The Rutgers Arm II Rehabilitation System—A Feasibility Study

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***Abstract*—The Rutgers Arm II (RA II) is a new system that trains the shoulder/arm motor control, strengthening, arm speed of motion, endurance, and grasp strength in a single rehabilitation session. The system components are a tilted low-friction table, a forearm support with markers and wireless transmitter, a shoulder appendage to detect compensatory leaning, infrared vision tracking, a large display and a PC running custom virtual reality games. Three participants in the chronic stage post-stroke were trained on the RAII for four weeks (12 sessions) and had a follow-up evaluation after three months. The results of this study indicate that the participants were able to use the technology, and preliminary results are encouraging. One participant showed improvement in all timed Jebsen–Taylor test tasks, all participants had a larger shoulder range-of–motion and pinch strength of the affected hand post-training. Computerized measure of supported arm reach area increased in two participants post-training and in all participants at follow-up. Participants reported an improved ability to perform activities of daily living with the affected arm. There was good compliance by the participants, each of whom attended all sessions. The participants accepted the training length, even with some sessions lasting 1 h (excluding rest periods). The participants' subjective evaluation rated the system an average 3.7 out of 5 (see also the accompanying taped video interview of one of the participants).**

***Index Terms*—Grasp strength, gravity, infrared tracking, stroke, upper extremity, virtual reality.**

I. INTRODUCTION

STROKE in adults is a celebrovascular accident caused by hemorrhage or blockage of the blood vessels in the brain. This results in paralysis of the contra-lateral half of the body. In United States there are about 780 000 new cases of stroke yearly [1]; survivors typically undergo up to eight days of acute in-hospital physical rehabilitation [2]. After discharge from hospital many clients are admitted to specialized in-patient rehabilitation facilities, followed by outpatient rehabilitation. After six to nine months from the onset of stroke, the clients are considered chronic, facing a life of disability [3].

Advances in neuroscience have shown that upper extremity (UE) function can be improved in the chronic phase post-stroke, as long as therapy is intensive, repetitive, rewarded, attended and goal-driven [4]. Improvement in the UE of these clients is due to axonal sprouting from the cortex contralateral to an infarct into the cervical spinal cord and brainstem ipsilateral to the infarct [5], as well as to neuroplasticity [6], the ability of the brain to reorganize neural pathways in response to new experiences. Neuroplasticity observed post-stroke is an adaptive mechanism by which active neurons in the adjacent areas are recruited to the function lost in the area affected by stroke, or dormant neurons become active [7]. This process creates new pathways which in turn allow a degree of recovery in UE motor control and function. Unfortunately, the repetitions and time needed to induce brain plasticity may also produce boredom, which may reduce the effectiveness of the prescribed therapy by diminishing client participation and engagement.

Robotics has previously been proposed as a means to help the therapist during the required long, repetitive training period. Robots have been successfully used to train arm movement in the acute [8] and chronic post-stroke phases [9]. The need to maintain client safety when using or wearing a robot is well understood, and various hardware and software redundancies are utilized [10]–[12]. However, these robotic mechanisms, together with structures constructed to provide gravity offloading of the affected limb [13] tend to increase the overall system cost and complexity.

One way to address the need for a lower-cost, safe and engaging UE rehabilitation, while maintaining gravity support, is to use a rehabilitation table, coupled with a graphics display showing games. Pioneering work in the use of games to increase motivation in clients with chronic stroke training their upper extremity was done by Bach-y-Rita [14]. It has been reported that therapy using virtual reality games should improve patient motivation through gradated task success [15], by improving game design. Several computerized table-type rehabilitation systems are currently being developed worldwide. Chen *et al.* proposed an UE training system that uses an "arm skate" (wrist support on wheels) that is moved by the client on a horizontal table [16]. The client's movements are tracked magnetically through a combination of a permanent magnet embedded in the arm skate and an array of electromechanical relays in the table. A computer displays a variety of patterns to be replicated on the training table. Visual feedback in the form of a trace of the actual pattern "drawn" by the client's arm skate is presented in order to improve motor control.

Manuscript received July 08, 2009; revised November 20, 2009; accepted March 27, 2010. Date of publication June 07, 2010; date of current version October 08, 2010. This work was supported in part by a grant from the Coulter Foundation and in part by Cristian and Andreea Francu1.

A supplementary downloadable video to this article provided by the authors is available at http://ieeexplore.ieee.org.

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Digital Object Identifier 10.1109/TNSRE.2010.2052128

Kuttuva *et al.* later developed a system called the “Rutgers Arm” where clients used a low-friction forearm support with no wheels and moved their affected arm on a horizontal low-friction table [17]. Movement of the arm was tracked magnetically through a Polhemus Fastrak sensor (Colchester, VT), which provided higher resolution than the 45 × 25 reed relay array used by Chen. Clients sitting at the Rutgers Arm table interacted with several virtual reality exercises, with the therapist present in the room or located at a distance. A client with chronic stroke showed a 15% improvement after using this system for five weeks, as measured by the UE portion of the Fugl–Meyer Assessment [18]. He maintained training intensity and duration even when the therapist was observing over the Internet from a location 30 miles away. However, the magnetic tracker used increased system cost, interfered with arm movement due to the cable associated with the sensor on the client’s wrist, and induced position errors due to its sensitivity to adjacent magnetic fields.

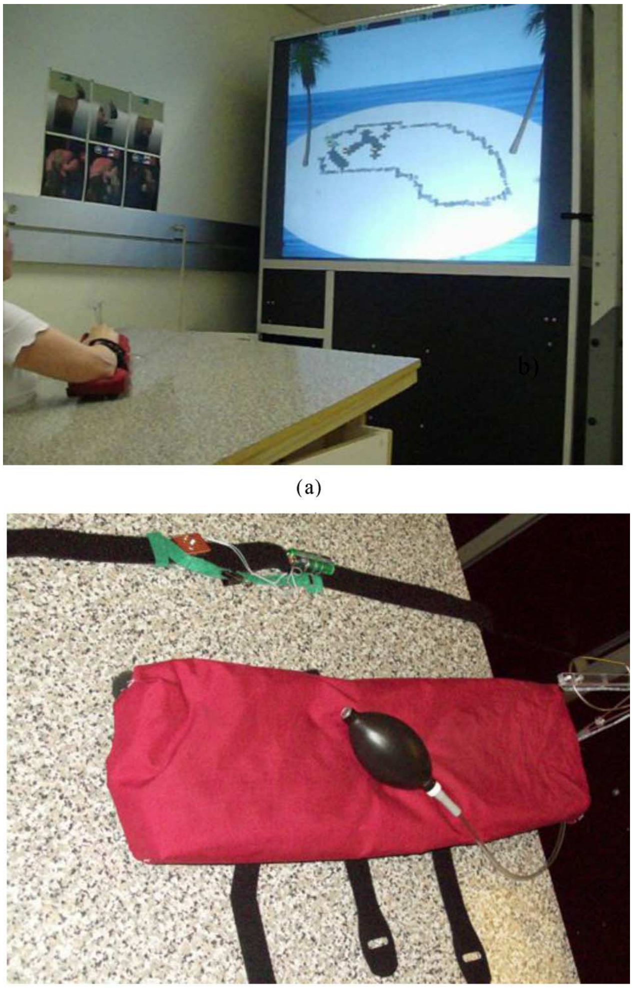
Mumford *et al.* have more recently developed a computerized system in which the horizontal table is itself a high-definition display. Clients use a cylinder containing a Wii wireless remote in pick-and-place tasks where the pick and place locations are interactively presented on the table display [19]. Tracking of the cylinder (and thus of the arm movement) is accomplished by using a combination of infrared LEDs, the Wii infrared camera and an overhead video camera. This low-cost vision tracking arrangement unencumbers the client and is a cheaper alternative than either magnetic trackers or vision trackers using reflective markers and specialized cameras [20]. However, since no UE gravity support is provided, this system is more appropriate to clients who are able to overcome the gravity loading on their affected arm.

A commercial system which does provide gravity support is “Armeo” (Hokoma AG, Switzerland). It is not a table-like system but a passive exoskeleton that provides gravity support to arm reaching movements. Similarly to the system described in this study, Armeo measures grasp strength, which, in addition to arm movement, is used to play rehabilitation video games [21].

The Rutgers Arm II system, presented here, is designed around the principles of low-cost infrared tracking, gravity modulation, combined strengthening of the arm and hand and the use of custom virtual reality games [22]. This paper reports on a feasibility study of the system, which had as aims: 1) to examine potential changes in impairment and hand function following training on the Rutgers Arm II and the retention of these gains, and 2) to examine acceptance of this technology by adults in the chronic phase post-stroke and determine any necessary changes to the system.

II. METHODS

A. Hardware Setup



(a)

(b)

Fig. 1. The Rutgers Arm II: (a) System view; (b) detail view of the forearm support and the shoulder assembly. Rutgers University Tele-Rehabilitation Institute. Reprinted by permission.

TABLE I
SYSTEM HARDWARE COMPONENT COSTS. RUTGERS UNIVERSITY TELE-REHABILITATION INSTITUTE. REPRINTED BY PERMISSION

Hardware component	Approx. Cost ($)
PC multi-core workstation	3,000
Video camera	130
Large flat rear projection TV 183 cm diagonal	2,200
Electronics in arm support	500
Table and chair	1,000
Software	custom
Total cost	>6,830

A view of the Rutgers Arm II system is shown in Fig. 1(a). Clients sit at a square table with a corner cut out, facing a large custom rear-projector display (150 cm × 112 cm, or 183 cm diagonal). A Dell Dimension XPS 720 quad core workstation renders the graphics which the client sees projected on a monoscopic display. The configuration shown in Fig. 1(a) corresponds to the setting for training the right arm and shoulder. For left arm/shoulder training, the table is rotated 90° counter clockwise. The system hardware components and their cost are listed in Table I.

1) Low-Friction Tilting Table: The rehabilitation table has a special construction that tilts four ways, pitching up or down, and rolling left or right. The dimensions of the table are 117 cm on the long edges, 61 cm on the short edges and 74 cm height when the table top is flat. Tilting is intended as a way to apply additional gravitational loading on the trained arm, without the need for actuators. Tilting is performed manually, with values of 0°, 10°, 15°, 20°, 25°, and 30° possible by placing pairs of spacers under the top surface frame. The length of the pair of spacers determines the tilt angle, while the direction of tilting depends on which side of the table is lifted by the spacers. For example, when the spacers are placed under the distal edge, the table is pitched up [Fig. 1(a)]. It is thus possible to either assist or resist the desired movement. A client with weak shoulders and small arm movement might benefit from tilting the table such that the proximal table edge is higher than the distal one, causing gravity to pull their arm down and away from the body. The reverse is true for clients that are further in their recovery, and thus are resisted by having to move their arm up a slope. While the table top can tilt in multiple ways, in the feasibility study described here, the table was only tilted upward. The three corners of the table surface, which correspond to the long sides, have infrared LEDs powered by a dc source placed near the table, as part of the vision tracker assembly described later.

2) Sensorized Forearm Support: The affected arm is placed onto a rectangular forearm support, shown in Fig. 1(b). The forearm support weighs about 0.5 kg, and is 51 cm in length, and 15 cm in width. The support is formed of two plastic sheets separated by 1.3 cm spacers. The top of the support is padded with foam for increased comfort and has a removable fabric that can be washed to improve hygiene. The underside of the forearm support has a number of small Teflon balls which minimize friction with the tilted table. The forearm support includes three Velcro straps used to secure the client's forearm and hand, and a retractable extension with two infrared LEDs that are located above the hand. A 5 V rechargeable battery set, located between the support plastic sheets, powers these LEDs and other electronics related to grasp strength sensing. The forearm support contains a custom grasp-strength sensor with deformable rubber pear connected to an air pressure sensor. The sensor analog signal is digitized by electronics in the forearm support and sent by an embedded wireless transmitter to the PC, allowing the PC to determine in real time whether and how hard a participant is grasping. This information is used to add features and gradate difficulty levels of the games. A micro-switch in the proximal end of the forearm support detects if the elbow lifts off the table (at extreme flexion), thus detecting a form of compensatory arm movement that had previously been observed.

3) Shoulder Assembly: Conventionally, leaning movements are limited by strapping the client's trunk in the chair. A more dignifying approach is proposed here. In this study, the clients wore a Velcro strap on the shoulder contra-lateral to the arm being trained. The shoulder assembly [Fig. 1(b)] incorporates a small board with a single infrared LED, a rechargeable battery and connecting wiring. The role of the shoulder assembly is to detect unwanted (compensatory) trunk leaning. Software is able to detect leaning in any direction above a therapist-set threshold and can send feedback to the client by, for instance, producing a beeping sound and displaying an "avoid leaning" message on the game screen.

4) Active Vision Tracker: Apart from the infrared LEDs described previously the vision tracker system includes a low-cost overhead digital camera (Creative WebCam Live) with a resolution of 320 × 240 pixels. The camera is mounted on the ceiling (145 cm above the table), and its position does not change with the table tilt. This allows the camera to image the entire table surface, as well as the client's shoulder assembly. The placement of the camera on the ceiling replaces an earlier heavier version of the system which used a U-shaped aluminum camera support attached to the table. The camera is connected via an USB port to the PC, with a tracking rate of 30 frames per second (fps) and a forearm movement resolution of 7 mm. While better resolution could be obtained with newer camera models, the current frame rate and resolution were found to be sufficient. The camera is a regular vision camera retrofitted with an infrared filter (RG-780 Long Pass Filter 12.5 mm diameter), to view only the infrared LEDs of this active marker tracker.

The active-marker tracker solution presented here is simpler, cheaper, and easier to implement than a passive marker solution. Furthermore, unlike passive marker approaches, active vision tracking is unaffected by the level of ambient lighting, allowing lighting adjustments per the client's preference. The vision tracker used here has additional advantages compared with the magnetic trackers used in the earlier version of the system in that it is unaffected by metal and magnetic fields in the vicinity, is significantly cheaper, and, being wireless, unencumbers the client. Its disadvantage is the need to periodically recharge the batteries for the shoulder assembly and forearm support markers. In the current arrangement the batteries need to be recharged after every 30 h of continuous use.

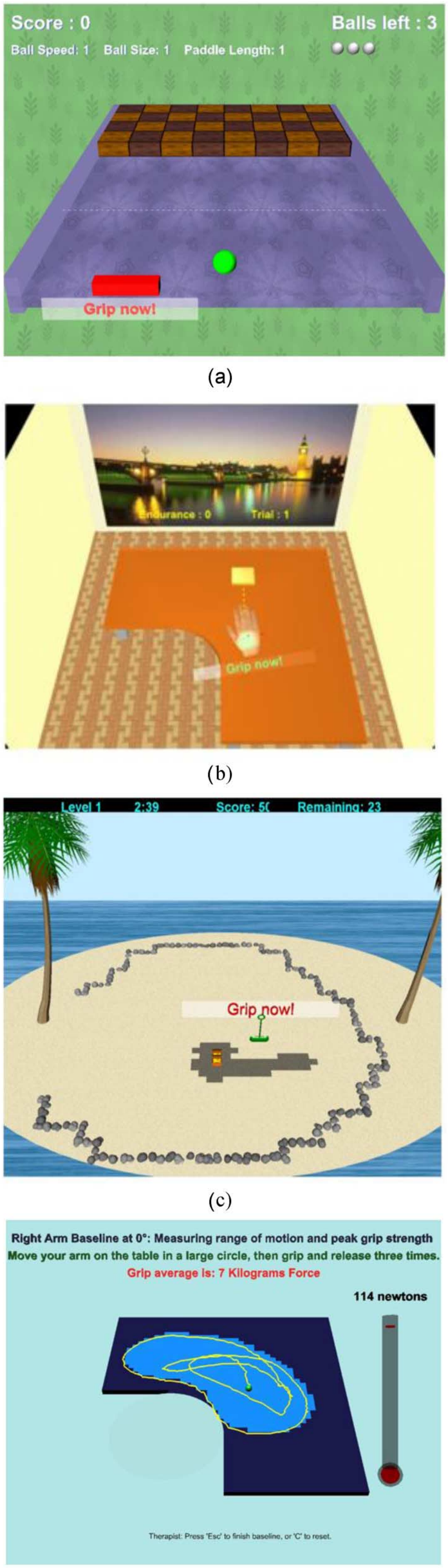
B. Software Setup

1) Tracking Software: The vision tracking software was developed in Java with Java Media Framework API (JMF) [23] and Java Advanced Imaging API (JAI) [24]. Java Media Framework provides support for audio, video, and other time-based modalities. In the Rutgers Arm II vision tracking software, JMF is used to capture the camera image while JAI processes that image. At program execution, the first image is used for camera calibration, imaging the three LEDs at the table corners. The calibration process checks for any difference between the table and camera coordinates and compensates for such differences. A method, based on three channels per pixel, returns the position of each LED. This is in turn used to determine the position of the forearm support and shoulder assembly.

2) Physical Rehabilitation Games: Three Java3D [25] games were custom designed due to the need to allow play by participants for which off-the-shelf games may not be practical and to support the clinical function, allowing better control on levels of difficulty and better adaptability to each client. Under these conditions, games become reasonably winnable by any client, providing a positive effect on morale and determination, and keeping the client interested in applying maximum effort. The games used in this study are aimed at improving response time, hand–eye coordination, UE motor control, range-of–motion (ROM), shoulder strength, endurance, grasp strength and coordination of grasp and reach.

The *Breakout 3D* game [Fig. 2(a)] was developed to train hand–eye coordination and arm speed of movement. The client is tasked with destroying an array of cubes by bouncing a ball off a paddle avatar controlled by the affected arm. Depending on the orientation of the cube array, the game induces mainly flexion/extension (in–out) or abduction/adduction (left–right) arm movements. The extent of arm reach in either direction, measured at baseline, is mapped to the paddle excursion on the playing board, so that the client is able to reach any location on the board. The difficulty of the game is increased by making the balls faster and the paddle smaller. Additionally, participants are required to grasp above their baseline-dependent threshold just before the ball hits the paddle, otherwise the ball passes though the paddle and is lost. After each bounce off the paddle, the ball can destroy at most one cube. This feature is intended to maximize the movement needed to destroy the whole array. Participants have found this game to be engaging. Knowledge of results (KR) is implicit in the ability to dynamically bounce the ball, as well as seeing the number of cubes diminish throughout the game. If the client does not move sufficiently fast, does not grasp in time, or has diminished hand–eye coordination, then the number of allowed balls is expanded early, and the cube array is only partially destroyed. Additional KR is provided as a percentage of cubes destroyed, and applause is heard once all cubes are destroyed.

The *Pick-and-Place* game [Fig. 2(b)] trains the UE motor control and grasp strength. The client is asked to closely follow a prescribed path. The location of the ball and target is a function of the arm reach baseline, assuring that the client is capable of executing the extent of the movement. The client first overlaps a hand avatar over the ball and squeezes above a threshold to pick the ball up. Subsequently the client can relax the grasp and place the ball into a rectangular target area, while following a prescribed path. Depending on the relative positions of the ball and the target, the trained movement requires in alternating sequences, abduction/adduction, flexion/extension, or combination of both. When the table is tilted up, movement away from the body is resisted by gravity, and that towards the body is assisted. The game displays a trace of the actual hand movement, overlaid on the prescribed path. This KR allows the participant to judge immediately how close the prescribed path is followed. At the end of a number of pick-and-place repetitions, KR is provided in the form of a bundle of traces. The more uniform the arm movement and the closer to the prescribed path, the tighter this trace bundle is, and the less wavy it is. This graphical KR is supplemented numerically by the path error representing the closeness between the actual path and the prescribed one, over a number of trials. The design of this game is in line with motor learning theory [26] which emphasizes practice through repeated execution of a movement, and transfer to function. The transfer to function relates to pick-and-place activities where hand motion generally follows a straight trajectory.



Right Arm Baseline at 0°: Measuring range of motion and peak grip strength

Move your arm on the table in a large circle, then grip and release three times.

Grip average is: 7 Kilograms Force

Therapist: Press 'Esc' to finish baseline, or 'C' to reset.

Fig. 2. Game scenes: (a) *Breakout 3D* game; (b) *Pick-and-Place* game; (c) *Treasure hunt* game; (d) *Baseline* game. Rutgers University Tele-Rehabilitation Institute. Reprinted by permission.

The *Treasure Hunt* game [Fig. 2(c)] is aimed at increasing arm endurance and speed, and grasp strength. The game depicts an island on which a number of treasures are buried in the sand. The participant controls a shovel avatar by grasping above a threshold and digging out as many treasures as possible in the allowed amount of time. The session baseline is used to map an area the island where treasures are hidden, which is delineated by a wall of boulders. Treasures buried closer to the boulders are worth more points if discovered, as they require movement at the extreme of arm reach. If leaning is detected, treasures remain hidden, even if the shovel avatar overlaps them, and auditory and text prompts advise the client to stop leaning. Depending on the level of difficulty, treasure location cues are visible as **X**s on top of the virtual sand, or visual cues require participant's repeat squeezes of the force sensor in the forearm support. The difficulty of the game is further increased by periodic sand storms which partially cover the already-discovered treasure chests, in turn requiring more arm movement. Thus the client is motivated to move quickly, before the onset of the next storm. The more treasures are uncovered, the more points the participant scores. KR is provided through graphics and sound by the appearance of uncovered treasures and numerically through the total gold coins found, and the number of chests remaining to be found. Additional KR is the percentage of treasures found displayed once the allowed time had lapsed. To further motivate the client, the game has the relaxing sound of waves washing on the beach, and plays applause when the client has high scores.

The *Baseline exercise* [Fig. 2(d)] is aimed at measuring the affected arm ROM and hand grasping strength while the forearm is supported by the table. The area that the client can reach with the affected arm, while sitting comfortably without leaning, represents the reach baseline. It is measured at the start of each session and is client-, date-, and table tilt-specific. The client is instructed to "clean" the table avatar as much as possible, by moving the affected arm without leaning. The area the client is reaching is interactively updated [27], while the tracking software monitors trunk leaning. Depending on the leaning threshold, the arm reach baseline exercise records an approximation of the client's actual capability that day. The grasp strength baseline exercise immediately follows the arm reach baseline. The client squeezes the rubber pear in the arm support, while a thermometer-like gage to the side of the screen shows the peak grasp force. The system averages three maximum voluntary grasps, and the value is displayed at the top of the screen. A percentage of this average (set by the therapist at 25% in this study) is subsequently used as a threshold to detect momentary grasping during games. This percentage is in line with studies on post-stroke grasp strength and fatigue as a percentage of Maximum Voluntary Contraction [28].

C. Experimental Protocol

The training on the Rutgers Arm II system consisted of 12 sessions over four weeks, with a duration that progressed from 40 min (week 1), to 50 min (week 2), and 1 h (weeks 3, 4). The intensity of training was also increased from training on a horizontal table (weeks 1, 2) to training on a table tilted up at 10° (week 3) and tilted up 20° (week 4). Each session consisted of a baseline exercise followed by a sequence of exercises (*Pick-and-Place*, then *Breakout 3D*, followed by *Treasure Hunt)* and the sequence repeated as needed to produce the prescribed session duration. Each exercise difficulty was progressed from easier games in weeks 1 and 2 to more difficult ones in weeks 3 and 4.

D. Recruitment

Three clients in the chronic phase post-stroke participated in this feasibility study. They had been recruited from local aphasia support groups and were receiving speech therapy at Kane University, Union, NJ. None were receiving other physical or occupational therapy (PT/OT) during the study. Speech disability was not an exclusion criterion here, since participants did not interact with the simulations through voice commands. The exclusion criteria were stroke which occurred less than six months prior and limited cognition, such that clients could not understand what was expected of them in the study.

Participant 1: a 61-year-old female suffered an occluded carotid artery and a left hemisphere stroke which occurred 42 months prior to the study. After the stroke the participant underwent six days of intensive care followed by three weeks of in-patient rehabilitation at a major regional hospital. This was followed by two months of PT/OT outpatient rehabilitation and a longer period of speech therapy. This participant reported she had major loss of hearing on the right side which occurred six months post-stroke. She had a history of high cholesterol and depression, for which she was taking Zochor and Lexapro, respectively. The participant did not practice physical exercises outside the study.

Participant 2: a 67-year-old female, had a history of multiple strokes and seizures. She sustained a left-sided ischemic stroke 38 months prior to the study, for which she had one month of outpatient PT/OT. Subsequently she had a second possible ischemic stroke 33 months prior to the study and a seizure 29 months prior to the study. As a result of the multiple cerebro-vascular accidents the participant presented with bilateral visual field cut affecting her right inferior and left superior vision quadrants. She was taking Keppra to control seizures and did not practice physical exercises outside the study.

Participant 3: a 55-year-old male, who had sustained a left ischemic stroke 18 months prior to the study. He was in intensive care for one week which was followed by one month of in-patient PT/OT and speech therapy. Following discharge from the hospital this participant had 23 days of subacute therapy, and six months of outpatient PT/OT. Participant 3 had a history of high blood pressure, high cholesterol, and smoking. The participant had seizures prior to the study and was taking Keppra to control them. He was training for strength at a local gym, which he was allowed to continue during the study.

All participants received medical clearance from their physician and signed a Consent/Assent Form approved by the Rutgers Institutional Review Board (IRB). Training took place at the Rutgers Tele-Rehabilitation Institute, Piscataway, NJ. The physical therapist that performed the evaluations was not blinded to the study and is a coauthor of this paper.

III. OUTCOMES

Outcomes reported here represent four weeks of therapy and a follow-up evaluation session at three months post-training. They refer to clinical measures, computerized measures and self-reported questionnaires.

A. Clinical Measures

The primary standardized test used in this study was the Jebsen–Taylor Test of hand function [29]. This test was administered in the first session, the last session and the follow-up evaluation. A secondary standardized test was the change in active ROM in the affected arm and fingers, which was measured using mechanical goniometers. Changes in hand grasp and in pinch grasp forces were measured with a Jamar mechanical dynamometer and pinchmeter, respectively. Grasp strength was

TABLE II
Changes in Jebsen-Taylor Test of Hand Function (Session 1, Session 12, and Three-Months Follow-Up). Time in Seconds. Rutgers University Tele-Rehabilitation Institute. Reprinted by Permission

Task	Participant 1			Participant 2			Participant 3		
	PR	PO	FU	PR	PO	FU	PR	PO	FU
Writing	46	35	31	27	23	31	146	160	131
Page turning	12	8	11	5	5	5	26	36	19
Lift small objects	46	26	35	7	8	6	110	147	180
Simulated Feeding	32	22	20	8	11	8	28	26	15
Stack checkers	81	12	45	5	5	5	30	49	77
Lift large light objects	16	12	21	4	4	4	27	16	30
Lift large heavy objects	10	6	12	4	5	4	36	16	26
Total time	243	120	176	60	60	63	403	449	478
Average Time	35	17	25	9	9	9	56	64	68

measured three times in each category and the three readings were averaged. These examinations were done in session 2, at the start of the last training session and at the follow-up evaluation.

B. *Computerized Measures*

Measurements were provided by data sampled transparently by the Rutgers Arm II system. The primary indicator in this category is the change in arm reach area measured at baseline. For this measure the table was made flat in the last rehabilitation session and arm reach was measured, so as to maintain the same table tilt with that in the first week of training. Session 12 then resumed, with the table tilted at 20° and another baseline taken, since the baseline is tilt-specific. Another computerized measure presented here is the trace bundle (20 repetitions) of hand trajectory during pick-and-place exercises (session 2 versus session 12). Space limitations prevent the inclusion of more computerized measures here.

C. *Self-Reported Questionnaires and Video*

Activities of Daily Living (ADLs) performed with the affected arm/hand were reported by participants or their care givers by completing a standardized form [30] at the start of therapy, at the end of therapy and at three-months follow-up. All participants were compliant in returning their questionnaires on time. Another self-report was a subjective system evaluation completed by the participants online at the end of every rehabilitation week. This form was not standardized and consisted of nine questions rated on a five-point scale, with 1 corresponding to the least desirable outcome and 5 to the most desirable one. A postintervention interview was taped with one of the participants (video included with this article).

IV. RESULTS

Aim I: Changes in UE impairment and hand function

A. *Clinical Measures*

Table II shows the Jebsen–Taylor test results for the three participants measured at start of training (PR), end of training (PO), and after three months (FU). Times are given for the affected arm, for each test component task (writing, page turning, lifting small and large objects, simulated feeding, and stacking checkers), as well as the total time to complete these tasks and the task average time. Participant 1 improved: she was able to complete the battery of tasks in half the time at the end of therapy as compared to PR. Participant 2 had no change, while Participant 3 performance worsened by 11%. At follow-up Participant 1 maintained some of the gains (she was 28% faster than prior to training), Participant 2 performance had not changed, and Participant 3 took 19% longer to perform the timed tasks compared to PR.

TABLE III
Changes in Shoulder, Arm, and Hand Active ROM (in Degrees) for the Affected Hand. Rutgers University Tele-Rehabilitation Institute. Reprinted by Permission

	Participant 1			Participant 2			Participant 3		
Joint	PR	PO	FU	PR	PO	FU	PR	PO	FU
Shoulder flexion	133	133	129	155	163	170	130	140	121
Shoulder extension	47	48	65	44	40	62	45	50	50
Shoulder abduction	105	135	130	157	165	168	95	115	104
Shoulder Internal rotation	74	80	84	55	55	90	44	65	60
Shoulder External rotation	74	87	72	80	85	84	60	72	54
Elbow flexion	142	148	144	130	142	140	140	138	138
Elbow extension	8	6	4	0	0	0	7	8	6
Elbow pronation	53	60	78	78	80	90	90	72	90
Elbow supination	64	70	56	88	72	90	77	60	60
Thumb PMP flexion	48	48	55	50	67	68	38	53	41
Thumb PMP extension	0	0	4	0	0	23	0	0	7
Thumb abduction	47	48	-	69	73	-	42°	48°	-
Index PMP flexion	82	87	89	69	92	90	86	86	76
Index PMP extension	8	10	11	13	18	7	5	0	8
Middle PMP flexion	87	88	88	90	90	88	78	86	83
Middle PMP extension	14	18	26	5	20	6	2	1	2
Ring PMP flexion	88	89	88	76	91	87	80	82	83
Ring PMP extension	42	38	28	10	34	22	2	5	2
Little PMP flexion	80	90	96	85	94	88	88	77	90
Little PMP extension	63	50	32	10	35	36	12	12	8

Table III shows the shoulder, elbow, and fingers active ROM (in degrees) for the affected UE measured at PR, PO, and FU. All participants improved in their shoulder abduction and maintained these gains three months post-training. All three also improved at the end of training in their shoulder external rotation. Participant 2 had substantial increases in finger extension (38%

TABLE IV
CHANGES IN PARTICIPANTS' GRASP AND PINCH STRENGTH (NEWTONS). RUTGERS UNIVERSITY TELE-REHABILITATION INSTITUTE. REPRINTED BY PERMISSION

	Participant 1			Participant 2			Participant 3		
Test	PR	PO	FU	PR	PO	FU	PR	PO	FU
Grip strength (dynamometer)	184	177	142	182	151	153	242	240	245
Pinch strength pulp-to-pulp Thumb with index	28	51	22	24	24	18	9	38	15
Pinch strength pulp-to-pulp - Thumb with third finger	39	30	-	13	13	-	unable	21	-
Pinch strength Key grip- Thumb with index	67	59	71	22	27	28	68	48	87
Pinch strength three tips grip - Thumb-index-middle	40	53	41	18	18	16	4	19	9

Rounded to the nearest Newton

TABLE V
PARTICIPANTS CHANGES IN ACTIVITIES OF DAILY LIVING OVER THE FOUR WEEKS OF TRAINING AND AT FOLLOW-UP. RUTGERS UNIVERSITY TELEREHABILITATION INSTITUTE. REPRINTED BY PERMISSION

Activities	Participant 1			Participant 2			Participant 3		
	PR	PO	FU	PR	PO	FU	PR	PO	FU
Any of your usual work, household or school activities	2	3	4	4	4	5	2	3	2
Your usual hobbies, recreational or sporting activities	2	3	4	3	3	4	3	3	2
Lifting a bag of groceries to waist level	3	4	4	3	4	4	1	3	3
Lifting a bag of groceries above your head	1	3	3	2	3	4	1	2	3
Grooming your hair	2	4	4	5	5	5	3	3	1
Pushing up on your hands (e.g. from bathtub or chair)	4	5	4	3	4	4	2	4	4
Preparing food (e.g. peeling, cutting)	3	4	4	4	4	5	2	2	1
Driving	4	4	4	1	1	1	3	4	4
Vacuuming, sweeping, or raking	3	3	3	3	4	3	2	3	2
Dressing	4	5	4	5	5	5	3	4	1
Buttoning Clothes	1	3	3	3	4	4	2	4	1
Using tools or appliances	1	4	3	2	4	5	2	3	1
Opening doors	3	4	4	4	5	5	4	4	1
Cleaning	3	4	3	5	4	5	2	3	2
Tying or lacing shoes	3	4	3	4	4	5	1	1	1
Sleeping	5	5	5	2	2	5	5	5	3
Laundering clothes (e.g. washing, ironing, folding	3	4	4	4	4	5	3	4	2
Opening a jar	2	3	3	2	3	4	4	4	2
Throwing a ball	2	4	3	5	3	4	3	4	3
Carrying a small suitcase	3	4	3	5	4	5	3	4	2

PR = pre-study, PO=post-study, FU=follow-up;
1=extreme difficulty or unable to perform, 2=quite a bit of difficulty, 3=moderate difficulty, 4=a little bit of difficulty, 5=no difficulty.

index PMP, 400% middle PMP, 240% ring PMP, and 250% little PMP) and maintained to some extent these gains at follow-up.

Table IV gives the grasp strength on a Jamar dynamometer, as well as the finger pinch strength for the participants' affected hand measured at PR, PO, and FU. These results are rounded to the nearest Newton. There was no change in grip strength (power grasp on the dynamometer) in Participant 3, and a 5% decrease in Participants 1. Participant 2 had a 17% reduction in power grip strength during training. However Participants 1 and 3 improved substantially during therapy in their thumb-to-index pinch strength (82% and 422%, respectively) and in their thumb–index–middle three tip grip (33% and 333%, respectively). These gains were extinguished for Participant 1 at follow-up, but were maintained for Participant 3, who had 67% more thumb-to-index pinch strength and 125% more three-tip pinch strength, compared to pre-training. Participant 2 improved 20% in key grip, maintained at follow-up (27%).

B. *Computerized Measures*

Changes in the arm reach supported on the table kept horizontal (Fig. 4) were measured by the vision tracker as part of the baseline. Participant 1 UE reach area increased from 983 cm^2 in Session 2 to 1237 cm^2 (26% more) in session 12, Participant 2 UE reach area went from 1796 cm^2 to 881 cm^2 (51% less), and Participant 3 UE reach changed from 1031 cm^2 in session 2 to 1400 cm^2 in session 12 (36% more). At the follow-up session, all three participants reach areas had increased on the horizontal table. These were 1 486 cm^2 for Participant 1, 2230 cm^2 for Participant 2 and 2007 cm^2 for Participants 3. This represents 51% more, 24% more, and 95% more at follow-up compared with session 2, for Participants 1, 2, and 3, respectively.

The above changes in reach are also reflected in game play, such as the distance moved to pick a ball and place it in the target area during the *Pick-and-Place* game. For a group of 20 repetitions in the left–right direction, Fig. 3 shows longer traces, with the bundle being thinner (more uniform movement) and straighter (less jerky movement) in session 12 compared to session 2. Session 2 was chosen for computerized measures instead of session 1, in order to minimize system learning effects that affect game play.

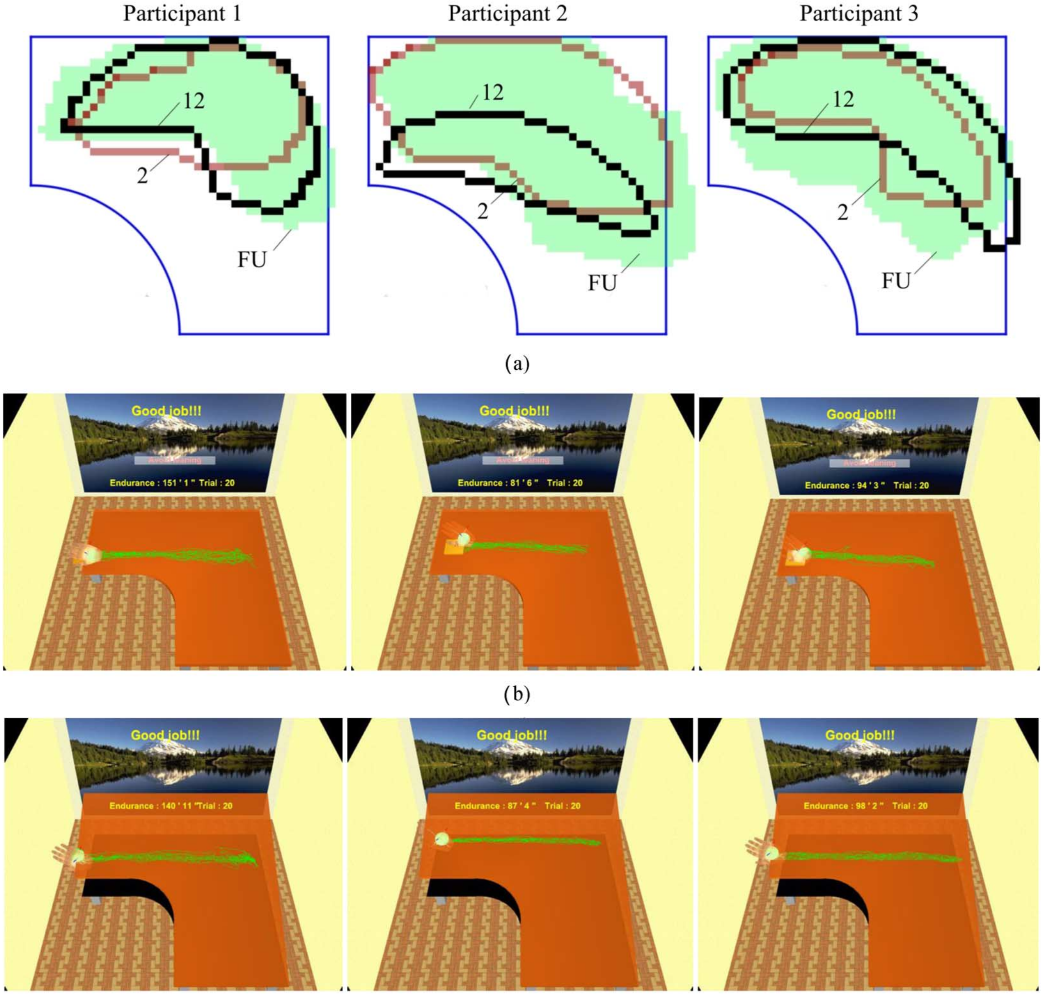
C. *Activities of Daily Living*

Table V shows the participants' self-reports on ADLs they could perform with their affected arm/hand, and the degree of difficulty with such tasks. For each question, the participant's response scaled from 1 to 5 on degree of difficulty performing the respective task: 1-extreme difficulty (or unable); 2-quite a bit of difficulty; 3-moderate difficulty; 4-little bit of difficulty; 5-no difficulty. Apart from this standardized questionnaire, participants were asked at follow-up, what activities they could do now that they were not able to do prior to the study. Participant 1 reported that she could now turn the ignition key and shift speeds using her right arm while driving. Participant 2 reported she could now reach top shelves when placing dishes in the kitchen cabinet, and wanted to know if she could do more training on the system. Participant 3 reported he could carry objects with his impaired arm more than before, that he had less pain in that arm and he now used his right hand to type on the computer.

Aim II Participants' acceptance of the system

D. *Subjective Evaluation*

The participants' acceptance and rating of the system is an important factor when evaluating the benefits end users see in this prototype. Table VI lists the nine questions posed to the



(a)

(b)

(c)

Fig. 3. Computerized measures: (a) arm baselines for session 2, session 12, and FU; (b) Pick-and-Place trace (session 2); (c) Pick-and-Place trace (session 12). Rutgers University Tele-Rehabilitation Institute. Reprinted by permission.

participants on the online questionnaire, as well as their responses. These ratings are tabulated for each of the four weeks of training, as well as the score average for a given question and participant. The table includes an average of scores for a given question for all three participants (Av123) and an overall average, which gives a global subjective evaluation of the system. The participants agreed that the instructions given to them were useful (4.1), that they were not bored during training (3.9), and that they would encourage others to use the system (4.1). They scored lowest on frequency of technical problems (2.7), characteristic of a prototype system. Their overall rating was 3.7 out of a maximum score of 5. In an unscripted interview (see video attached) one participant stated that she liked the system compared to conventional therapy, including the length of training the new system made possible.

V. Discussion

A. Training Effect

While each participant started with a different degree of UE impairment, they all seemed to benefit from the training. The Jebsen–Taylor outcomes data (Table II) show that Participant 1 improved in all manual tasks, in some substantially. For example, in the stacking of checkers, which requires fine motor function, she was more than six times faster post training; and at three-months follow-up, she did the same task in half the time required pre-training. Overall she maintained gains in five out of seven tasks at three months post-training. Participant 2, who was the highest functioning of the three, did not change overall, yet her writing was 18% faster post-training. Participant 3's overall time increased (negative effect); however, he was 55% faster lifting large heavy objects post-training compared to his pre-training time for that task. This gain was maintained at follow-up, although a confounding factor is his strengthening exercises at the gym. Whether due to the training on the Rutgers Arm II or his other activities, Participant 3 did report he was now using his arm more in carrying objects, which is very encouraging.

The ROM data in Table III show an interesting pattern with regards to shoulder and finger range increases. At follow-up, shoulder ROM in extension, abduction, and internal rotation had increased for all participants with respect to their pre-training measures, indicating benefit and retention. This was to be expected as the shoulder was the primary group of joints trained.

TABLE VI
PARTICIPANTS SUBJECTIVE EVALUATION OF THE RUTGERS ARM II SYSTEM OVER THE FOUR WEEKS OF TRAINING. RUTGERS UNIVERSITY TELE-REHABILITATION INSTITUTE. REPRINTED BY PERMISSION

	Participant 1					Participant 2					Participant 3					Avg123
Question\Week	W1	W2	W3	W4	Avg	W1	W2	W3	W4	Avg	W1	W2	W3	W4	Avg	
The system was easy to use	4	4	4	4	4	4	4	4	4	4	5	3	3	3	3.5	3.8
The games were interesting	4	4	4	4	4	4	4	4	4	4	4	5	3	2	3.5	3.8
I had no muscle pain or discomfort	5	4	2	4	3.75	4	4	4	4	4	3	3	3	3	3	3.6
The instructions given to me were useful	4	4	4	4	4	4	4	4	4	4	5	5	3	4	4.25	4.1
I was not bored while exercising	5	4	4	4	4.25	4	4	4	4	4	5	4	2	3	3.5	3.9
The length of exercising in a day was appropriate	4	4	3	4	3.75	4	4	4	4	4	5	3	3	3	3.5	3.7
There were few technical problems	4	4	3	4	3.75	4	2	1	2	2.25	4	2	1	2	2.25	2.7
I would encourage another patient to use it	4	4	4	4	4	5	4	4	4	4	5	5	3	3	4	4.1
I liked the system overall	4	4	4	4	4	4	4	4	4	4	5	4	2	3	3.5	3.8
Average of all scores					3.9					3.8					3.4	3.7

W1,... W4 = week 1,... week 4. AWG= average of score over 4 weeks. Avg123= score average over all participants for a given question
1 = strongly disagree, 2=disagree, 3 neither agree nor disagree, 4=agree, 5=strongly agree

However, post-training the participants showed improvement in their affected hand finger extension, something that was not trained; it is possible that there was some transfer of training from the UE proximal joints to the hand, or some plasticity effects to adjacent neural areas in the brain. That may be one of the causes of improved dexterity reported by Participant 3, who gained the ability to type with the affected hand. It is also possible that this gain is an artifact of less reliable finger joint measurements owing to the spasticity with which the participants presented.

Grasp training results (Table IV) were mixed, with a decrease in power grasp strength in two participants and an increase in pinch grasp in all three. It is possible that this was due to the way the participants squeezed the sensor pear, or that four weeks were insufficient for benefiting power grasp, or that games settings only required momentary grasping, making grasp intensity training suboptimal.

B. Deviation From Protocol

Initially the protocol prescribed sustained (continuous) grasping in weeks 3 and 4. For example, in weeks 1 and 2 momentary grasping was all that was needed to pick up the ball during *Pick-and-Place*. After that the ball became "glued" to the hand avatar, and remained there until the avatar overlapped the target area, where it automatically dropped. With sustained grasp condition set, the participant would have to grasp continuously once the ball was picked up, or the ball would drop en route and needed to be picked up again to continue the path to the target. During the first session to implement this more demanding sustained grasp condition, the first participant to attempt it reported hand pain/discomfort after 10 min of training. The physical therapist in the room decided to discontinue this condition and revert to the momentary grasping that the participant had trained with in the prior weeks. The participant was able to continue the session after a short pause, and completed it without further problems. In retrospect we realized that the threshold used in the sustained grasp condition was set at the same value of 25% of MVC used in the momentary grasp condition. It should have been set substantially lower than that, as a way to prevent fatigue during sustained grasps.

Another deviation from protocol was necessary for the Participant 2 who had dual visual cut. The ball speeds that the other participants trained with during the *Breakout 3 D* game were too fast for Participant 2 as she had little time to intercept the ball so to bounce it to the cube array. Once balls were made slower and extra balls given during the game, Participant 2 was able to play without any other problems.

C. Changes in Activities of Daily Living

Table V shows that the training on the Rutgers Arm II resulted in ADL changes. Participant 1, who had not been able to lift a bag of grocery above her head PR, reported she could do so with moderate difficulty PO, and maintained this ability at FU. The same participant had extreme difficulty buttoning clothes, something she could do PO with moderate difficulty, maintaining this improvement at three months post training. Participant 2 had quite a bit of difficulty using tools and appliances, but she reported being able do so with only a bit of difficulty PO. At follow-up she reported having no difficulty doing this activity. The same participant had quite a bit of difficulty opening a jar PR, while she could do so with moderate difficulty PO and reported having only a little bit of difficulty at FU. Participant 3 had extreme difficulty lifting a bag of groceries at waist level PR, but only moderate difficulty with that task PO, a gain he maintained at FU. He progressed also in pushing up on his hands, a task for which he reported quite a bit of difficulty PR, but only a little bit of difficulty PO, maintained at follow-up. Certainly not all gains were maintained three months post-training. For example Participant 3 reported having quite a bit of difficulty opening a jar or moderate difficulty throwing a ball at three months post-, while reporting only a little bit of difficulty with those same tasks PO. Participant 1 who reported no difficulty dressing PO had a little bit of difficulty at FU.

D. Participants' Acceptance of the Technology

All participants were compliant with the protocol and attended all 12 sessions and the follow up on time. They were engaged in the training, as attested by the length of training (up to 1 h of actual training/session) which they completed. Participants did not complain about the intensity or length of training, with the exception of the one session involving sustained grasp. Their evaluation of the system was higher with Participants 1 and 2, who volunteered that they wanted to participate again in this training if given the chance. These findings are in line with other studies which describe good engagement with, and acceptance of VR-mediated UE training post-stroke [31]–[33]. A confounding factor is the effect of various medications the participants were taking during the study, including antidepressants and antiseizure medication (with known depression side effects) [34].

E. Future Directions

The Institute is currently conducting another feasibility study on the Rutgers Arm II, also training clients with chronic stroke. The length of therapy was increased to address grasping strength and duration, two of the issues uncovered by this study. Other issues remain, and will need to be addressed during the redesign phase, including the ability to change the table tilt automatically to ease system use. Reach baseline accuracy could be improved by discouraging patient leaning, so to avoid exaggerated reach, as was the case with Participant 2 in session 2 (Fig. 3).

ACKNOWLEDGMENT

The authors would like to thank M. AbdelBaky for providing technical support. M. J. Santo Pietro Ph.D. and W. Greenspan M.A. of the Institute for Adults Living with Communication Disabilities at Kean University were instrumental in patient recruiting.

REFERENCES

[1] W. Rosamond *et al.*, "Heart disease and stroke statistics-2008 update," *J. Am. Heart Assoc.*, vol. 117, no. 4, pp. 25–146.

[2] A. Russo and R. Andrews, "Hospital stays for stroke and other cerebrovascular diseases," 2005. Statistical Brief #51, Agency for Healthcare Research and Quality. 11 pp. [Online]. Available: http://www.hcup-us.ahrq.org/reports/statbriefs/sb51.pdf

[3] Am Heart Ass. Heart Disease Stroke Stats 2008.

[4] N. Byl *et al.*, "Effectiveness of sensory and motor rehabilitation of the upper limb following the principles of neuroplasticity: Patients stable poststroke," *Neurorehab. Neural Repair*, vol. 17, no. 3, pp. 176–191, 2003.

[5] T. Carmichael, "Translating the frontiers of brain repair to treatments: Starting not to break the rules," *Neurobiol. Dis.*, vol. 37, pp. 237–242, 2010.

[6] W. Jenkins and M. M. Merzenich, "Reorganization of neocortical representations after brain injury: A neurophysiological model of the bases of recovery from stroke. In," in *Progress in Brain Research*, F. Seil, E. Herbert, and B. Carlson, Eds. New York: Elsevier, 1987, pp. 249–266.

[7] J. Liepert *et al.*, "Treatment-induced cortical reorganization after stroke in humans," *Stroke*, vol. 31, pp. 1210–1216, 2000.

[8] H. I. Krebs, N. Hogan, M. L. Aisen, and B. T. Volpe, "Robot-aided neurorehabilitation," *IEEE Trans. Rehabil. Eng.*, vol. 6, no. 1, pp. 75–87, Mar. 1998.

[9] R. Loureiro, C. Collin, and W. Harwin, "Robot aided therapy: Challenges ahead for upper limb stroke rehabilitation," *Proc. ICDVRAT*, pp. 33–39, 2004.

[10] M. Nokata and N. Tejima, "A safety strategy for rehabilitation robots," in *Advances Rehabilitation Robotics*. New York: Springer, 2004, ch. 10, pp. 177–185.

[11] S. Roderick and C. Carignan, "An approach to designing software safety systems for rehabilitation robots," in *Proc. 9th IEEE Int. Conf. Rehab. Robotics*, Chicago, IL, 2005, pp. 252–257.

[12] M. Van der Loos and D. Reinkensmeyer, "Rehabilitation and health care robotics," in *Handb Robot*, K. Siciliano, Ed. New York: Springer, 2008, ch. 53, pp. 1223–1249.

[13] G. Burdea, "The role of haptics in physical rehabilitation," in *Haptic Rendering*, Lin and Otaduy, Eds. : AK Peters, 2007, ch. 25, pp. 517–529.

[14] P. Bach-y-Rita *et al.*, "Computer-assisted motivating rehabilitation (CAMR) for institutional, home, and educational late stroke programs," *Top Stroke Rehab.*, vol. 8, no. 4, pp. 1–10, 2002.

[15] E. Flores *et al.*, "Improving patient motivation in game development for motor deficit rehabilitation," in *Proc. Int. Conf. Adv. Comput. Entert. Tech.*, Dec. 2008, pp. 381–384.

[16] Y. L. Chen, T. S. Kuo, and W. Chang, "Aid training system for upper extremity rehabilitation," in *Proc. 23rd EMBS Int. Conf.*, 2001, pp. 1360–63.

[17] M. Kuttuv *et al.*, "The Rutgers Arm: An upper-extremity rehabilitation system in virtual reality," *CyberTherapy Behavior*, vol. 9, no. 2, pp. 148–152, 2006.

[18] P. W. Duncan, M. Probst, and S. G. Nelson, "Reliability of the Fugl-Meyer assessment of sensorimotor recovery following cerebrovascular accident," *Phys. Therapy*, vol. 63, pp. 1606–1610, 1983.

[19] N. Mumford *et al.*, "A virtual tabletop workspace for upper-limb rehabilitation in Traumatic Brain Injury (TBI): A multiple case study evaluation," in *Proc. Virtual Rehab. Conf.*, Canada, 2008, pp. 175–180.

[20] Resolution Revolution [Online]. Available: http://www.vicon.com/_pdfs/t_cameras.pdf Vicon Motion Systems

[21] S. J. Housman, K. M. Scott, and D. J. Reinkensmeyer, "A randomized controlled trial of gravity-supported, computer-enhanced arm exercise for individuals with severe hemiparesis," *Neurorehab. Neural Repair*, vol. 23, no. 5, pp. 505–14, 2009.

[22] G. Burdea *et al.*, "The Rutgers Arm II rehabilitation system," in *Proc. Virtual Rehab. Conf.*, Canada, 2008, p. 76.

[23] Java Media APIs [Online]. Available: http://java.sun.com/javase/technologies/desktop/media/ Sun Microsystems Inc.

[24] Java Advanced Imaging API [Online]. Available: http://java.sun.com/javase/technologies/desktop/media/jai/ Sun Microsystems

[25] J. Barrilleaux, *3 D User Interfaces With Java 3 D*. Greenwich, CT: Manning, 2000.

[26] G. Thompson, "Motor learning and practice," Children With Severe Disabilities and the MOVE Curriculum East River Press, 2005 [Online]. Available: http://www.rifton.com/resources/MOVE_book/articles/motor.pdf

[27] D. Fensterheim, Improvements to the Rutgers Arm. A virtual Reality-Based Rehabilitation System Electr. Comput. Eng. Dept., Rutgers Univ., New Brunswick, NJ, 2007.

[28] J. Yamauchi and A. Hargens, "Effects of dynamic and static hand grip exercises on hand and wrist volume," *Eur. J. Appl. Physol.*, vol. 103, pp. 41–45, 2008.

[29] R. H. Jebsen *et al.*, "An objective and standardized test of hand function," *Arch. Phys. Med. Rehabil.*, vol. 50, pp. 311–19, 1969.

[30] P. Stratford, J. M. Binkley, and P. O. W. Stratford, "Development and initial validation of the upper extremity functional index," *Physiotherapy Canada*, vol. 281, pp. 259–266, 2001.

[31] M. K. Holden, T. A. Dyar, and L. Dayan-Cimadoro, "Telerehabilitation using a virtual environment improves upper extremity function in patients with stroke," *Trans. Neural Syst Rehab. Eng.*, vol. 15, no. 1, pp. 36–42, 2007.

[32] L. Piron *et al.*, "Reinforced feedback in virtual environment facilitates the arm motor recovery in patients after a recent stroke," in *Proc. Virtual Rehab*, Venice, Italy, 2007, pp. 121–123.

[33] A. Henderson, N. Korner-Bitensky, and M. Levin, "Virtual reality in stroke rehabilitation: A systematic review of its effectiveness for upper limb motor recovery," *Top Stroke Rehab.*, vol. 14, no. 2, pp. 52–61, 2007.

[34] K. Monson and A. Schoenstadt, Keppra Side Effects 2009 [Online]. Available: http://epilepsy.emedtv.com/keppra/keppra-side-effects.html

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