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Motor Retraining in Virtual Reality: A Feasibility Study for Upper-Extremity Rehabilitation in Individuals With Chronic Stroke

Grigore Burdea, PhD, Daniel Cioi, PhD, Joseph Martin, Bryan Rabin,
Angad Kale, and Phillip DiSanto

Background and Purpose. Individuals with stroke can improve upper-extremity function in the chronic phase, providing rehabilitation is intensive, attended, and of sufficient duration. Virtual reality has been used in motor retraining; however, off-the-shelf game consoles may not be appropriate for those with marked motor impairment and high finger or arm spasticity. The objective of this study was to investigate the feasibility and effects of training in individuals with chronic stroke who are either high-functioning or low-functioning, and also spastic.

Grigore Burdea is a professor of electrical and computer engineering and director at Rutgers University Tele-Rehabilitation Institute, 96 Frelinghuysen Road, 7th Floor, Piscataway, NJ 08854 (burdea@jove.rutgers.edu). Please address all correspondence to Grigore Burdea.

Daniel Cioi, at the time of this study, was a postdoctoral associate at Rutgers University Tele-Rehabilitation Institute, New Jersey.

Joseph Martin, at the time of this study, was a laboratory assistant at Rutgers University Tele-Rehabilitation Institute, New Jersey.

Bryan Rabin, at the time of this study, was a laboratory Assistant at Rutgers University Tele-Rehabilitation Institute, New Jersey.

Angad Kale, at the time of this study, was a laboratory assistant at Rutgers University Tele-Rehabilitation Institute, New Jersey.

Phillip DiSanto, at the time of this study, was a visiting summer intern at Rutgers University Tele-Rehabilitation Institute, New Jersey.

This study was approved by the Rutgers University Institutional Review Board.

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Conflict of Interest

Grigore Burdea and Daniel Cioi are co-inventors on a pending patent application related to the technology described in this article. They, together with Bryan Rabin, have a financial interest in the Rutgers Arm II prototype system.

Case Descriptions. Four volunteers, 3 men and 1 woman, were recruited from a local aphasia support group. All individuals were chronic post stroke with right-side hemiplegia. Training took place at the Tele-Rehabilitation Institute at Rutgers University. The intervention was performed on the Rutgers Arm II, a prototype training table that senses supported arm movement and grasp strength and tilts to resist or assist reach. Participants played games that adapted automatically to each individual's motor abilities. The games were practiced over 6 weeks, 3 sessions every week, with sessions lasting up to 1 hour. The 4 participants were evaluated by a senior physical therapist before, immediately following, and 6 weeks after the intervention. No occupational or physical therapist was present during the training sessions.

Outcomes. The primary outcomes were changes in the affected upper-extremity subset of the Fugl-Meyer test and self-reported changes in the participants' activities of daily living. Improvements in active range of motion and grasp strength were secondary outcomes. All individuals improved in Fugl-Meyer scores and retained these gains (participant 1, 45 to 50; participant 2, 16 to 22; participant 3, 12 to 20; participant 4, 42 to 51). Participants 2 and 3, who presented with severe motor impairment, began using their affected arms in daily activities subsequent to training. All participants improved in their shoulder, elbow, and finger flexion active range of motion. Remarkably, participants 2 and 3, who were unable to exert force in grasping or pinching pre-training, could now do so and retained these gains at 6 weeks following the intervention. Well-being and mood seemed to improve in all participants.

Discussion and Conclusion. Results show that motor retraining in virtual reality is feasible, well-tolerated by participants, and benefitting them. The Rutgers Arm II system was able to train participants, who varied greatly in their degree of motor impairment, but without a clinician being present. The present study contributes to the body of knowledge on novel virtual rehabilitation interventions for the upper extremity.

Key Words: Upper extremity, Virtual reality, Sustained grasp, Rutgers Arm, Stroke.

BACKGROUND AND PURPOSE

The direct and indirect costs associated with head injuries from stroke or trauma approach \$200 billion a year in the United States alone.^{1,2} At the completion of standard-of-care motor retraining (6 to 9 months post stroke), individuals present with varying levels of upper-extremity (UE) functional recovery. Their recovery depends not only on the type and severity of the initial injury to the central nervous system, but also on the intensity and length of rehabilitation subsequently provided. Diminished upper-extremity function in the chronic phase post stroke negatively affects the individual's degree of independence in activities of daily living (ADLs), mental health, and social life.

The person's motivation to improve and the important role knowledge of results feedback plays in motor relearning³ both point to the need to investigate virtual reality as an element of therapy. Virtual worlds⁴ have been shown to provide rich knowledge of results and to increase motivation if tailored to the individual's abilities.^{5,6} Virtual reality previously has been investigated as a way to conduct motor rehabilitation following a stroke. Merians and colleagues⁷ used a combination of real and virtual object manipulation tasks to train 3 individuals who were in the chronic

phase following stroke. During 2 weeks of daily exercises (10 sessions), the participants trained their range, speed, and fractionation in the affected fingers and thumb, as well as grasping force. All 3 participants improved in grasping strength (as measured by a dynamometer), and in finger/thumb range of motion. This translated to better performance on the Jabes test of hand function⁸ for 2 of the individuals. Holden and colleagues⁹ found that it was possible to train participants at a distance, when the physical therapist interacted with the individual in a shared virtual reality. In that study, 11 participants who were in the chronic phase following stroke participated in thirty 1-hour training sessions in virtual reality, resulting in significant improvement in UE function as measured by standard clinical tests (Fugl-Meyer test of motor recovery,¹⁰ Wolf motor test,¹¹ and shoulder strength). Rand and colleagues¹² investigated the use of a virtual mall (or "VMall") together with a video capture system as an intervention tool to train the weak UE of individuals post stroke. Participants received ten 1-hour treatment sessions in their homes, over a period of 3 weeks, which resulted in improved clinical measures as well as increased use of the weak arm in ADLs. A controlled study¹³ of subacute individuals (fewer than 12 months post stroke) showed that the addition of 30 minutes per day of PlayStation-based videogame intervention to the conventional therapy received by the experimental group produced more functional independence, compared to participants in a control group who only watched the games without physical involvement and had the same amount of conventional therapy.

Several VR computerized systems for UE motor retraining are now commercially available, such as the Armeo[®], the Armeo[®]Boom (both from Hocoma AG, Switzerland) and the IREX[®] system (from GestureTek, Canada). The Armeo passive exoskeleton provides gravity support during arm reach and measures grasp strength, which, in addition to arm movement, is used to play rehabilitation video games.¹⁴ The ArmeoBoom is a low-cost, less complex, gravity unloading system, consisting of a pole, 2 tilting weights, 2 ropes, a camera used for motion capture, and rehabilitation games shown on a computer monitor. It has been reported that low-functioning patients with their UEs supported by the ArmeoBoom had natural arm movement in the horizontal plane but found movement in the vertical plane too difficult.¹⁵

The IREX system uses chroma key techniques and a vision camera to project the image of the patient directly into a mostly 2-dimensional game scene. The chroma key

technique uses a green background screen; vision processing allows the patient to be computer-extracted from the physical background and inserted into a virtual background (the game scene). This results in high patient motivation and enjoyment. However, the IREX provides no haptic feedback,¹⁶ and its lack of gravity support makes it more appropriate for higher-functioning individuals who are able to lift and move their affected upper extremities.

The Wii[™] game console system has been studied recently as a tool for motor retraining following traumatic brain injury,¹⁷ post stroke,^{18,19} and for individuals with cerebral palsy.²⁰ While the Wii system is inexpensive and readily available, reliance on off-the-shelf games may prove problematic for those who are challenged by arm gravity loading or those with severe finger spasticity, which makes it difficult to hold the Wiimote, or press its buttons.²¹ Moreover, overuse-induced tendonitis (called "Wii-itis") has been reported²² in healthy players. It follows that individuals with disabilities who play the Wii unsupervised and intensely may be at increased risk of complications.

In order to successfully provide motor retraining on a game system that can accommodate individuals with either low or high levels of UE function, without the risk of tendonitis, and without requiring dexterity or weight-bearing ability in the affected arm, we have developed the Rutgers Arm II.^{23,24} The prototype system uses infrared tracking of arm movement; gravity modulation; combined strengthening of shoulder, arm, and hand; and custom virtual reality games²⁵ that have attributes for motor rehabilitation. This article reports on 4 participants who are in the chronic phase post stroke: 2 who are very low-functioning and 2 with moderate-to-high function in their affected upper extremities. The objectives of this study were to: (1) examine changes in UE function following training on the Rutgers Arm II and the retention of these gains; (2) determine if UE motor gains in virtual reality map to changes in ADLs and improved patient morale; and (3) determine if training on this computerized system is possible without the physical therapist being present during training (either locally or remotely). We hypothesized that computerized virtual reality-based systems and training methods such as the one described here, if proven successful, may be one way to alleviate the burden on society, by training individuals who are in the chronic phase following stroke regardless of their level of function. However, implementing dedicated VR motor rehabilitation systems may require additional training and credentialing

for physical and occupational therapists. This may be accompanied by a change from the current "hands-on" approach in therapy to a computer-mediated one.

CASE DESCRIPTIONS

Participants

Four individuals, 3 men and 1 woman, participated in the intervention (Table 1). All had had a left hemisphere stroke that had occurred between 12 months and 35 months prior to the study. The participants were recruited from the aphasia support group at Kean University. They were receiving speech therapy (and were allowed to continue it during this study), but none were receiving occupational or physical therapy at the time. Since our VR system prototype did not use voice input, speech therapy overlapping the study was not considered a confounding factor. The 4 participants received medical clearance from their attending physicians and subsequently signed a consent/assent form approved by Rutgers University Institutional Review Board. The individuals were evaluated and trained at the Tele-Rehabilitation Institute at Rutgers University in fall 2009.

Participant 1, a 57-year-old man, had experienced a left hemisphere ischemic stroke 35 months prior to the study. After the stroke he underwent 38 days of inpatient physical and occupational therapy, followed by 9 months of outpatient physical and occupational therapy and a longer period of speech therapy. This participant had major loss of touch and loss of proprioception. He was taking antidepressant and antiseizure medication at the time of the study and was walking with a cane. At the start of the study his affected handgrip strength was 123 N, pulp-to-pulp pinch strength (thumb-index) was 21 N, key pinch (thumb-index) was 55 N and 3-tip pinch (thumb-index-middle) was 30 N. He reported having moderate-to-severe difficulty in using his affected UE in daily activities.

Participant 2, a 46-year-old woman, underwent a hemorrhagic stroke 14 months prior to the study. She received 3 weeks of inpatient physical and occupational therapy, followed by 8 months of outpatient physical and occupational therapy. She was taking anti-depressant and anti-seizure medication and did not practice physical exercise prior to the study. Her affected arm presented with high spasticity of the elbow and fingers and had low blood circulation; the arm felt cold to the touch and looked bluish in color. She could walk independently, but was unable to grasp or pinch with her affected hand. She also was unable to use her arm in any daily activities.

Participant 3 was a 62-year-old man who had sustained a left-side ischemic stroke 12 months prior to the study. He was in intensive care for 32 days, followed by 6 weeks of inpatient physical, occupational, and speech therapy. After discharge from the hospital, this participant received 8 months of outpatient physical and occupational therapy. He was taking antidepressant and memory improvement medication. The man was able to walk with a quad cane for a short distance, but chose to be pushed in a wheelchair. As with participant 2, he was unable to grasp or pinch with his affected hand. He kept his affected arm in a sling, and his spouse reported that he was not using his affected arm at all. As a result, he had low blood circulation and weakness in the affected UE.

Participant 4 was a 70-year-old man who had experienced a left-side ischemic stroke 14 months prior to the study. He was in intensive care for 6 weeks, followed by 2 months of inpatient physical, occupational, and speech therapy. After discharge from the hospital, this participant received 30 days of outpatient physical and occupational therapy. The man had sustained a heart attack approximately 10 years prior to the study and had a stent implanted. At the time of the study he was taking medications to lower his blood pressure and prevent blood clots. He was ambulating independently but had severe aphasia and spoke no English. His affected handgrip strength at the start of study was 49 N, and his pulp-to-pulp, key, and 3-tip pinch strengths were 9 N, 12 N, and 6 N, respectively.

Data Collection Instruments and Methods of Collection

Data were collected at evaluation sessions before, immediately following, and 6 weeks after the intervention and transparently during each training session. Evaluation sessions primarily involved collection of clinical motor and functional UE measures and were performed by a senior PT. While she was not present during the training sessions, she was aware of the purpose of the study and the therapy methodology, which is a limitation of this study. Another limitation is the lack of data on the participants' central vision system abilities. Because visual feedback plays a crucial role in VR-based training protocols, the researchers should have accounted for possible visual cut, visual neglect, other degradations to the participants' visual acuity, or their possible visuomotor associative impairments. Instead the researchers relied on participants' reporting no visual channel or visuomotor associative impairments before the study, which is a limitation.

The primary standardized measures used

Table 1. Case Characteristics Pre-training^a

	Case 1	Case 2	Case 3	Case 4
Age (years)	57	46	62	70
Gender	male	female	male	male
Type of stroke	left ischemic	left hemorrhagic	left ischemic	left ischemic
Time since stroke (months)	35	14	12	14
Motor impairment level	moderate	marked	marked	moderate
Initial Fugl-Meyer UE score subset (66 score max)	45	16	12	42
Co-morbidities	aphasic loss of touch loss of proprioception	aphasic spastic elbow spastic hand	aphasic depression spastic hand	aphasic implanted stent
Ambulation	cane	independent	wheelchair	independent
Language	English	English	English	non-English
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in this study were the UE subset of the Fugl-Meyer (FM) test of hand function,¹⁰ and the changes in activities of daily living (ADLs) self-reported on a standardized questionnaire.²⁶ The secondary measures were the affected UE active range of motion, measured with mechanical goniometers, and the affected hand grasp strength and finger pinch strength measured with a mechanical Jamar dynamometer and a mechanical pinch meter, respectively. A limitation of these measurements is the static nature of the collected data versus the dynamic changes in forces needed in skilled ADLs. Similarly, goniometer readings are static, measuring joint values (range), but not the time taken (velocities or accelerations) to actively achieve those joint values.

Intervention

Computerized system. Participants sat against a custom low-friction square table with 1 corner cut out, facing a large display and resting their affected forearms on a low-friction sensing support. The support had embedded electronics to detect grasp strength, as well as a micro-switch to detect when the elbow was lifted off the table. A combination of an overhead infrared camera, light-emitting diode (LED) markers at the corners of the table and

on the forearm support, and image analysis software allowed a personal computer (PC) to detect arm movement in the plane of the table. A separate LED attached to the contralateral shoulder was used to detect unwanted trunk rotation. The table could tilt to resist or assist movement. The PC rendered a number of custom video games designed specifically for upper-extremity rehabilitation. The participant controlled a hand avatar, which responded in real time to supported arm movement, and which closed its virtual fingers in response to the grasping of the rubber pear on the forearm support. At the start of each training session the participant was asked to baseline the arm reach area and maximum grasp (Figure 1). The arm reach and hand grasp baselines were used to adapt the games to each participant, allowing even those with very small arm movement to be trained. Games required either momentary grasp of 25% of maximum grasp or sustained grasp at 10% of maximum. These thresholds were chosen to prevent the fatigue and discomfort observed in earlier trials.²⁴

Four Java 3D™ games were custom-designed to support the clinical function, allowing better control on levels of difficulty and better adaptability to each participant com-

Figure 1. Screen Image Showing the Arm Reach and Grasp Strength Baselines

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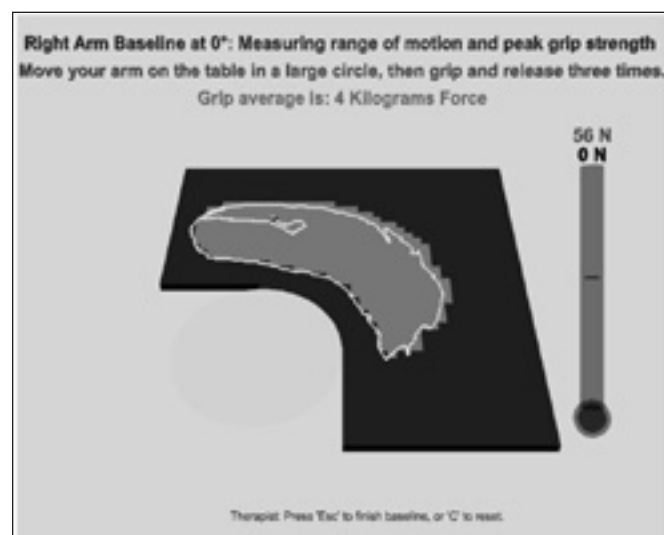
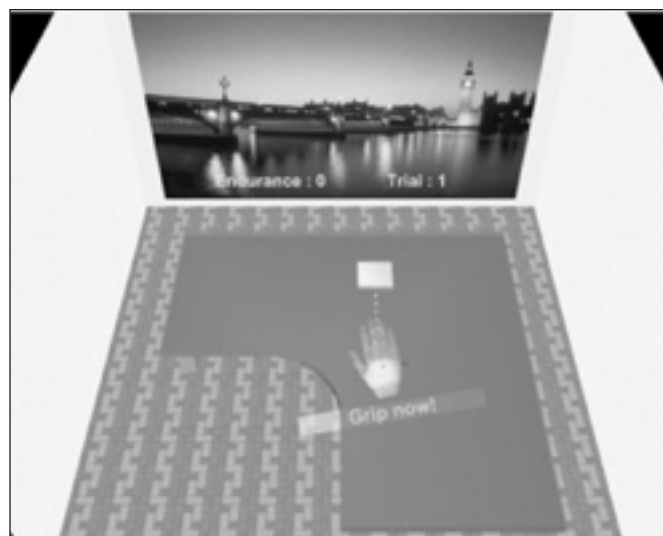


Figure 3. Pick-and-Place Game Configuration to Train Shoulder Flexion/Extension Movements

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pared to off-the-shelf games.²⁷ The *Breakout 3D*²⁸ game (Figure 2) required participants to destroy an array of cubes by bouncing a ball off a paddle avatar controlled by the affected arm. Faster balls and smaller paddles increased game difficulty, as did the table tilt and the requirement to grasp as a condition of bounce. The *Pick-and-Place*²⁹ game (Figure 3) trained UE motor control, shoulder and grasp strength, and coordination. The participant was asked to closely follow a prescribed path, which varied depending on the placement of a virtual ball and a target square on the screen. Each pick-and-place iteration produced a trace of the actual movement overlaid on the prescribed path. Summative

Figure 2. Breakout3D Game Configuration to Train Mainly Shoulder Abduction-Adduction and Executive Function

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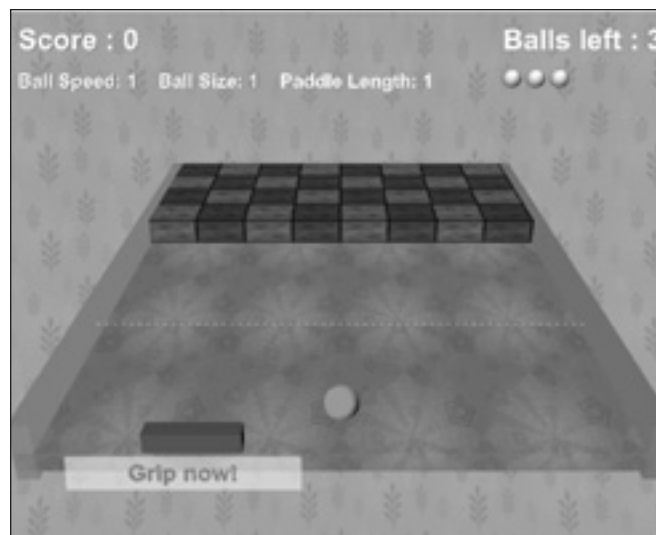
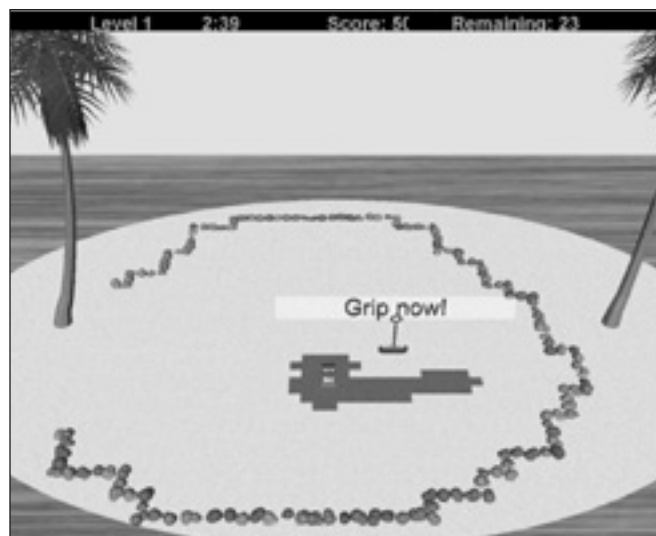


Figure 4. Treasure Hunt Game to Train Arm Endurance

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knowledge of results (KR) was provided at the end of a number of pick-and-place repetitions, in the form of a bundle of traces and numerically by the path error representing the closeness of the actual path to the prescribed one. The *Treasure Hunt*³⁰ game (Figure 4) depicted an island on which a number of treasures were buried within an area delineated by a wall of boulders. The participant controlled a shovel avatar by grasping above a specific threshold and dug out as many treasures as possible in the allowed amount of time. Depending on setting, sand storms covered some of the already dug-up treasures, requiring more arm movement to dig them up again. The *Card Island*³¹ game was aimed

at training short-term memory, visual memory, grasp coordination, shoulder strength, and arm endurance. The game presented the same island, but this time showed an array of playing cards arranged face down. The participant was required to overlap a given card with the hand avatar and then squeeze to turn it face up. If the individual selected 2 matching cards, the pair of cards disappeared from the island. To motivate participants, the game was customized with cards that had images of pets, relatives, or other scenes of interest to each individual. The game's difficulty increased when more cards were presented. Further details on the computerized system setup can be found in Burdea et al.²⁴

Table 2. Changes in Upper-Extremity Fugl-Meyer Test Scores and in Activities of Daily Living Over the 6 Weeks of Training and at 6-week Follow-up

	Case 1			Case 2			Case 3			Case 4		
	PR	PO	FU	PR	PO	FU	PR	PO	FU	PR	PO	FU
Fugl-Meyer (max score 66)	45	48	50	16	18	22	12	17	20	42	50	51
Activities of Daily Living^a	PR	PO	FU	PR	PO	FU	PR	PO	FU	PR	PO	FU
Any of your usual work, household activities	2	4	4	1	1	1	1	1	1	3	3	3
Your usual hobbies, recreational or sporting activities	1	2	3	1	1	1	1	2	1	3	3	4
Lifting a bag of groceries to waist level	2	5	5	1	1	2	1	3	1	2	4	3
Lifting a bag of groceries above your head	1	4	4	1	1	1	1	1	1	1	2	1
Grooming your hair	3	5	5	1	1	1	1	2	3	5	4	4
Pushing up on your hands (eg, from bathtub or chair)	3	5	5	1	1	1	1	4	3	3	4	3
Preparing food (eg, peeling, cutting)	1	1	3	1	1	1	1	1	1	2	1	1
Driving	1	1	1	1	1	1	1	1	1	1	1	1
Vacuuming, sweeping, or raking	3	3	4	1	1	1	1	1	1	4	3	2
Dressing	4	4	5	1	1	2	1	4	2	5	4	4
Buttoning clothes	2	3	3	1	1	1	1	5	1	3	2	4
Using tools or appliances	1	3	4	1	1	1	1	2	1	2	2	4
Opening doors	3	5	5	1	2	3	1	3	2	1	5	5
Cleaning	3	5	5	1	1	1	1	1	1	2	4	4
Tying or lacing shoes	1	1	2	1	1	1	1	1	1	2	1	2
Sleeping	5	5	5	5	5	5	5	5	5	5	5	5
Laundrying clothes (eg, washing, ironing, folding)	3	5	5	1	1	2	1	1	1	5	3	1
Opening a jar	2	4	4	1	1	2	1	1	1	1	2	1
Throwing a ball	2	3	4	1	1	1	1	1	1	4	4	4
Carrying a small suitcase (with affected limb)	1	5	5	1	1	1	1	3	2	2	3	4
<p>Abbreviations: PR, pre-study; PO, post-study, FU, follow-up.</p> <p>^aRated on a scale from 1 to 5: 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.</p> <p>Reprinted by permission of the Rutgers Tele-Rehabilitation Institute.®</p>												

Figure 5. Participant 1 Self-Feeding Following Therapy (He Was Unable to Do So Pre-training)

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Figure 6. Participant 1 Shoveling Snow Following Therapy (He Was Unable to Do So Pre-training)

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Experimental protocol. The therapy on the Rutgers Arm II system consisted of 18 training sessions over 6 weeks (3 sessions per week), with a duration that increased from 40 minutes of actual play (week 1) to 50 minutes (week 2) to 1 hour (weeks 3 to 6). The intensity of training was also increased from training on a horizontal table (weeks 1 and 2), to training on a table tilted up at 10° (week 3) and at 20° (weeks 4 to 6). Each session consisted of a baseline exercise followed by a sequence of exercises (*Pick-and-Place*, then *Breakout 3D*, followed by *Treasure Hunt* and *Card Island*) and the sequence repeated as needed to produce the prescribed session duration. The level of exercise difficulty was increased from easier games in week 1 (no grasp required) to momentary grasp being required in weeks 2 to 4 and sustained grasp in weeks 5 and 6. Difficulty was increased further by making the balls in the *Breakout 3D* game travel progressively faster, by making the targets smaller in the *Pick-and-Place* game, and by introducing progressively more frequent sand storms in the *Treasure Hunt* game.

At the end of training sessions in weeks 5 and 6, participants were asked to briefly practice functional tasks, such as carrying a small suitcase, put on and zip their jackets prior to exiting the lab, help their caregivers put on jackets, and to open the laboratory door with the affected arm.

OUTCOMES

Participant 1

Upper-extremity Fugl-Meyer score prior to training was 45 points, representing moderate motor impairment.³² The participant did

not need assistance during training and instead practiced against a 25° table tilt in week 6. He was able to do so without a problem for the prescribed 1 hour of therapy per session. Post training, the participant's Fugl-Meyer score increased to 48 (7% improvement) (Table 2). His independence in ADLs, as reported on the standardized questionnaire, increased in 14 activities at the end of the intervention. This participant now was able to hold a spoon, as his grip geometry resembled that which he used when grasping the rubber pear of the forearm support. Subsequently he began feeding himself with a spoon using his affected arm (Figure 5). The individual now could hold his wife's jacket, something that, according to her, was the first time he had done in the 3 years following his stroke.

Post training, the participant had statistically significant increases in affected UE active range of motion in shoulder flexion (9%), shoulder abduction (25%), elbow pronation (18%), elbow supination (50%), and pinkie proximal-metacarpal-phalanx (PMP) joint flexion (11%). His affected hand pinch strength, measured with a mechanical pinch meter, had increased 57% for pulp-to-pulp (thumb-index) pinch and 36% for 3-tip pinch (thumb-index-middle). At follow-up, the participant's UE Fugl-Meyer score had increased further to 50, 11% higher than before therapy. He was even more independent than he was before training, performing 18 of the 20 ADLs in the set. The individual spontaneously had begun to use the affected arm in shoveling snow (Figure 6), an activity he had not performed with the affected arm since his neural accident 3 years prior. At follow-up, he maintained some of the gains in active range of motion: shoulder abduction had increased

by 37%, elbow pronation by 27%, and elbow supination by 53%. His index and pinkie could flex 21% and 11% more, respectively, than before training. He now had normal PMP extension in middle and ring fingers. Gains in pinch strength were also maintained, with pulp-to-pulp pinch being 48% stronger and 3-tip pinch 53% stronger than before training.

Participant 2

Participant 2 was very low-functioning, with marked motor impairment³² and a pre-training UE Fugl-Meyer score of 16. For her the table was tilted down 15° weeks 2 to 5 to facilitate movement away from the trunk, and it was horizontal in weeks 1 and 6. Since she had difficulty with shoulder abduction and elbow extension due to spasticity, she was assisted and constantly encouraged by the laboratory technical staff. Participant 2 was also constantly reminded to relax, something that helped her extend the elbow further. The speed of the balls in *Breakout 3D* was kept at the slowest setting, allowing this participant to play and enjoy that game. There was however no grasp requirement in the games for this participant, due to her high finger spasticity. Her post-therapy Fugl-Meyer score was 18, an increase of 12%. Before training, the participant was unable to perform any of the ADLs in the set, except for sleeping. She had extreme spasticity in her shoulder and fingers, was unable to extend the fingers of her affected hand, and had no strength in either gripping or pinching. After training, she was able to open doors (Figure 7), although with significant difficulty. She had statistically significant increases in active range of motion of her affected shoulder and finger exten-

Figure 7. Participant 2 Opening Door (She Was Unable to Do This Activity Pre-training)

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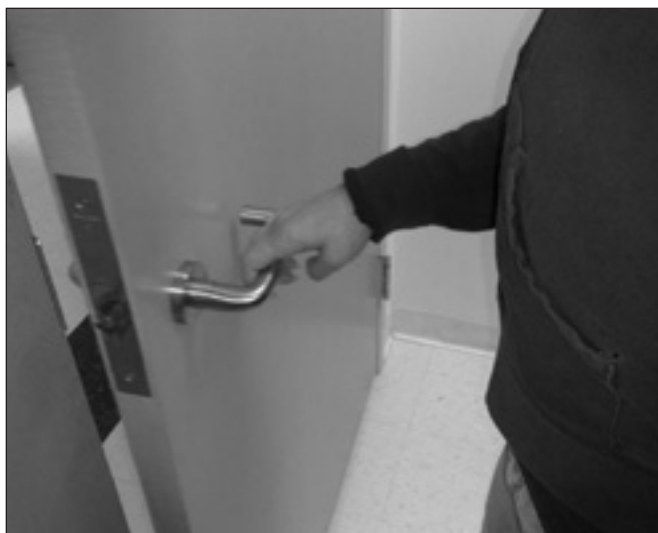


Figure 8. Participant 3 Opening Door With His Affected Arm (He Was Unable to Do So Pre-training)

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sion. Her shoulder extension range increased 100%, from 10° to 20°, her shoulder internal rotation range was 21% greater, her elbow flexion improved by 14%, her elbow extension was increased by 23%, and her elbow pronation improved by 40%. Her PMP flexion ranges improved for all fingers (thumb, 27%; index finger, 35%; middle finger, 29%; ring finger, 26%; pinkie finger, 50%). Remarkably, after the intervention participant 2 was able to apply force with her affected hand (grip = 18 N; pulp-to-pulp pinch = 16 N; key grip pinch = 10 N), but still was unable to perform a 3-tip pinch. At follow-up, the individual's Fugl-Meyer score had increased further to 22 (37% more than before training). Her independence in ADLs continued to grow: She was now able to lift a bag, dress, launder clothes, and open a jar, having quite a bit of difficulty in all these activities. Participant 2 experienced a marked decrease in her elbow spasticity, which diminished further at follow-up. Due to performing more activities using her affected arm, her blood circulation (based on skin color and temperature) had visibly improved. The individual reported having only moderate difficulty in opening doors. At follow-up she continued to improve in active range of motion of her affected arm and fingers. Compared to before training, her active range of motion had increased 150% in shoulder extension, her shoulder abduction had improved from 0° to 24°, elbow extension had increased 40%, and elbow pronation improved 106% (from 35° to 72°). Although she was still unable to extend her fingers, flexion improved further. Compared to pre-training, values of her PMP joint flexion were better by 66% for thumb, 67% for index finger, 40% for

middle finger, 40% for ring finger, and 109% for pinkie finger. She continued to be able to exert force in grip (15N) and pulp-to-pulp pinch (12N), while her key pinch grew by 110% compared to post-training measurements (from 10 N to 21 N).

Participant 3

Participant 3 was low functioning, with marked motor impairment and a pre-training Fugl-Meyer score of 12. Prior to the study, he did not use his affected arm in any activities of daily living (Table 2). His elbow and fingers were spastic, so he was unable to extend his fingers or to exert any force in either grip or pinch. Due to his marked motor impairment, participant 3 was unable to train at 20° of table tilt, so his training in weeks 4 to 6 was conducted at 15° of table tilt, 1 hour per session. This participant had difficulty with shoulder abduction and elbow extension and was assisted and constantly encouraged by the laboratory technical staff. Post training, his Fugl-Meyer score had increased 5 points (42% better). Participant 3 had stopped holding his arm in a sling and instead (with encouragement) had begun using his affected UE in ADLs. He had only moderate difficulty lifting a bag, opening a door (Figure 8), or carrying a small suitcase. Overall, the individual now could perform 8 activities of the standardized set reported in Table 2. Due to an increase ADLs post training, participant 3 had improved blood circulation in his affected arm (based on skin color and temperature). He had a remarkable increase in active range of motion. Compared to pretraining measurements, he was able to extend his shoulder 40% further, and shoulder abduc-

tion range had increased 33%. The participant was now able to extend his elbow fully (from 58° before training to 0° post training). While still unable to extend fingers, his finger PMP joint ranges in flexion had improved 62% for thumb, 20% for index finger, 12% for middle finger, and 8% for ring finger. Post training, participant 3 was able to exert force in all measured grasping configurations (grip = 16 N; pulp-to-pulp pinch = 19 N; key pinch = 27 N; and 3-tip pinch = 19 N, with thumb, index, and middle fingers). At the 6-week follow-up evaluation, participant 3's Fugl-Meyer score had increased to 20, a 67% improvement over his pre-training score. The individual had lost a bit of independence in daily use of his affected arm, but was still able to perform 6 of the 20 ADLs in the standardized set. Due possibly to psychological causes, this participant had returned to the intermittent use of a wheelchair, something he had stopped doing during training. He maintained gains in active range of motion and being able to exert force with his affected hand. Compared to pre-training measurements, at follow-up his shoulder flexion range was 22% greater, shoulder extension increased 37%, and shoulder abduction had improved 33%. He maintained gains in elbow active extension, which was now 5°, compared to 58° before training. The participant's elbow pronation range was 16% greater, and supination had increased from 0° before training to 49° at follow-up. While still unable to extend fingers in his affected hand, he maintained gains in finger PMP joint flexion range compared to pre-training measurements (40% greater for thumb, 11% for index finger, and 14% for middle finger). The participant's ability to ex-

ert force was maintained at follow-up in all measured categories (grip = 19 N; pulp-to-pulp = 12 N; key grip = 22 N; and 3-tip grip = 19 N).

Participant 4

Participant 4 was higher-functioning, with moderate motor impairment and a pre-training UE Fugl-Meyer score of 42. He was able to perform 16 of the 20 ADLs in the standardized set, albeit with varying degrees of difficulty. During the intervention the individual did not need assistance during training and instead practiced against a 25° table tilt in week 6. This was more than the 20° table tilt specified by the protocol for that week. Post training, his UE Fugl-Meyer score had increased 8 points to 50 (19% improvement). The participant now was able to open a jar, lift a bag above the head, and open a door, activities he could not do before. He had less difficulty carrying a small suitcase. Participant 4's joint active range of motion had improved 38% for shoulder extension, 18% for elbow pronation, and 13% for elbow supination. The participant's thumb active flexion range had improved 11% for the PMP joint and extension went from 13° to 0° (normal). His range of overextension had increased from 2° to 45° for the index PMP joint, from 10° to 18° for the middle finger, and from 19° to 32° for the ring finger. The individual's force exertion capability in the affected hand had improved substantially post training (63% for grip strength; 50% for key pinch; and 266% for 3-tip pinch). At follow-up, participant 4 had maintained gains in UE Fugl-Meyer score, which was now 51 (9 points higher than at pre-training, a 21% improvement). He reported being able to perform 15 of the 20 ADLs in the set. However, in 6 tasks he reported having more difficulty than at the completion of training. According to the participant's spouse, despite the research team's advice to keep using his arm more at home, he was not doing so. Compared to his pre-training active range of motion, he had maintained statistically significant gains in shoulder extension (28%) and elbow pronation (21%). The individual also had maintained gains in thumb and middle-finger PMP joint flexion (20% and 18%, respectively). He still was overextending the index to 15° and ring finger to 45°. The participant had maintained his gains in force exertion, which, compared to pre-training measurements, had increased 43% for grip strength, 77% for pulp-to-pulp, 175% for key pinch and 216% for 3-tip pinch.

DISCUSSION AND CONCLUSION

Training Results

Even though all 4 participants began with different degrees of impairment, after the intervention functional outcomes had improved for each individual with respect to his or her initial level of activity. All were able to play the games with the affected UE, we believe due to the capability of the experimental system to customize the intervention to each participant's functional level at each training session. We assumed that participants with the greater levels of impairment most likely would not have been able to use off-the-shelf gaming systems for therapy, and our study results showed that it was feasible, and indeed beneficial, for them to train on the Rutgers Arm II system. At follow-up, 6 weeks after the end of therapy, all cases had continued to improve their Fugl-Meyer scores by as much as 5 to 9 points. This positive outcome exceeds results from other studies using virtual reality-based training and gravity unloading.^{33,34} At follow-up, participant 1 had continued to improve in his degree of independence performing daily tasks (Table 2). Except for driving and sleeping, he had improved in all standardized tasks. Participant 2 had made further gains in the use of her affected arm, while participant 3 had lost some gains, but still was using his affected arm in 5 tasks, as compared to none before training. All participants had maintained gains in active range of motion in their affected UE joints. All participants improved in finger flexion, a movement that was practiced in the games. Naturally, enthusiasm is tempered by the small number of participants in this study, and further controlled trials are needed to determine the most effective training methods or systems. Furthermore, in some cases there were deviations from the protocol due to individual limitations, or better-than-expected abilities. The impact of these protocol changes on the results will need to be examined further.

Grasp training results were also very good: Participants 2 and 3, who were unable to grasp or pinch prior to training, were now able to do so. All participants improved in pinch strength (something trained during the games) and participant 3 improved in grasp strength, with gains maintained at follow-up. These results were much better than those obtained in our prior study²⁴ where grasp strength improvements were mixed. We attribute the better results in the present study to longer training (6 weeks versus 4 weeks in the prior study) and to the requirement of sustained grasp at higher game difficulty levels. Maintaining grasp and pinch strength improvements at follow-up in the absence

of training may also have been due to an increased use of the affected UE at home, which the participants were encouraged to do.

Changes in Activities of Daily Living

The self-reports in the standardized questionnaire²⁶ in Table 2 show that the 6 weeks of training on the Rutgers Arm II prototype were associated with improvements in ADLs for all participants. These included the ability to use tools and lift a bag of groceries or a suitcase (participants 1, 3, and 4). Participant 2, who had a greater degree of impairment, at follow-up was able to lift a bag, dress, open a jar, and open a door with difficulty, while she had been unable to do any of these activities before training.

The 4 participants were in the chronic phase post stroke and were not undergoing other physical or occupational therapy during the study. We argue that the clear gains after training can be attributed both to the intensive use of the Rutgers Arm II system during training and increased use of the affected arm in ADLs. We assume that the participants gained confidence to perform such tasks when they first practiced them under supervision at the completion of training sessions in weeks 5 and 6. It may be possible that some of the requested ADLs were tasks the participants did not know that they could do. However, the connection with our training and encouragement and the resulting improvement in arm use cannot be ignored. While this is a small study, and each participant had individual characteristics and family environment, our findings nonetheless point to the continuum that has to exist between clinic and home. The best results were obtained by the participant who had an encouraging caregiver (based on team observations during training sessions), while home conflicts clearly did not help. These findings are in line with studies showing that strong social support improves outcomes, especially in patients with severe physical or cognitive deficits.^{35,36}

Participants' Acceptance of the Technology

All participants were compliant with the protocol. They either attended the therapy and evaluation sessions on time or made up the training sessions they missed. They were engaged in the training, as attested to by the length of training which they completed (up to 1 hour of actual exercise per session). No participants complained about the intensity or length of training. Participant 3 volunteered that he wanted to train again on the system 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.^{37,38} Importantly, unlike our earlier study,²⁴ the participants trained without a physical or occupational therapist being present. Nevertheless, we did not observe any diminished interest or diminished attention to games, nor a diminished intensity of training in the absence of a therapist in the room.

Changes in Participants' Well-Being and Morale

No standardized evaluation was done to quantify the participants' improvement in cognition, well-being, and morale. Nonetheless, certain changes were apparent to the research team. Prior to training, 3 of the participants exhibited negative behavior, including a lack of smiling and cursing their caregivers. As training progressed, their spirits improved: They started smiling, being nicer to their caregivers, wearing more colorful clothes, and attempting to do new tasks with their affected arms. These changes need not be attributed to the technology or therapy they received. They could be associated with more self-confidence (in winning the games or doing tasks with their affected arm) and to the increased attention they received. To clarify these findings, we plan to add depression and cognitive evaluations in future studies.

The present study contributes to the body of knowledge that indicates that long durations of motor retraining on a VR system are feasible for low-functioning as well as higher-functioning patients who are in the chronic phase post stroke. Furthermore, the training in the present study was done without a physical or occupational therapist present, which has implications for cost and therapist availability as limitations to conventional therapy. Longer durations of training may be possible, once the computer can be relied upon to assist with repetitive task training.

While a PT or OT was not involved in the motor retraining in this study, the 4 participants occasionally needed the assistance of another person. Although this assistance and monitoring was performed by the technical staff in this research, it is a role that in the future may be covered by a physical therapist or occupational therapist assistant. Our experience was that the system was easily understood by the clinician, due to its interactive graphical user interface. If enough care is paid in the design of new virtual rehabilitation systems to ensure clear instructions, we can envision a new type of therapist emerging. This "virtual therapist" will be a skilled clinician that administers VR interventions for several patients with various impairments and functional levels, either locally or remotely.

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