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

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Abstract

We present 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 system trains finger range of motion, finger flexion speed, independence of finger motion and finger strength. Eight chronic post-stroke subjects participated. In keeping with variability in both the lesion site and in initial upper extremity function, each subject showed improvement on a unique combination of movement parameters in VR training. Six of the eight subjects improved significantly on VR trained parameters of range of finger motion and ability to move fingers independently, and four of them also improved on speed of finger flexion. Finally, 3 subjects improved their ability to generate mechanical work with their affected hand during 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 feasibility of this exercise system for rehabilitation in patients with hand dysfunction resulting from neurological impairment.

Keywords

stroke, hand function, virtual reality (VR), CyberGlove, Rutgers Master II-ND, grasping

INTRODUCTION

Recent experimental evidence suggests that intensive training that entails new motor skill acquisition is required for inducing long-term brain plasticity [13]. 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 massive supervised training. Computerized robot-assisted therapy systems have been shown to be suitable for providing for the clinical delivery of training of the required intensity [21]. The systems currently under development are focusing on the rehabilitation of elbow-shoulder [8, 9, 22, 16, 5] and wrist [17] 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 improve substantially his 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 our system hardware and software can be found elsewhere [6, 2, 10]. It uses two types of instrumented gloves, one of them with force feedback. A unique aspect of the system is the use of augmented virtual reality. Virtual reality has been shown to be an engaging, motivating, adaptable tool which is currently under investigation 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 clinician with 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. One aim of this study was to show feasibility of the current implementation of the system for retraining hand function in patients in the chronic phase post-stroke.

Although recent technological advances including the use of interactive virtual reality environments promise to advance hand rehabilitation, the transfer process of the skills acquired during the VR-augmented, or VR-based therapy to real world movements is poorly understood. Knowledge of how rehabilitation in VR will transfer to everyday life is very limited. Therefore a second goal of this study was to determine the degree to which the new motor skills acquired during training of the hemiplegic hand in VR transferred to non-trained natural real-world arm movements in the patients with chronic hand dysfunction as a result of a stroke. In order to estimate the degree to which the improvements in the VR exercises might have generalized to the activities of everyday life, we analyzed coordination of the arm and finger joints during reach-to-grasp movements.

METHODS

Subjects

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 one 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° [20]. None of the subjects were receiving therapy at the time of the study.

VR Therapy

Two hand input devices were used, 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 [3]. Four hand exercise simulations were developed using the commercially available WorldToolKit graphics library [1]. The exercises were in the form of simple games that provided frequent feedback about the success of the action as well as the quality of the performance to encourage participation and concentration (see Fig. 1). The subjects received auditory, visual and numerical feedback about their target goal and their ongoing performance. First, after each trial "performance meters" on the computer screen, both numerical and graphical, 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 receive constant information about their performance [2]. Each game was 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. All of the patients participated in an intensive program consisting of 13 days of training and two

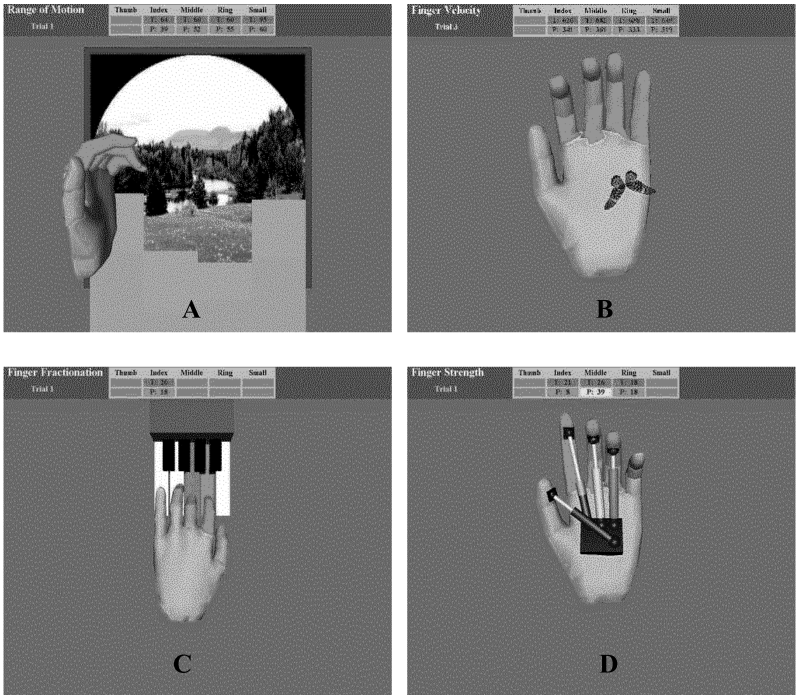

Figure 1. Screen snapshots for the four VR exercises (A) range of motion, (B) speed of movement, (C) finger fractionation and (D) finger strength (adapted from Boian et al., 2002). © Rutgers University 2001.

weekend breaks for a total of nearly 3 weeks of training. One subject (LD) missed two days during the second week of the therapy. 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 subjects trained for 2 to 2 and one-half hours each day.

Generalization Tests

We utilized both clinical tests and kinematic analyses of prehension movements to evaluate the degree of transfer of the gains acquired by the subjects in the VR exercises to real life hand movements. Subjects were tested on the Jebsen Test of Hand Function [7] which consists of seven subtests that provide a broad sampling of functional tasks. These 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 tasks that involved picking 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

Real-World Grasping Tests.

Data Acquisition

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 resistive bend sensors embedded in a glove (CyberGlove, Immersion Co.). The flexion/extension of the metacarpophalangial (MCP) and proximal interphalangial (PIP) joints of the five fingers, the abduction/adduction joints of the index-middle and middle-ring fingers (ABD), as well as the thumb rotation and abduction were included in the analysis. Both devices were connected to a SGI Octane/SSE workstation. All experimental sessions were videotaped for offline analysis of error patterns. During the experiment, objects were presented in a pseudo-randomized fashion. Subjects were instructed to maintain the 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., he 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 (these movements are not analyzed here).

Data Analysis

Wrist trajectories were inspected visually using a system for 3D graphic analysis of human movements that permits the precise localization of movement onsets and offsets as a function of speed and acceleration [14, 15]. Onset and offset were defined as the points in which the wrist sensor reached 5% of the peak velocity during the initial acceleration phase and during the acceleration phase of the lifting phase of the movement, respectively. We analyzed the following parameters of the hand motion: peak velocity and movement time (MT). We divided MT into two sections: onset – time of peak velocity and time of peak velocity to time of object lifting.

Multivariate statistical analysis

All trial data were normalized in time. Subsequent analyses were conducted on 5% epochs of the movement, from 5 to 95%. Data matrices containing the angle of flexion/extension or abduction/adduction for each joint for each trial for grasps of each object at each time interval were produced for input to the statistical analysis. Two different types of discriminant analysis were used: Stepwise Discriminant Analysis (SDA) and Canonical Discriminant Analysis (CDA). The former (SAS STEPDISC) is a forward stepwise procedure which selects discriminating variables by establishing a statistical criterion (Wilk's Lambda). CDA produces a classification of the data into a set of previously determined categories by defining a centroid per category and calculating the distance [11] between each data point and each of the centroids. A data point was included by CDA into the category whose centroid is closest. A measurement of error, therefore, becomes available when data points are classified into the wrong groups (misclassifications).

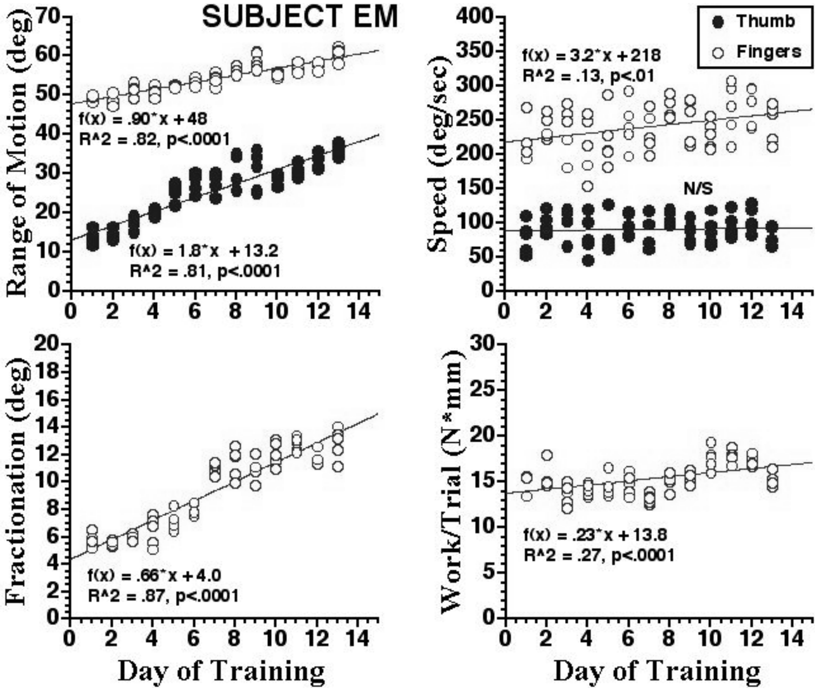

Figure 2. The regression analysis of the performance in each VR exercise for subject EM.

RESULTS

Progress in VR

Figure 2 shows for one subject the relationship between the performance in each VR exercise and number of days of training. Subject EM showed improvement on each of the four parameters: range, speed, fractionation and power, except for the thumb speed. Overall, 6 out of 8 subjects increased significantly their finger and thumb range of motion ($p<.05$, unpaired t-test, averaged across all fingers, the first two days versus the last two days of the therapy, see Fig. 3). Similarly, 4 subjects improved significantly in finger speed and 2 in thumb speed, 7 in fractionation and 3 in strength exercise. Gains in finger strength 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 four subjects. Patients showed good retention when measured at one-week post intervention.

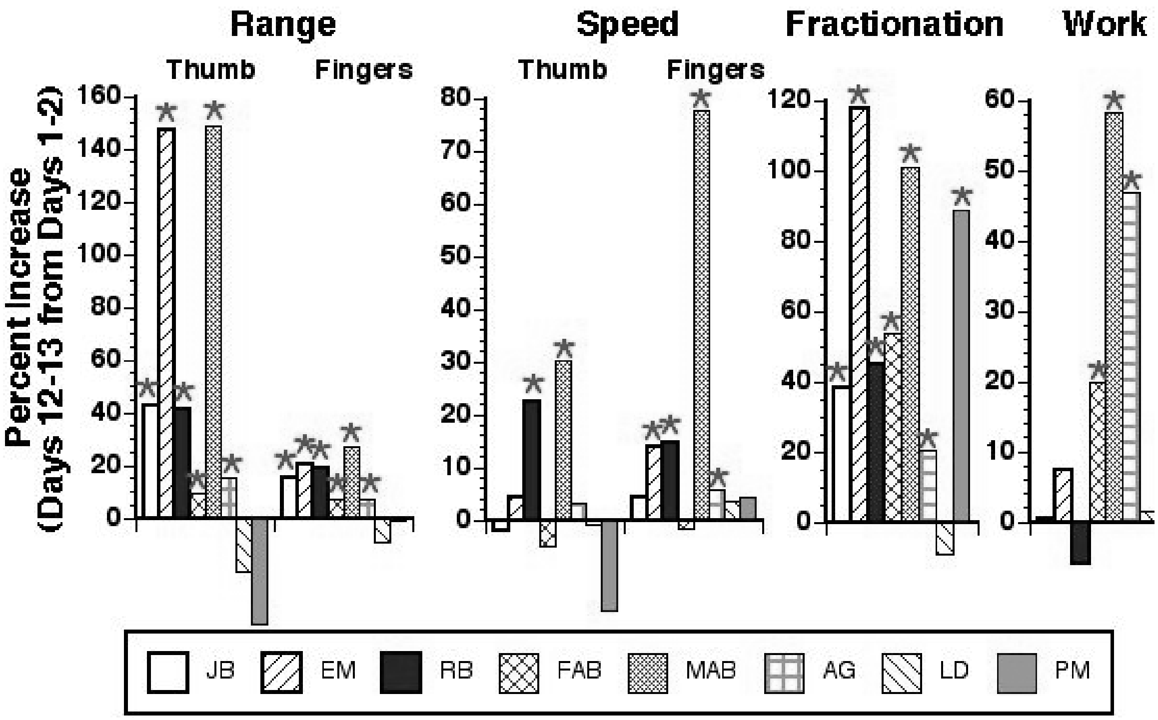

Figure 3. Percentage increase between the first two days and the last two days of the therapy for four exercises: range of motion, flexion speed, fractionation and mechanical power. Significant increases are marked by asterisks.

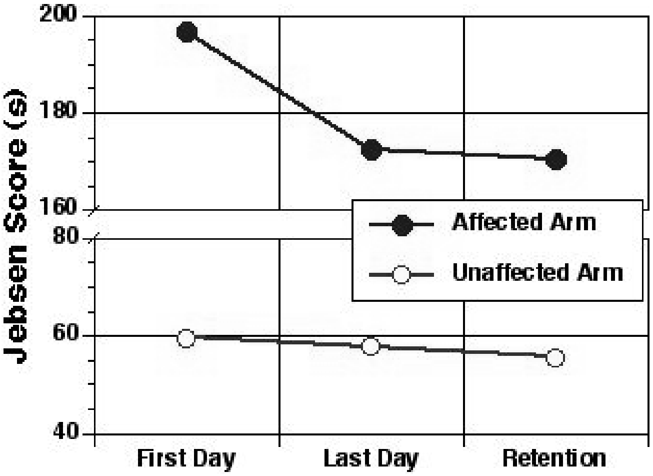

Figure 4. Jebsen Test of Hand Function scores before and after the three-week VR therapy averaged across 8 subjects. Lower scores indicate better performance.

Generalization Tests

To determine whether the skills gained in the VR environment transferred to real-world movements, we utilized clinical tests and kinematic analysis of prehension movements. Clinical evaluation using the Jebsen Test of Hand Function showed a reduction in task completion time for the affected hand after the therapy (paired t-test, t=2.4, p<.05, see Fig. 4). In contrast, no changes were observed for the unaffected hand (t=.59, p=.54).

Furthermore, we studied finger and hand kinematics during reach-to-grasp movement. When tested before the beginning of the therapy, each subject showed various severe deficits in both the transport component (slowness, excessive trunk involvement, elbow-shoulder discoordination) and the grasping component (abnormal finger flexion-extension patterns, increased variability and desynchronization between the hand and finger motion). After the therapy, subjects showed some improvement in various aspects of the hand kinematics during grasping. Neither time to peak velocity nor peak velocity of the affected hand changed after the therapy (F(1,7)=.55, p=.48 and F(1,7)=.97, p=.35. This result could be expected since elbow and shoulder were not trained during the VR therapy. In contrast, time from hand peak velocity to the moment when the object was lifted from the table decreased significantly after the therapy (F(1,7)=5.78, p=.04). On average, the task was performed 22% faster after the intervention illustrating transfer of their improvement in the VR to a real-world functional task (Fig. 5). This was achieved through improved patterns of finger coordination. In particular, subject FAB showed the largest decrease in the duration of grasping. She had a severe desynchronization of the arm and finger degrees of freedom before the therapy and showed a substantial increase in the temporal stability of finger motion after the therapy. 3 subjects did not perform this task faster after the therapy (improvement under 10%). Nevertheless, each of these subjects improved on at least one of the aspects of prehension kinematics. In particular, subject RB with an abnormal finger flexion–extension synergy significantly reduced finger inter–trial variability after the therapy. Subject AG showed improved patterns of hand preshaping (see below). Subject FAB, the least

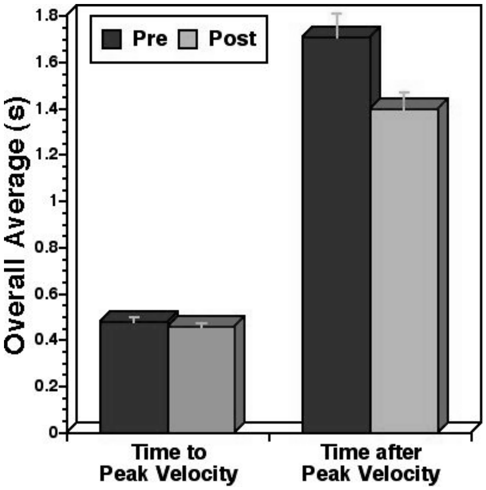

Figure 5. Overall mean (SE) time to peak hand velocity and time from peak velocity to movement offset for the hemiparetic arm tested before (darker bars) and after the therapy.

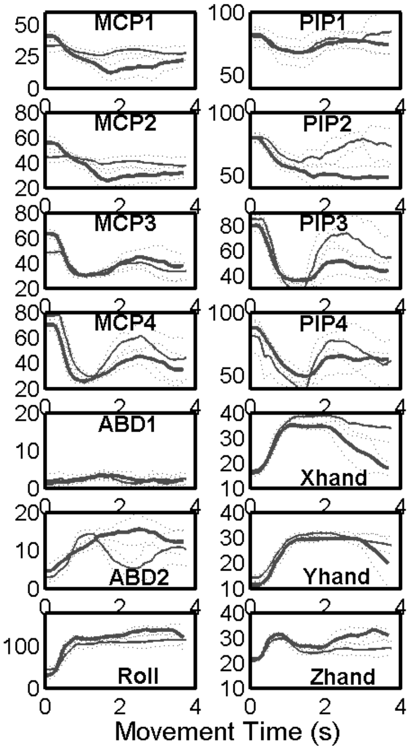

Figure 6. Mean (SD) time traces of 10 finger angles (deg), hand coordinates (cm), and arm pronation/supination angle (deg) during a prehension movement for subject EM. Averages of 10 trials before (thick lines) and after (thin lines) the therapy are shown.

affected in the group improved on grasping of objects of more complex shapes.

Figure 6 shows the kinematics of a reach-to-grasp movement for another subject with severely reduced range of finger motion due to spasticity in the index and middle fingers. Mean finger angles, hand roll angle and hand position are shown over time before and after the therapy. Dotted lines indicate standard deviations about the mean. The subject showed a modest post-therapy decrease in movement duration. Note, however, a substantial post-therapy increase in the range of motion for the two spastic fingers (Fig. 6, two upper rows of panels, compare to Fig. 2, left upper panel). We used a sophisticated method of analyzing finger coordination during grasping objects of various sizes and shapes by means of linear discriminant analysis [18, 19]; see Methods). One example of this analysis for the subject EM is shown in Fig. 7. Handshape classification errors pooled over trials for picking up a roll of tape and picking up a small rectangular object are presented over the course of the movements. The level of discrimination error reflects the degree to which the hand is preshaping as the movement evolves. Note that the late decrease in error levels for the unaffected arm is an artifact of time normalization, since movements of the unaffected arm were 3 times shorter than movements of the affected arm. The subject showed only a moderate decrease in the duration of the post-therapy movements of the affected arm (see Fig. 6). However, the discriminant analysis clearly shows a marked improvement in the subject's ability to control his fingers – late into the movement the level of classification error reaches normal levels.

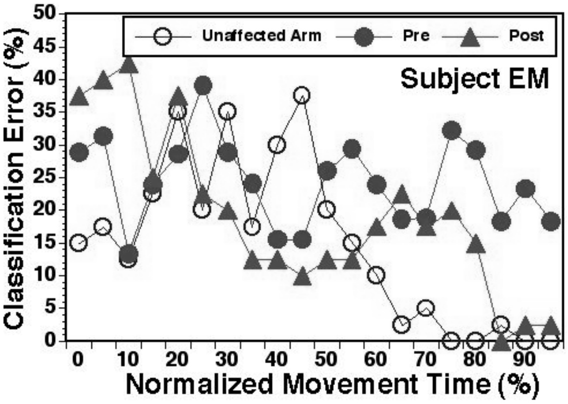

Figure 7. Patterns of handshape classification errors during a reach-to-grasp movement for subject EM.

DISCUSSION

In this preliminary study we demonstrated the feasibility of our recently developed exercise system for hand rehabilitation in patients with hand dysfunction resulting from neurological impairment. Several systems have been developed by other research groups to retrain upper extremity function in patients post-stroke. However, no system has been developed to re-train hand coordination and dexterity. 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. 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, 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 subject's hand function, as well as progress during the therapy. We tested this system on 8 hemiparetic subjects. Six of the eight subjects improved in both the VR measures and the clinical tests. In keeping with clinical outcomes of patients that 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). The patients with more severe impairments did not recover as much function as those with greater abilities. We have noticed this trend previously [10]. It is interesting to speculate whether this might be due to the particular lesion location or the need for a greater variety of VR games that could more directly target the lower impairment levels.

We believe that functional plasticity will likely underline many of the effects that we are getting in VR-based rehabilitation. Recent animal studies demonstrated the importance of motor learning versus unskilled repetitive movements in producing changes in motor maps. 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 [13]. 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 [13] drives representational plasticity and perhaps engenders improved motor control [12]. 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. One of the outcome measures used in this study to test generalizability of the VR practice was the Jebsen Test of Hand [7]. 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 appeared to transfer to real-world function. Moreover, this generalization was also evident in several of the kinematic measures of grasping. In particular, we observed on average a reduction in time needed to pick up objects of simple shapes from a table. The decrease resulted exclusively from the reduction in the deceleration phase of the movement indicating the improvement occurred in the grasping component but not in the transport component of the movement. Subjects with abnormal finger flexion–extension synergies or abnormal desynchronization of the finger motion reduced the inter-trial variability after the therapy. Moreover, subjects with severe spasticity increased the range of finger motion. This in turn resulted in the improved preshaping of the hand during reaching for objects of different shapes (see [19]).

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 less side effects (e.g. dizziness) seen in the fully-immersive VR environments using head-mounted displays It provides precise kinematic and kinetic data on subjects' baseline performance and learning history and 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 [4].

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