 

# Development and application of virtual reality technology to improve hand use and gait of individuals post-stroke

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**Abstract**. Development and application of virtual reality (VR) systems for rehabilitation is an iterative process produced by collaboration of an inter-disciplinary team of engineers, neuroscientists and clinician-scientists. In this paper the use of virtual reality technology for the rehabilitation of individuals post-stroke is described. The development of the hardware is based on principles of motor control. Development of the software uses findings from the enrichment and motor plasticity and training literatures as well as principles of motor learning. Virtual environments are created to afford individuals post-stroke opportunities to practice tasks for which they require rehabilitation. These tasks, related to hand function and gait, are trained both at the impairment and functional level. The training engages users to allow for the repetitive intensive practice required for behavioral motor plasticity. Results from a series of upper and lower extremity studies indicate that use of VR technology to augment rehabilitation of individuals post-stroke merits further study.

Keywords: Virtual reality, rehabilitation, motor learning, haptics

## 1. Introduction

Basic science pertaining to enriched environments and to neural plasticity for sensorimotor function, clinical evidence, and principles of motor control and motor learning have informed the development and refinement of virtual reality technologies presented in this article. Two virtual reality systems, one that focuses on upper extremity use (Rutgers Master) and the other on lower extremity use (Rutgers Ankle) have been created and refined using an iterative process consisting of repeated proof of concept and pilot experiments. This article reviews the development and refinement of these technologies, presents a summary of the findings related to the rehabilitation of chronic post-stroke individuals, and speculates on their future use and relevance.

Development of the hardware components used in rehabilitation was based on knowledge of motor control. The two virtual reality (VR) systems use novel interfaces, which provide the user with sensory input. The Rutgers Master is a sensing exoskeletal structure integrated with force feedback actuators placed in the palm. It provides computer controlled forces to fingers in flexion and can assist in extension (see Fig. 1) [9]. The Rutgers Ankle is a compact six degrees of freedom parallel-kinematics robot placed under the foot. It uses dual-acting pneumatic actuators to provide forces and torques to the patient's ankle (see Fig. 2) [24]. In both systems the distal segment (hand or foot) is used to in-

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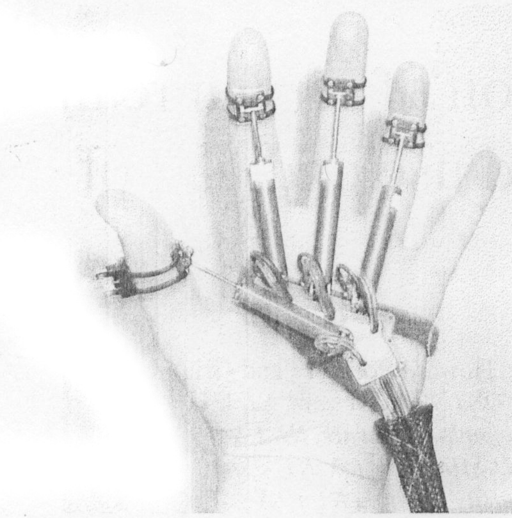

Fig. 1. Rutgers Masters II. © Rutgers University, 2002 reproduced with permission.

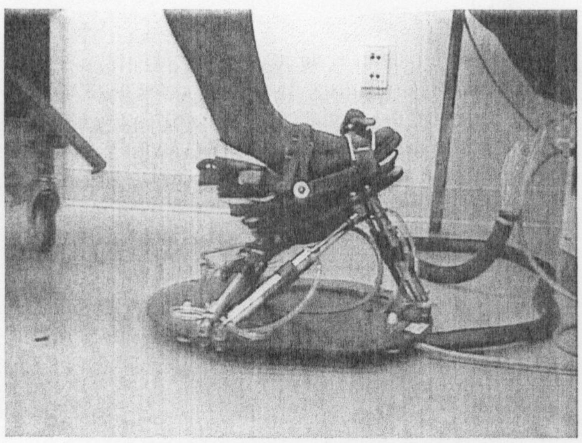

Fig. 2. Rutgers Ankle. © UMDNJ, 2003 reproduced with permission.

terface with a virtual world. This allows for action with respect to visual or kinesthetic sensory information to be mediated by the distal effectors. In the upper extremity (UE), use of the distal point of control has been related to end-point programming for reaching [1] frame of reference programming and path selection [34]. For the lower extremity (LE) the ankle has been identified as the control point of forward trajectories [22].

Each VR system has several simulations that were created as enriched environments, which engage the user in a task that requires problem-solving in order to acquire a skill. The basis for this decision was the preclinical and basic science evidence, specifically the enrichment literature on animals, which has been used to argue for the application of VR to the rehabilitation of patients with neurologic diagnosis [61]. Animals (primarily rats) trained in enriched environments perform better on functional tasks and in solving problems when compared to animals trained in impoverished environments [53]. This difference is accentuated when the complexity of the problem increases [56]. Sensorimotor plasiticity in the form of synaptogenesis has been shown to be greater when the training of a task requires some problem solving and complex motor skill learning [30,31]. Indeed, more recently several investigators [32,51,55] have demonstrated in animal studies, that the type of behavioral experiences that induces long-term plasticity in the motor cortex appears related to those experiences that require the development of new motor skills. Therefore the virtual environments we have created require patients to solve problems in order to acquire a skill.

In addition to skill training in enriched environments, the virtual environments were designed to promote both behavioral changes and sensorimotor plasticity by using intense repetitive practice. Animal and human models of training post-stroke have been used to demonstrate that behavioral training can induce recovery at the neural [47,49], as well as the behavioral levels [14]. There is evidence to support intensive training to decrease walking disability for stroke survivors even a year post-stroke [70]. This is consistent with the findings in re-training the upper extremity of patients post-stroke [65,66,73]. The efficacy of training appears to require high intensity [36,37,71] and repetition [13]. Early in the application of VR technology a proposed benefit was the ability of individuals to execute many repetitions because of the engaging environment [52, 68].

Individuals post stroke present with a specific set of impairments that interfere with functional abilities. The virtual environments developed by the authors were designed to apply rehabilitation principles to promote both impairment and task specific training [62]. The UE tasks were designed to address specific impairments of range of motion, strength, fractionation and speed using discrete tasks. The lower extremity tasks were created to increase range of motion, strength, endurance, speed and coordination either discretely or in combination.

As has been shown in the rehabilitation of individuals post-stroke, the strategic use of feedback can enhance training and retention of skill. Schedules of practice and type of feedback were carefully crafted in the VR simulations described here. These decisions were based on the human literature describing the training of healthy individuals as well as those post-stroke [41, 64,72]. Specificity and frequency of the feedback provided to the patients was related to both the knowledge of their performance (KP) and the knowledge of the results of their actions (KR). Augmented feedback in the form of either KP (feedback related to the nature of the movement pattern that was produced) or KR (feedback related to the nature of the result produced in terms of the movement goal) [42] is known to enhance motor skill learning in normal adults [39], in older healthy populations [63] and more recently in individuals post stroke [72]. Augmented feedback was also provided in the form of sensory feedback using haptic cues. Haptic feedback (from the Greek term "hapthai" – touch) groups the modalities of force and touch feedback to the user [10]. The systems developed by the authors of this article provided sensory input using haptic cues and feedback in a variety of ways, which included KP, KR and summary feedback (at the end of the group trials).

Clinicians using the prototype VR systems can monitor patient's performance and progress using behavioral measures of motor plasticity. These data are collected using position and force sensors. Position sensors (Hall-effect sensors, linear potentiometers and infrared LED/transistor pairs) are used to detect the fingertip location vs. the palm (for the UE), or the ankle position and orientation vs. the floor (for LE). The force sensor incorporated in the Rutgers Ankle measures forces and torques applied by the foot during the simulations. All sensors are sampled in real time and at high rates (hundreds of times/second), with data sent to a host PC running the VR simulation. More hardware details can be found in [9,24]. Data are also available remotely, through web-based monitoring [8,40]. The VR rehabilitation systems hardware and software, were refined, using behavioral measures of motor plasticity, in a series of experiments that will be described below:

## 2. Experiments

### 2.1. Upper extremity experiments

#### 2.1.1. First experiment

In the first experiment a system composed of a CyberGlove, a Rutgers Master glove and a host PC was used [27] to train patients in the chronic phase post stroke in a VR augmented environment. Four target-based simulations were created for training of finger range of motion, fractionation, flexing speed and strength as shown in Fig. 3.

The pilot trials were conducted to determine whether a two-week training period of VR and non-VR exercises would improve motor function of the hemiplegic hand in three patients post- stroke. Each simulation was designed to exercise one parameter of hand movement; either range of motion, speed of movement, fractionation of individual finger motion or strengthening of the fingers. Each subject'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. After each practice session the distribution of the patient's actual performance was compared to the pre-set targets and these data were used to set subsequent goal targets thereby encouraging improved performance. The simulation software provided both knowledge of results (a performance meter) and knowledge of performance (success in executing the particular simulation) feedback in multiple modes. (In addition to the performance feedback specific to each game, summary feedback was provided at the end of each trial. The patient was shown a graphical digital "performance meter" that displayed the target level and the actual performance. This was used to inform patients exactly how close or how far away they were from the desired performance goal. All kinematic and kinetic measures of range, speed, fractionation and strength were computed on-line in order to drive the graphics display and provide feedback to the patient. An Oracle database transparently stored all exercise data for later retrieval and analysis.

Three patients, two male and one female, participated in this first study. They were all right-hand dominant and had sustained a left hemisphere stroke, which had occurred between three and six years prior to the study. The patients were selected based upon the criteria established by Taub et al. [66]; specifically, they had to be able to actively extend the wrist of their hemiplegic limb at least 20° and extend the metacarpophalangeal finger joints at least 10°. Three types of measurements were captured: computer measures of changes in range, speed, fractionation and strength, clinical measures and affective measures. To measure relevant functional changes each patient was evaluated pre and post training using the Jebsen Test of Hand Function [28]. Additionally, there were tests on a dynamometer to measure hand grasping strength, before, midway and after the rehabilitation intervention. The subjects trained for five days, had a weekend break and then trained for another four days. The VR simulations

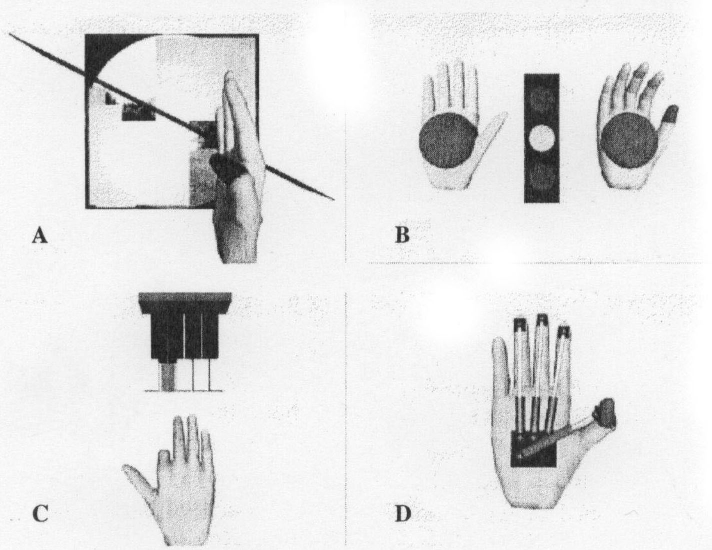


Fig. 3. Simulations for First UE Experiment. Screen snapshots for the four VR exercises (A) range of motion, (B) speed of movement, (C) finger fractionation and (D) finger strength © ACM Jack et al., 2000.

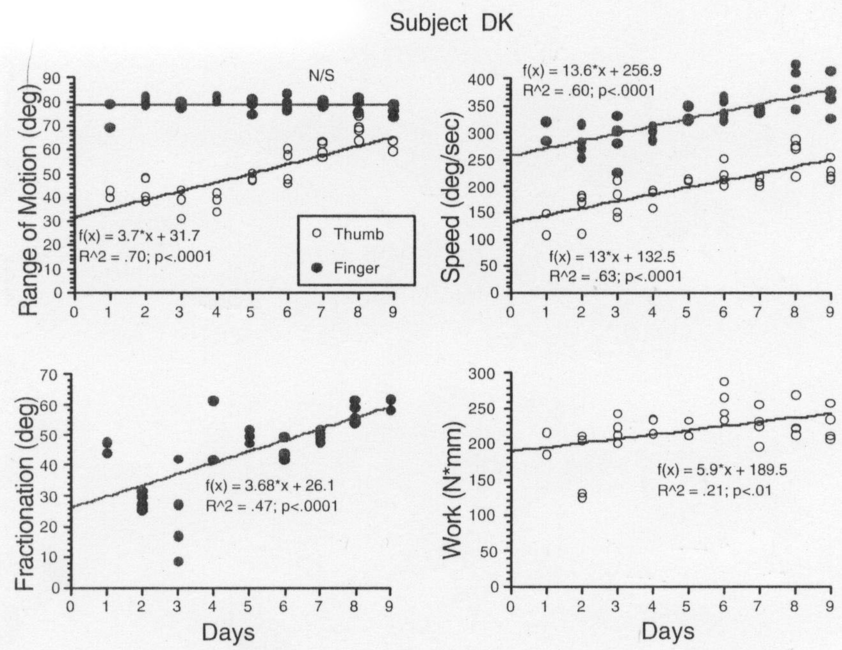


Fig. 4. Performance History for a single subject. Changes in the movement parameters over the course of the therapy are shown for each of the four virtual reality exercises. Each symbol denotes an average of 10 trials. Also shown are linear regression lines, their equations, R^2 values and p values for the ANOVA tests. ©

were interspersed with real-world tasks. These manual tasks consisted of tracing 2-D drawings, stacking cards, placing paper clips and similar light tasks, which had no hand strengthening component. The total number of hours trained per day was approximately 5 hours.

At the conclusion of this training each patient showed distinct improvement on a particular subset of movement parameters with transfer of this improvement to functional activities of the Jebsen Test on which they were not trained. Figure 4 shows improvement for one patient over the nine-day training period in the range of motion and strength of his thumb, the

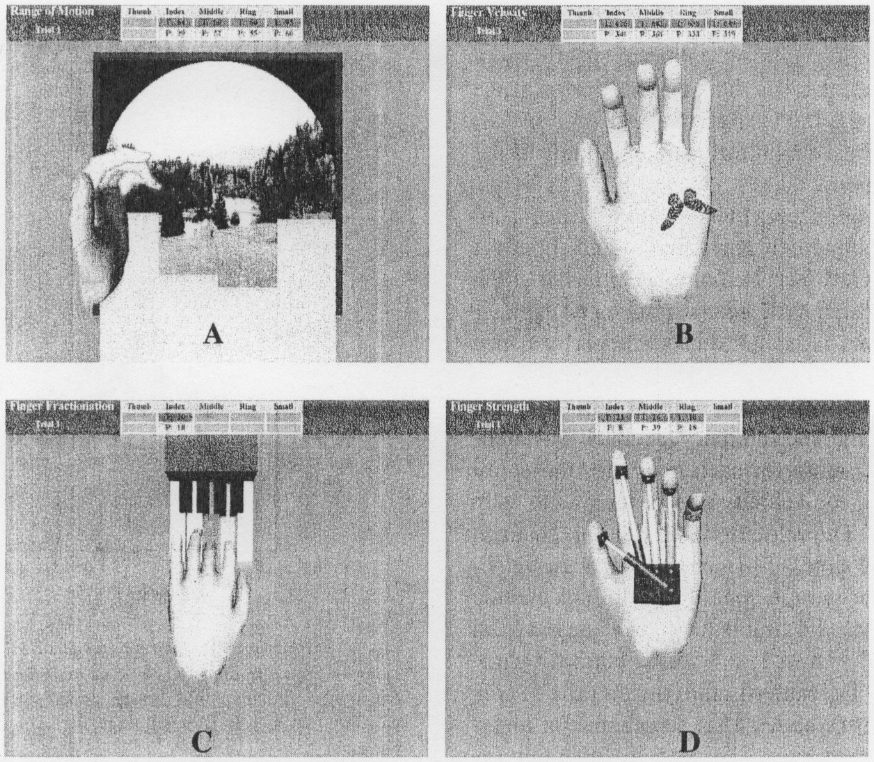


Fig. 5. Simulations for second UE study. Screen snapshots for the four VR exercises (A) range of motion, (B) speed of movement, (C) finger fractionation and (D) finger strength (adapted from Boian et al., 2002). © Rutgers University 2001.

fractionation of his fingers and the speed of both his thumb and fingers. Analysis of variance of the regression indicates that this subject's range of motion $[F(1,31) = 2719.3, p =< 0.0001; R^2 = 0.67]$, and strength $[F(1,29) = 6340.8; p =< 0.02; R^2 = 0.19]$ of the thumb improved significantly. Additionally, both finger $[F(1,31) = 36436.6, p =< 0.0001]$ and thumb speed $[F(1,31) = 37684.8, p =< 0.0001]$ improved significantly from baseline measures during the nine day training period as well as his ability to fractionate his fingers $[F(1,31) = 3207.1, p =< 0.0001; R^2 = 0.51]$ [44].

All three patients showed improvement in range of motion, speed, strength and fractionation. (except for finger range in one subject whose range of motion was within normal limits at the beginning of the training). Overall, the mean percent of improvement in range of motion of the thumb was 30% (range 13–54%), 9% for finger motion (range 0–20%), 38% for thumb speed (range 15–66%), 39% for finger speed (range 20–60%) and 20% for mechanical work of the thumb. The greatest improvement was seen in the ability to fractionate the fingers. This ranged from 10–103% with a mean improvement of 64% for the three subjects.

Two of the three patients showed good improvement in functional use of their hand after intensive training in hand activities and one of the patients did not show substantial changes in the Jebsen Test [44]. The patient with more severe impairments did not recover as much function as those with greater initial abilities [44]. An important finding was that each patient demonstrated a particular set of changes in both the VR based exercises and the clinical tests thereby demonstrating the versatility and adaptability of this exercise system.

### 2.1.2. *Second experiment*

Based upon the design of the first study it was not possible to determine whether the major gains were due to the virtual reality component or the real world component of training. A second experiment was then performed to investigate whether exercising in a VR based system alone would improve hand function in patients in the chronic post-stroke phase.

In the second experiment, in addition to changing the training parameters, substantial modifications were made to the hardware to improve the ease of donning the Rutgers Glove, decrease it's weight, improve its endurance, improve the quality of output forces and increase its capability to fit a wider variety of hand sizes. The software was fine-tuned to enhance specificity of the visual feedback, provide more explicit performance feedback, adjust the target algorithms [5,43], and allow remote web-based monitoring and graphing of the patient's performance.

The subjects now received visual, numerical and auditory feedback about their performance and about the target goal for each finger. Red numbers in a bar graph at the top of the screen indicated the goal for each finger and green numbers indicated the online performance during the movement. When the goal target for each finger was exceeded, the green number turned yellow and flashed (Fig. 5). The summary feedback was modified to provide a score for each finger for the entire trial. The goal of the velocity parameter was to train movement speed. The velocity simulation was changed so that the revised simulation measured only the velocity components of the movement and did not include reaction time. Thus the simulated game changed from the ball grasping seen in Fig. 3 to the butterfly game shown in Fig. 5. The butterfly flies away if the fingers are closed fast (at or above a set target speed), otherwise it circles in the palm. An additional simulation was developed to exercise extension of the fingers and thumb. Before each trial began the patient had to extend their fingers to match a ghost like hand image on the screen. The extension in the ghost image was set to a predetermined target.

For the second set of experiments, in addition to the dynamometer measures and the Jebsen Test of Hand Function, another clinical measure of hand function was included, the Nine-hole Peg test [29]. Eight subjects (6 male, 2 female, 7 right hemisphere damage, 1 left hemisphere damage) between one and four years post-stroke were subsequently exercised exclusively in the VR environment for about 2–3 hours/day, five days/week, for three weeks. The inclusion criteria for this UE experiment remained the same as for the previous one.

Figure 6 presents an example of a performance history showing the improvement in range of motion for one subject for all fingers and thumb, during each session, on each day of the training period and for the retention test. It can be seen that this subject's range of motion improved over the practice period and that these changes were maintained during the two-week retention period.

Improvement in another of the practice parameters, fractionation is shown in Fig. 7. This graph shows the angular movement of the middle, ring and small fin-

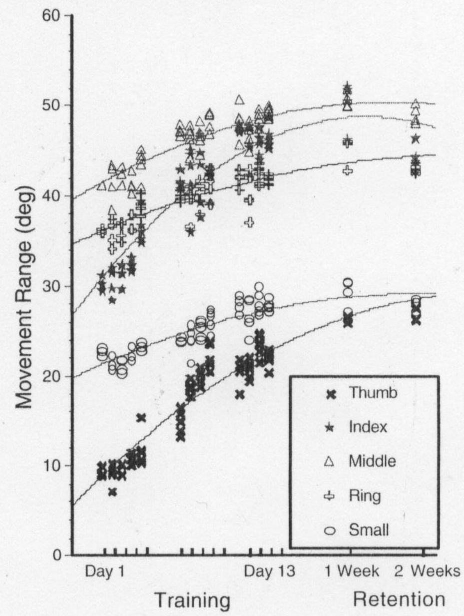


Fig. 6. Performance History for Range of Motion. Changes in the range of finger motion over the course of the therapy are shown for one subject. Each symbol denotes an average of 10 trials. The data was fitted separately for each finger by using 4th order polynomial regressions.

gers while the patient was actively moving his index finger. Figure 7 also presents the specific target setting and performance for the index finger. On day 1, the joint kinematics clearly indicate that when patient EM attempted to flex the index finger, all of his other fingers moved in a similar way. However, by the end of training) the joint kinematics show greater isolation of finger movement: whereas the index finger flexed 50°, the other fingers only flexed between 10° and 15°.

Similar to the findings in the first UE experiment, each patient showed variability in upper extremity function (as well as in lesion site), and as often seen in the clinic, each patient's outcomes on both the VR measures and functional tests were different. However, regardless of lesion site, initial level of function, or level of initial impairment in range of motion, velocity, strength or fractionation, all but one of the patients showed improvement in several movement parameters and in several functional measures. Overall, 6 out of 8 subjects significantly increased their finger and thumb range of motion ($p < 0.05$, unpaired t-test). Similarly, 4 subjects improved significantly in finger speed ($p < 0.05$, unpaired t-test) and 2 in thumb speed ($p < 0.05$, unpaired t-test), 7 in fractionation ($p < 0.05$, unpaired t-test) and 3 in their ability to perform mechanical work in flexion ($p < 0.05$, unpaired t-

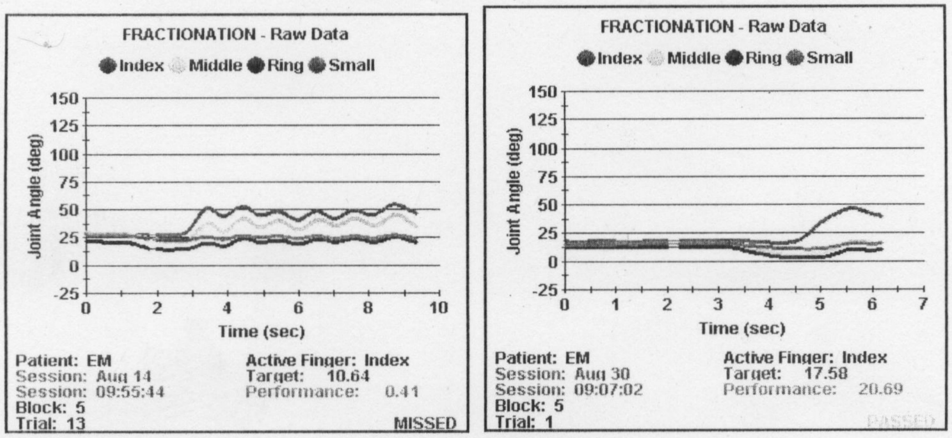


Fig. 7. Changes in fractionation of Index finger on day1 (left) and day 13 (right) of VR training for subject EM.

test). Similar to the first experiment the largest percentage of improvement was seen in the changes in fractionation (average change 57%; range −9% to 118%). The overall percent of improvement was 43% for thumb motion (range −40% to 148%), 10% for finger motion (range −9 to 27%), 4% for thumb speed (range −17 to 30%) and 15% for finger speed (range-1to 78%). In terms of the ability to perform work the range of improvement was −18 to 102% with a mean change for all subjects of 46%). Two subjects did not show improvement in some of the tasks. One of the subjects was 83 years old and appeared to lack the ability to sustain attention to the task, whereas the other subject did not follow the guidelines for the thumb range and speed exercises at the beginning of the training, thereby artificially inflating the initial scores.

Clinical evaluation using the Jebsen Test of Hand Function showed a reduction in time completion for the affected hand after the therapy (paired t-test, $t = 2.4$, $p < 0.05$). In contrast, no changes were observed for the unaffected hand ($t = 0.59$, $p = 0.54$) [2].

### 2.2. Lower extremity experiments

#### 2.2.1. First experiment

In the first experiment the Rutgers Ankle system and an airplane simulation were used to answer the question whether an individual post-stroke might reduce impairments and improve function after two weeks of training. The airplane simulation task required that the subject navigate, by using his foot to control the plane position, through a series of targets without contacting them. The general goal of the exercise was to "fly through" all the targets without committing errors. Exercise parameters were referenced to a baseline procedure where maximum speed and excursion were measured. The clinician could change the target location (and therefore the foot trajectory and movement between plantar/dorsiflexion, inversion/eversion or a combination motion) and distance, the speed of the targets and the resistance of the platform (see Fig. 8) [17].

Feedback was provided in the form of knowledge of results. Successful navigation through a hoop produced a change in color from yellow to green with the word "GREAT!" appearing on the screen. Colliding with, or missing, a target changed the target color to red and produced a somewhat unpleasant "oh-oh" auditory cue. Knowledge of performance was provided by use of color bars, which were referenced to the baseline. These bars changed color once the patient exceeded his baseline measures. Summary feedback, in the form of knowledge of results was provided at the end of the trial as the total number of targets that were navigated successfully, the number contacted and the number missed.

A 69 year old male, who was ten months post right middle cerebral artery cerebrovascular accident participated in the pilot experiment. His self-report on the Stroke Impact Scale [20] section related to mobility and home community indicated that he could not walk one block, walk fast or climb one flight of stairs or several flights of stairs. He reported that it was very difficult to get out of a chair without the use of his hands. Standing and walking without losing his balance, and moving from bed to chair were only slightly difficult. Sitting and getting in and out of the car were not difficult at all. With the exception of cutting his food and going shopping, he reported that activities that were executed in a typical day were not difficult at all. On a scale of 0–100 he reported that he was 55% recovered from his stroke.


Fig. 8. Plane simulation. © Rutgers 2001, Deutsch et al., 2001 reproduced with permission.

He participated in six sessions. In the first session, baseline testing was preformed on the VR system, clinical measures were collected and he was oriented to the system. He then trained for four one-hour sessions and was post-tested on the sixth session. Data from each training session were collected using the systems linear potentiometers that are in parallel with the pneumatic actuators and the force transducer that resides below the footplate [22].

Exercise duration and intensity were based on clinical decision-making using basic principles of exercise. For example the stiffness of the platform was increased in a strengthening exercise if the subject successfully completed ten repetitions at a lower stiffness setting. Similarly range of motion, was increased by setting the targets the subject had to reach at a greater distance apart once he was observed to have ease at a lower distance setting. The training took place in a working patient physical therapy clinic. The patient was engaged in the simulations and completed all training sessions without distractions. He reported enjoying working on the system.

At the conclusion of training the subject demonstrated improvements in the VR-based measures, as well as the clinical tests of impairments and function. Impairments of strength and range of motion were ameliorated. Using manual muscle testing he demonstrated a one grade increase in strength of his everters. He also improved his functional status by increasing his gait distance and comfort as well as speed of elevations [17] Increases in power and torque on the VR measures matched the clinical findings of increased strength. Increased accuracy on the VR simulations (from 58% for combination movements before training to 88% after training) were attributed to an improved sensorimotor coordination. We speculated that the improvements in coordination and strength were the basis for the improvements on timed stair climbing [4]. The impairment findings might have been expected but the transfer to function for a patient trained in the sitting position was not. These findings suggested the relevance of impairment training [62] at least for this patient post-stroke.

### 2.2.2. *Second experiment*

In the second LE experiment important modifications were made to both the hardware and software to increase the sense of realism, provide additional sensory input and increase the flexibility by which the VE could be configured to customize the exercise programs. In this experiment, patients were also remotely monitored over the web. Specifically, we sought to answer the question if training in these virtual environments transferred to improvements in over-ground walking speed. In addition we wanted to know if the use of haptic effects would interfere with the patient's performance and whether delivery of the therapy using

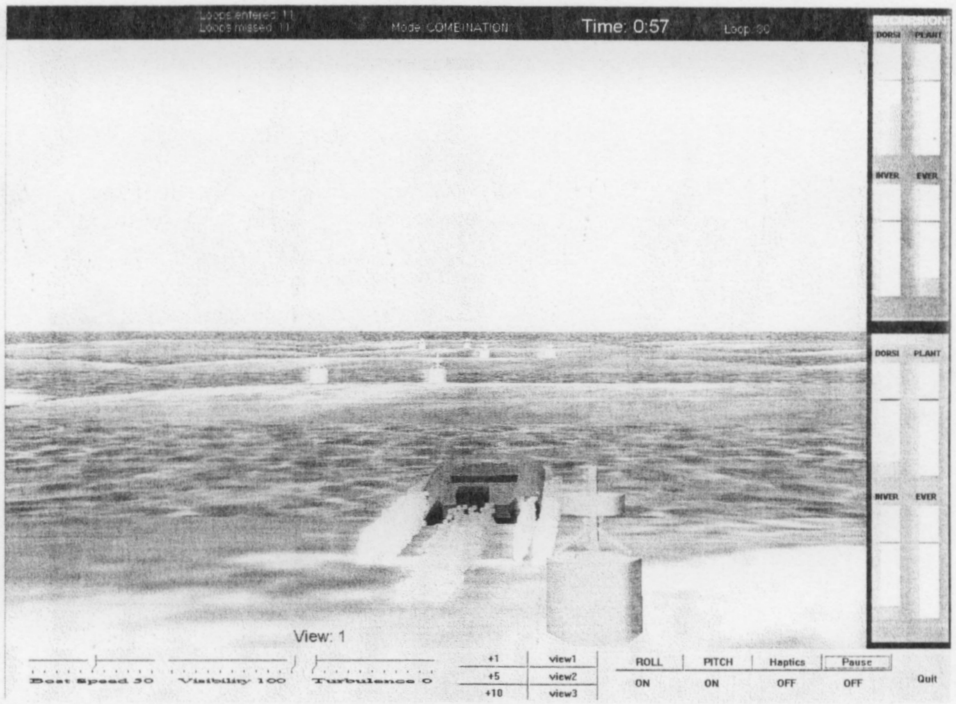


Fig. 9. Boat Navigation in the Seascape Simulation. © Rutgers 2002, Boian et al., 2001 reproduced with permission.

remote monitoring (telerehabilitation) would affect the intensity at which the patient could work.

The hardware was modified so that the robot could deliver sensory input to the foot using haptic effects [6]. Haptic effects were programmed into the platform so that it could oscillate in an anterior posterior fashion to simulate turbulence, or provide a sensation of contact when individuals hit a target. The haptic effects combined with the visual effects were termed environmental parameters. The use of haptic effects enhanced the delivery of knowledge of performance with errors being both "seen" and "felt."

A new simulation was added that increased the accuracy constraints for the foot trajectories. This simulation required that subjects use their foot as a joystick to navigate a boat through a seascape (Fig. 9) [8]. Waves created the need to dorsi and plantar flex and buoy placement stimulated inversion and eversion. The accuracy constraints for this task were greater than for the airplane exercise, because subjects were required to contour the wave to achieve a correct trajectory. When flying the plane through the targets the trajectory is not restricted, the only requirement for successful completion of the task is entering the hoop without contacting it. The plane simulation used in the first experiment was enhanced to include the environmental parameters and offer greater customization of the exercise parameters. Training was done using both simulations with all subjects, the training schedule is presented in Table 1.

Environmental parameters were provided for both simulations using visual and haptic cues. The haptic cues were jolts experienced when a vehicle (either a plane or a boat) contacted a target and turbulence (an anterior posterior oscillation), which simulated either windy conditions for the plane or choppy seas for the boat. The visual stimuli were lighting, and visibility. Lighting changed in a linear fashion with the turbulence. As turbulence increased lighting of the sky decreased. At a specific threshold lightning also appeared in the sky. (See Fig. 10) Visibility related to the number of targets the user could see. Normal visibility allowed 16 targets to be visible, which could be reduced to zero, where no target was visible in advance.

Flexibility in creating the exercise program was enhanced and additional feedback features were added. The exercise parameters that could be manipulated were: time of training, platform resistance, range of motion, speed of targets, the presence or absence of haptics and degrees of freedom. These exercise parameters were configured to create different forms of exercise such as warm up, endurance, strengthening, coordination, and range of motion. Feedback was now

Table 1
Training Schedule for the Second LE Experiment

| Week one | Week two | Week three | Week four |
|---|---|---|---|
| Plane | Plane with haptics | Plane and haptics<br>Boat | Plane and haptics<br>Boat and haptics<br>Remote Monitoring |

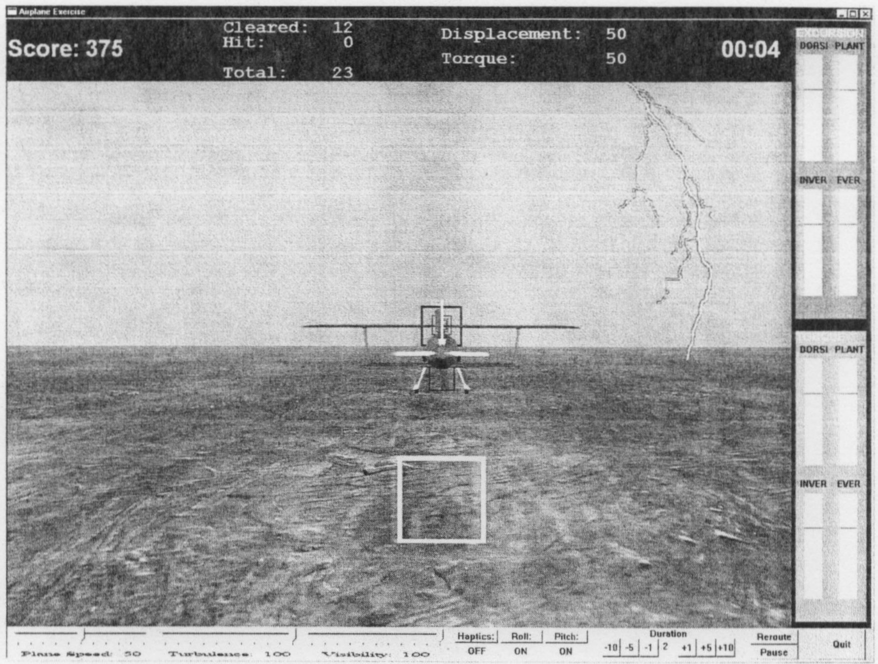


Fig. 10. Plane simulation with lightning effects. © Rutgers 2001, Boian et al., 2002 reproduced with permission.

provided using the haptic cues as well as the visual and auditory cues. In the boat simulation error messages were provided when a patient did not contour the wave. Contact with a target also provided knowledge of performance as a physical consequence to the action.

The research protocol was more stringent than in the first LE experiment. A double base-line period was used to establish the stability of the relevant outcome variables. Interestingly gait speed was stable for only one subject but increased in the second measurement for two subjects. Therefore baseline data were averaged between the two collection points. Temporal distance measures of gait were collected using a sensorized foot mat in order to quantify speed. A six-minute walk test was added to measure endurance and the Berg Balance test [3] to characterize balance. In addition, foot strength measurements were obtained using a dynamometer.

Three individuals 1–8 years post stroke whose average walking speed (80 ft/min), range of Berg Balance scores of 51–53 (out of 56) and lower extremity Fugl Meyer [21] scores of 33–37, participated in the experiment. They reported being between 60 and 75 % recovered on the Stroke Impact Scale [20]. The subjects represented a high functioning post-stroke group, all of whom were community ambulators [50]. Two had sub-cortical and one had a cortical stroke. They trained for one hour three times a week for four weeks using the schedule summarized in Table 1. Subjects attended all sessions, with the exception of one subject who skipped one session due to muscle soreness from over-working on the system.

Consistent with the findings from the first LE study, all subjects demonstrated strength gains. Subject 1 increased strength in all four muscle groups, subject 2 in two muscle groups and subject 3 in three muscle groups [8]. There was an increase in walking speed from an average of 80 ft/min to 95 ft/min [16]. The self selected walking speed increase from baseline to post-testing ranged from 0–21%. Therefore the strength findings from the first study were replicated and extended to gait velocity findings.

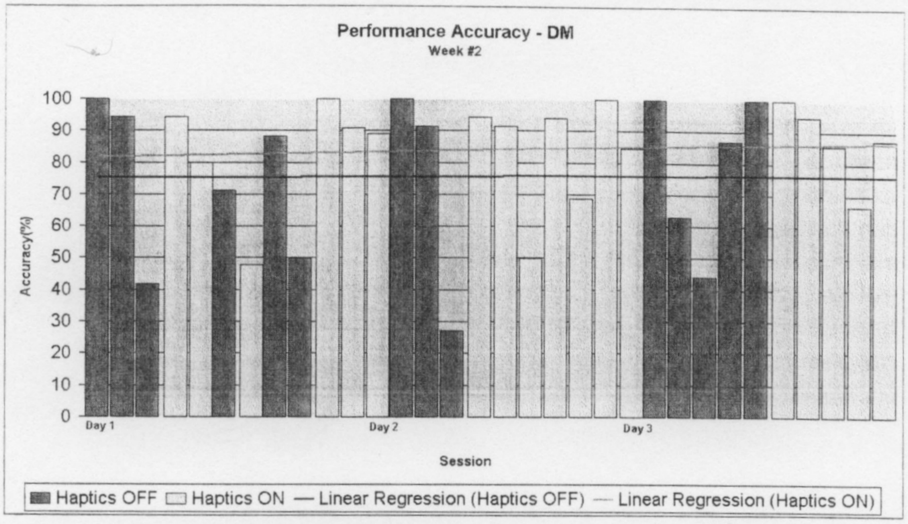


Fig. 11. Accuracy of Target Clearance With Haptics On and Off Accuracy with the haptic effects off (dark grey line) is lower than the accuracy with the haptic effects on (light grey line).

The addition of haptic effects, through perturbations such as jolts and turbulence, did not interfere with their ability to function in the VR world. Subjects' exercise accuracy was compared across several days to determine if performance degraded with the addition of haptic effects. There were two subjects for whom the addition of haptics enhanced accuracy and for the third it interfered with accuracy. A graph illustrating how the addition of haptics increased the accuracy and consistency of performance of one subject is presented in Fig. 11. The delivery of the therapy remotely did not adversely affect patient's ability to exercise [13]. There was no decrease in accuracy, total time of exercise, and subjects' ability to generate power. This finding is encouraging as it suggests that we may use technology to create and remotely deliver virtual environments for rehabilitation.

*2.2.3. Third experiment*

Encouraging results from the first two studies have prompted the development of a gait rehabilitation system in standing with simulations that resemble ambulation. This third experiment will have two new simulations. The system in standing consists of two Stewart platforms based on the original design of the Rutgers Ankle 6DOF pneumatic robot [7]. However, they can sustain heavier loads and can be programmed with haptic effects to simulate a variety of support surfaces. The new simulations allow the user to navigate through two VE's, one in which the task is to successfully cross a street before the light changes and the other a walk-in-the-park that affords the user an opportunity to negotiate elevations and obstacles in the path. The complexity of these VE's will be manipulated by altering the support surface, environmental conditions and rate of presentation of the objects in the VE [7]. Studies to test the validity of the gait pattern used with the new system are underway.

It is hypothesized that individuals post-stroke will improve their gait speed and their ability to ambulate in complex environments.

## 3. Discussion

Two VR systems with parallel sets of experiments designed to refine the technology and test the possibility of using it for the rehabilitation of hand and gait have been described. In a series of pilot experiments we have determined that for a subset of individuals who have chronic strokes these technologies can be used for training that produced positive effects at the impairment and functional levels.

The promise that practice in a virtual world allows for a high degree of repetition was achieved in both UE and LE experiments on the limited number of subjects we have studied. Subjects were able to train a high number of repetitions in both applications (See Figs 12 and 13). In the UE study subjects executed on average 4,140 repetitions over a 30-hour training period and in the LE study subjects executed on average 4,312 repetitions over 11 hours of training. These numbers are comparable to the numbers of repetitions reported in animal studies that were designed to measure plasticity

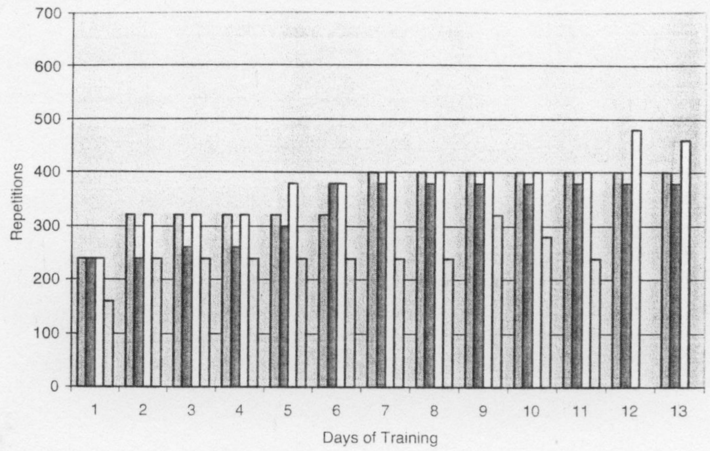


Fig. 12. Repetitions for the Second Upper Extremity Experiment. Each bar indicates a different subject. Subject four with the diagonal bars (right-side bar for each day) completed only 11 days of training.

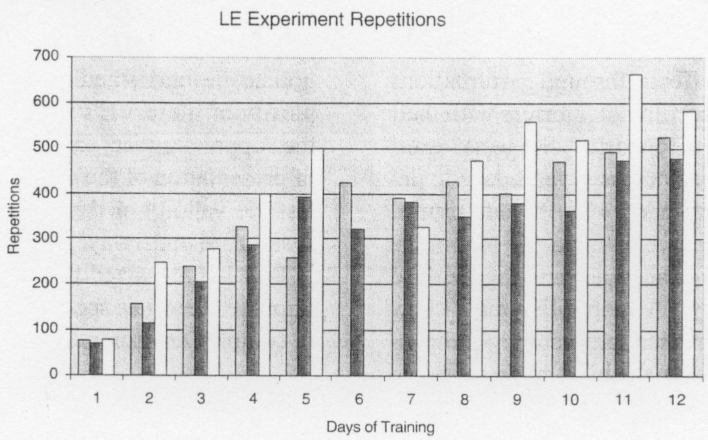


Fig. 13. Repetitions for the Second Lower Extremity Experiment. Each bar represents a different subject. The subject with the yellow bar did not exercise on the sixth session.

of the motor system as a result of training in a variety of forms [31,49,51]. Comparison of numbers of repetitions with the human post-stroke studies was not possible as they reported intensity of training based on time [13,37]. Total training time for both of our studies (30 hours over a 3 week period for the UE study and 12 hours over a four week period for the LE study), were substantially lower than those reported by Kwakkel et al. [37], 50 hours over a 20 week period. Thus training in our virtual environments appears to provide a strong enough intensity to produce behavioral effects over a shorter period of time relative to other stroke recovery studies. Interestingly, a comparable intensity of training is achieved in the LE VR studies compared to UE VR studies over a shorter period of time.

The ability to manipulate feedback in the VE's we believe strongly enhanced the skill acquisition and therapeutic experience. Augmented feedback is thought to play several roles in skill acquisition. One is to assist achievement of the movement goal by providing information about the success of the skill in progress so that the learners can determine if what they are doing is appropriate for that action. The second role is to motivate the learners to continue striving toward the movement goal by comparing their actions with a standard or with previous actions and to adhere to exercise and rehabilitation programs [42]. We have found that patients practicing in a VR environment that provided both KR and KP feedback in multiple modes improved both the kinematics and the kinetics of their hemiplegic hand function and use of their affected ankle. In addition they were able to transfer this learning to real-world tasks [17,18,44]. Transfer of training from a VR environment to a real-world environment has been found in both normal subjects [67] and in patients post stroke [69]. Transfer of learning becomes most advantageous when there is a degree of similarity between the component parts of the skill and/or a similarity in the cognitive processing requirements for the acquisition of the skill [38].

In our first UE experiment training was executed in the virtual world in combination with table manual tasks and then in the second experiment in the virtual world alone. We were able to demonstrate that the behavioral effects of training in the virtual world alone were comparable to those of combined treatments. In the LE studies, training has occurred in the virtual world alone and in the seated position. While individuals have executed tasks, these tasks were not directly related to walking. Rather, important elements of walking such as lower extremity strength and coordination were being trained. This is supported by the findings that for all LE patients there was an improvement of gait speed. While our studies have shown that VR alone can produce positive effects, it remains to be determined what the best use of VR will be to promote motor plasticity.

Most of the individuals that we have studied would be characterized as being in the top quartile in terms of function. This would be based on the criteria for inclusion in the UE studies [66] and the measured gait speed in the LE studies [50]. We found however, that they could be further stratified into two levels. In the UE studies the individuals in the upper level had better carry over of the VR training into activities of daily living. For the UE studies we speculate that lower functioning patients have impairments that may not be ameliorated as effectively through training as the higher functioning patients. Patients with severe impairments who have been shown to have less chance of recovery [46] might also show lower training effects in VE. In contrast, for the LE training, all patients regardless of their functioning level improved on gait speed, but the higher functioning patients did not improve on stair climbing. We speculate that for the higher level patients, LE traiile seated addressed some of the impairments such as strength that may be required for stair climbing [4], but not higher-level impairments such as balance. Therefore higher functioning patients may need to be trained in standing for them to derive enough of a benefit to carry over to a complex task like stair climbing.

While subjects in both the UE and LE studies improved their motor behavior after training we speculate that the mechanisms underlying those improvements differ. Improvements in the UE studies can be attributed to a reversal of learned non-use [65]. As these individuals are able to use their less affected side to compensate for the hemiplegic side, the VR training forces and facilitates the use of the affected side. This is illustrated by the shape of the UE improvement curves, which are linear. In contrast an explanation for the LE study improvements would be that as individuals are using both lower extremities, albeit asymmetrically [56] they must learn a new gait pattern in order to become efficient. As they acquire the new gait pattern there is a decrease in their gait speed, followed by a subsequent increase as the new pattern is acquired. This hypothesis is amenable to testing using either kinematics or electromyography to characterize gait pattern changes [57].

## 4. Conclusion

Exercising in a computerized VR environment is in the nascent stage of exploration as a therapeutic intervention for retraining coordinated movement [11,12, 25–27,35,43,44]. The research presented here and that of others have shown that virtual environments appear to be well suited for rehabilitation of impairments as well as function. By engaging participants they permit the repetition required for neural and behavioral recovery. This technology has the capability to create functionally based practice conditions where skill development gained through the repetition and intensity of practice can be objectively and systematically manipulated. Several studies in normal subjects have shown that VR can be a beneficial environment for learning a complex motor task [33,59,67]. This has also been demonstrated in a patient population. Eight subjects with chronic hemiplegia were trained in a virtual environment on two upper-extremity reaching tasks. The average improvement across all subjects on the Fugl-Meyer was 15% and on the Wolf Test of Upper Extremity Function 31% [26].

The novelty, inter-activeness, and real-time characteristics of virtual environments appear to support the requirements of engagement and problem solving that may be required for learning. VR-based rehabilitation has been described for patients with neurologic [19,27, 54,69], orthopedic [18,23], cognitive and behavioral deficits [60] as well as for disability awareness and prevention of neuro trauma pedestrian injuries [45].

An important question that will need to be answered in the future is whether the use of technologies such as virtual reality and telerehabilitation will replace existing forms of training, complement them or eventually be discarded [15]. It is our impression that given the current state of these technologies it is likely that they will continue to be developed and complement existing forms of therapy. This development should be influenced by principles of motor control and learning to guide the design of the hardware and software, as well as evidence from the motor plasticity literature to design the VE. Importantly, as has been the experience of these authors, collaboration between clinician scientists, basic scientists, engineers and users is likely to yield the most relevant VR rehabilitation systems. Future studies of VR rehabilitation will measure plasticity of the motor system not only from a behavioral standpoint as we have, but from a neural standpoint. The addition of brain imaging measures will serve to elucidate some of the mechanisms underlying the success of VR therapies. Then selection of the most suitable individuals post-stroke for VR therapies will be possible.

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## References

[1] W. Abend, E. Bizzi and P. Morasso, Human arm trajectory formation, *Brain* **105** (1982), 331–348.

[2] S.V. Adamovich, A. Merians, R. Boian, M. Tremaine, G. Burdea, M. Recce and H. Poizner, *A virtual reality based exercise system for hand rehabilitation post-stroke*, Proc. Second Int. Workshop on Virtual Rehabilitation, 2003, pp. 74–81.

[3] K.O. Berg, B.E. Maki, J.I. Williams, P.J. Holliday and S.L. Wood-Dauphinee, Clinical and laboratory measures of postural balance in an elderly population, *Arch Phys Med Rehabil* **73** (1992), 1073–1080.

[4] R.W. Bohannon, Association of paretic lower extremity strength and balance with stair climbing ability in patients with stroke, *Journal of Stroke and Cerebrovascular Disease* **1** (1999), 65–69.

[5] R. Boian, A. Sharma, C. Han, G. Burdea, A. Merians, S. Adamovich, M. Recce, M. Tremaine and H. Poizner, *Virtual Reality-Based Post-Stroke Hand Rehabilitation*, Proceedings of Medicine Meets Virtual Reality 2002, IOS Press 2002, pp. 64–70.

[6] R.F. Boian, J.E. Deutsch, C.S. Lee, G.C. Burdea and J. Lewis, *Haptic Effects for Virtual Reality-based Post-Stroke Rehabilitation*, Proceedings of the Eleventh Symposium on Haptic Interfaces For Virtual Environment And Teleoperator Systems 2003, pp. 247–253.

[7] Boian, R.F. Kourtev, K.M. Erickson, J.E. Deutsch, J.A. Lewis and G.C. Burdea, *Dual Stewart-Platform Gait Rehabilitation System for Individuals Post-Stroke Proc*, Second Int. Workshop on Virtual Rehabilitation, 2003, pp. 92.

[8] R.F. Boian, C.S. Lee, J.E. Deutsch, G.C. Burdea and J.A. Lewis, *Virtual reality-based system for ankle rehabilitation post-stroke*, Proceedings First International Workshop on Virtual Reality Rehabilitation. VRMHR 2002, 2002, pp. 77–86.

[9] M. Bouzit, G. Burdea, V. Popescu and R. Boian, The Rutgers Master Force Feedback Glove, *IEEE/ASME Transactions on Mechatronics* **7** (2002), 256–263.

[10] G. Burdea, *Force and Touch Feedback for Virtual Reality*, Wiley, New York, 1996.

[11] G. Burdea and P. Coiffet, *Virtual Reality Technology*, 1st Ed., Wiley, New York. 1994.

[12] G. Burdea and P. Coiffet, *Virtual Reality Technology*, 2nd., Wiley, Hoboken NJ, 2003

[13] C. Butefisch, H. Hummelsheim, P. Denzler and K.H. Mauritz, Repetitive training of isolated movements improves the outcome of motor rehabilitation of the centrally paretic hand, *Journal of the Neurological Sciences* **130** (1995), 59–68.

[14] C.M. Dean and R.B. Shepherd, Task-related training improves performance of seated reaching tasks following stroke: a randomised clinical trial, *Stroke* **28** (1997), 722–728.

[15] J.E. Deutsch, Physical therapists and technology: Emphasis on the potential of virtual reality, *Neurology Report* **26** (2002), 53–54.

[16] J.E. Deutsch, R. Boian, G. Burdea and J. Lewis, *Virtual Reality-Based Gait Rehabilitation Of Individuals Post-Stroke Using Real-Time Web-Based Telerehabilitation Monitoring*, Proceedings of the XIV International World Congress of Physical Therapy 2003.

[17] J.E. Deutsch, J. Latonio, G. Burdea and R. Boian, *Post-Stroke Rehabilitation with the Rutgers Ankle System – A case study Presence* **10** (2001), 416–430, MIT Press.

[18] J.E. Deutsch, J. Latonio, G. Burdea and R. Boian, *Rehabilitation of Musculoskeletal Injuries Using the Rutgers Ankle Haptic Interface: Three Case Reports*, Eurohaptics 2001, 2001, pp. 11–16.

[19] J.E. Deutsch, A.S. Merians, G. Burdea, R. Boian, S. Adamovich and H. Poizner, Haptics and Virtual Reality Used to Increase Strength and Improve Function in Chronic Patients Post-stroke: Two Case Reports, *Neurology Report* **26** (2002), 78–85.

[20] P.W. Duncan, D. Wallace, S. Min Lai, D. Johnson, S. Embretson and L. Jacobs, The Stroke Impact Scale Version 2.0-Evaluation of Reliability, Validity and Sensitivity to Change, *Stroke* **30** (1999), 131–2140.

[21] A. Fugl-Meyer, L. Jaasko, S. Leyman Ilsson and S. Steglind, The post-stroke hemiplegic patients: A method of evaluation of physical performance, *Scand J Rehabil Med* **56** (1975), 713–731.

[22] A. Gentile and M. Skill Acquisition, in: *Movement Science: Foundations for Physical Therapy in Rehabilitation*, (2nd ed)., J. Carr and R. Shepherd, eds, 2000, pp. 142.

[23] M. Girone, G.C. Burdea, M. Bouzit, V. Popescu and J.E. Deutsch, *Orthopedic Rehabilitation Using the Rutgers Ankle Interface*, in: Proc. of Medicine Meets Virtual Reality 2000, J.D. Westowood, ed., 2000, pp. 89–95.

[24] M. Girone, G. Burdea, M. Bouzit, V. Popescu and J.E. Deutsch, A Stewart platform-based system for ankle telerehabilitation, *Autonomous Robots* **10** (2001), 203–212.

[25] M. Holden, E. Todorov, J. Callahan and E. Bizzi, Case Report: Virtual environment training improves motor performance in two stroke patients, *Neurology Report* **23** (1999), 57–67.

[26] M.K. Holden and T. Dyar, Virtual environment training: a new tool for rehabilitation, *Neurology Report* **26** (2002), 62–71.

[27] D. Jack, R. Boian, A. Merians, M. Tremaine, G.C. Burdea, S.V. Adamovich, M. Recce and H. Poizner, Virtual reality-based stroke rehabilitation, *IEEE Transactions on Neural Systems and Rehabilitation Engineering* **9** (2001), 308–318.

[28] R.H. Jebsen, N. Taylor, R.B. Trieschmann, M.J. Trotter and L.A. Howard, An objective and standardized test of hand function, *Arch Phys Med Rehabil* **50** (1969), 311–319.

[29] M. Kellor, J. Frost, N. Silberberg, I. Iverson and R. Cummings, Hand strength and dexterity, *Am. Journal of Occupational Therapy* **25** (1991), 77–83.

[30] J.A. Kleim, E. Lussnig, E.R. Schwarz, T.A. Comery and W.T. Greenough, Synaptogenesis and Fos Expression in the Motor Cortex of the Adult Rat After Motor Skill Learning, *J. Neuroscience* **16** (1996), 4529–4535.

[31] J.A. Kleim, R.A. Swain, K.A. Armstrong, R.M. Napper, T.A. Jones and W.T. Greenough, Selective synaptic plasticity within the cerebellar cortex following complex motor skill learning, *Neurobiology of Learning & Memory* **69** (1998), 274–289.

[32] J.A. Kleim, S. Barbay, N. Cooper, T. Hogg, C.N. Reidel, M.S. Remple and R.J. Nudo, Motor learning-dependent synaptogenesis is localized to functionally reorganized motor cortex, *Neurobiology of Learning and Memory* **77** (2002), 63–77.

[33] J.J. Kozak, Transfer of training from virtual reality, *Ergonomics* **36** (1993), 777–784.

[34] J.W. Krakauer, M.F. Ghiraldi and C. Ghez, Independent Learning of internal models for kinematic and dynamic control of reaching, *Nature Neuroscience* **2** (1999), 1026–1031.

[35] H.I. Krebs, N. Hogan, M.L. Aisen and B.T. Volpe,. Robot-aided neurorehabilitation, *IEEE Transactions on Rehabilitation Engineering* **6** (1998), 75–87.

[36] G. Kwakkel, R.C. Wagenaar, T.W. Koelman, G.J. Lankhorst and J.C. Koetsier, Effects of intensity of rehabilitation after stroke: a research synthesis, *Stroke* **28** (1997), 1550–1556.

[37] G. Kwakkel, R.C. Wagenaar, J.W.R. Twisk, G.J. Lnkhorst, and J.C. Koesier, Intensity of Leg and Arm Training after Primary Middle Cerebral Artery Stroke: A Randomised Trial, *Lancet* **354** (1999), 191–196.

[38] T.D. Lee, Transfer – appropriate processing: a framework conceptualizing practice effects in motor learning, in: *Complex Motor Behavior Elsevier: Holland*, O.G. Meijer, K. Roth, eds, 1998, pp. 201–215.

[39] T.D. Lee, M.A. White and H. Carnahan, On the role of knowledge of results in motor learning: Exploring the guidance hypothesis, *J Motor Behav* **22** (1990), 104–122.

[40] J. Lewis, R.F. Boian, G.C. Burdea and J.E. Deutsch, *Real-time Web-based Telerehabilitation Monitoring Proceedings of Medicine Meets Virtual Reality*, IOS Press, 2003, pp. 190–192.

[41] R.A. Magill, Augmented feedback and skill acquisition, in: *Handbook on research in sports psychology*, (2nd ed)., R.N. Singer, H.A. Hausenblaus and C. Janelle, eds, Wiley: New York, 2001.

[42] R.A. Magill, *Motor Learning: Concepts and Applications*, Mc Graw Hill Boston, 2001.

[43] A. Merians, R. Boian, M. Tremaine, C. Burdea, S. Adamovich, M. Recce, C. Han, A. Sharma and H. Poizner, Rehabilitation in a virtual reality environment modifies hand function, *Neurorehabilitation and Neural Repair* **16** (2002), 15–16.

[44] A. Merians, D. Jack, R. Boian, M. Tremaine, C. Burdea, S. Adamovich, M. Recce and H. Poizner, Virtual reality-augmented rehabilitation for patients post stroke: three case studies, *Physical Therapy* **82** (2002), 898–915.

[45] J. McComas and H. Sveistrup, Virtual reality applications for prevention, disability awareness and physical therapy rehabilitation in neurology: Our recent work, *Neurology Report* **22** (2002), 55–61.

[46] H. Nakayama, H.S. Jorgensen, H.O. Raaschou and T.S. Olsen, Recovery of upper extremity function in stroke patients: The Copenhagen Study, *Arch Phys Med Rehabil* **75** (1994), 394–398.

[47] R.J. Nudo, Role of Cortical Plasticity in Motor Recovery After Stroke, *Neurology Report* **22** (1998), 61–67.

[48] R.J. Nudo, E.J. Plautz and S.B. Frost, Role of adaptive plasticity in recovery of function after damage to motor cortex, *Muscle Nerve* **24** (2001), 1000–1019.

[49] R.J. Nudo, B.M. Wise, F. Sifuentes and G.W. Milliken, Neural substrates for the effects of rehabilitative training on motor recovery after ischemic infarct, *Science* **272** (1996), 791–1794.

[50] J. Perry, M. Garrett, J.K. Gronley and S.J. Mulroy, Classification of walking handicap in the stroke population, *Stroke* **26** (1995), 982–989.

[51] E.J. Plautz, G.W. Milliken and R.J. Nudo, Effects of repetitive motor training on movement representations in adult squirrel monkeys: role of use versus learning, *Neurobiol. Learn. Mem.* **74**(1) (2000), 27–55.

[52] V. Popescu, G. Burdea, M. Bouzit, M. Girone and V. Hentz, Orthopedic Telerehabilitation with Virtual Force Feedback, *IEEE Transactions on Information Technology in Biomedicine* **4** (2000), 45–51.

[53] A. Risedal, B. Mattsson, P. Dahlqvist, C. Nordborg, T. Olsson and B.B. Johansson, Environmental influences on functional outcome after a cortical infarct in the rat, *Brain Research Bulletin* **58** (2002), 315–321.

[54] T.J. Reiss, Gait and Parkinson's Disease: A conceptual model for an augmented-reality based therapeutic device, in: *Virtual Environments in Clinical Psychology and Neuroscience*, G. Riva, B.K. Wiederhold and E. Molinari, eds, Washington, D.C.: IOS Press, 1998, pp. 200–208.

[55] M.S. Remple, R.M. Bruneau, P.M. Vandenberg, C. Goertzen and J.A. Kleim, Sensitivity of cortical movement representations to motor experience: evidence that skill learning but not strength training induces cortical re-organization, *Behavioral Brain Research* **123** (2001), 133–141.

[56] M.J. Renner and M.R. Rosensweig, *Enriched and Impoverished Environments: Effects on Brain and Behavior*, Springer-Verlag: New York, 1987.

[57] C.L. Richards, F. Malouin and C. Dean, Gait in stroke: assessment and rehabilitation, *Clinics in Geriatric Medicine* **15** (1999), 833–855.

[58] C.L. Richards and S. Olney, Hemiparetic gait following stroke: Part II Recovery and physical therapy, *Gait and Posture* **4** (1996), 149–162.

[59] G. Riva, B.K. Wiederhold and E. Molinari, eds, *Virtual Environments in Clinical Psychology and Neuroscience Methods and Techniques in Advanced Patient-Therapist Interaction*, IOS Press, Amsterdam. 1998.

[60] A. Rizzo, J. Buckwalter, C. van der Zaag, U. Neumann, M. Tiebaux, C. Chua, A. van Rooyen, L. Humphrey and P. Larson, Virtual Environment Applications in Clinical Neuropsy-

chology, Proc. of IEEE Virtual Reality 2000, March, 2000, pp. 63–70.
[61] F.D. Rose, E.A. Attree, B.M. Brooks and D.A. Johnson, Virtual environments in brain damage rehabilitation: a rationale from basic neuroscience, in: *Virtual Environments in Clinical Psychology and Neuroscience*, G. Riva, B.K. Wiederhold and E. Molinari, eds, Washington, D.C.: IOS Press, 1998, pp. 233–242.
[62] M. Schenkman, S.T. Bliss, D.L. Day, S. Kemppainen and J. Pratt, Multisystem Model for Management of Neurologically Impaired Adults- An Update and Illustrative Case, *Neurology Report* **24** (1999), 145–157.
[63] L.R. Swanson and T.D. Lee, Effects of aging and schedules of knowledge of results (KR) in reduced relative frequency presentations of KR, *J of Gerontol* **47** (1992), 406–411.
[64] S.P. Swinnen, Information feedback for motor skill learning. A Review, in: *Advances in motor learning and control Human kinetic Il*, H.N. Zelaznik, ed., 1996, pp. 37–66.
[65] Taub, N.E. Milllner and T.A. Novack, A technique for improving chronic motor deficit after stroke, *Archives of Physical Medicine and Rehabilitation* **74** (1993), 347–354.
[66] E. Taub and S.L. Wolf, Constraint induced movement techniques to facilitate upper extremity use in stroke patients, *Top Stroke Rehabil* **3** (1997), 38–61.
[67] E. Todorov, R. Shadmehr and E. Bizzi, Augmented feedback presented in a virtual environment accelerates learning of a difficult motor task, *Journal of Motor Behavior* **29** (1997), 147–158.
[68] C.G. Trepagnier, Virtual environments for the investigation and rehabilitation of cognitive and perceptual impairments, *NeuroRehabilitation* **12** (1999), 63–72.
[69] B.T. Volpe, H.I. Krebs, N. Hogan, L. Edelsteinn, C.M. Diels and M.L. Aisen, (Robot training enhanced motor outcome in patients with stroke maintained over 3 years, *Neurology* **53** (1999), 1874–1876.
[70] D.T. Wade, F.M. Collen, G.F. Robb and C.P. Warlow, Physiotherapy Intervention Late After Stroke and Mobility, *BMJ* **304** 609–613.
[71] R.A. Werner and S. Kessler, Effectiveness of an Intensive Outpatient Rehabilitation Program for PostAcute Stroke Patients, *Am. J. of Physical Medicine* **75** (1996), 114–120.
[72] C.J. Winstein, A.S. Merians and K.J. Sullivan, Motor learning after unilateral brain damage, *Neuropsychologia* **37** (1999), 975–987.
[73] S. Wolf, D. LeCraw, L. Barton and B. Jann, Forced use of hemiplegic upper extremities to reverse the effect of learned non-use among chronic stroke and head injured patients, *Exp. Neurology.* **104** (1989), 125–132.