown in Appendix 2.

Intervention

Virtual reality exercise system. The VR exercise system did not require special 3D head-mounted displays to give a stereo 3D view of the exercise world. Instead, 3D graphics were displayed on a flat personal computer screen using only shadows and perspective cues to give the illusion of depth. The patients received haptic

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* Sammons Preston, 4 Sammons Ct, Bolingbrook, IL 60440.

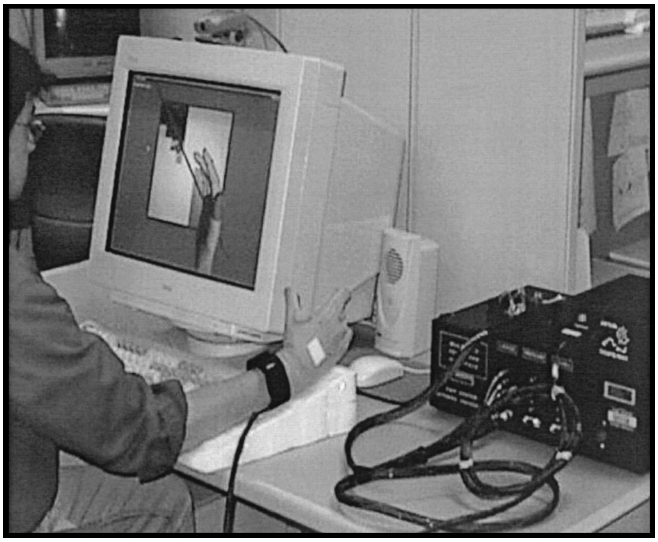

Figure 1.
The personal computer-based virtual reality rehabilitation system. The user is wearing a CyberGlove that is connected to the interface unit on the right. Also shown is the haptic control interface for the Rutgers Master II-ND force feedback glove.[19] © Association for Computing Machinery (ACM). Reprinted by permission of ACM.

(force), visual, and auditory feedback as they performed the exercises. This VR system (Fig. 1) uses a personal computer (Pentium II 400 MHz[†]) with a FireGL 4000 graphics accelerator.[‡] Two hand input devices were used, a CyberGlove[§] and the Rutgers Master II-ND (RMII) force feedback glove prototype developed in the Human-Machine Interface Laboratory at Rutgers University. Two devices were used because each device has advantages for certain types of exercise. The CyberGlove was used for range of motion, speed, and fractionation movement exercises, and the RMII force feedback glove was used for finger strengthening. The gloves, their integration with the personal computer, and the calibration of the joint angles have been described elsewhere.[24,25] Four hand exercise programs were developed using the commercially available World Tool Kit graphics library.[‖] The exercises were in the form of computer games that used graphics feedback to encourage participation and concentration. Different exercises were designed to focus on the development of different skills, with each game designed to exercise one of the aspects of hand movement (range of motion, speed of movement, fractionation of individual finger motion, or strengthening of the fingers) (Fig. 2). These exercises are described in Appendix 1.

Although the RMII force feedback glove worked well for the thumb, the patients tended to translate the piston assembly of the fingers with the MP joints rather than depressing them, and thus bypassed working against the programmed resistance. At other times, the patients would use a twisting motion rather than a planar motion of the fingers, which could break the delicate inner piston assembly of the haptic glove. These problems did not arise for thumb motions. Based on this experience, the RMII glove is now being redesigned to work under these conditions.

Calibration. To minimize measurement errors due to the variability in the patients' hand size, the system was calibrated for each patient before the exercises were initiated. For the CyberGlove, every joint was placed in 2 known positions: 0 and 60 degrees. From these positions, measurements were obtained for 2 variables (gain and offset) that specified the linear relation between the raw sensor output and the corresponding joint angles being measured. For the RMII force feedback glove, every joint was calibrated in the 0-degree position.

Feedback. The exercise software provides both knowledge of results (feedback related to the nature of the result produced in terms of the movement goal)[11] and knowledge of performance (feedback related to the nature of the movement that was produced)[11] in multiple modes (visual, auditory, and haptic). In addition to the performance feedback specific to each game, after each exercise trial the patients were shown a graphical digital "performance meter" that displayed the target level and the actual performance. This "performance meter" was used to inform the patients exactly how close or how far away they were from the desired performance goal. All of the variables such as range, speed, fractionation, and strength were estimated in real time through the computer software to drive the graphics display and provide immediate feedback to the patients. An Oracle database[#] running on the same personal computer transparently stored all exercise data for later retrieval and analysis.

Goal setting. Each patient's angular range, speed, fractionation, and strength for the thumb and fingers were quantified before the exercises were initiated to set an initial difficulty level for that patient. This evaluation exercise was performed 10 times for each exercise, and the results were used to set the initial goal targets for each exercise. Goal targets were drawn from a normal distribution around the mean and standard deviation given by the initial evaluation tests. A normal distribution ensures that the majority of the targets will be within the patient's performance limits, but the patient will find some targets easy or difficult, depending on whether they come from the low or high end of the target

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[†] Intel Corp, 2200 Mission College Blvd, Santa Clara, CA 95052.

[‡] ATI Technologies, 33 Commerce Valley Dr E, Thornhill, Ontario, Canada.

[§] Immersion Technologies Inc, 801 Fox Ln, San Jose, CA 95131.

[‖] Engineering Animation Inc, 2321 North Loop Dr, Ames, IA 50010.

[#] Oracle Corp, 500 Oracle Pkwy, Redwood Shores, CA 94065.

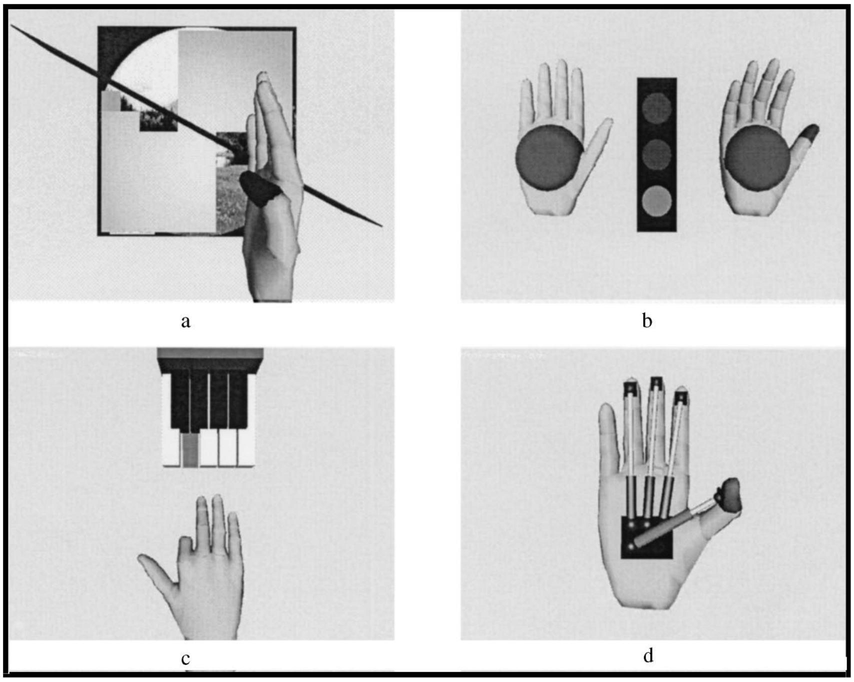

Figure 2.
The 4 virtual reality exercises: (a) range of movement, (b) speed of movement, (c) finger fractionation, and (d) strength of movement.[19] © Association for Computing Machinery (ACM). Reprinted by permission of ACM.

distribution. Initially, the targets were set one standard deviation above the patient's actual measured mean performance to obtain a target distribution that overlaps the high end of the patient's performance levels. Goal targets were increased or decreased for each patient according to a specific algorithm. A description of this process is given in Appendix 3.

Training procedures. All patients participated in an intensive 2-week program consisting of 5 days of training, a weekend break, and another 4 days of training. The patients began their exercises at 10 AM and concluded by 3 PM each day. Each VR exercise session consisted of 4 training blocks: range of motion, speed of movement, fractionation of individual finger motion, and strengthening of the fingers. For the range of motion and speed of movement exercises, there were 10 trials for thumb motion and 10 trials for finger motion in each block. For the fractionation exercise, there were 5 trials each for fingers 2, 3, 4, and 5 in each block. For the strengthening exercise, there were 10 trials for the thumb and 10 trials each for fingers 2, 3, and 4. The timing of the trials was controlled by the therapist, who initiated each trial by pressing the keyboard spacebar.

Each VR exercise session took approximately 20 to 25 minutes, with 4 sessions of VR exercise taking about 1 to 1½ hours each day. The goal was to have 4 VR sessions per day, which generally occurred except for the following: ML had 2 sessions on day 1, 3 sessions on day 5, and 2 sessions on day 10; LE had 1 session on day 1, 3 sessions on days 2 and 5, and no sessions on day 10; and DK had 2 sessions on day 1, 3 sessions on days 4 and 5, and no sessions on day 10. ML had a total of 35 sessions, of which 31 were strength sessions; LE had a total of 31 sessions; and DK had a total of 32 sessions, of which 31 were strength sessions. While one patient was using the VR training system, the other 2 patients used their affected right hands to perform a variety of fine motor tasks. Each task was practiced for 20 to 25 minutes. The criteria for the choice of tasks was that each task required fine motor hand control and was not a duplication of a task used in the Jebsen Test of Hand Function. The tasks used included playing checkers, picking up coins and putting them into a bank, putting pegs into a peg board, putting paper clips onto a piece of paper, tracing geometric designs, a game that involved shaking and tossing dice from a cup, a game that required putting checkers into a vertical holder, and eating lunch. All of the tasks were supervised by a physical therapist or occupational therapist. The order of the activities was not planned, and the choice of activities was not related to the patients' impairments. The patients chose whichever activity they wanted to do. This use of fine motor activities with real objects for an intensive period of time is modeled on constraint-induced movement therapy developed by Taub[15] and Wolf and colleagues.[20] The cumulative time patients spent on these fine motor non-VR tasks was approximately 3½ hours per day. This interspersing of fine motor activities with the VR practice as patients rotated off of the VR station allowed for the continual use of the right hand in all activities for approximately 5 hours per day.

Outcomes

ML showed improvement in the thumb and fingers in range of motion and speed of movement. As an example of the kinematic changes in speed of movement, Figure 3 shows the improvement in flexion velocity of the middle finger between day 1 (top) and day 9 (bottom) of training. The upper and lower portions depict the velocity of the MP and proximal interphalangeal (PI) joints, the mean peak speed for these 2 joints, and the velocity target setting (horizontal line). These graphs show that at day 1, session 1, trial 10, at a target setting of 178°/s, ML's mean peak velocity for the middle finger was 170°/s. By the third trial of session 1, on day 9, the target was elevated to 364°/s, and her mean peak performance speed for the middle finger had increased to 436°/s. Table 1 shows means and standard deviations for each of the outcome measures for ML averaged across the first 2 days of the therapy and the last 2 days of the therapy. Although ML increased her scores in all of the computer measures, she showed the best and most consistent improvement in the range of motion of her fingers and thumb and the speed of her fingers and thumb.

The overall increases in range of motion, velocity, fractionation, and thumb strength are reflected in the changes in performance of the Jebsen Test of Hand Function as shown in the Table 2. ML was slower than the other patients in performing many of the tasks even when using her unaffected hand. This could be due to the fact that, at 83 years of age, her motor skills had slowed compared with the other patients. A positive correlation between age and time required to complete the Jebsen Test of Hand Function subtests has been reported for both men and women.[33] Although her performance remained consistent in her unaffected hand on the 2 tests, ML showed more rapid performance times after training in her affected hand when compared with the pretest. Her performance improved in 4 of the 7 items tested: writing, card turning, simulated feeding, and picking up large light objects. In addition, although ML was slower in some tests after training, she was able to increase the number of completed items from 2 of 6 items to 4 of 6 items when picking up small objects and from 0 of 4 items to 3 of 4 items when stacking checkers. Both the number of beans picked up and the speed with which they were picked up increased in the simulated feeding task. In the dynamometer readings, ML showed a 59% increase in grasping strength after training in her affected hand. ML reported several meaningful changes as a result of the intervention; she was now able to use her right hand to

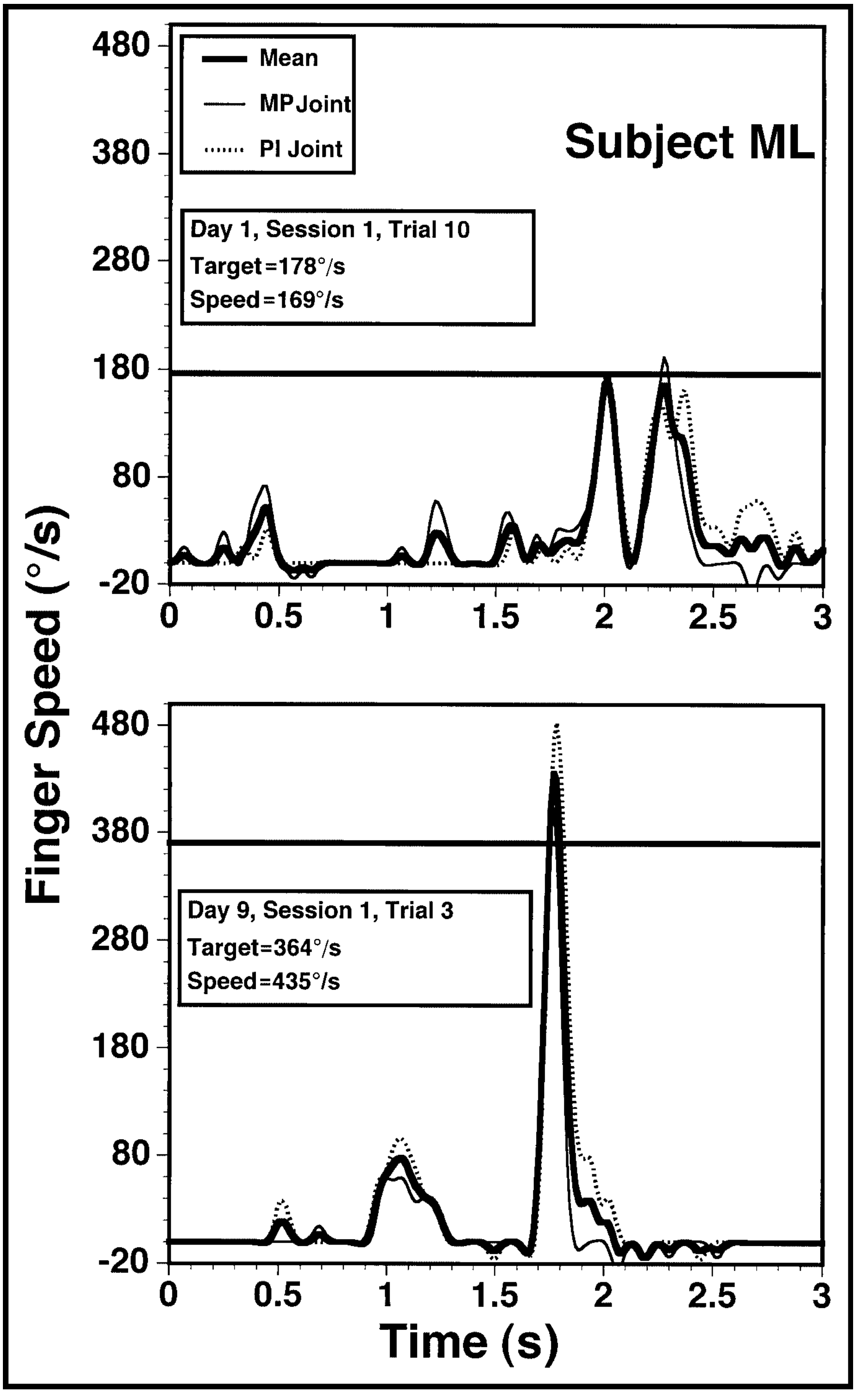

Figure 3.
The velocity profile for the metacarpophalangeal (MP) joint, the proximal interphalangeal (PI) joint, and the mean peak speed of the middle finger for ML during trial 1 of session 1 on day 1 (top) and during trial 3 of session 1 on day 9 (bottom). The target goal is depicted as a horizontal line. Flexion velocity improved over the course of the training.

Table 1.
Performance of Each Patient Averaged Across Days 1 and 2 of the Therapy (Start) and Days 8 and 9 of the Therapy (End)

	Subject											
	ML				**LE**				**DK**			
	Start		**End**		**Start**		**End**		**Start**		**End**	
	$\bar{X}$	**SD**	$\bar{X}$	**SD**	$\bar{X}$	**SD**	$\bar{X}$	**SD**	$\bar{X}$	**SD**	$\bar{X}$	**SD**
Finger range of motion (°)	80.3	3.2	87.9	2.9	65.2	6.6	80.1	4.2	78.3	4.6	78.1	2.7
Thumb range of motion (°)	79.6	9.7	97.9	4.4	57.6	5.8	65.4	5.3	43.0	4.3	65.1	5.1
Fractionation (°)	59.6	13.4	63.8	6.6	28.4	4.9	54.9	9.5	34.2	9.3	58.7	3.1
Finger speed (°/s)	251.0	29.7	385.5	40.2	235.3	46.3	285.7	18.8	286.6	26.3	379.3	35.6
Thumb speed (°/s)	279.6	46.5	337.7	51.8	212.5	20.2	235.9	28.4	150.1	32.8	245.4	29.3
Work (N·m)	204.5	30.9	229.7	22.4	118.5	17.1	143.3	21.2	178.6	40.9	229.3	22.9

Table 2.
Pretest and Posttest Scores (in Seconds) for Jebsen Test of Hand Function

	Subject					
	ML		**LE**		**DK**	
	Pretest	**Posttest**	**Pretest**	**Posttest**	**Pretest**	**Posttest**
Right hand						
Writing	225	76	73	68	58	55
Card turning	26	16	19	29	15	11
Picking up small objects	41 (2/6[a])	59 (4/6[a])	59 (1/6[a])	61 (6/6[a])	11	11
Simulated feeding	71 (0/5[a])	42 (5/5[a])	44	76	19	15
Stacking checkers	30 (0/4[a])	56 (3/4[a])	37	41	8	4
Picking up large light objects	22	21	41	23	8	10
Picking up large heavy objects	23	28	26	22	8	7
Left hand						
Writing	164	169	25	27	55	50
Card turning	10	9	7	6	7	6
Picking up small objects	12	16	8	7	7	6
Simulated feeding	56 (4/5[a])	39	15	17	13	14
Stacking checkers	6	5	7	4	2	3
Picking up large light objects	8	9	7	6	5	5
Picking up large heavy objects	8	9	6	5	5	5

[a] Ratio of number of completed items to total number of items in subtest. The time needed to complete activities performed with the unaffected hand remained consistent between testing sessions.

move the lever on her recliner, a chair she used every day, and she could use a spoon with her right hand to eat soft items.

LE showed improvement in fractionation and range of motion of his thumb and fingers. Figure 4 presents an example of the kinematic changes that occurred between day 1 (top) and day 9 (bottom) of training. This example displays the increases in range of motion in LE's index finger. Both the upper and lower portions of the graphs depict the changes in the joint angles over time (MP joint, PI joint, mean), as well as the target setting (horizontal line). As shown in the graphs, the target was set at 48 degrees in trial 1 of session 1 on day 1, and LE achieved a mean range of motion for the index finger of 53 degrees (measured as the difference between the maximum and minimum of the average finger angles). By the seventh trial of session 2 on day 9, however, the target was elevated to 73 degrees, and his mean range of motion for the index finger had increased to 73 degrees.

A comparison of the outcome measures for LE averaged across the first 2 days and the last 2 days of the therapy is shown in Table 1. The performance during the last 2 days of training improved when compared with the performance during the first 2 days of training on 4 out of 6 measures. Although there was improvement in his finger speed, this aspect of movement remained quite variable and nonmonotonic over the course of the training.

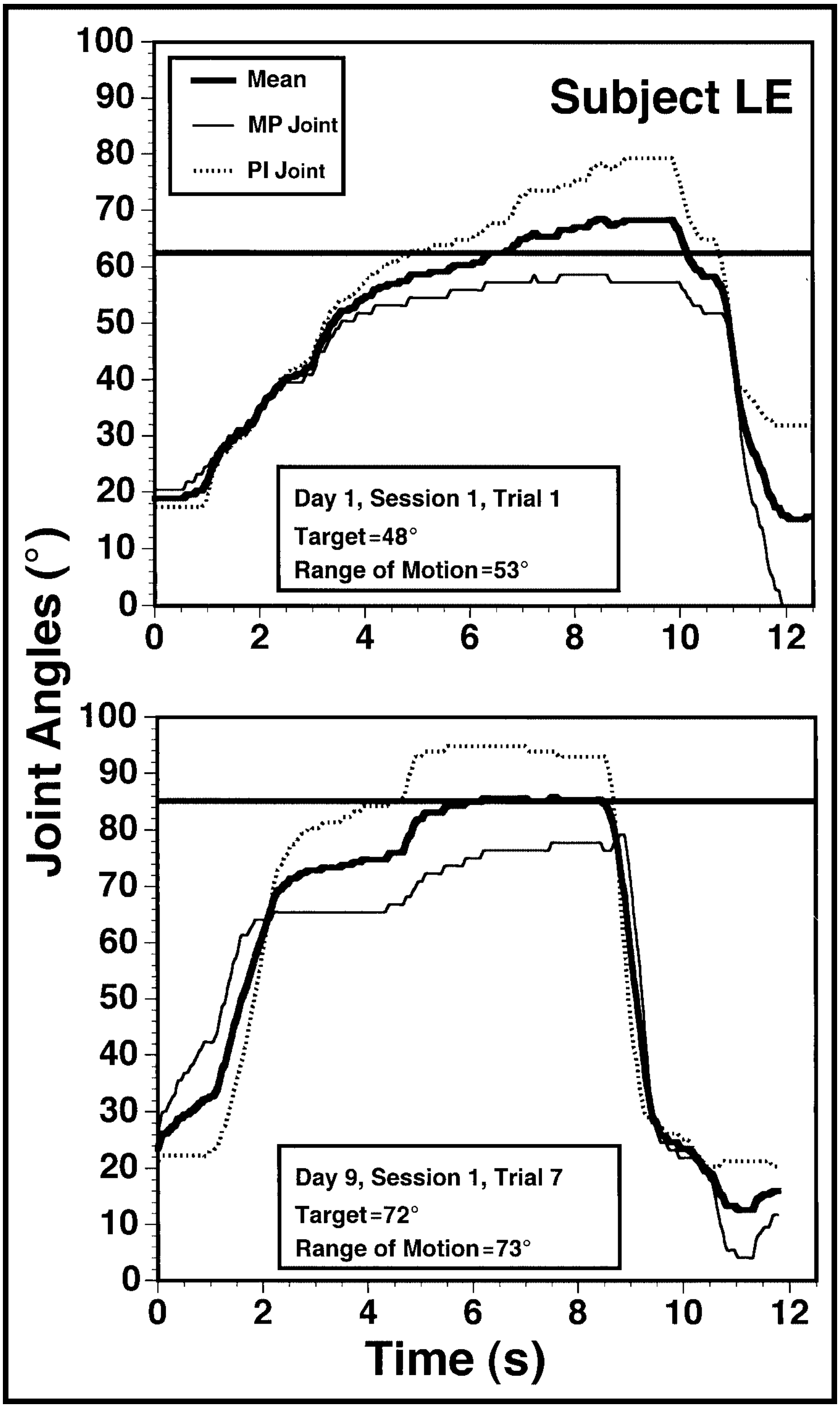

Figure 4.
Changes in the joint angles over time (metacarpophalangeal [MP] joint, proximal interphalangeal [PI] joint, mean), as well as the target setting (horizontal line) for the index finger for LE during trial 1 of session 1 on day 1 (top) and during trial 7 of session 2 on day 9 (bottom). The score for the target range of motion is the difference between the maximum and minimum of the average finger angles. Range of motion improved over the course of the training.

The improvement measured by the Jebsen Test of Hand Function shown in Table 2 reflects the overall increases in range of motion, velocity, fractionation, and thumb strength. LE's performance with his unaffected hand remained consistent over the 2 tests. His affected hand, however, showed more rapid performance times after training compared with the pretest in 3 of the 7 items tested using the Jebsen Test of Hand Function: writing and picking up large light and heavy objects. Although his overall time increased when picking up small objects, he was able to pick up more objects than in the pretest. He was able to pick up 6 out of 6 objects after training rather than 1 out of 6 objects before training. LE showed increased times on card turning, simulated feeding, and stacking checkers. In the dynamometer readings, LE showed a 59% increase in grasping strength after training in his affected hand. Although he showed gains in the computer measures, he did not improve on the Jebsen Test of Hand Function, nor did he report meaningful changes in the use of his hand at home. Perhaps more intense training would be needed for this patient to make measurable functional gains.

DK showed improvement in range of motion and strength of the thumb, velocity of the thumb and fingers, and fractionation. An example of the changes in DK's ability to isolate the motion in each of his fingers is shown in Figure 5. This figure presents the angle of movement for the middle, ring, and small fingers while DK was actively moving his index finger, as well as the specific target setting and performance for the index finger. In trial 4 of session 1 on day 1 (top), the target goal was set to be able to achieve a ratio of 30% of isolated movement of the index finger when compared with the other 3 fingers. At that time, DK was able to achieve 28% of isolated movement. The joint kinematics indicate that when DK attempted to move his index finger, all of the other fingers flexed to a similar degree. By trial 2 of session 2

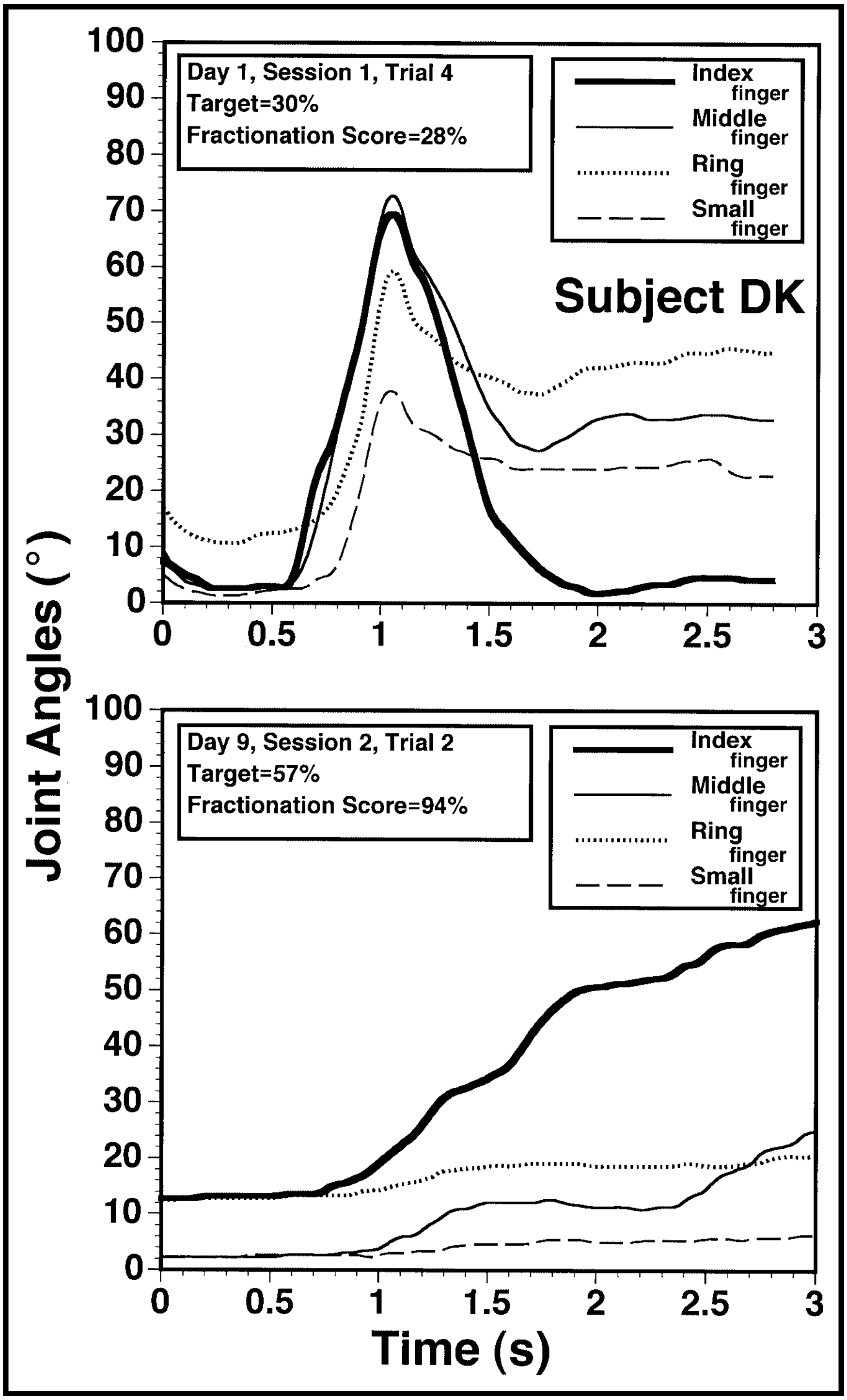

Figure 5.
Target goal and performance for fractionation of the fingers for DK during trial 4 of session 1 on day 1 (top) and during trial 2 of session 2 on day 9 (bottom). The ability to isolate the motion of each finger improved over the course of the training.

on day 9 (bottom), the target was able to be set for a ratio of 57% of isolated movement of the index finger, and DK was able to achieve 94% isolated motion. The joint kinematics depict this isolation indicating 60 degrees of index finger flexion while the other fingers flexed between 10 and 35 degrees.

A comparison of the outcome measures for DK averaged across the first 2 days and the last 2 days of training is shown in Table 1. The performance during the last 2 days was better than during the first 2 days of training on all outcome measures, except for the finger range of motion which showed normal range at the beginning of the intervention.

The changes in performance on the Jebsen Test of Hand Function are shown in Table 2. DK's performance when using the unaffected side was also consistent on the 2 tests. Both DK and LE performed similarly on the unaffected side, but on the affected side DK performed the best of the 3 patients both before and after the training. He showed more rapid performance times after training in 5 of the 7 items tested: writing, card turning, simulated feeding, stacking checkers, and picking up heavy objects. DK showed a 13% increase in grasping strength after training in his affected hand. This is the smallest gain in grip strength among the 3 patients. However, as mentioned earlier, DK was at the highest functioning level and had attained a post-intervention grip strength of 320 N in his affected hand. DK reported that by the end of the intervention he was able to use his right hand to assist his left hand on the car steering wheel and he was practicing using his right hand to move the computer mouse. He was observed buttoning his shirt in the second week of training, an activity he could not do before the intervention. Increases in grip strength as measured by the dynamometer have been reported elsewhere.[24]

Summary of Progress on the VR Outcome Measures

The changes in the outcome measures are summarized on Figure 6. It shows the percentage of improvement for each of the patients for range of motion, speed, fractionation, and mechanical work. The percentage of improvement was calculated as the mean of the last 2 days of therapy minus the mean of the first 2 days divided by the mean of the first 2 days. The resulting quotient was then multiplied by 100. Performance was pooled over the first 2 days of therapy to derive a start measurement and over the last 2 days to derive an end measurement in order to obtain a large data sample at each end of the training period for enhanced data stability and to minimize any possible effects that might be due to patients acclimating to the system on day 1.

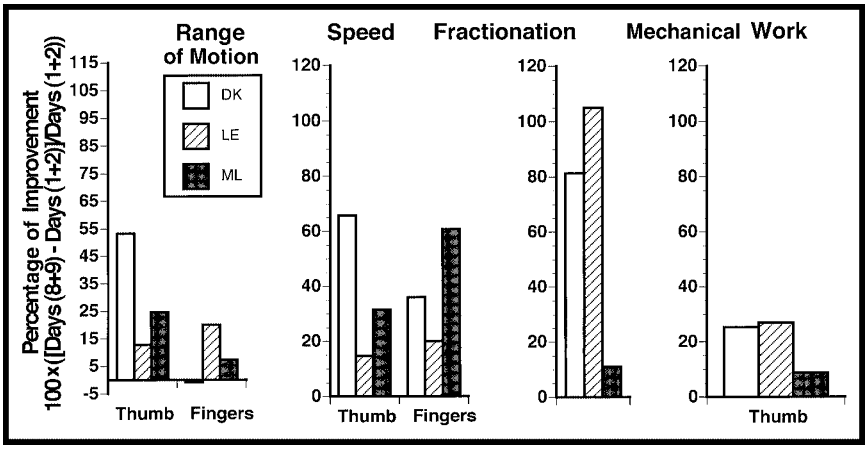

Figure 6.
Percentage of improvement for each of the patients for range of motion, speed, fractionation, and mechanical work.

ML had the most impairment at the beginning of the intervention, but with training she made small gains in fractionation (10%) and in the ability to perform work with her thumb (7%) (Tab. 1). Thumb range of motion improved 24%, and finger range of motion improved 7%. ML's greatest improvement was seen in the speed of her hand grasp in which her thumb improved by 32% and her fingers by 60%.

Looking at LE's percentage of improvement, his thumb range of motion and the amount of mechanical work the thumb was able to perform increased by 13% and 27%, respectively. He had a 20% improvement in finger range of motion, as well as increases in speed of movement of 15% for the thumb and 20% for his fingers. His ability to fractionate the fingers improved by 103%.

DK's finger range of motion averaged over the 4 fingers did not show any increase. DK began the study with his 4 fingers exhibiting normal range of motion. DK made the greatest gains among the 3 patients in thumb range of motion, which improved by 54%; in velocity of his grasp, which improved by 66% (thumb) and 36% (fingers); in his ability to fractionate his fingers, which improved by 80%; and in the ability of his thumb to perform work, which improved by 25%. DK had thumb strength that quickly attained the RMII force feedback glove output limit set in this experiment; thus, his thumb strength was limited by the experimental setup capabilities and may have improved even more.

Prior to the study, the patients felt neutral about the VR-based therapy and its potential to improve their motor function. The questions on the pretest questionnaire gathered data about the patients' perceptions of their current motor function in the affected hand and of the expectations they had for improving their hand motor function. A question also requested information about prior musical instrument experience, because a loss of this skill might have had more impact on a patient's expectations and motivation. Because computers can be intimidating to nonusers, especially VR environments, we also asked questions about how much prior computer experience the patients had. Two of the patients, DK and LE, had substantial computer experience, and the third patient, ML, had no computer experience. None of the participants had played musical instruments in their lives. All of the patients thought that the movement in their right hand was not good, and 2 of them had only neutral expectations about the effect of the intervention. LE had less than average expectations (Fig. 7). Thus, although the patients indicated that they were willing to participate, they were not optimistic about the outcome.

The questions on the posttest questionnaire were grouped into 4 categories. Figure 8 displays these categories, the mean of each patient's response in each category, and the mean response of the 3 patients. The means are the average scores of the combined question responses on a 7-point Likert scale, with 1=strongly disagree and 7=strongly agree with the question's statement. Some of the questions needed to be written in reverse form (eg, "the computer tasks took too long"). The scores for these questions were reversed before they were averaged into the index for the category.

The patients perceived that the motor function of their affected hand had improved, and they expected further improvement with continued VR exercises. The first category measured the patients' perceptions of their

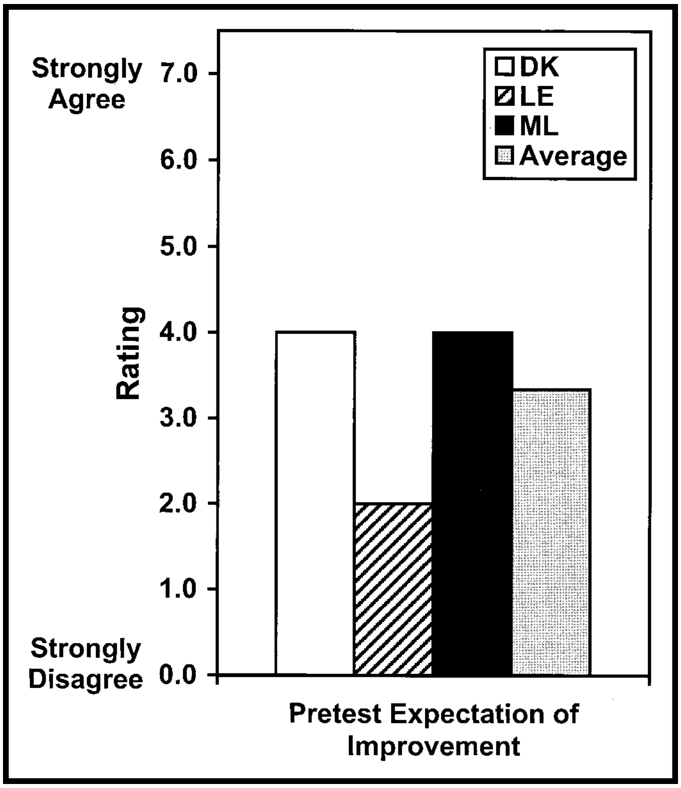

Figure 7.
Responses of patients on the pretest question that assessed their perception of the intervention's potential. Patients responded on a scale from 1 to 7 to a positive statement about the intervention's impact on the patients' hand motor function, with 1=strongly disagree and 7=strongly agree.

right-hand motor improvement and future promise of additional motor improvement if they continued with the exercises. Although, as noted earlier, the computer program had measured improvement in each of the patients' hands, the patients were not informed of this improvement. Instead, as patients worked with the exercises, the program continually set higher thresholds for success. The left bar graph in Figure 8 shows that all patients believed that their hand function had improved and that if they continued the exercises they would have additional improvement. Patients scored an average of 5.7 (agree range) for this category, but a potential for response bias existed for these 2 questions. The administrator of the posttest questionnaire had worked closely with the patients. Thus, they would be more inclined to indicate that they felt they had improved, because it was the desired response. DK, however, indicated that he was not interested in continuing with the intervention and thought that the computer tasks took too long. He still believed he had improved and would continue to improve even if he did not find the exercises very stimulating. DK also showed the most improvement in hand function of the 3 patients.

The second category measured the patients' enjoyment of the computer task. This category included 6 questions (questions 3, 4, 5, 7, 9, and 15). The second bar graph in Figure 8 shows that the patients had an average score of 5.4 out of 7 (agree range). The one outlier was the response of DK, who indicated that he was not interested in continuing these tasks for another 2 weeks, but who did indicate that he was willing to perform the computer tasks at home or in competition with others through a Web-based interface.

The third category combined 2 questions (questions 6 and 16) to assess whether patients would enjoy performing the VR therapy in conjunction with other patients over the Web. This category received the strongest negative response from LE. Overall, the score was 5.2 (Fig. 8), with the other 2 patients indicating an interest in this approach, more so, if it were carried out over the Web. LE also indicated on the pretest questionnaire that he had the least expectations for improvement and that he was not optimistic about participating in the intervention.

The final category combined 6 questions (questions 8, 11, 12, 13, 14, and 19), which asked for detailed evaluation of each of the 4 exercises. This group received the lowest score, with an average of 4.5. The low score for the evaluation of the computer tasks related directly to the fractionation task, which the patients found to be quite difficult. Although patients found the strength task difficult and fatiguing, they responded more positively to the task (Fig. 9). The strength task also provided more direct feedback to the patient about performance during the exercise. All patients found the computer tasks to be too long, and 2 patients (LE and ML) found it difficult to determine how well they were doing in the exercises. A follow-up usability interview with 2 of the patients revealed that the fractionation task was the most difficult to understand. In particular, patients could not tell, from the visual feedback given in the task, how they needed to move their hand to improve motor function. They also had similar difficulties with the range of motion task. This task was particularly susceptible to the start position of the hand, which needed to be in a fully extended position to do well on the task. Patients often forgot to fully extend their hand, causing them to miss their full target range of movement. Thus, the individual evaluation of the computer exercises reflected actual problems in the exercise design that the patients encountered.

Discussion

This case report describes a new technology developed to be used in the clinic to augment the rehabilitation of patients with diminished upper-extremity function. Each patient showed improvement in a subset of variables,

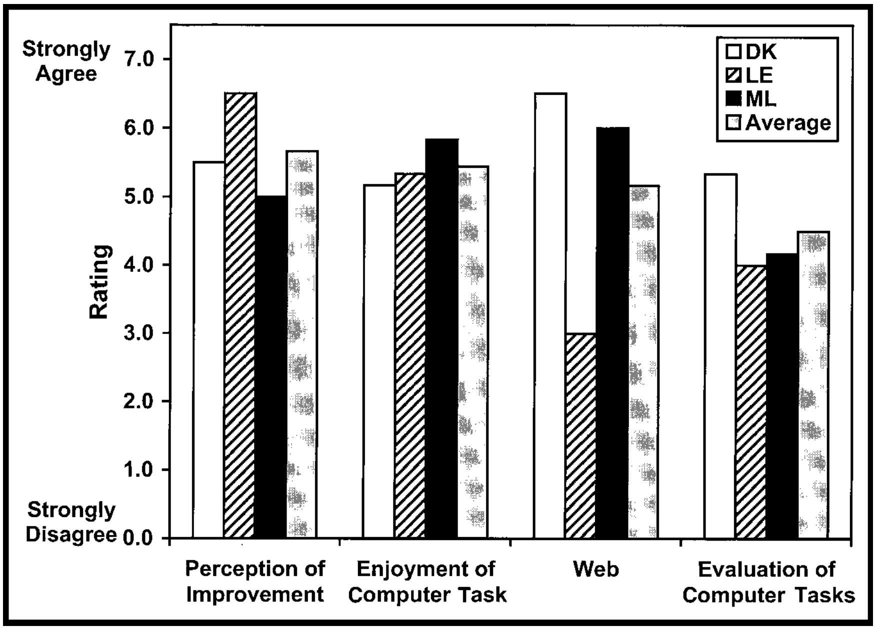

Figure 8.
Patients' posttest perception of exercises and results. The questions are grouped into 4 categories, and the scores for the questions for each patient in a given category were averaged. The averages for the categories are presented for each patient and then as an overall mean of all patients' responses in the category. Group 1 (first set of bar graphs reading from left to right) represents patients' perception of their improvement after the trials; group 2 (second set of bar graphs) represents patients' enjoyment of the computer task; group 3 (third set of bar graphs) is patients' willingness to participate in similar virtual reality computer activities with others; and group 4 (rightmost set of bar graphs) represents an evaluation of the computer tasks. The patients responded to each question by indicating their attitude on the question on a 7-point Likert scale, with 1=strongly disagree and 7=strongly agree.

with transfer of this improvement to function on the Jebsen Test of Hand Function, on which they were not trained. Two of the 3 patients showed improvement in the use of their hand in several functional ADL tasks as well as on the Jebsen Test of Hand Function after this intervention, and 1 of the patients did not transfer this improvement to functional activities. Activities were performed in a computerized VR environment, alternating with hand activities performed in a real-world environment. Several studies[34–36] have shown that in patients without disabilities, training in a VR environment is beneficial for learning a complex motor task. The literature on the use of VR training for the rehabilitation of people with brain damage is limited, however, and relatively few studies have investigated the use of VR training for movement re-education. Virtual reality training has been reported to be helpful in overcoming gait akinesia in patients with PD,[27] to enhance spatial awareness in children with cerebral palsy,[37] and to successfully teach these children to operate motorized wheelchairs.[38] Holden et al[23] described the use of VR training for the rehabilitation of people with upper-extremity motor dysfunction resulting from a stroke. The patients in their study were similar to ours; the patients were in the chronic phase following stroke, past the time one would expect spontaneous recovery, and had completed their formalized rehabilitation. Similar to our outcomes, Holden et al indicated that the patients improved on the VR task, with 1 patient able to transfer that improvement to real-world tasks.

The lesion site and upper-extremity function of our patients varied, and each patient's outcome in the VR-based exercises and the clinical tests was different. Although the patients with more severe impairments did not recover as much function as those with greater abilities, all of the patients demonstrated improvement in several movement variables and in several functional measures, thereby suggesting the versatility and adaptability of this exercise system. We believe that an important component of this individually prescribed exercise system is the amount of immediate quantifiable measures of movement kinematics and movement outcomes that are provided to the therapist to assess progress and implement modifications. This system has the potential to be used clinically to document initial measures of the

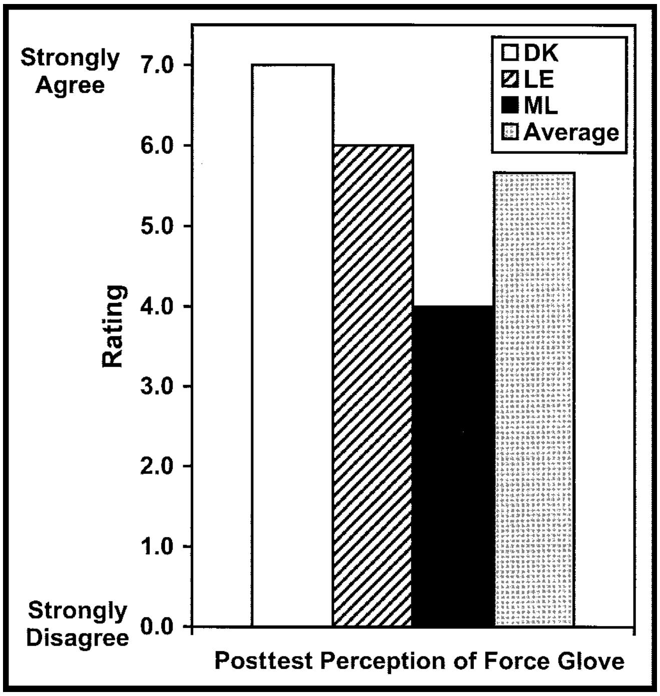

Figure 9.
Responses of patients to the strength task.

quality and quantity of multiple movement variables and to be specifically tuned to patients' needs in terms of goal setting and practice schedules.

What were some of the factors that may have contributed to the improvements and the transfer of these improvements to the tasks on the Jebsen Test of Hand Function? The patients were trained only on the VR exercises and table activities, which were different from the tasks included in the Jebsen Test of Hand Function. Improvement may have occurred simply because these patients had not had therapy for some time. The intensity of the training also may have been a factor. Constraint-induced movement therapy is an intervention that uses an intensive, massed schedule of practice. This intervention differs from traditional therapy in that the patients are required to use only their hemiplegic arm during all waking hours. The consistent and repeated use of the hemiplegic upper extremity in a 2-week period of constraint-induced movement therapy has been reported to improve the amount of use of that extremity.[15,20] The improvement in our patients' finger range of motion, speed, and fractionation could have been due to either the intensity of the VR practice or the intensity of the real-world activities, as in constraint-induced movement therapy, or perhaps to the integration of both forms of training. However, it is improbable that the 59% increase in handgrip strength (as measured by the Jamar dynamometer) in 2 of the patients was due to fine motor task training on real objects. The only strengthening training was provided by the VR component of the intervention.

Recent studies in our laboratory have addressed the separation of the benefits of training in a VR environment and training in a real environment by eliminating the tasks performed on real objects altogether.[39,40] Importantly, all 4 patients improved after 3 weeks of training. These studies also responded to the needed software and hardware modifications based on patient feedback and tested the possibility of accessing patient data remotely via the Web.[39,40]

Perhaps the method of delivery is not the crucial issue, but the intensity and the repetitive, massed practice structure of the training. Another study using traditional rehabilitation combined with intensive use of robot-assisted therapy to enhance motor recovery in patients' hemiplegic arms also showed improvement.[41] Aisen et al noted that the benefits of the additional robot-assisted therapy could be due to the effect of the intensity of the training, and they suggested that "more therapy is better."[41(p446)] Given the value attributed to intensive massed training for movement re-education, including its effect on the reorganization of neural structures, this VR exercise system may have the capacity to specifically modulate the distribution, frequency, intensity, and duration of practice in a novel and motivating manner.

A second factor contributing to the learning of the movements may be the specificity and frequency of the feedback provided to the patients by the system regarding both the knowledge of their performance and the knowledge of the results of their actions. Augmented feedback in the form of either knowledge of performance or knowledge of results is known to enhance motor skill learning in younger adults[42] and older adults[43] without motor impairments and in individuals following stroke.[44] Feedback provides information about the success of the action, it informs the learner about movement errors, and it is known to motivate the learner by providing information about what has been done correctly.[11] It is generally thought that frequent feedback enhances performance but is detrimental to learning.[44] Researchers,[44] however, found no difference in the learning of individuals following stroke or older people without motor impairments when they received very frequent feedback and more limited feedback. Frequent knowledge of results was not detrimental to learning in either group.[44]

Each of our 4 exercises provided frequent feedback about the success of the action as well as the quality of the performance. This augmented feedback was displayed in several ways. First, after each trial, a "performance meter" indicated the level of success in relation to the target goal. Second, the patients always had a view of their virtual hand as well as of their real hand, so they received constant information about their performance. Feedback to the patients about their performance was also provided directly through the computer graphics. The importance of specific feedback was suggested by the patients' response to the fractionation exercise. They gave the poorest rating to this task. The measure of success for this task depended on both the movement in the one active finger and the lack of movement in the 3 inactive fingers. Because the feedback about movement in the inactive fingers was related to the average movement of the inactive fingers, the patients found it difficult to ascertain which finger needed additional control.

We asked the patients different questions about each of the exercises, but we did not ask them to rank the exercises. Thus, we could not assess which exercises were more fun and engaging for the patients. The small number of patients also made all of the responses subject to individual bias. Their responses, therefore, do not represent any strong conclusions on how patients in general would respond to the computer exercises. In addition, the very nature of the intervention, with the therapists working closely with patients for 2 weeks, is likely to cause the patients to answer questions positively, in particular questions about the patients' interest in the computer tasks and the belief that performing the computer exercises would give them more upper-extremity function. To counter this potential response bias, the patients performed the series of real-life tasks as well as the VR-based exercises. All patients had experience with prior therapy sessions in which they performed the non-VR tasks, and all of them came in with low expectations for improvement in motor function. The questions that asked the patients' perception of whether they would continue to improve did not mention the computer exercises, only the overall therapy sessions. This suggests that their positive responses toward the sessions was not completely a response bias. In summary, the patients were positive about the VR-based therapy and its potential to improve their motor function, and they were motivated to use the system. The measures also suggested that improvements need to be made in some of the graphic displays and in providing appropriate motor performance feedback to the patients.

The purpose of this case report was to describe the use of movement re-education in a VR environment to augment existing therapy. The structure of this therapeutic intervention was based on research indicating that both the intensity of training and the quality and quantity of feedback are important variables to which the motor system responds. The development of the kinematic and performance measures was based on the need for more quantitative outcome measures. Although the VR system is not yet ready for clinical application, we believe that it has potential for clinical use. Because this approach is in the development phase, the financial and human resource costs of the exercise system are high. Further development will decrease the costs and increase the ability of patients to use the system more independently. Research is needed to further develop this system, because the rate at which patients can relearn their motor skills, the extent of improvement, and the environment in which they are treated affect the duration, effectiveness, and cost of patient care.

Conclusions

The improvements shown by the 3 patients suggest that VR has the capability of creating an interactive, motivating environment where intensity of practice and feedback can be manipulated to create individualized treatment sessions. Following VR-based training and other exercises, the patients' strength, range of motion, fractionation, and speed improved. These changes appeared to transfer to changes in function.[44] The full potential of VR in rehabilitation probably is related to its future use at home, in a telerehabilitation setting. Our vision is that of a multiplexed telerehabilitation where one therapist oversees the training of several patients, each exercising on a computerized system in his or her home.[45]

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Appendix 1.

Exercises

The exercise to improve range of movement is illustrated in Figure 2a.[19,21] In this exercise, flexion of the patients' fingers or thumb moved a "window wiper" to uncover an attractive landscape displayed on the personal computer monitor. The scene was initially hidden behind a mask of dense fog. The angular positions of the patients' fingers and thumb were measured in a coordinate system in which an open hand corresponded to 0 degrees and a fist corresponded to 90 degrees. This angle was calculated for each finger at each time period by averaging the angular positions of the metacarpophalangeal and proximal interphalangeal joints. The angle data were filtered to remove high-frequency noise, and the range of motion was measured as the difference between the maximum and minimum of the average finger angles in the filtered data. The movement of the "window wiper" was scaled to the angle data so that the larger the angular range of motion of the thumb or fingers, the more the wiper rotated and cleared the window. The window cleared completely when the target setting was achieved. The patients viewed a graphical model of their hands, which was updated in real time to accurately represent the flexion range of motion of the user's fingers and thumb. This exercise was performed 10 times for the thumb and 10 times for the fingers.

For the speed of movement exercise, the green light on a "traffic light" signaled the patients to close either the thumb or all of the fingers together as fast as possible to catch a red ball (Fig. 2b). A computer-controlled "opponent hand" shown on the screen to the left of the patient's hand in Figure 2b also closed its thumb or fingers around a red ball. The angular velocity of the "opponent hand" was set to equal the target angular velocity. If the patients surpassed this target velocity, then they won the game and kept the red ball. If they did not exceed the target velocity, they lost, and their red ball dropped and the "opponent hand" kept the virtual red ball. The instantaneous speeds of the finger and thumb movements were calculated from the filtered angular positions at subsequent points in time. The maximum forward speed within a trial was taken as the measure of the patients' performance. The computer algorithm for velocity was modified for ML during the early training to adapt to her need to decrease the reaction time component of the speed exercise and concentrate instead on the grasp velocity component. This exercise was performed 10 times for the thumb and 10 times for the fingers.

The activity for the fractionation exercise (Fig. 2c) was designed around a piano keyboard. As the patients flexed 1 of the 4 fingers (index, middle, ring, small) with as much isolation as possible, the corresponding key on the piano was depressed and shown in green. If any other fingers were coupled to the active finger during the movement, the corresponding keys turned red. The goal for the patients was to move the hand so that only one virtual piano key was depressed at a time. In the fractionation trials, the range of movement of each finger was calculated using the same methods as in the range of motion trials. The patients' performance ranged from a minimum of 0% to a maximum of 100%, in which 100% corresponded to movement of the active finger but no average movement of the other fingers, 50% corresponded to half range of movement of the other fingers, and 0% corresponded to an equal range of motion in both the active finger and the average of the other fingers. This was repeated 5 times for every finger.

The fourth exercise was designed to improve the patients' strength of movement. The Rutgers Master II-ND (RMII) force feedback glove applied forces to either the user's thumb or 3 fingers (index, middle, ring). In the strength task, the patients attempted to move 80% of their initial range of motion against the glove's resistive force. The initial range of motion corresponded to the patients' maximum range of motion in the first trials used to set the initial targets. As the patients' strength increased, the level of the resistive force was gradually increased. The patients were presented with a graphical representation the hand showing 4 pistons (Fig. 2d). As each piston on the RMII glove was squeezed, the corresponding graphical piston started to fill with the color yellow and filled completely if the patients moved the desired range at the opposing force of the RMII glove. Mechanical work was estimated as the force exerted by the thumb or fingers multiplied by the displacement of the pistons.

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Appendix 2.

Preintervention and Postintervention Questionnaires

Preintervention Questionnaire (1=Strongly Disagree, 7=Strongly Agree)

1. I feel that movement in my right hand is very good.
2. I don't expect much improvement in my right hand motion to come from participating in these studies.
3. I am very eager to participate in this project.
4. I would be very happy to spend 4 weeks on this project, if needed.
5. I am very comfortable using computers.
6. Before my stroke, I frequently played a musical instrument.

Postintervention Questionnaire (1=Strongly Disagree, 7=Strongly Agree)

1. These studies improved my right-hand motion.
2. With more practice in the computer tasks, I feel that my hand might improve more.
3. I would be very willing to continue the project for another 2 weeks.
4. I would be very willing to do the computer exercises at home if they were available.
5. I found the computer tasks to be engaging.
6. It would be fun to do these tasks on the World Wide Web with other individuals who have had a stroke.
7. I wish that these computer tasks had been part of my original therapy.
8. The computer tasks took too long.
9. The table tasks were more interesting than the computer tasks.
10. The pushing the piston task was engaging.
11. The scenes used in the cleaning the window task made the task more interesting.
12. The catching the ball task was easy to understand.
13. It was fun to press down the piano keys.
14. It was hard to tell how well I was doing in the tasks.
15. I prefer doing real-world tasks to the computer tasks.
16. I would like to compete against others of equal skill when doing the computer tasks.

Appendix 3.

Incrementing Performance Targets

After each practice session, the distribution of the patients' actual performance for each of the 4 blocks was compared with the preset target mean and standard deviation. If the mean of the patients' actual performance for any block in that session was greater than the target mean, then that target was raised by one standard deviation. If the patients' performance for any exercise fell below the target mean, the target for the next session was lowered by the same amount. Lower and upper bounds prevented the targets from varying too much between the sessions. For the range of motion, speed, and fractionation exercises, the target mean was never allowed to increase or decrease by more than 5% or less than 0.3% for any subsequent block of trials. For the strengthening exercise, the target changes depended on whether the patients achieved or did not achieve the target goal in the previous block. If the patients attained the previous goal, the target goal was increased by 0.15 N; if the previous goal was not attained, the target goal was decreased by 0.15 N. The force output for the Rutgers Master II-ND (RMII) force feedback glove was capped at 9 N. The data collected from each of the 8 joints of the fingers (4 metacarpophalangeal joints and 4 proximal interphalangeal joints) was used to set the subsequent target goals, and the mean of these joint angles was used to calculate the performance and display the visual feedback. For the thumb, the mean of the angles of the metacarpophalangeal joints and proximal interphalangeal joints was used to set the subsequent targets, to calculate the performance, and to display the visual feedback. Updating the targets in this manner encouraged the patients to continually improve their performance.