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Virtual Immersion for Post-Stroke Hand Rehabilitation Therapy

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Abstract—Stroke is the leading cause of serious, long-term disability in the United States. Impairment of upper extremity function is a common outcome following stroke, often to the detriment of lifestyle and employment opportunities. While the upper extremity is a natural target for therapy, treatment may be hampered by limitations in baseline capability as lack of success may discourage arm and hand use. We developeda virtual reality (VR) system in order to encourage repetitive task practice. This system combined an assistive glove with a novel VR environment. A set of exercises for this system was developed to encourage specific movements. Six stroke survivors with chronic upper extremity hemiparesis volunteered to participate in a pilot study in which they completed 18 one-hour training sessions with the VR system. Performance with the system was recorded across the 18 training sessions. Clinical evaluations of motor control were conducted at three time points: prior to initiation of training, following the end of training, and 1 month later. Subjects displayed significant improvement on performance of the virtual tasks over the course of the training, although for the clinical outcome measures only lateral pinch showed significant improvement. Future expansion to multi-user virtual environments may extend the benefits of this system for stroke survivors with hemiparesis by furthering engagement in the rehabilitation exercises.

Keywords—Stroke, Rehabilitation, Virtual reality, Interactive environments, Upper extremity.

ABBREVIATIONS

3D	Three-dimensional
ARAT	Action research arm test
BBT	Box and blocks test
CMSA_A	Chedoke-McMaster stroke assessment, stage of arm
CMSA_H	Chedoke-McMaster stroke assessment, stage of hand
FMUE	Fugl-Meyer assessment for the upper extremity
FMWH	Fugl-Meyer assessment for the wrist and hand
GUI	Graphical user interface
HMD	Head mounted display
VR	Virtual reality

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INTRODUCTION

Stroke is the fourth leading cause of death and the leading cause of major, long-term disability in adults in the U.S.[7] Every 40 s someone in the United States has a stroke,[19] which accounts for an incidence of about 795,000 stokes per year.[7] While the 1-year mortality rate for individuals experiencing a stroke has been declining, a majority of the more than 7 million stroke survivors in the U.S. face chronic impairment,[7] impacting each individual's life on multiple levels: physical, psychological, and social. Around 50% of all stroke survivors will have residual hemiparesis involving the upper extremity,[14] which, in particular, can have profound, adverse impact on self-care, employment, and overall quality of life. Repetitive movement practice seems to be crucial for maximizing therapeutic benefits.[11] Yet, even if stroke survivors are initially motivated to practice, the repetitive therapy regimen can become monotonous and arduous, eventually leading to reduced adherence and compliance with therapy.[4,5,13] Lack of motivation, disengagement, and boredom contribute to impeded progress in rehabilitation.[10]

Virtual reality (VR) and serious games have emerged as new therapy methods in stroke rehabilitation. These methods possess inherent advantages in providing the opportunities for repetitive practice of activities beyond what is possible with conventional occupational therapy. For example, even very limited movements in the physical world can be made to have functional, rewarding outcomes in the virtual world. In addition, VR can automatically update task difficulty based on each user's progress, thus creating custom learning environments for individualized therapy. Maintaining the proper level of challenge has been shown to be important for motor learning in rehabilitation.[20] VR appears to be a promising intervention, as it may provide more engaging, motivating and adaptable environments for stroke rehabilitation,[20] than conventional therapy. Indeed, VR training paradigms have demonstrated encouraging results for use in upper extremity rehabilitation after stroke.[2,9,17]

Yet, while gaming consoles are commonplace in clinical settings, the number of specialized VR programs designed for rehabilitation is relatively small.[12] Additionally, the majority of the VR and serious game interventions created for rehabilitation have had limited creative and aesthetic input from artists and designers. VR is a highly visual medium. Therefore, the quality of visuals, graphics, animation, and images are important for influencing perception and emotion to encourage therapeutic practice. This is true across generations. When asked to explicitly rank different versions of a VR game according to the player experience, elderly adults preferred high-fidelity graphics.[21] While video games continue to become increasingly sophisticated and engaging, serious games tend to remain very simplistic, lacking the quality of graphics, narrative scenarios, and interactive game play found in their video game counterparts. One of the goals of our project was to create an appealing environment with sufficient complexity to maintain the participant's attention throughout a demanding training session with a high number of repetitions. The engaging graphics and diverse special effects were employed to enhance immersion and involvement in the environment to facilitate practice.

Many VR/game rehabilitation applications focus on either the arm or the hand alone. Human task performance, however, predominantly requires coordinated use of both the arm and hand. For example, the arm may stabilize hand position during object manipulation or the hand may maintain grasp of an object while the arm moves the object to a new location. Few systems actively train the arm and hand together and the effects of integrated training have not been sufficiently examined. We targeted the development of a rich VR environment that promotes repetitive practice of integrated arm and hand tasks.

Previously, we assessed the response of stroke survivors to initial exposure to the environment during a single training session.[22] Participants were largely positive about the environment and the exercises performed. The majority described the VR exercises as "fun" (86%), "challenging" (79%), and "engaging" (64%); they expressed interest in utilizing the system for rehabilitation. Here we present this novel VR system, along with results of a subsequent pilot study conducted to examine feasibility of the system. We hypothesized that the stroke survivors would improve performance of the virtual tasks, which required coordinated movement of the arm and hand, with repeated training sessions in the virtual environment. We further hypothesized that this intervention would lead to gains on clinical outcome measures. Partial, preliminary results of the intervention study were previously presented.[23]

MATERIALS AND METHODS

Virtual Reality System

VR Environment

Incorporating feedback from stroke survivors and therapists, we developed an immersive VR environment based on the classic story of *Alice in Wonderland* (Fig. 1). Specifically, a fully 3D version of the March Hare's cottage was rendered, complete with walls, ceiling, floor, table, chairs, and numerous virtual objects. The user sees the room and the virtual arm and hand for his avatar from a first-person perspective. Through the virtual arm and hand, controlled by the user, the participant can interact with objects in the room.

The setting lends itself to supernatural occurrences in which the objects suddenly become animated, possibly even morphing into other objects. Practice of specific movements is encouraged through interaction with these enchanted virtual objects. Accordingly, 10 separate exercises were created, each designed to address facets of upper extremity motor control, such as reach-to-grasp, lateral pinch, and finger individuation:

- cookies on the table morph into crabs which scurry away from the participants, thereby requiring tracking arm movements with an open hand to capture them (see Fig. 2);
- Bluebirds painted on the China pattern on the plates come to life and hover above the table,

thus requiring arm movements to recapture them (see Fig. 2);

- Flowers need to be cut with shears, which must be operated with a lateral pinch motion (see Fig. 2);
- A teapot must be manipulated to fill a teacup, thereby requiring combined control of grasp and arm rotation;
- Sugar cubes must be grasped with a pinching movement and moved from the bowl to the teacup;
- Spoons must be grasped appropriately while circular arm movement is created simultaneously in order to stir the tea;
- A teacup must be picked up with a palmar pinch and brought to the mouth for drinking;
- Cream pitchers contain various colors for finger painting in the air, thereby emphasizing practice of finger individuation as a single finger must be dipped into each pitcher prior to painting;
- A napkin suddenly flies above the table indicating that each finger must be wiped separately, thus necessitating finger individuation;
- A sherry glass must be grasped with a 3-finger pinch and brought to the mouth for drinking. A March Hare avatar guides the user through the different exercises.

FIGURE 1. VR system and interaction with the immersive VR environment. Magnetic trackers are affixed to the baseball cap to track the head and to the PneuGlove to track the arm. Bend sensors on the PneuGlove provide digit joint angles. The scene is continuously updated according to these sensor readings.

Each task is scalable both in terms of difficulty of performance and number of repetitions required for task completion. Visual and audio feedback of task performance are provided to the user. For example, if the sherry glass is grasped too lightly, it slips from the hand and falls to the floor with a loud sound of breaking glass. If it is grasped too tightly, it explodes, with accompanying visuals and sounds. Additionally, a score based upon the amount of time required to complete each exercises displayed to the user after the completion of each exercise. Characters, 3D environments, textures, and some animations were developed in Maya (Autodesk Inc., San Rafael, CA), which supports all stages of the 3D modeling, including surface creation and manipulation, texturing, lighting, rigging, and animation. We imported the characters, environments, textures, and animations from Maya into 3DVIAVirtools (Dassault Systems, Paris, France) to design our interactive scene. Behaviors, such as the ability to detect collisions, were added to characters by using the behavioral blocks within Virtools. Animations were also incorporated into the scene by using Virtools in order to further encourage engagement. Both playback and interactive animations were employed. The playback animations were used for movements too complex to be computed in real-time, such as movement of the March Hare avatar as it speaks. Playback animations, prepared in Maya, were generated from motion capture data of the torso and limb movements produced by a volunteer actor in a motion capture studio. These animations provide

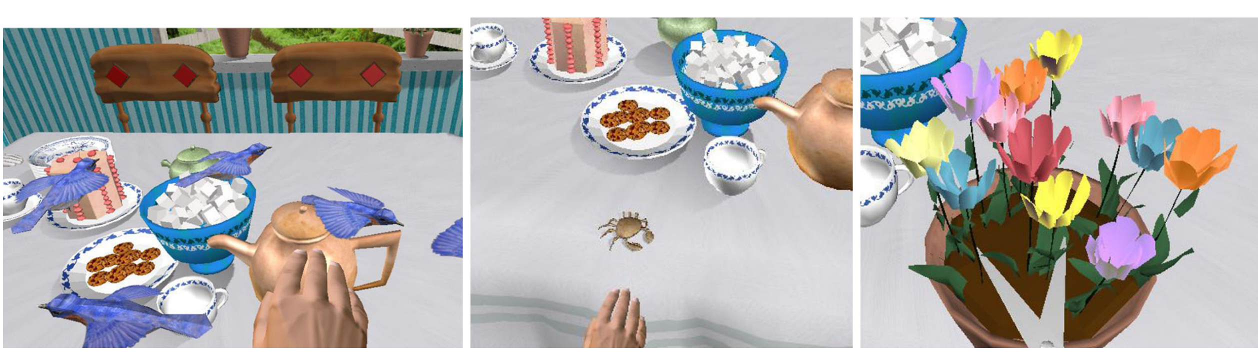

FIGURE 2. Three of the exercises created to promote repetitive practice of specific movements. Left: bluebirds fly from plates; Center: cookies morph into crabs; Right: flowers must be cut.

naturalistic gestures to accompany the speech of the March Hare avatar as it guides the user through the rehabilitation exercises. The interactive animations, created in Virtools, are played in response to events occurring in the VR environment. For example, the bluebirds hover over the table along predefined paths, waiting for the participant to catch them. With interactive animations, an object can be made to appear or disappear, change in texture or color, or even deform.

System Architecture

The user directly controls the virtual arm and hand, in addition to the scene displayed. Magnetic trackers (Flock of Birds®, Ascension Technologies, Burlington, VT) are attached to both the wrist, in order to control the position and orientation of the virtual hand, and to the head, in order to control the view within the room. The commercial electromagnetic tracking sensors (Flock of Birds®) have been widely employed. In this study, the sensors were used within their optimal operating range from the transmitter, a region for which positional and rotational errors have been shown to be less than 2%.[18] Hand joint angles are tracked from bend sensors (Flexpoint Sensor Systems, Inc., UT) located within a custom actuated glove, the PneuGlove,[2] worn on the hand. A custom calibration is performed with the PneuGlove for each subject to improve accuracy.

The tea party scene is continuously updated according to the orientation and position of the head, and the virtual hand is moved in accordance with the user's actual movements. The signals from the Flock of Birds can be read directly into Virtoolsby utilizing standard tools (building blocks and scripts) and used to update the scene. The signals from the glove are transmitted wirelessly (XBee, Digi International) to a separate computer controlling the PneuGlove (the "Glove Computer"). The joint angles are then transmitted to the display computer running Virtools (the "VR Computer") and the hand posture is updated accordingly. A detailed diagram showing the system architecture is shown in Fig. 3.

In addition to measuring digit joint angles, the PneuGlove can provide pneumatic assistance to digit extension to help with hand opening or resistance to finger flexion to provide haptic feedback. A custom Visual Basic program running on the Glove Computer controls the PneuGlove. This software also provides a dedicated graphical user interface (GUI) that facilitates control of the entire system for the therapist. Specifically, the GUI guides calibration of the bend sensors in the PneuGlove, allows the therapist to focus on movement of specific digits by selecting which digits will be monitored for successful task performance, and enables the therapist to map the challenge level to subject capabilities by adjusting the amount of assistance provided by the PneuGlove as well as the amount of hand opening or closing needed to complete the task. The PneuGlove was used for all exercises for every subject during training.

Communication between the VR Computer and the Glove Computer was implemented through custom, two-tiered dynamic-link libraries (DLL).Virtools receives the joint angles of the fingers and the thumb, as well as control signals, from the Visual Basic program on the Glove Computer; it sends back status information about the current exercise to the VR Computer. The lower tier handles the communication between the two software packages through TCP. The upper tier exposes classes that can be imported into Virtools, such as *PneuGloveWaiter*, which can be used to send and receive data from any external application that sends data to a specific port over TCP.

This real-time communication is utilized to determine successful grasp of an object, in addition to updating the visual scene. Finger joint angles, along with the criteria for threshold angles needed for successful object grasp, are sent from the Visual Basic program to Virtools. The VR software then determines: (1) whether the hand has collided with the target object; and (2) whether the joint angles meet the criteria for appropriate grasp of the object in question. Only if both conditions are met is the object "grasped" and subsequently attached to the virtual hand. When the hand posture meets the criteria for "release", the object disassociates from the virtual hand. These events are relayed to the Visual Basic routine.

While we had originally intended to use a head mounted display (HMD), adverse incidences such as mild eyestrain and transient nausea arose during pilot studies with a high-end HMD (nVisor SX60, NVIS, Inc., Reston, VA).[22] These occurrences, along with complaints about comfort, prompted us to switch from the HMD to two large 30-inch displays, positioned to create 120° horizontal field-of-view. The richness of the scene provided a sense of depth even without use of the HMD. Indeed, we have found that environmental cues can be at least as effective as stereoscopic vision in providing perceived size constancy of a virtual object as it is moved to different depths in a VR environment.[15]

Pilot Study

Participants

Six stroke survivors with chronic right-side hemiparesis volunteered to participate in an intervention

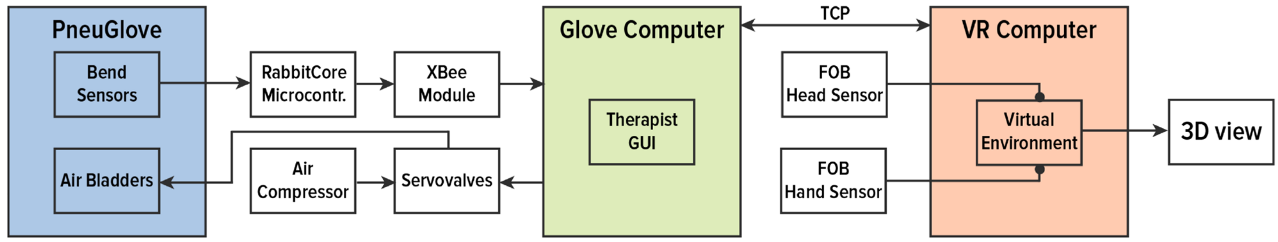

FIGURE 3. A schematic diagram of the system architecture.The Glove computer and the VR computer are connected by TCP/IP network architecture. The Glove computer receives the signals from the PneuGlove, which has Rabbit Core microcontroller sampling bend sensors and then transmitted wirelessly by Xbee module. The Glove computer also provides a GUI through which the therapist can monitor therapy. The Glove computer directly controls the pneumatic servovalves which in turn regulate air pressure in the air bladders in the glove. The VR computer collects data from the FOB (Flock of Birds®, Ascension Technologies Corp.) magnetic trackers and updates the virtual scene accordingly.

TABLE 1. Subject demographics.

Subject	Gender	Age (years)	Years post stroke	CMSA_A	CMSA_H	FMWH	FMUE	# of intervention studies in last 2 years
A1	F	59	8	6[a]	5	10	33	1
A2	F	33	2	4	4	8	38	12
A3	F	54	2	5	6	16	50	12
A4	F	59	7	5	5	11	45	11
A5	F	69	6	5	4	13	50	11
A6	M	54	4	4	4	6	28	13
Mean (SD)	5F/1 M	55(12)	5(2)	5(1)	5(1)	11(4)	41(9)	12(1)

CMSA_A Chedoke-McMaster Stroke Assessment, Stage of Arm; *CMSA_H* Chedoke-McMaster Stroke Assessment, Stage of Hand; *FMWH* Fugl-Meyer Assessment for the Wrist and Hand; *FMUE* Fugl-Meyer Assessment for the Upper Extremity.
[a]Indicates a previous measurement.

study intended to examine the viability of the VR system. Subjects were at least 6 months post-stroke and had no contracture or pain in the digits. All subjects had moderate right-handed impairment as rated by an occupational therapist to be between Stage 4 and Stage 6 (ordinal scale running from 1–7) on the Stage of Hand and Stage of Arm sections of the Chedoke-McMaster Stroke Assessment scale.[8] Subjects at these Stages for the Hand exhibit voluntary finger flexion but have some difficulty with finger extension, individuation, and coordination with fine motor tasks. All subjects had sufficient cognitive abilities to follow simple one-step instructions and did not have severely limited vision or hearing. All subjects provided informed consent in accordance with the Northwestern Institutional Review Board prior to enrollment in the study (Table 1).

Protocol

Each participant completed 18 one-hour training sessions with the VR system over a 6-week period in the Coleman Hand Rehabilitation Laboratory within the Rehabilitation Institute of Chicago. Each training session was directed by an occupational therapist and consisted of one or more cycles of the 10 exercises previously described. Exercise order was randomized. In accordance with clinical practice, the duration of each training session was fixed, but the number of repetitions varied depending on the capabilities of the subject. During the first sessions, participants could often complete only one cycle of 10 exercises during an hour session, while in the later sessions, multiple cycles could be completed by some subjects. The occupational therapist could adjust exercise order to focus on specific movements. Each exercise started at the original default difficulty for the next cycle. The chosen level of extension assistance was provided to the digits involved in a given exercise.

Outcome Measures

During the training sessions, the type of exercises performed, the score achieved in each exercise, and the number of completed trials for each session was recorded. In addition, another research therapist, who was not involved in the training sessions, performed clinical evaluations at three time points: prior to beginning the treatment, after completion of the training sessions, and 1 month later. Eight different measures were used for evaluation: Fugl-Meyer Assessment for the Upper Extremity (FMUE),[6] Chedoke-McMaster Stroke Assessment for both the arm (CMSA_A) and the hand (CMSA_H), Action

Research Arm Test (ARAT),[16] Box & Blocks test (BBT).[3] Grip and palmar and lateral pinch strengths were measured with a dynamometer (JAMAR 5030J1 Hand Dynamometer) and a pinch gauge (PG-60, B&L Engineering), respectively, to assess both strength and force coordination. Both the impaired and unimpaired limbs were tested for the ARAT, BBT, grip, and lateral and palmar pinch measures.

Analysis

Changes in performance of the exercises in the VR environment across sessions were evaluated by examining the completion times. Specifically, the average completion time across the first three assessments for each exercise was computed for each participant. These values were summed to obtain a total completion time for "early" training. The same methodology was employed for the last 3 assessments for each exercise to yield a total completion time for "late" training. The early and late total times were compared across subjects using a paired t test. Changes in individual exercises were assessed using the non-parametric Wilcoxon Signed-Rank Test. To help visualize relative changes across different exercises, total completion times for each session were normalized by the mean value across all sessions in subsequent plotting.

Data from the clinical outcomes were compared across the pre-, post-, and 1-month follow-up evaluations. Values for the CMSA_A, CMSA_H, FMUE and the wrist-hand portion of the FMUE (FMWH), ARAT, BBT, and grip and pinch strength were analyzed using non-parametric Friedman Test for repeated measures and *post hoc* Wilcoxon Signed-Rank Testsfor outcomes showing a significant effect of Evaluation session.

RESULTS

All 6 of the subjects enrolled completed the 18 training sessions and the three clinical evaluations. Performance of the VR exercises over time was assessed for 5 of the subjects. Namely, the time needed to complete the tasks was tracked across sessions. Data for the first subject, A1, are available only for the latter sessions due to system modifications and, thus, were excluded from the time-completion analysis. Data for the remaining subjects showed a substantial reduction in the total completion time for all 10 exercises over the course of the training sessions. Overall, there was a statistically significant decrease in the total completion time, as measured by the computer, across all 10 tasks from the first 3 assessments, 476 ± 112 s, to the last three, 296 ± 90 s,($t(4) =$; 7.10 $p < 0.05$, paired t test), for a mean time decrease of 38% (see Fig. 4). Each of the 5 subjects exhibited an improvement of at least 99 s. For the individual exercises, the Wilcoxon Signed-Rank Tests showed significant improvement ($Z = -2.20$; $p < 0.05$) for the following exercises: flowers, teapot, spoons, and cookies.

The downward progression for completion time with session was readily apparent for most tasks (Fig. 5).

This was especially true for some of the most difficult tasks (as gauged by time to completion): cutting the flowers, pouring tea from the teapot, and catching the cookies after they morphed into crabs. These tasks involve substantial coordination between control of the arm and of the digits (Fig. 6).

Statistically significant improvement after training was also observed across subjects in one of the clinical outcome measures, namely lateral pinch. The Friedman test revealed a significant effect of Evaluation session ($\chi^2(2) = 6.33$; $p = 0.042$) and a subsequent *post hoc* Wilcoxon signed-rank test revealed that lateral pinch increased from pre- to post-training ($Z = -2.20$; $p = 0.028$), although this increase was not maintained at the 1-month follow-up (pre-training vs. follow-up, Wilcoxon signed-rank test: $Z = -0.42$; $p = 0.674$).No significant changes were obtained for any of the other clinical outcome measures. Some subjects, however, did exhibit substantial gains. For example, subjects A4 and A5 improved from 20 to 28 blocks and from 24 to 34 blocks, respectively, from the pre-treatment to the 1-month post evaluations for the BBT. These gains of 8 and 10 blocks, respectively, represent 15 and 22% of the total number of blocks successfully moved with the ipsilesional (less impaired) upper extremity. These same two subjects also showed increases on the ARAT from 44 to 47 and 47 to 50 from pre-training to 1-month post-training (Table 2).

DISCUSSION

A novel VR training environment was developed to provide motivation for and engagement in therapy to facilitate combined arm and hand rehabilitation after stroke. The environment uses graphics and aesthetics to introduce challenging exercises and to bridge the boundary between game and therapy. The 3D objects were purposefully designed and arranged to promote exploration by the user. The therapeutic exercises were created with the intent to be sufficiently flexible such that the challenge could be readily adjusted according to the user's skill level in order to support further development. Position of both the hand and arm are monitored simultaneously to permit exercises requiring coordinated arm and hand movement. Assistance of digit extension, provided by the PneuGlove, expands

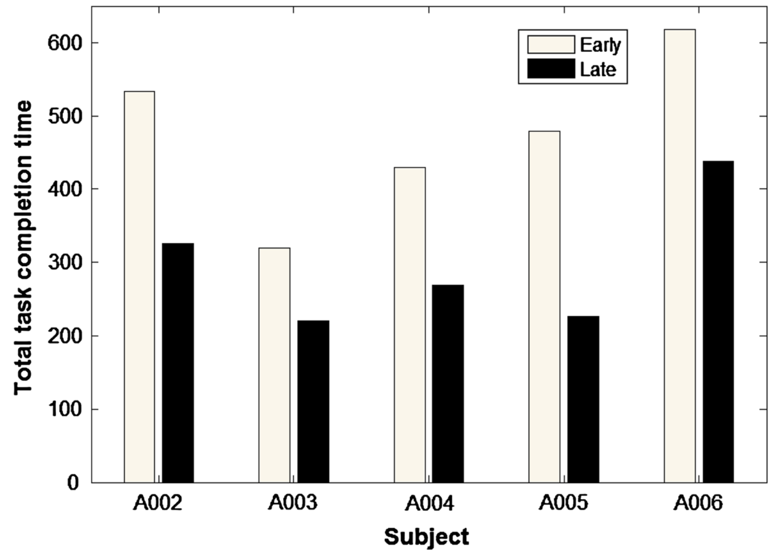

FIGURE 4. Total completion time for the 10 exercises for the: (i) (white bars) early training sessions (first 3 timed assessments of each exercise) and (ii) (black bars) late training sessions (last 3 timed assessments of each exercise). Completion time is measured by a computer system clock.

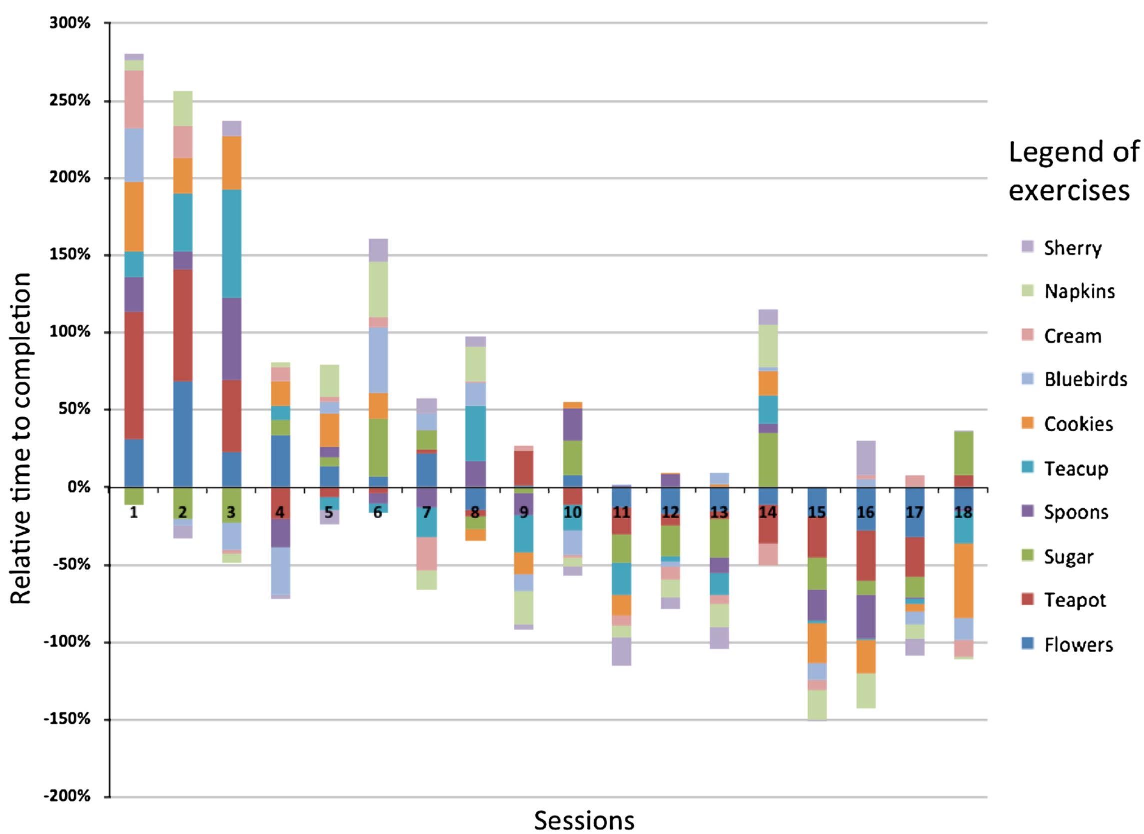

FIGURE 5. Deviations from the average rates of exercise completion of all participants for all exercises across the 18 sessions. The individual rates of completion were calculated for each subject (relative to the individual average time spent for completion) and used to generate the average rate of exercise completion for each exercise. The graph shows the deviations from the average completion time for each exercise. The 18 different sessions are shown across the *x*-axis, where the 10 different exercises are stacked on the *y*-axis. Extended completion times are stacked on the positive (upper) half, while shortened completion times are stacked on the negative (lower) half, which allows for visual perception of overall spread. While results for single exercises vary, the combined effect graph for all ten exercises across subjects shows a strong downward trend overall.

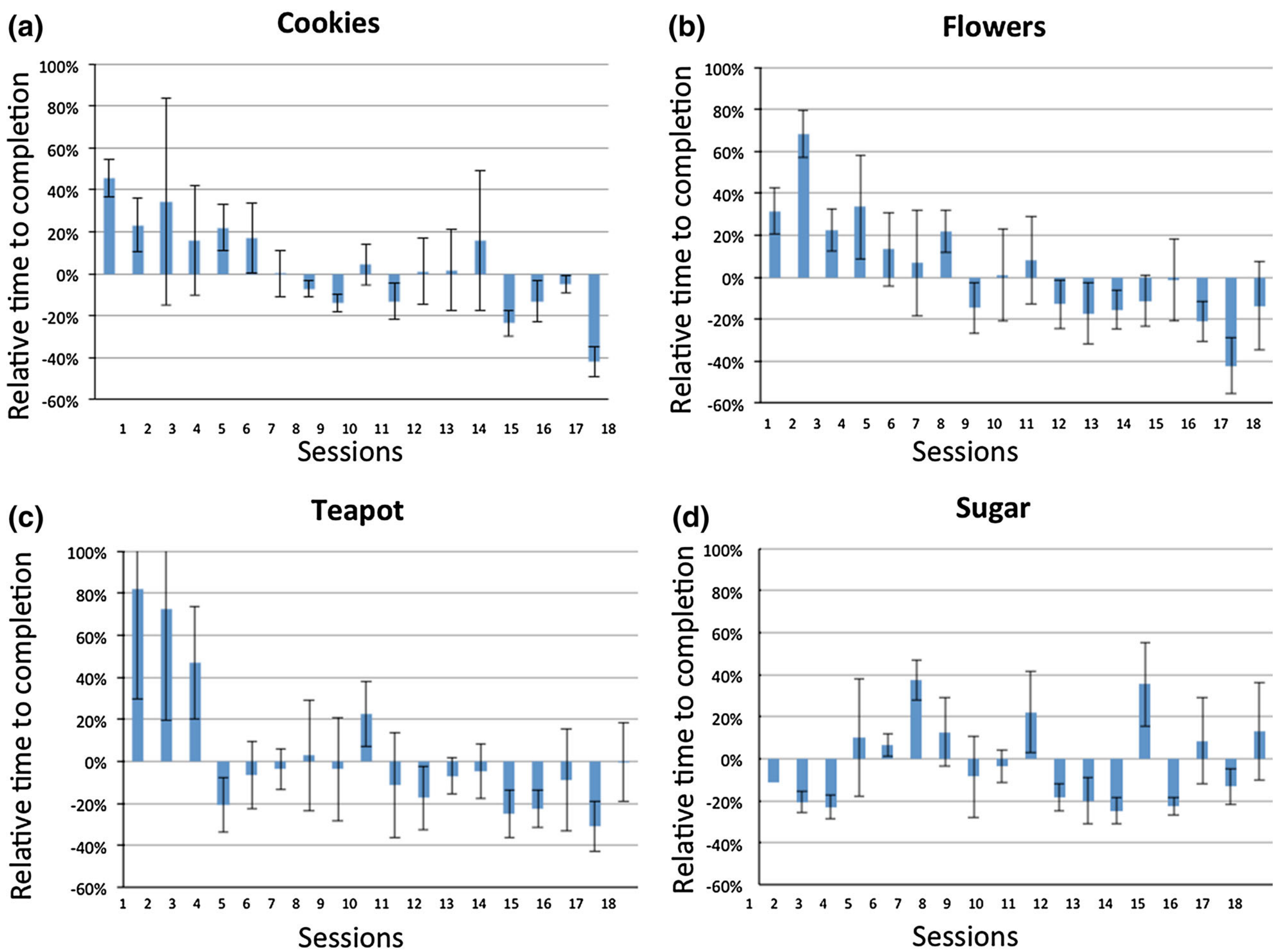

FIGURE 6. This figure shows deviations from the average completion times and their stand error from the mean across the 18 sessions for selected individual tasks. Individual exercises had various outcomes. 'Cookies' and 'Flowers' (a, b) show gradual improvement over subsequent sessions, 'Teapot' (c) displays early improvement (steep drop after 3 sessions), while completion time for 'Sugar' (d) shows little dependence on training session.

TABLE 2. Clinical outcome measures.

Outcome	Pre-treatment Mean (SD)	Post-treatment Mean (SD)	1-month follow-up Mean (SD)
CMSA_H	4.7 (0.8)	4.5 (0.5)	4.5 (0.5)
CMSA_A	4.8 (0.8)	4.8 (1.3)	4.5 (0.8)
FMUE	40.7 (9.2)	41.7 (9.3)	40.3 (8.0)
FMWH	10.7 (3.6)	10.5 (4.2)	9.7 (4.1)
ARAT	42.5 (10.7)	42.7 (10.5)	44.2 (8.8)
BBT	23.7 (11.5)	23.8 (10.4)	25.0 (12.6)
Grip strength (N)	41.2 (23.5)	43.3 (20.3)	37.4 (16.6)
Lateral pinch (N)	15.2 (7.0)	16.3 (6.5)	12.6 (6.2)
Palmar pinch (N)	9.4 (6.0)	9.9 (6.8)	8.3 (4.8)

CMSA_H Chedoke-McMaster Stroke Assessment, Stage of Hand; *CMSA_A* Chedoke-McMaster Stroke Assessment, Stage of Arm; *FMUE* Fugl-Meyer Assessment for the Upper Extremity; *FMWH* Fugl-Meyer Assessment for the Wrist and Hand; *ARAT* Action Research Arm Test; *BBT* Box and Blocks Test.

the capabilities of the subject such that new tasks can be performed, further encouraging upper extremity therapy.

Training with the VR System

Our pilot study confirmed the feasibility of using this system in longitudinal interventions with stroke survivors. Participants displayed considerable improvement in the speeds of exercise completion over the course of the training. This was especially true for more difficult tasks that required substantial coordination of arm and hand motor control; e.g., subjects improved maintaining a grasp while moving their hand and a captured virtual object through space with their arm. This led to are duction in the time required to complete exercises such as manipulation of the teapot.

These gains not only demonstrated improved control over upper extremity movement, they also enabled increased repetitive practice; participants could complete more cycles of a given exercise during later training sessions. According to our subjects and therapists, hand/arm coordination was the major improvement during the intervention. One subject stated that he could reach and fold his own laundry at home after he started his VR therapy. In a prior study, researchers suggested that training the arm and hand as a coordinated unit following stroke might be more effective than training each separately.[1] While our study did not directly address this debate, our experiences suggest potential merit in the combined training.

Participants did exhibit a modest but significant increase in lateral pinch strength after completion of the training sessions, although this improvement was not apparent at the follow-up evaluation. While increased strength may have arisen from increased muscle mass, we believe it was more likely due to altered muscle coordination. The task involving cutting flowers, in particular, was focused on creation of lateral pinch. Practice of this task may have led to improved control. Further practice may be necessary to sustain improvement.

For the most part, however, the gains suggested by the reduction in exercise completion time were not manifested during the evaluations with the clinical outcome measures. One issue may have been the lack of arm assistance provided during the training. Coordinated movement of the hand and arm places additional burdens on control of the arm. Our participants often found this to be quite challenging, even those for whom moving the arm in isolation was relatively easy. Providing active-assist or even gravity cancellation for the arm might foster improved arm kinematics, thereby giving proper sensory feedback. Additionally, the instruments used to evaluate arm-hand motor control may not be as sensitive as the VR system. CMSA, FMUE, and the strength measurements tend to look at the arm or hand in isolation. The two measures that involve arm-hand coordination, BBT and ARAT, showed the strongest trend of improvement out to 1 month post-training. The arm movements for these evaluations, however, are relatively limited in comparison to the virtual exercises.

Study Limitations

There are several limitations to this pilot study. Foremost, due to the small sample size, these results may not be generalizable to the greater population of stroke survivors. Additionally, there was no control group. The positive results that were seen could be due to assessor bias, natural recovery (although subjects were at least two and up to 8 years post-injury), varying emotional states, or other phenomenon. Future randomized controlled trials are needed to assess the efficacy of this VR immersive rehabilitation system in improving upper extremity motor control. As noted, the participants in this study were well into the chronic phase of recovery; the mean time since stroke was 5 years. Greater benefits might be attained in using the VR system with stroke survivors earlier in the recovery period. Additionally, subjects had already participated in two research intervention studies, on average, in the 2 years prior to enrollment in this study. Thus, our subjects may already have come close to realizing their rehabilitative potential before even starting participation in the current study. It is interesting to note that two of the subjects who exhibited some of the largest gains (A4 and A5), had only participated in one other study, as opposed to 2–3 for some of the other subjects. It is possible that trials with naïve subjects may lead to greater improvement. Finally, the clinical outcome measures we selected may not have been optimal for quantifying arm-hand coordination. While other instruments, such as the Wolf Motor Function Test,[24] could be adopted, these measures may not fully capture motor control capabilities (e.g., when faced with perturbations). New standardized tests for hand and arm coordination are needed.

While the exercises remained challenging, there were components of the narrative that became tiresome with repeated exposure. First among these was the March Hare avatar intended to further draw users into the scene by providing a narrative. The limitations of this pre-programmed guide, however, became apparent. Participants tired of the instructions/cues provided by the March Hare avatar, to the point where the option was created to mute him. As noted, no HMD was employed due to the difficulties cited with comfort and eyestrain. Thus, the participant could see both her own arm/hand and the virtual arm/hand, potentially leading to conflict. In our experience, however, subjects largely focused on the virtual upper extremity rather than their actual limb as the virtual objects could only be seen on the screen.

CONCLUSIONS

Participants found the VR exercises to be challenging and the system to be fairly engaging. Repeated training sessions led to substantial reductions in the time needed to complete the exercises, although translation to significant improvement on clinical outcome measures was limited to increased lateral pinch. One drawback with the system was the lack of real interaction with other avatars; the March Hare had a limited repertoire that soon became repetitive. Thus, in the next evolution of this system we are developing a multi-user VR environment, which will allow stroke survivors to interact with each other, as well as therapists, in the same virtual room even though they may be physically separated by large distances. This interaction with another human being affords an almost unlimited number of possibilities for any scenario, as well as strong motivation. In accordance with our philosophy, this system will be explicitly designed to train movements important to rehabilitation and to provide feedback of performance to users and clinicians.

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