Virtual Reality-Enhanced Stroke Rehabilitation

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***Abstract*—A personal computer (PC)-based desktop virtual reality (VR) system was developed for rehabilitating hand function in stroke patients. The system uses two input devices, a CyberGlove and a Rutgers Master II-ND (RMII) force feedback glove, allowing user interaction with a virtual environment. This consists of four rehabilitation routines, each designed to exercise one specific parameter of hand movement: range, speed, fractionation or strength. The use of performance-based target levels is designed to increase patient motivation and individualize exercise difficulty to a patient's current state. Pilot clinical trials have been performed using the above system combined with noncomputer tasks, such as pegboard insertion or tracing of two-dimensional (2-D) patterns. Three chronic stroke patients used this rehabilitation protocol daily for two weeks. Objective measurements showed that each patient showed improvement on most of the hand parameters over the course of the training. Subjective evaluation by the patients was also positive. This technical report focuses on this newly developed technology for VR rehabilitation.**

***Index Terms*—CyberGlove, haptic glove, rehabilitation, Rutgers Master II-ND, stroke, virtual reality (VR).**

I. Introduction

STROKE is the leading cause of adult disability, with 65% of the nearly four million people in the United States who have survived a stroke living with minor to severe impairments [28]. Impairments such as muscle weakness, loss of range of motion, and impaired force generation create deficits in motor control that affect the stroke survivor's capacity for independent living and economic self-sufficiency. Many traditional therapeutic interventions have been used in rehabilitation to promote functional recovery, with outcome studies yielding inconsistent results [7]. Recent evidence has demonstrated that intensive massed and repeated practice may be necessary to modify neural organization [16], [18], [24], [25], [29] and effect recovery of functional motor skills [33], [47]. The structure of the current health care system, which provides limited amounts and duration of therapy, challenges us to design innovative rehabilitation programs [33], [38]. These should incorporate intensive and repetitive training, a method that has been shown to be effective in promoting cortical plasticity and behavioral recovery.

A. Stroke Rehabilitation

Several researchers have shown, both in animal and human studies, that important variables in relearning motor skills and in changing the underlying neural architecture are the quantity, duration, and intensity of training sessions. Focal ischemic lesions in monkeys, similar to the damage caused by a stroke, usually result in a loss of cortical territory. Three to four weeks of intensive, repetitive hand training prevented such loss and, in some instances, led to an expansion of this cortical region [29]. A similar phenomenon has been demonstrated in the sensory cortex [16]. Looking at the effects of different intensities of physical therapy treatment, several authors [23], [36], [38] have reported significant improvement in activities of daily living as a result of higher intensities of treatment. In a further review of the literature, Kwakkel [22] found that in the rehabilitation of patients who had a stroke, there was a small but statistically significant treatment effect related to the intensity of the rehabilitation.

When traditional therapy is provided in a hospital or rehabilitation center, the patient is usually seen for half-hour sessions, once or twice a day. This is decreased to once or twice a week in outpatient therapy. Typically, 42 days pass from the time of hospital admission to discharge from the rehabilitation center [31]. It is evident that in this service-delivery model, it is difficult to provide the amount or intensity of practice needed to effect neural and functional changes.

B. Virtual Reality and Rehabilitation

Virtual reality (VR) technology [3] is currently being explored in several areas of rehabilitation [42]. VR head-mounted displays (HMDs) have been used to present visual cues overlapping the real visual scene during ambulation of patients with Parkinson's disease. This is being investigated as a tool to facilitate a more normal gait pattern [43]. VR training has been used for children with cerebral palsy to enhance spatial awareness and the operation of motorized wheelchairs [9], [13]. VR-based rehabilitation has also been investigated for orthopedic patients following hand surgery [4] or ankle accident [12]. Robot training using a virtual environment has recently been shown to enhance stroke rehabilitation [1], [21], [40], [41]. Motor function of the affected arm was improved following robot-assisted sensorimotor activity of that arm. Subjects were able to relearn patterns of shoulder and elbow coordination in order to smoothly and efficiently move the handle of a robot to acquire targets.

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This technology provides the capability to create an environment in which the intensity of feedback and training can be systematically manipulated and enhanced in order to create the most appropriate, individualized motor learning paradigm. The potential benefits of training in VR would be the ability to increase the duration, frequency, and intensity of therapy that could be provided to patients by using semiautomated programs. Furthermore, lower cost personal computer (PC)-based VR equipment is now available that will eventually allow rehabilitation stations to be placed in locations other than the rehabilitation center, such as a patient's home. The Internet can be used for data transfer, allowing a therapist to remotely monitor progress and to modify the patient's therapy program [4], [30]. 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. Therefore, developing new methods to accelerate and improve the level of motor retraining is a very important societal consideration.

VR-based rehabilitation systems have several other advantages, as well. VR rehabilitation exercises can be made to be engaging, such that the patient feels immersed in the simulated world. This is extremely important in terms of the patient motivation [30], which, in turn, is key to recovery. VR sensor technology can also be used to fully quantify any progress made by the patient, especially in terms of motor-control improvement. Although most neurologic recovery is attained by three months after the stroke [17], several studies investigating the outcome of treatment six months after the stroke have shown significant gains in dexterity, strength, and function [5], [32], [44]. If VR-based rehabilitation of patients who experienced stroke years ago is proven successful, then treatment options become available past the traditional period of inpatient hospitalization and rehabilitation.

It has been shown, in normal subjects, that VR can be a beneficial environment for learning a motor task. Todorov *et al.* [39] used a VR system for table-tennis training, including virtual paddles for the teacher and the subject, as well as a virtual ball. Augmented feedback was used to indicate to the trainee the movement variables most relevant for successful performance of the task. Results indicated that subjects who received the virtual environment training did better than subjects who received a comparable amount of training in a real environment. Another experiment comparing VR training and real-world training in a pick-and-place task showed improvement in both groups, but those trained in the real-world task did better [19]. This is not surprising, because the VR group used low-resolution HMDs and gloves with no force feedback.

Two patients with hemiplegia were trained in a virtual environment on an upper-extremity-reaching task that progressed sequentially through six levels of difficulty [12]. Each subject received 16 trials from 1 to 2 h duration. Both patients improved in the task in the virtual environment and were able to progress to the sixth level of difficulty. However, only one of the subjects showed clinical and functional motor improvements; the second showed no improvements.

In addition to sorting out the effects of motor training in a virtual environment, it is important to determine whether the skills gained in that environment transfer to real-world conditions. Wilson *et al.* [45], [46] studied children with a variety of disabilities and found that internal representations resulting from exploration of simulated space transferred to the real environment. However, although subjects trained on a motor task in a virtual environment demonstrated the ability to improve performance on the task in that environment, the learning did not always transfer to the real-world task [12], [19]. This conflict in findings could be reflective of differences in the learning requirements of perceptual skills and motor skills, or it could be reflective of the current paucity of investigations into the use of VR for motor skill training. The experiments on motor-task training and transfer of that task to the real-world environment indicate that the effects of training in a virtual environment are not fully understood, nor entirely conclusive.

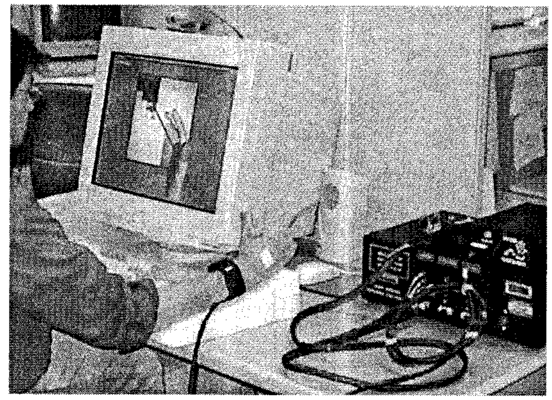

Fig. 1. The PC-based VR rehabilitation system. The user is wearing a CyberGlove connected to the interface unit on the right. Also shown is the haptic control interface (HCI) for the RMII glove [14]. (© Association for Computing Machinery (ACM). Photo courtesy of ACM.)

The literature investigating virtual reality as a tool for rehabilitation training does indicate potential benefits. These should be more fully explored in order to ascertain the use of VR as an enhancement to traditional therapy. To that end, this technical report focuses primarily on the technological innovations for the use of VR-enhanced rehabilitation of stroke patients. The clinical data for these patients is the focus of a companion article [27]. Section II presents the PC-based experimental system and Section III details the protocol used in pilot trials. Section IV discusses trial results and Section V concludes this report, offering possible directions for future research.

II. Experimental System

The experimental system used in this study consists of a PC-based rehabilitation workstation (running VR simulation exercises and a database), as well as a more traditional therapeutic station.

A. PC Rehabilitation Workstation

Fig. 1 shows the PC system and interfaces used in this study. It consists of a Pentium II 400 MHz PC with a FireGL 4000 graphics accelerator and two input–output gloves. These are the CyberGlove [20] (Immersion Co., San Jose, CA 95131) and the Rutgers Master II-ND (RMII) force feedback glove prototype [30].

The gloves' characteristics make each of them more suited for certain hand rehabilitation exercises. The RMII force feedback structure limits the range of motion of the hand. The elasticity of the CyberGlove does not restrict the user's movement, but it cannot provide an opposing force in the exercises. Thus, the CyberGlove is used in the VR exercises that primarily involve position measurement of the patient's fingers, and the RMII glove is used in force-exertion exercises.

1) CyberGlove: The CyberGlove is a sensorized structure worn on the hand. It has 18 embedded strain-gauge sensors that measure the metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joint angles of the thumb and fingers as well as finger abduction and wrist flexion. The system uses only the MCP and PIP angles of the thumb and fingers.

In order to minimize measurement errors due to hand-size variability, the glove is calibrated at the beginning of each experiment. Every hand joint is placed into two known positions, 0° and 60°. From these measurements, two parameters (gain and offset) are obtained that determine the linear relation between the raw glove-sensor output (voltages) and the corresponding hand-joint angles being measured. The data sets are read through the serial port at a rate of 70 hand configurations per second.

2) RMII Glove: The RMII glove is an exoskeleton device that applies force to the user's fingertips and uses noncontact position sensors to measure the fingertip position in relation to the palm. Lightweight custom pneumatic actuators are attached to the tips of the thumb, index, middle, and ring fingers. Each finger actuator can apply up to 16 N of force when pressurized at 100 psi. The air pressure is provided by a portable super-quiet air compressor.

Infrared sensors inside the actuators measure the displacement of the fingertip with respect to the exoskeleton base attached to the palm. Hall-Effect sensors mounted at the base of the actuators measure their flexion and abduction angles with respect to the base [30].

The glove is connected to an HCI that reads RMII sensors and controls the desired fingertip forces. In order to determine the hand configuration corresponding to the values of the exoskeleton position sensors, the joint angles of three fingers and the thumb, as well as finger abduction, need to be estimated. This computation is based on a kinematic model similar to the one shown in Fig. 2 [11].

The equations for the inverse kinematics are

$$a_1 \cdot S_1 + a_2 \cdot S_{1+2} + a_3 \cdot S_{1+2+3} = D \cdot S_P + h$$
$$a_1 \cdot C_1 + a_2 \cdot C_{1+2} + a_3 \cdot C_{1+2+3} = D \cdot C_P - 1.$$

Additionally, the following constraint equation can be imposed for Θ_3 and Θ_2 [24]:

$$\Theta_3 = 0.46 \cdot \Theta_2 + 0.083 \cdot (\Theta_2)^2 .$$

The system is solved using least-squares linear interpolation. The calibration of the RMII glove consists of reading the sensors while the hand is completely opened. The values read are the maximum piston displacement, minimum flexion angle, and neutral abduction angle. During the experiment, the calibration of the RMII glove is performed before each session.

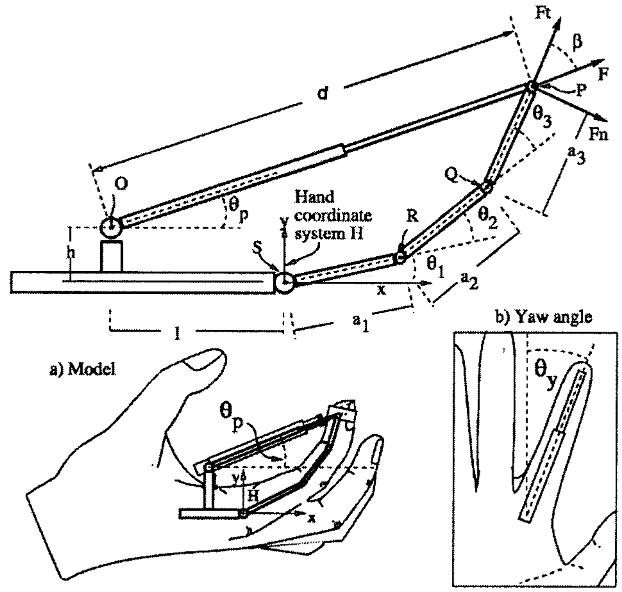

Fig. 2. Finger kinematics [11]. (© Rutgers University. Reprinted by permission.)

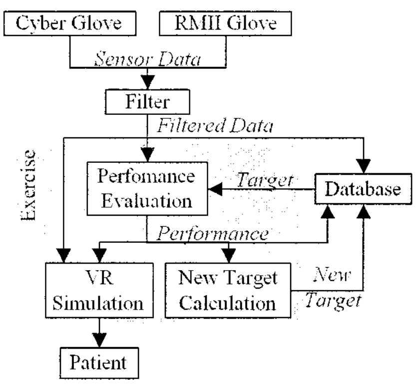

Fig. 3. System software architecture. (© Rutgers University. Reprinted by permission.)

The actuator forces are controlled by the HCI at a rate of 500 Hz [30]. This is done through a servo loop implemented in software on a Pentium 233-MHz embedded board of the HCI. By performing local computations on the embedded Pentium, the host PC is freed to perform mostly graphics computations at a high frame rate needed in the simulations. Communication between the host PC and the HCI is done on a serial line at a rate of 38 400 baud. At this rate, the host receives 157 data sets (hand configurations) per second.

B. Rehabilitation Exercises

The overall software architecture organization for the PC rehabilitation workstation is shown in Fig. 3. The VR simulations consist of four exercises. Each of them concentrates on one particular parameter of the hand movement: range, speed, fractionation, and strength.

The range-of-motion exercise is designed to improve the patient's finger flexion and extension. The patient is asked to flex the fingers as much as possible and then open them as much as possible. In the speed-of-motion exercise, the patient is asked to fully open the hand and then close it as fast as possible. The

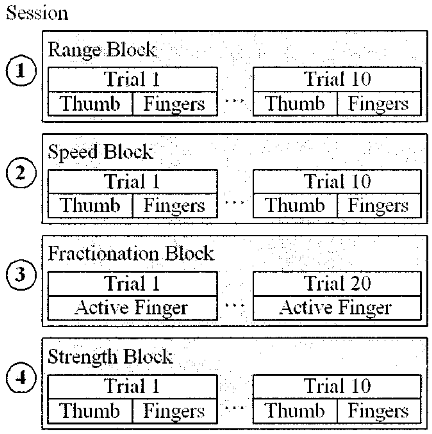

Fig. 4. PC rehabilitation session structure. (© Rutgers University. Reprinted by permission.)

fractionation exercise involves the use of the index, middle, ring, and small fingers. The goal of the exercise is to flex one finger as much as possible while the others are kept open. The exercise is executed separately for each of the four fingers. The strength exercise is designed to improve the patient's grasping. The fingers involved are the thumb, index, middle, and ring. The patient is asked to close the fingers against the forces applied to his fingertips.

To reduce fatigue and tendon strain, the fingers are moved together and the thumb is moved alone for all exercises except fractionation. The exercise is executed separately for the thumb because, when the whole hand is closed, either the thumb or the four fingers does not achieve full range of motion. Executing the exercise for the index, middle, ring, and small fingers at the same time is fine because, here, the fingers do not affect each others' range of motion.

The rehabilitation process is divided into sessions, blocks, and trials. A trial consists of one execution of each exercise. For instance, closing the thumb or fingers is a range-of-motion trial. A block is a group of trials of the same type of exercise. A session is a group of blocks, each of a different exercise. Fig. 4 shows the components of a PC rehabilitation session.

C. Performance Evaluation

During each trial, the exercise parameters are estimated online in order to drive the graphics display and provide feedback to the patient. After the trial has been completed, data collected on the patient's movements are low-pass-filtered at 8 Hz to reduce sensor noise. The parameters are reevaluated and stored, along with the filtered data, into the database.

The patient's performance is calculated per trial and per block. The block performance is the mean and the standard deviation of the performances of the trials involved.

For the range-of-motion and strength exercises, the flexion angle of the finger is considered to be the mean of the MCP and PIP joint angles. The performance measure is

$$\max\left(\frac{\mathrm{MCP}+\mathrm{PIP}}{2}\right)-\min\left(\frac{\mathrm{MCP}+\mathrm{PIP}}{2}\right).$$

The finger velocity in the speed of motion exercise is taken as the mean of the angular velocities of the MCP and PIP joints. The performance measure is

$$\max\left(\frac{\mathrm{speed(MCP)}+\mathrm{speed(PIP)}}{2}\right).$$

Finger fractionation or independence of finger movement is

$$100\%\cdot\left(1-\frac{\sum PassiveFingerRange}{3\cdot ActiveFingerRange}\right)$$

where *ActiveFingerRange* is the current average joint range of the finger being moved and *PassiveFingerRange* is the current average joint range of the other three fingers combined. Moving one finger alone results in a measure of 100%, which decays to zero as more fingers are coupled in the movement. The patient is prompted to move only one finger while trying to keep the others stationary. This is repeated four times for each finger.

D. Baseline Test and Performance Targets

Implementing target-based exercises requires an initial test to evaluate the patient's baseline movement. The evaluation test has the same structure as that of the PC rehabilitation session presented in Fig. 4.

A special case during the baseline test is the strength exercise, which uses the RMII glove. As mentioned above, the range of movement in this glove is somewhat limited, so another set of range evaluations is performed to obtain the patient's mean range while wearing the RMII. The patient's finger strength is established by doing a binary search of force levels and comparing the range of movement at each level with the mean obtained from the previous range test. If the range is at least 80% of that previously measured, the test is passed, and the force is increased to the next binary level. If the test is failed, then the force is decreased to the next binary level, and so on. Test forces are applied until the maximal force level attainable by the patient is found.

The set of targets for the first session is drawn from a normal distribution around the mean and standard deviations given by the initial evaluation baseline test. A normal distribution ensures that the majority of the targets will be within the patient's performance limits. However, the patient will find some new targets easy or difficult depending on whether they came from the low or high end of the target distribution. Initially, the target means are set one standard deviation above the patient's actual measured performance to obtain a target distribution that overlaps the high end of the patient's performance levels. After a block is completed, the distribution of the patient's actual performance is compared to the preset target mean and standard deviations. If the mean of the patient's actual performance is greater than the target mean, then that target is raised by one standard deviation. Otherwise, the target for the next session is lowered by the same amount. To prevent the block targets from varying too little or too much between sessions, lower and upper bounds are placed upon their increments. These parameters allow the therapist to choose how aggressively each training exercise will proceed. A high upper bound means that the targets for the next session are considerably higher than the previous ones. As the targets change over time, they provide valuable information to

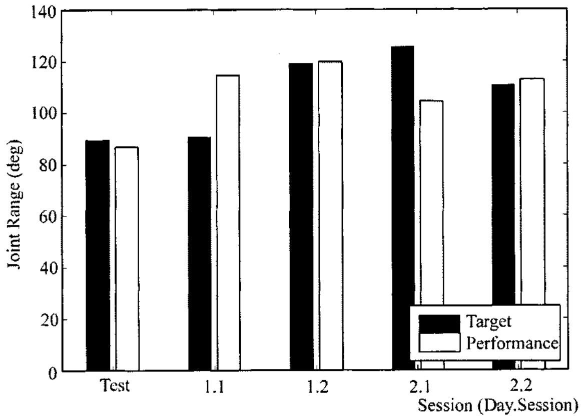

Fig. 5. The mean performance and target levels for the range of movement of a control subject's index finger. The y axis is labeled in degrees [14]. (© ACM. Photo courtesy of ACM.)

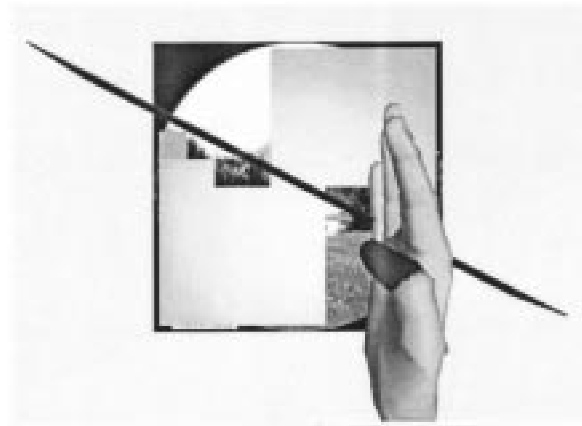

Fig. 6. Range-of-motion VR exercise [14]. (© ACM. Photo courtesy of ACM.)

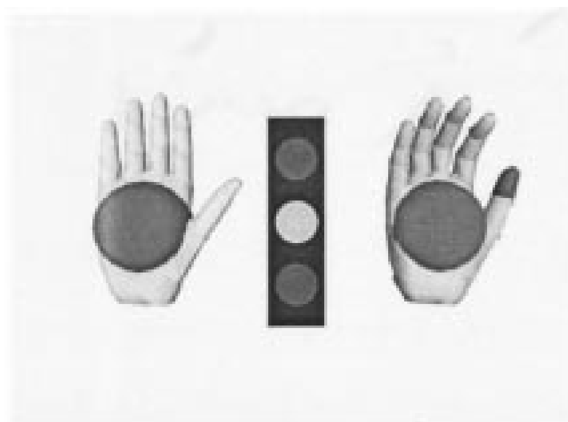

Fig. 7. Speed-of-motion VR exercise[14]. (© ACM. Photo courtesy of ACM.)

the therapist as to how the patient is coping with the rehabilitation training.

Fig. 5 shows a typical set of blocks gathered from a normal subject [14]. The block targets and actual mean performance of the index finger during the range exercise are shown for four sessions taken over a two-day period. The first two columns are the result of the initial subject evaluation, the target being set from the mean actual performance plus one standard deviation. As the exercises proceed, it can be seen how the targets were altered based upon the subject's performance. The block target was increased when the subject matched or improved upon the target level, or decreased otherwise.

E. VR Simulations

For each of the exercises presented above, a VR simulation was developed using the commercially available WorldToolKit graphics library [8]. The simulations take the form of simple games in which the patient performs a number of trials of a particular task. The programs are designed to attract the patient's attention and to challenge him to execute the tasks.

The VR simulations are coupled to the sensing gloves and the performance evaluation modules as shown in Fig. 3. During the trials, the patient is shown a graphical model of his own hand, which is updated in real time to accurately represent the flexion of his fingers and thumb. The patient is informed of the fingers involved in the trial by highlighting the appropriate virtual fingertips in green. The hand is placed in a virtual world that is acting upon the patient's performance for the specific exercise. If the performance is higher than the preset target, then the patient wins the game. If the target is not achieved in less than one minute, the trial ends.

1) Range of Movement: The range-of-movement exercise is illustrated in Fig. 6 [14]. In this exercise, the patient moves a window wiper to reveal an attractive landscape hidden behind the fogged window. The higher the measured angular range of movement of the thumb or fingers, the more the wiper rotates and clears the window. The rotation of the wiper is scaled so that if the patient achieves the target range for that particular trial, the window is cleaned completely.

The fogged window consists of a two-dimensional (2-D) array of opaque square polygons placed in front of a larger polygon mapped with a landscape texture. Upon detecting the collision with the wiper, the elements of the array are made transparent, revealing the picture behind it. Collision detection is not performed between the wiper and the middle vertical band of opaque polygons because they always collide at the beginning of the exercise. These elements are cleared when the target is achieved. To make the exercise more attractive, the texture (image) mapped on the window is changed from trial to trial.

2) Speed of Movement: The speed-of-movement exercise is designed as a catch-the-ball game, as illustrated in Fig. 7 [14]. The patient competes against a computer-controlled opponent hand (on the left in the screen). On a "go" signal (green light on a traffic signal), the patient is required to close either the thumb or all the fingers together as fast as possible to catch a red ball. At the same time, the opponent hand also closes its thumb or fingers around its red ball. The angular velocity of the opponent hand goes from zero to the target angular velocity and then back to zero, following a sinusoid.

If the patient surpasses the target velocity, then he beats the opponent (yellow) hand and gets to keep the red ball. Otherwise, the patient loses, and his ball falls, while the other red ball remains in the opponent's hand.

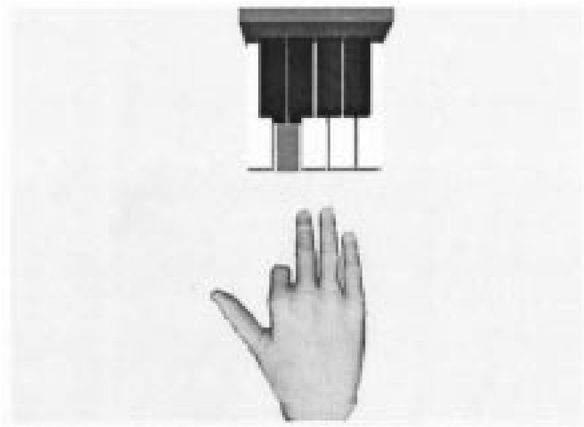

Fig. 8. Finger-fractionation VR exercise [14]. (© ACM. Photo courtesy of ACM.)

Fig. 9. Strength-of-motion VR exercise [14]. (© ACM. Photo courtesy of ACM.)

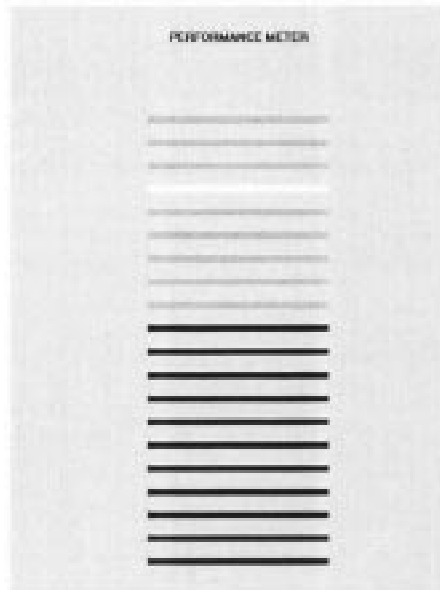

Fig. 10. The digital performance meter shown to the user after every trial. The target level is shown (white bar), as well as the actual performance of the user (black bars) [14]. (© ACM. Photo courtesy of ACM.)

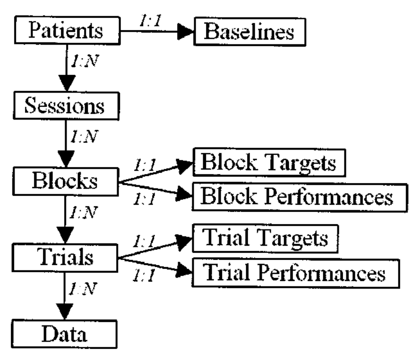

Fig. 11. Database main tables. (© Rutgers University. Reprinted by permission.)

3) Finger Fractionation: The fractionation exercise illustrated in Fig. 8 [14] shows a piano keyboard. As the active finger is moved, the corresponding key on the piano is depressed and turns green. Nearing the end of the move, the fractionation measure is calculated online, and if it is greater than or equal to the trial target measure, then only that one key remains depressed. Otherwise, other keys are depressed, and turn red to show which of the other fingers had been coupled during the move. The goal of the patient is to move his hand so that only one virtual piano key is depressed for each trial.

4) Strength of Movement: In the strength exercise, a virtual model of the RMII glove is controlled by the patient, as shown in Fig. 9 [14]. The forces applied for each individual trial are again taken from a normal distribution around the force level found in the initial evaluation. As each actuator on the RMII is squeezed, the graphical pistons start to fill from top to bottom in a green color, proportional to the percentage of the target that had been achieved. The piston turns yellow and is completely filled if the patient manages to move the desired distance against that particular force level.

Each piston has two fixed points: one in the palm, attached to the base, and one attached to the fingertip. The virtual piston is implemented with the same fixed points; the cylinder is a child node of the palm graphical object, whereas the shaft is a child node of the fingertip graphical object. To implement the constraint of the shaft sliding up and down in the cylinder, for each frame, the transformation matrices of both parts are calculated in the reference frame of the palm. Then, the rotation of the parts is computed such that they point to one another.

After every trial is completed for any of the previously described simulations, the patient is shown a graphical digital performance meter similar to the one illustrated in Fig. 10 [14]. This visualizes the target level and the patient's actual performance during that exercise. It informs the patient of how his performance compares with the desired one.

F. Database Design

The PC exercise data stored in files is subsequently loaded into an Oracle database. In order to fit future developments, the database is designed in a modular fashion that maps to the real-world system. A simplified diagram showing only the main database tables is shown in Fig. 11.

The PATIENTS table stores information about the condition of the patient, prior rehabilitation training, and results of various medical tests. The SESSIONS table contains information about a rehabilitation session such as date, time, location, and hand involved. The BLOCKS table stores the type of the exercise, the glove used (i.e., CyberGlove or RMII Glove), and the version of the data. The version of the data is linked to an auxiliary table containing information about the data stored and the algorithms used to evaluate it. For each exercise, there is a separate TRIALS table containing mainly control information about the status of a trial. There are four DATA tables, one for each exercise. The DATA tables store the sensor readings taken during the trials. For each exercise, there is a separate BASELINES table storing the results of the initial evaluation.

The main purpose of the database is to provide quick access to the data. The targets and performances of the trials can always be computed from the stored sensor readings, but this approach would be very slow due to the high amount of data to be processed. Because the calculation of the targets and performances are always the same, it is a lot faster to do them once and then just access the stored results. The target and performance tables in the lower right corner of Fig. 11 contain this information.

A very frequent operation on the database is to find out to whom an entry belongs. For instance, one may need to know which patient executed a certain trial. To speed up such queries, the keys of the tables on the top of the hierarchy are passed down more than one level. Due to the large size of the DATA tables, the only foreign key passed to them is the trial key.

The data access is provided through a user name and password assigned to each patient and member of the research team. To respect the patient's privacy and to avoid potential undesirable mistakes in handling the data, all the data is stored into a ROOT account. Only the database developers know the root password. The database users (for now, the researchers, but, in the future, this will include the patients) are granted only the appropriate reading and writing privileges [2].

III. Clinical Study

The rehabilitation system described above has been tested on patients during a two-week pilot study. All subjects were tested clinically, pre- and posttraining, using the Jebsen test of hand function [15] and the hand portion of the Fugel-Meyer assessment of sensorimotor recovery after stroke [6]. Grip strength evaluation using a dynamometer was obtained pre-, intra-, and posttraining. In addition, subjective data regarding the subjects' affective evaluation of this type of computerized rehabilitation was also obtained pre-, intra-, and posttrial through structured questionnaires. Each subject was evaluated initially to obtain a baseline of performance in order to implement the initial computer target levels. Subsequently, the subjects completed nine daily rehabilitation sessions that lasted approximately five hours each. These sessions consisted of a combination of VR-based exercises using the PC-based system that alternated with noncomputer exercises. Cumulative time spent on the VR exercises during each day's training was approximately 1–1.5 h per patient. The remainder of each daily session was spent on traditional rehabilitation exercises. Although a patient's "good" arm was never restrained, patients were encouraged to use their impaired arms and were supervised in these activities by a physical or occupational therapist. The latter exercises consisted of series of game-like tasks such as tracing 2-D patterns on paper, peg-board insertion, checkers, placing paper clips on paper, and picking up objects with tweezers.

A. Patient Information

Three subjects, two male and one female, ages 50–83, participated in this study. They had sustained left hemisphere strokes that occurred between three and six years prior to the study. All subjects were right hand dominant and had had no therapy in the past two years. Two of the subjects were independent in ambulation and one required the assistance of a walker. None of the subjects was able to functionally use his or her hemiparetic right hand except as a minimal assist in a few dressing activities.

B. Baseline Patient Evaluation

Each VR-based exercise session consisted of four blocks of 10 trials each. Multiple sessions were run each day for five days followed by a weekend break and another four days. An individual block concentrated on exercising one of the aforementioned parameters of range, speed, fractionation, or strength of movement. Similar to the evaluation exercises, the patients were required to alternate between moving the thumb alone and then moving all the fingers together for every exercise except fractionation. Most trials were started and stopped by the therapist pressing the spacebar, although there were a few patient-initiated trials. As mentioned previously, the patient had to attain a certain target level of performance in order to successfully complete every trial. For a particular block of trials the first set of targets were drawn from a normal distribution around the mean and standard deviation given by the initial evaluation baseline test. A normal distribution ensured that the majority of the targets would be within the patient's performance limits, but the patient would find some targets easy or difficult depending on whether they came from the low or high end of the target distribution. Initially, the target means were set one standard deviation above the patient's actual measured performance to obtain a target distribution that overlapped the high end of the patient's performance levels.

The four blocks of exercises were grouped in one session that took 15–20 min to complete. The sessions were target-based, such that all the exercises were driven by the patient's own performance. The targets for any particular block of trials were set based on the performance in previous sessions. Therefore, no matter how limited the patient's movement actually was, if their performance fell within their parameter range then they successfully accomplished the trial. Each VR-based exercise session consisted of four blocks (range of motion, speed, fractionation, strength) of 10 trials each of finger and thumb motions, or for fractionation only finger motion. The blocks were presented in a fixed order. Either three or four sessions were run each day for five days followed by a weekend break and another four days.

The VR interface and exercises evolved through a series of pilot studies first on users with no hand deficits and, finally, with a user who had suffered a stroke but had nearly normal hand function. The exercises were initially designed to involve single-finger movement, but the number of trials per patient had

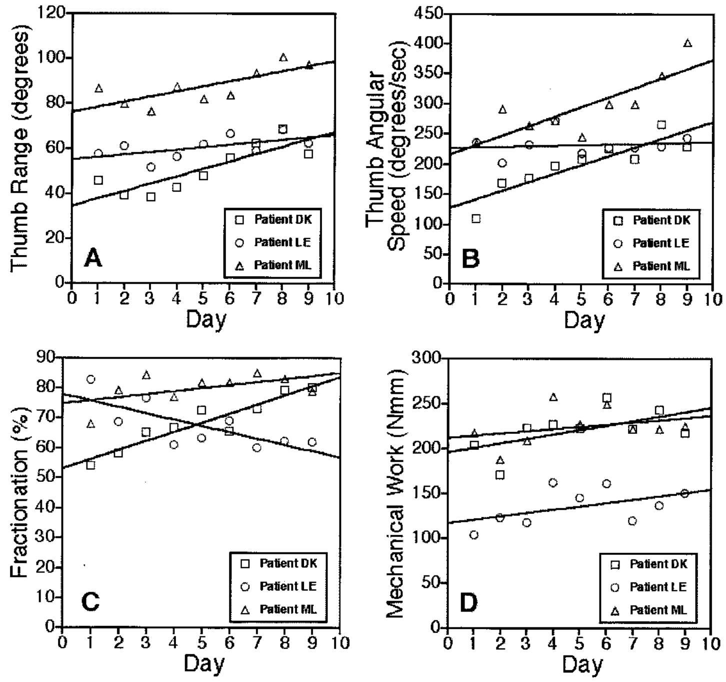

Fig. 12. Clinical study results for all patients. (A) Thumb range of movement. (B) Thumb angular velocity. (C) Index finger fractionation. (D) Thumb average session mechanical work.

to be reduced significantly to counter fatigue. Moving to four fingers and thumb exercises removed this difficulty.

IV. Discussion of Study Results

The great advantage for the therapist of using VR-based exercises is the wealth of objective measures of a patient's performance. Thus, the present study's experimental data consist of objective measures, as well as subjective patient's evaluations.

Fig. 12(A) represents the change in thumb range of motion for the three patients over the duration of the study. Data are averaged across sessions within each day's training. Calculation of improvements or decrements is based on the regression curves fit to the data. It can be seen that there is improvement in all three subjects, ranging from 16% in subject LE, who had the least range deficit, to 69% in subject DK, who started with a very low range of thumb motion of 38°. Fig. 12(B) shows that the thumb angular speed remained unchanged (an increase of 3%) for subject LE and improved for the other two subjects by 55% and 80%, patient DK again showing the largest improvement. Fig. 12(C) presents the change in finger fractionation, i.e., the patients' ability for individuated finger control. For patients ML and DK, this variable showed improvement of 11% and 43%, respectively. Subject LE showed a decrease of 22% over the nine days. Finally, Fig. 12(D) shows the change in the average session's mechanical work of the thumb for the nine rehabilitation sessions. The three patients improved their daily thumb mechanical work capacity by 9–25%.

The data shown in Fig. 12 are, by necessity, limited, because similar measures were taken for the fingers as well. Full data sets have been submitted for publication in a companion clinical paper [27]. The data seem to indicate positive changes at the level of physical hand parameters over this limited clinical study.

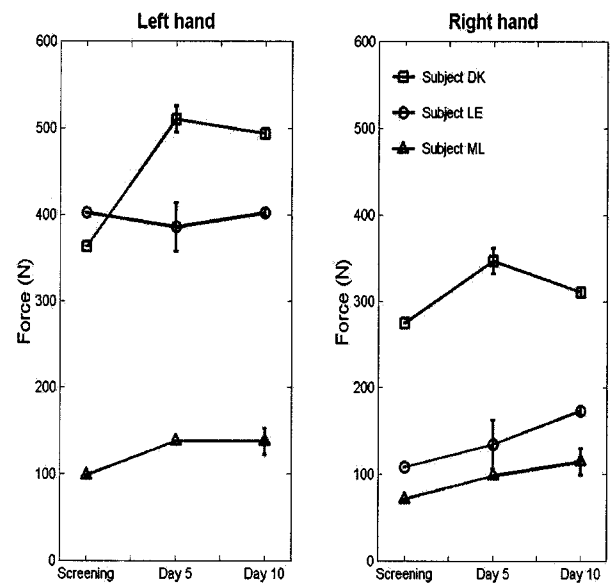

Fig. 13. Dynamometer readings for the three subjects before, during and at the end of trials for left ("good") and right (affected) hands.

Of all the VR exercises, the only one that required force exertion was the piston-pushing exercise using the RMII glove. None of the noncomputer exercises required force exertion above the minimum required to grasp a pen or a paper clip. Thus, if hand-grasping force improved, it was probably due to VR-based therapy. Fig. 13 shows the patients' grasping forces measured with a standard dynamometer at the start, midway and at the end of therapy, for both the "good" (left) and affected (right) hands. It can be seen that all three patients improved their grasping force for the right hand, this improvement varying from 13% for the strongest patient to 59% for the other two. This correlates somewhat with the 9–25% increase in thumb

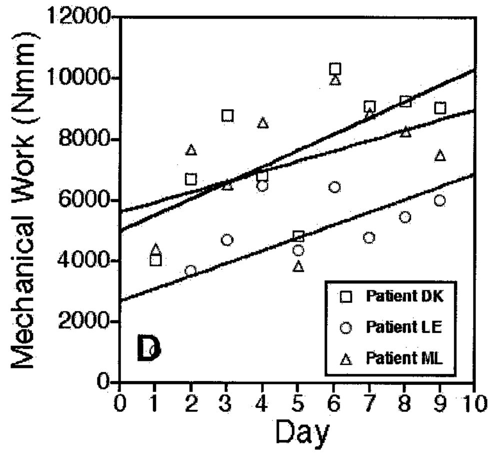

Fig. 14. Daily thumb mechanical work during VR exercises.

average session mechanical work ability shown in Fig. 12(D) for two of the patients. Patient LE had no improvement in his "good" hand, but did show 59% improvement in his right-hand grasping force. This improvement may be due to VR therapy. However, two of the patients had an improvement in the left-hand grasping force as well. In particular, patient DK has a remarkably similar pattern in the change in grasping force for both hands. This is suggestive of other factors influencing their grasping force capacity, such as self-motivation, confidence, and fatigue.

If patient fatigue occurred, that may be correlated with the drop in right-hand grasping force shown in Fig. 13 for patient DK between the middle and end of therapy. The total daily mechanical work (sum of thumb effort over all sessions in a day) is plotted in Fig. 14. Although the regression curve is positive for all three patients, daily values clearly plateau and then drop for patient DK.

An important question is whether the improvements seen in the VR-based exercises transfer to changes in activities of daily living. The results of the dynamometer testing do suggest an increased ability for force development. This is a necessary component of functional hand use. Additionally, the subjects showed changes in the Jebsen test of hand function. This clinical measure tests the time it takes to pick up common household objects of different sizes, weights, and configurations (e.g., beans, coins, food cans). All three subjects showed positive changes on the Jebsen test scores, with each subject showing improvement in a unique constellation of test items. None of the tasks that were a part of the Jebsen battery was practiced during the non-VR training activities. Anecdotally, Fig. 15 shows a patient buttoning his shirt in the second week of the training period. This subject was unable to do this activity prior to his participation in the study.

The changes that we found in the three patients could be due to either the nature or intensity of the VR training or the nature or intensity of the real-world tasks. Because both were incorporated into the two-week training protocol, it is currently not clear whether these improvements were due to the VR-based exercises, the real world tasks, or the combination of both. Constraint-induced (CI) movement therapy, an intervention that utilizes intensive practice of real-world tasks, has been reported

Fig. 15. Subject DK buttoning his shirt. He was not able to perform this task prior to the VR-enhanced rehabilitation training. (© Rutgers University. Reprinted by permission.)

to improve the amount of use of that extremity [33], [35]. It is, therefore, quite reasonable to assume that both contributed, to some degree. Subsequent experiments will be designed to investigate this issue further and distinguish these possibilities. It is conceivable that virtual reality-enhanced rehabilitation may be an innovative way of applying CI therapy. This procedure may be thought of as a particular form of shaping (see [34] for a discussion of shaping procedures).

Subjective evaluation data from the patients was also positive. In a follow-up questionnaire, all three patients strongly agreed that they wished the VR-based tasks had been part of their original poststroke therapy. All three agreed that their right hand motion improved and they felt that, with practice, it would improve more. Two of the three patients strongly agreed that they would be willing to continue undergoing the intensive training of this project.

V. Conclusion and Future Work

VR technology has the potential to impact traditional rehabilitation techniques. A PC-based VR system for rehabilitating hand function in stroke patients was developed. The system exercises four parameters of hand movement: range, speed, fractionation, and strength. A novel performance-driven exercise program was outlined, in which a patient's own performance dictates future session targets.

The VR rehab system was evaluated on three stroke patients in an intensive therapy program. Typically, three or four sessions of the four training exercises detailed here were run every day, five days a week, for a total of nine days followed, on the tenth day, by a reevaluation. Objective measurements revealed that each patient showed improvement on most of the hand parameters over the course of the training. Independent dynamometer measurements also showed significant grasp-force increases in two of the three patients' right hands. Two of the patients had improvements in their left ("good") hands, as well. One patient had no improvement in the left hand-grasping force, but did show a 59% increase in right hand grasping force. Because the VR-based therapy was the only training that included a force exertion exercise, this result may be indicative of positive effects.

The subjects showed improvement in functional activities of daily living, although is not possible, at this point, to distinguish the contributions of the VR training and the real-world training. Further studies are planned to elucidate these distinctions and to quantify the overall clinical efficacy of VR-based therapy for stroke patients. VR rehabilitation may become an interesting and useful adjunct to traditional therapy by providing objective quantification of the training process, as well as a motivating way of using massed practice.

A web interface to the Oracle database is being developed to provide easy access for data retrieval and analysis. A left-handed RMII glove is under development to support patients with left-handed deficits. Also, other haptic devices for applying force feedback to the elbow and shoulder are under consideration.

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