Virtual Activities of Daily Living for Recovery of Upper Extremity Motor Function

Richard J. Adams, *Senior Member, IEEE*, Matthew D. Lichter, Allison Ellington, Marga White, Kate Armstead, James T. Patrie, and Paul T. Diamond

***Abstract*— A study was conducted to investigate the effectiveness of virtual activities of daily living (ADL) practice using the SaeboVR software system for the recovery of upper extremity (UE) motor function following stroke. The system employs Kinect sensor-based tracking to translate human UE motion into the anatomical pose of the arm of the patient's avatar within a virtual environment, creating a virtual presence within a simulated task space. Patients gain mastery of 12 different integrated activities while traversing a metaphorical "road to recovery" that includes thematically linked levels and therapist-selected difficulty settings. Clinical trials were conducted under the study named Virtual Occupational Therapy Application. A total of 15 chronic phase stroke survivors completed a protocol involving three sessions per week over eight weeks, during which they engaged in repetitive task practice through performance of the virtual ADLs. Results show a clinically important improvement and statistically significant difference in Fugl–Meyer UE assessment scores in the study population of chronic stroke survivors over the eight-week interventional period compared with a non-interventional control period of equivalent duration. Statistically significant and clinically important improvements are also found in the wolf motor function test scores. These results provide new evidence for the use of virtual ADL practice as a tool for UE therapy for stroke patients. Limitations of the study include non-blinded assessments and the possibility of selection and/or attrition bias.**

***Index Terms*— Upper extremity rehabilitation, stroke therapy, virtual reality, human computer interaction, human motion tracking, human motor performance.**

Manuscript received May 19, 2017; revised September 5, 2017 and October 23, 2017; accepted October 30, 2017. Date of publication November 8, 2017; date of current version January 8, 2018. This work was supported by the National Institutes of Health, Eunice Kennedy Shriver National Institute of Child Health and Human Development, under Grant 2R44HD071745-02. *(Corresponding author: Richard J. Adams.)*

R. J. Adams and M. D. Lichter are with Barron Associates, Inc., Charlottesville, VA 222901 USA (e-mail: adams@barron-associates.com; lichter@barron-associates.com).

A. Ellington is with the Murphy Deming College of Health Sciences, Mary Baldwin University, Staunton, VA 24401 USA (e-mail: aellington@marybaldwin.edu).

M. White and K. Armstead are with UVA-HealthSouth Rehabilitation Hospital, Charlottesville, VA 22908 USA (e-mail: marga.white@healthsouth.com; kate.armstead@healthsouth.com).

J. T. Patrie is with the Department of Public Health Sciences, University of Virginia, Charlottesville, VA 22908 USA (e-mail: jp4h@virginia.edu).

P. T. Diamond is with the Department of Physical Medicine and Rehabilitation, University of Virginia, Charlottesville, VA 22908 USA (e-mail: ptd2m@virginia.edu).

Digital Object Identifier 10.1109/TNSRE.2017.2771272

I. Introduction

THE scope of the healthcare challenge posed by stroke is massive, both in the number of affected persons and the related cost burden. Approximately 795,000 strokes occur each year in the U.S., about one every 40 seconds [2]. Stroke-related hospitalizations represent 77 stays per 10,000 persons over 45 years of age [3]. Approximately 50% of these individuals suffer from chronic deficits in UE function [4]. For an individual sustaining a stroke, the functional impact can be profound. Stroke is the leading cause of serious long-term disability [5] and resulting hemiparesis can lead to substantial problems with occupational performance, including ADLs.

An important goal for UE stroke therapy is reacquisition of the functional skills necessary to perform practical tasks, as well as addressing underlying deficits, which can include lack of strength, motor control, range of motion, and/or cognition [6]. It appears that both dosage and training specificity play an important role in neuroplasticity, the regeneration of cortical function in regions of the brain responsible for related neurological activity [7]. Task-specific training may be defined as the organized and repetitive practice of functional tasks that involve integration of sensory and cognitive faculties with available voluntary motion. Repetitive activity that is non-specific to functional tasks appears to be less effective [8]. This realization has influenced development of new approaches to rehabilitation, including constraint-induced therapy that integrates skill acquisition to reinforce normal motion patterns through massed, task-specific practice [9], [10].

The effectiveness of ADL-focused therapy in improving patient performance in daily activities is well-established [11], [12]. The use of virtual worlds to emulate task-oriented practice is a natural extension of "real world" ADL practice. The virtual version presents potential advantages of task automation, scalability of motor and cognitive challenge, performance tracking, practice in a safe virtual environment, gamification of exercises, and an infinite range of possibilities for design of virtual spaces. Examples of previous ADL-related interventions in a virtual context include kitchen tasks [13]–[15], street crossing activities [16], and accessing public transportation [17].

A growing body of evidence exists to support the effectiveness of game-based virtual reality interventions to improve upper extremity motor function following a stroke. Use of

virtual reality as an adjunct to conventional therapy resulted in significantly greater motor gains than conventional therapy alone in the acute phase of recovery [18], [19]. A comparison of virtual reality-based therapy to conventional therapy showed similar gains in UE scales [20]. In addition to motor scale improvements, participation with virtual reality has been shown to increase activation in the primary motor cortex as evidenced by fMRI results [21]. Further, the results of two meta-analyses found statistically significant positive outcomes of virtual reality intervention on motor outcomes [22], as well as motor strength and function [23]. Studies investigating virtual reality games have shown promise in improving motor function in hemiparetic upper extremities [24], but there is a paucity of results on the effectiveness of ADL-specific virtual reality systems for improving motor function. This may be explained by the simple fact that development of complex ADL-centered virtual experiences is a more challenging and expensive endeavor than creation of simple arcade-like games.

The SaeboVR system was developed by Barron Associates, Inc. under the National Institutes of Health (NIH) sponsorship to enable computer-mediated ADLs that engage a patient in functional, mass practice UE therapy. The organization of virtual activities, algorithms for Kinect™ sensor-based tracking, and game-derived metrics have been previously documented [25]. A high level of technology acceptance by the stroke patient population for the prototype system has also been reported [26]. The number of virtual activities was subsequently expanded from two in the prototype system to 12 in the current SaeboVR system. This paper presents the motor outcome results of clinical trials investigating the effectiveness of virtual ADL practice using this expanded system, performed under the study name Virtual Occupational Therapy Application (VOTA) [1].

II. Approach

A. SaeboVR

The SaeboVR software system supports repetitive task practice exercises that are consistent with Standard of Care for UE rehabilitation. The system consists of a standard Windows personal computer, Microsoft Kinect™ sensor, and a high-definition video monitor. The software employs a specially-designed unscented Kalman filter-based kinematic pose estimation algorithm [25] and state-of-the-art game engine technology to create a compelling world in which patients practice realistic ADLs. Patient arm movements are translated into equivalent movements of a graphical avatar that represents the patient in a virtual environment rendered on the computer display monitor. The virtual activities incorporate a wide range of UE movements involving the shoulder and elbow. The system does not currently track, or involve, digit and wrist movement. Tasks were developed with the input of therapists and rehabilitation doctors to be consistent with accepted clinical practice for repetitive task-directed therapy. Typical task elements include picking up, moving, and placing virtual objects. The medical professional is able to adjust the range of motion and movement repetitions required to complete the activities to a difficulty level appropriate for the individual patient.

For the purposes of this application, a broad definition of ADLs is used, encompassing both the traditional definition of ADLs [27] and instrumental activities of daily living (IADLs) [28], which are both primary areas of intervention for therapists [29]. The SaeboVR application used in the VOTA study included: Grocery Shopping, Putting Away Groceries, Preparing Breakfast, Pet Shopping, Pet Feeding, Pet Bathing, Garden Planting, Garden Harvesting, Preparing Dinner, Organizing a Closet, and Volunteering at a Soup Kitchen; as well as a Ball and Boxes practice activity.

In addition to the physical challenge, the virtual activities also require significant cognitive involvement, including attention, memory, visual-spatial planning, and sequencing. For example, the patient may be required to recall the location of an object in a cabinet, the proper placement of a grocery item in the refrigerator or pantry, or to turn off a stove burner after a pan is removed.

III. Methods

A. Participants

Participants were hemiparetic stroke survivors at least three months post-event with ongoing UE impairment related to the cerebral vascular accident. Study inclusion criteria included requirements for: antigravity strength at the elbow to at least 45 degrees of active flexion; antigravity shoulder strength to at least 30 degrees each in active flexion, abduction/adduction; and 15 degrees in active shoulder rotation from an upright seated position. Participants had visual acuity with corrective lenses of 20/50 or better and were able to understand and follow verbal directions. The study excluded patients with visual field deficit in either eye that would impair ability to view the computer monitor and/or with hemispatial neglect that would impair an individual's ability to process and perceive visual stimuli. Recruited subjects had completed a typical course of treatment to address UE deficits prior to enrollment and did not take part in any therapy program for the UE outside of the study during the period of participation.

Consent administration, virtual ADL practice sessions, and administration of assessments took place in the outpatient clinic of the UVa HealthSouth Rehabilitation Hospital in Charlottesville, VA between February 2016 and February 2017. The protocol was reviewed, approved, and conducted under the auspices of the UVa Institutional Review Board for Health Sciences Research (IRB-HSR). All patient interactions and assessments were administered by three licensed Occupational Therapists (the "study therapists") who were trained on human subject protections and IRB-approved procedures.

A total of 22 stroke patients meeting study inclusion and exclusion criteria were consented to participate in the full protocol. Of these, 15 individuals completed the study and 7 dropped out prior to completion of the post-intervention assessments. No adverse incidents were reported. The characteristics of the study population are summarized in Table 1. Note that all participants were 8 months or more post-stroke. Each had completed their prescribed course of therapy but continued to experience stroke-associated UE impairment.

TABLE I
STUDY CHARACTERISTICS

Subjects			*Age*		
Total	*Male*	*Female*	*Median*	*Min*	*Max*
15	6	9	68	46	91
Months since most recent stroke					
Median		*Min*		*Max*	
18		8		108	
Stroke Affected Upper Extremity			*Affected Side Dominance*		
Left	*Right*		*Dominant*	*Non-dominant*	
7	8		4	11	

B. Protocol

The primary investigational hypothesis is that practice of virtual ADLs using the SaeboVR system will lead to an improvement in UE motor function in chronic stroke survivors. A within-subjects non-interventional control period was used to control for spontaneous recovery. Prior to using the system, all participants underwent an initial "pre-control" assessment followed by 8 weeks with no prescribed UE therapy. Following this non-interventional period, subjects completed a "post-control" assessment. They then commenced participation in virtual ADL practice, with three sessions per week over an eight-week interventional period (24 total therapy sessions). Each session was approximately 1 hour in duration. A final "post-intervention" assessment was conducted after the last session.

C. Assessments

Assessment of motor function included administration of the FMUE instrument [30] (primary outcome measure) and the WMFT [31] (secondary outcome measure). FMUE is one of the most widely-used and accepted quantitative measures of motor function in stroke patients. It is used in both clinical and research settings. Individual patient movements associated with specific motor functions are scored using a 3-point ordinal scale (0, 1, or 2). Higher scores correspond to higher levels of motor function. The VOTA/SaeboVR clinical study employed a subscale of the full Fugl-Meyer assessment that incorporates 21 items relevant to shoulder and elbow function (thus creating a possible range of 0 to 42 points). These items included biceps and triceps reflex activity; shoulder, elbow, and forearm flexor and extensor synergy; mixed synergies; volitional movements with little or no synergy; coordination; and speed.

The WMFT test is a functionally-oriented clinical and research instrument that has been shown to have high inter-rater reliability, validity, and internal consistency [31]. The test consists of 15 motor tasks, nine of which are timed integrative functional movements. The remaining elements are timed joint-segment movements. The WMFT includes quantitative and qualitative scales. WMFT-TIME is a quantitative measure calculated using the average time to complete the tasks. A reduction in average completion time implies improved motor function. The WMFT Functional Assessment Score (FAS) is a qualitative assessment based on scoring of each functional task using a 6-point ordinal rating scale that ranges from 0 (no use of the affected side attempted) to 5 (normal function). A total WMFT-FAS is calculated by taking the average across all 15 UE tasks. An increase in WMFT-FAS score implies improved motor function.

All assessments were administered by non-blinded study therapists using a comprehensive checklist with well-defined rubrics. Study therapists were practiced in use of the instruments both from previous studies and from use in clinical practice. Prior to being certified to administer the protocol, the therapists received additional training and demonstrated proficiency in consistent application of the rubrics used in each assessment.

Fig. 1. Virtual therapist provides guided tour of the Road to Recovery.

Fig. 2. The patient chooses a personal avatar.

D. Virtual ADL Practice

In the first practice session, the patient received a guided tour of the environment and available activities. The tour is provided by a virtual therapist "Claire" (see Figure 1) who then becomes the patient's companion and assistant through all activities.

Each participant then selected his/her own virtual character, called an avatar (see Figure 2), and practiced using the avatar to perform a simple activity involving picking up balls and putting them in boxes.

Patients then started with the first virtual ADL on a path that represents a metaphorical "Road to Recovery" (see Figure 3). In each session, patients make progress along this path, eventually performing each activity at least four times.

The activities are thematically linked. For example, Grocery Shopping is followed by Putting Away Groceries, and

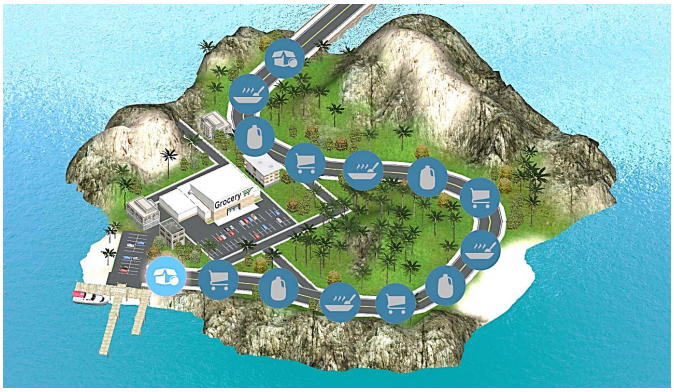

Fig. 3. Patient Dashboard showing first level of the Road to Recovery.

Fig. 4. Drinking a glass of water in Soup Kitchen Volunteering activity.

Fig. 5. Closing a cabinet during Preparing Dinner activity.

subsequently by Preparing Breakfast. By completing this Road to Recovery, patients thus gain mastery of twelve different integrated activities. Some examples of ADL-related functions performed during system use include eating and drinking (Figure 4), performing a sequence of food preparation tasks (Figure 5), and retrieving/placing items at various orientations and distances (Figure 6 and Figure 7). Note that haptic feedback is not provided.

A previous paper has described the integration of specific functional movements into the design of the virtual ADLs and provided a task-level analysis of UE involvement during system use [25]. Please refer to that paper for additional details.

Fig. 6. Hanging up a shirt in Organizing Closet activity.

Fig. 7. Picking red peppers in garden harvesting activity.

TABLE II
FMUE SUMMARY STATISTICS

	N	FMUE score				
		Mean	Median	Min	Max	SD
Pre-Control	15	22.0	20	14	34	6.3
Post-Control	15	22.5	23	15	32	5.5
Post-Intervention	15	28.7	28	18	38	6.8

IV. RESULTS

A. FMUE Assessment Results

Summary statistics for the 45 FMUE assessments administered during the VOTA study (3 for each patient) are presented in Table 2. The by-subject scores are graphically summarized in Figure 8. Red circles connected by dashed lines identify the subject-specific FMUE profiles, while the solid black line identifies the mean profile across all subjects.

Empirical distributions for the change in FMUE score for the intervention period (post-control to post-intervention) and control period (pre-control to post-control) are illustrated in Figure 9.

As a repeated measure, these data were analyzed via a linear mixed model (LMM). The hypothesis was that the mean change in the FMUE score differs depending on whether the mean change is for the SaeboVR interventional period (i.e. from the post-control assessment to the post- intervention assessment) or the control period (i.e. from the pre-control

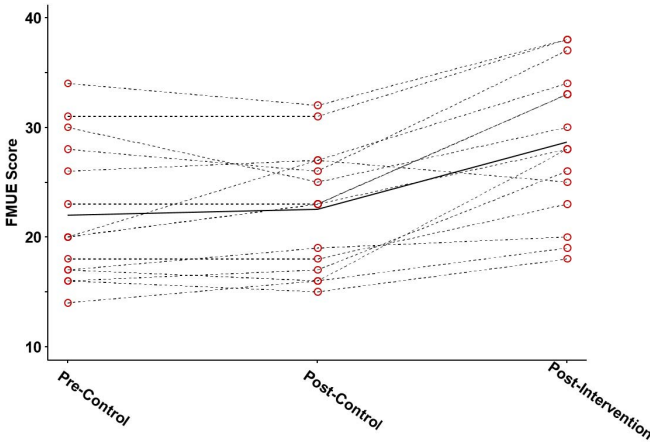

Fig. 8. By-subject summary of FMUE assessments.

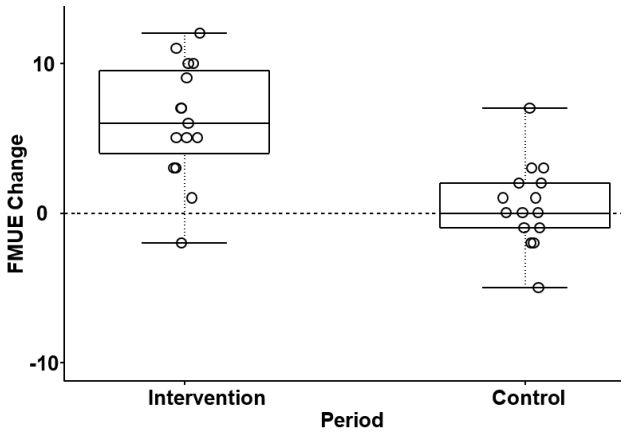

Fig. 9. Empirical distributions for change in FMUE score.

TABLE III
LMM ESTIMATES FOR CHANGE IN FMUE SCORE FOR INTERVENTIONAL VS. CONTROL PERIOD (BOLD VALUES INDICATE STATISTICAL SIGNIFICANCE)

Change Δ in FMUE	Estimate Mean Change	Bonferroni-corrected estimates		
		P-value	95% confidence interval	
			Lower	Upper
Δ Intervention Period	6.1	**<0.001**	3.8	8.4
Δ Control Period	0.5	1.000	-1.8	2.8
Δ Intervention - Δ Control	5.6	**0.004**	1.6	9.6

assessment to the post-control assessment). This hypothesis was tested via a linear contrast of the LMM least-squares means. Table 3 presents a summary of the results for the 15 individuals who contributed paired (control period and interventional period) data for change in FMUE scores. As secondary hypotheses, the mean pre-control to post-control change in the Fugl-Meyer Score, and the mean post-control to post- intervention change in the FMUE score were the foci, with the null hypothesis in each case that the mean change is equal to zero. A Bonferroni-corrected $p<0.05$ decision rule was used as the null hypothesis rejection criterion, in which the

TABLE IV
WMFT-TIME SUMMARY STATISTICS

	N	WMFT-TIME				
		Mean	Median	Min	Max	SD
Pre-Control	15	14.6	9.4	3.3	67.0	17.4
Post-Control	15	14.8	7.6	2.6	66.4	18.7
Post-Intervention	15	9.7	5.2	2.1	52.1	12.6

TABLE V
WMFT-FAS SUMMARY STATISTICS

	N	WMFT-FAS				
		Mean	Median	Min	Max	SD
Pre-Control	15	2.9	3.3	0.9	4.4	1.1
Post-Control	15	2.8	3.1	0.9	4.3	1.0
Post-Intervention	15	3.3	3.5	1.2	4.8	1.2

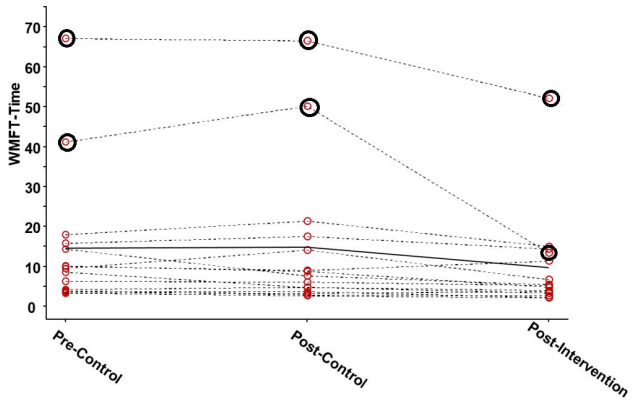

Fig. 10. By-subject summary of WFMT-TIME scores. Outlier points excluded from analysis are highlighted by bold circles.

correction was for a set of 3 hypothesis tests. The Bonferroni correction compensates for the increased likelihood of incorrectly rejecting a null hypothesis due to testing of multiple hypotheses.

B. WMFT Results

Summary statistics for the WMFT-TIME and WMFT-FAS assessment data collected during the VOTA study are presented in Table 4 and Table 5.

The by-subject scores are graphically summarized in Figure 10 and Figure 11. Red circles connected by dashed lines identify the subject-specific WFMT profiles, while the solid black line identifies the mean profile across all subjects. Figure 10 shows that two of the subjects had much higher WMFT-TIME scores in both pre- and post-control testing than the remainder of the study population. Both of these subjects subsequently realized a large improvement in WMFT-TIME score post-intervention, as seen in the corresponding points in the empirical distribution in Figure 12 (associated with the two largest reductions over the intervention period). As these WMFT-TIME data outlie the remainder of the distribution by two standard deviations or more, they were removed from the

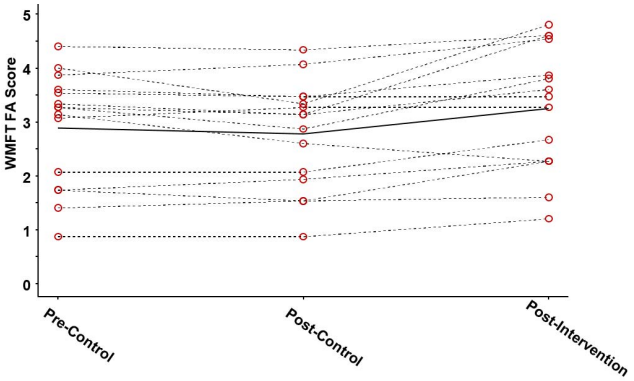

Fig. 11. By-subject summary of WMFT-FAS scores.

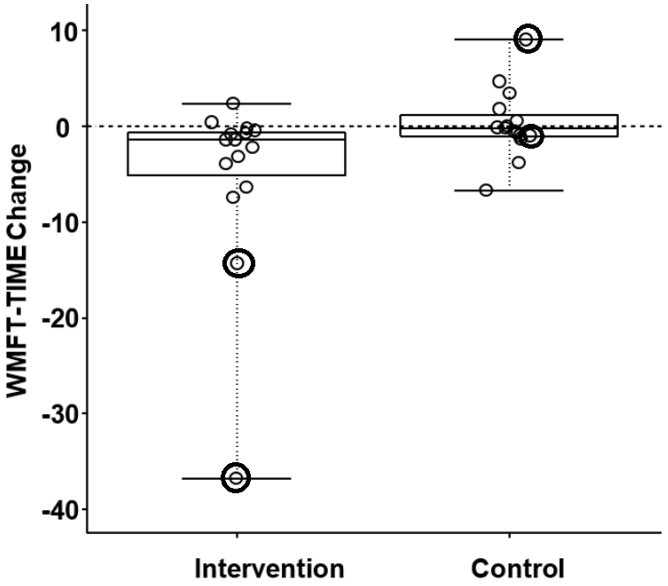

Fig. 12. Empirical distributions for changes in WMFT-TIME scores. Outlier points excluded from analysis are highlighted by bold circles.

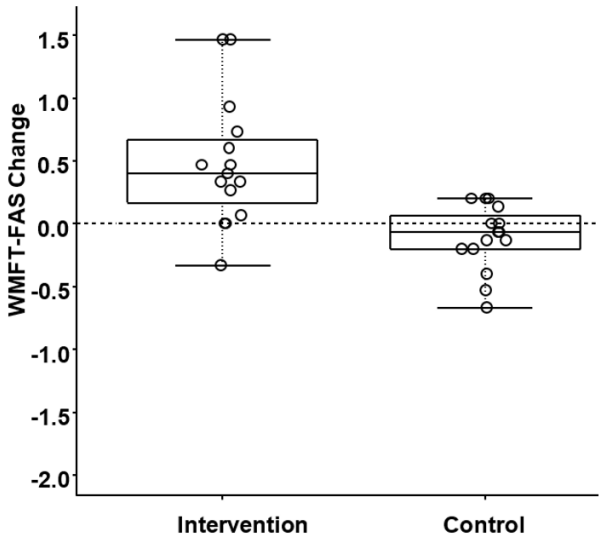

Fig. 13. Empirical distributions for changes in WMFT-FAS scores.

TABLE VI
LMM ESTIMATES FOR CHANGE IN WMFT-TIME SCORE FOR INTERVENTIONAL VS. CONTROL PERIOD (BOLD VALUES INDICATE STATISTICAL SIGNIFICANCE)

Change Δ in WMFT-TIME	Estimate Mean Change	Bonferroni-corrected estimates		
		P-value	95% confidence interval	
			Lower	Upper
Δ Intervention Period	-2.0	**0.049**	-3.6	-0.4
Δ Control Period	-0.4	1.000	-1.9	1.2
Δ Intervention - Δ Control	-1.6	0.704	-4.3	1.1

TABLE VII
LMM ESTIMATES FOR CHANGE IN WMFT-FAS SCORE FOR INTERVENTIONAL VS. CONTROL PERIOD (BOLD VALUES INDICATE STATISTICAL SIGNIFICANCE)

Change Δ in WMFT-FAS	Estimate Mean Change	Bonferroni-corrected estimates		
		P-value	95% confidence interval	
			Lower	Upper
Δ Intervention Period	0.48	**0.001**	0.19	0.77
Δ Control Period	-0.11	1.000	-0.40	0.18
Δ Intervention - Δ Control	0.59	**0.018**	0.09	1.10

subsequent statistical analysis (thus making the analysis more conservative regarding a potential improvement).

Empirical distributions for the change in WMFT scores for the intervention period and control period are illustrated in Figure 12 and Figure 13.

For each WMFT measure, the hypothesis was that the mean change in the WMFT measure differs depending on whether the mean change is for the SaeboVR intervention period (i.e. from the post-control assessment to the post-intervention assessment) or for the control period (i.e. from the pre-control assessment to the post-control assessment). This hypothesis was tested via a linear contrast of the LMM least-squares means. Table 6 and Table 7 summarize the results of LMM analysis of WMFT results.

During virtual ADL practice, SaeboVR tracks the actual UE movements of patients, providing an estimate of the dosage of functional reaching movements achieved. For the purpose of quantifying dosage, a functional reach can be defined as any reaching movement that accomplishes a practical task. The SaeboVR system accounts for each movement that successfully results in completion of an in-game objective (e.g. picking up or placing an object during performance of a virtual ADL). Extraneous movements and/or movements that do not successfully accomplish a goal are not counted. SaeboVR also distinguishes between time spent in a therapy session and time spent actually performing ADLs, defining the latter as "activity duration." Activity duration is calculated as the total time during a session that a patient spends actually performing tasks in the virtual space. Table 8 summarizes the participation history and effective dosage for the 15 subjects

TABLE VIII
PER-SESSION DOSAGE OBSERVED DURING SAEBOVR SESSIONS

	Mean	Median	STD
Functional reaches performed	198.3	198	78.5
Number of virtual ADLs completed	6.1	6	2.2
Activity duration (in minutes)	36.2	37.1	8.8

who completed both the control and interventional periods, including 24 SaeboVR sessions of approximately 1-hour duration.

V. DISCUSSION

An investigation into the effectiveness of virtual ADL practice for recovery of UE function following stroke has found that practice of virtual ADLs using the SaeboVR system was associated with significant and clinically important improvements in motor function measures for the study population of chronic stroke survivors. The primary investigational hypothesis is thus confirmed. A more detailed exploration of these results, study limitations, additional observations, and potential vectors for future research follow.

A. Primary Results

A statistically significant improvement was found in the primary outcome measure (FMUE score) for study participants who used VOTA for virtual ADL practice over an 8-week interventional period. As summarized in Table 3, the Bonferroni-corrected mean change in the FMUE score was 6.1 units (95% CI: [3.8, 8.4 units], $p<0.001$) for the SaeboVR interventional period, and 0.5 units (95% CI: [−1.8, 2.8 units], p=1.000) for the control period (Ho: ΔIntervention = Δ Control; p=0.004). We thus find that the improvement in FMUE score during the interventional period was statistically significant, and further that the difference between the estimated mean change during the intervention period and the estimated mean change during the control period is statistically significant. We also note that the estimated mean change in FMUE score (6.1) exceeds the FMUE change that is typically considered to be a clinically important difference (CID). CID can be defined as an improvement of at least 10% of the scale's range [32]. The FMUE sub-scale used in this protocol has a range of 0 to 42, thus a difference of 4.2 or greater can be considered clinically important. The estimated change in FMUE score for the control period is near zero. As expected, the chronic stage stroke patients did not exhibit spontaneous recovery.

Results of analysis of the secondary WMFT measures are consistent with the primary findings. The estimated mean change in WMFT-TIME for the SaeboVR intervention period was -2.0 seconds (95% CI: [−3.6, −0.4], p=0.049), a statistically significant improvement. For the control period, the estimated mean change in WMFT-TIME was small, at −0.4 seconds (95% CI: [−1.9, 1.2], p=1.000). We are unable to draw a statistical conclusion regarding the difference in the estimated mean change during the intervention period and the estimated mean change during the control period (Ho: Δ Intervention = Δ Control; p=0.704). The estimated mean change in WMFT-TIME (−2.0) is consistent with the 1.5 to 2.0 seconds reduction that has been associated with a CID in chronic stroke patients by other researchers [33].

The mean change in the WMFT-FAS score (functional assessment with range 0 to 5) was 0.48 units (95% CI: [0.19, 0.77], p=0.001) for the SaeboVR intervention period (statistically significant improvement), and -0.11 units (95% CI: [−0.40, 0.18], p=1.000) for the control period (Ho: Δ Intervention = Δ Control; p=0.018). The estimated mean change in the WMFT-FAS measure for the chronic stroke patients in this study is 0.48, which exceeds the range of 0.2 to 0.4 that has been defined in previous research results as a CID in chronic stroke patients [33].

Thus, for all three assessment scales used, a statistically significant and CID is found in UE motor performance for the study population of chronic stroke survivors. For two of the three measures (FMUE and WMFT-FAS), the difference in the estimated mean change during the intervention period and the estimated mean change during the control period is statistically significant. For all three measures, the observed change in scores during the control period was small and non-significant.

The ratio between the estimated mean change in the motor function score and the overall range of the assessment's scale is greater for the FMUE test (14.5%) than for WMFT-FAS (9.6%). The estimated mean change in WFMT-TIME is also near the limit of what can be considered a CID. The percentage-wise larger mean improvement in FMUE scores may be due to the fact that a sub-scale was used that only includes elements related to shoulder and elbow function. Conversely, 7 of the 15 items in WFMT assessment [31] involve some fine digit function (e.g. flipping cards and stacking checkers). Since the SaeboVR intervention used in this study did not involve practice of fine digit function or dexterous object manipulation, improvement in the dexterous hand function is not expected. Thus, when considering percentage change, improvements in elbow and shoulder function may be diluted in the WFMT results.

B. Limitations

Several limitations to our study warrant mention. Study therapists were not blinded, and participated in both the intervention and the assessments. The use of non-blinded assessments creates a risk of bias in estimates of treatment effects. The study employed rigorous test procedures and training on use of standardized assessments to improve interrater reliability, but the potential for ascertainment bias remains.

A potential for selection bias stems from the fact that the chronic stroke patients volunteering to participate in the study may have been predisposed to adhere to, and thus benefit from, a course of UE therapy. Attrition bias is also a possibility, in that it was infeasible to include in analysis the results of patients who did not complete the entire study through the post-intervention assessment visit. The reasons for dropout associated with the departure of 7 of 22 enrolled

participants were diverse, including: inconvenience in coming to an outpatient clinic three times per week over eight weeks; displeasure with withheld payments by the state university system due to unpaid medical bills or child support issues; and secondary (not study-related) medical issues resulting in violation of one or more study exclusion criteria.

The study design employed a within-subjects non-interventional control period to control for spontaneous recovery. The lack of an active control group precludes us from ruling out that improvements in UE function during the period of study participation could be associated with a placebo effect, a general elevation in activity level, improved emotional state due to increased social stimulation, or other confounders.

The ecological validity of virtual world based training for stroke rehabilitation has yet to be fully established. The outcome measures used in this study demonstrate improved motor function, but further study will be necessary to establish whether these gains translate to improved performance of real-world tasks. Also, this study explored the efficacy of virtual world-based training, but did not compare and contrast results with a standard of care training program. Therefore, we cannot assert superiority in motor outcomes for virtual world-based training versus standard of care. Virtual experiences can vary greatly in degree of immersion (the feeling of being part of a virtual world). Virtual reality head-mounted display systems such as the Oculus Rift are finding increasing use in medical applications [34], but it is unclear the degree to which the increased level of immersion might improve therapeutic outcomes for stroke rehabilitation. Benefits must outweigh the additional challenges of wearable systems, including fitting, donning/doffing, and sterilization in a medical setting. Application of immersive virtual reality must also consider the possibility of simulator sickness induced by devices that display optic flow [35], and potential complications from stroke-related visual perceptual disorders which can include impaired eye movement, difficulty judging depth and distance, visual field deficit, and low vision [36].

C. Additional Observations and Future Research

There exists strong evidence that the dosage of practice plays a primary role in affecting positive outcomes in therapy. A review of 467 randomized-controlled trials concluded that effectiveness of interventions is determined by repetition of practice and the specificity of motor training [37]. The potential for new technology, such as virtual reality, to assist therapists in achieving higher dosages of movement is thus of growing interest. Previous comparison of (non-ADL) video game therapy versus traditional UE rehabilitation showed that a game therapy group accomplished a median of 271 movements per session compared to 48 for a traditional therapy session [38]. Other researchers have also found that virtual reality-mediated therapy can support delivery of high movement dosage. In a study involving use of a (also non-ADL) gaming system by stroke patients (N=11) for UE therapy, subjects achieved 387 reaching movements per session [39]. In a separate investigation employing a convenience sample of 83 traditional (not virtual reality or technology mediated) therapy sessions across seven sites in the U.S. and Canada, researchers reported an average of 32 (95% CI: [20, 44]) functional movement repetitions per UE stroke therapy session [40]. Summary results for the present study regarding participation and achieved dosage are presented in Table 8. We find that within the group of chronic stroke patients (N=15) that participated in the SaeboVR study, participants performed an average of almost 200 functional reaches per virtual ADL practice session over the 8-week intervention. These data span a total of 70,612 recorded functional movements across all patients over a total of 356 therapy sessions.

These secondary findings may have important implications for therapy practice. It may thus be hypothesized that improvements in gold-standard scales observed in this study may, at least in part, be explained by the high dosage of repetitive task practice achieved by patients using the SaeboVR system. Additional research will be required to establish a causal connection between dosage achieved in virtual reality therapy and functional outcomes.

The SaeboVR system creates a multi-sensory experience to promote functional recovery. Patients first hear verbal cues to prompt actions and movements and then, if necessary, patients receive a visual cue, which is a cueing progression typical in occupational therapy. Patients have the ability to see arm movements and the results of their actions represented on the screen, which relates this technology to other evidence-based interventions such as mirror therapy [41] and mental imagery [42]. Future research into these connections may lead to further improvements in clinical outcomes.

The ADL-focused tasks within the SaeboVR system are designed to be meaningful and relatable to the patient, which may support a patient's desire to participate in therapy. This emphasis on participation in meaningful activities is a central tenet to the profession of occupational therapy. The ability to measure and track the repetitions and activity time within the SaeboVR system may also appeal to therapists, who often must document and justify the evidence-based purpose of interventions [43].

Acknowledgment

The authors would like to recognize the HealthSouth Corporation and Designing Digitally Inc. for their support of the VOTA/SaeboVR project. We would also like to thank Paula Adams, OTR/L and Eileen Krepkovich (Barron Associates, Inc.) for their contributions to the program.

References

[1] ClinicalTrials.gov. (Mar. 2016). *Virtual Occupational Therapy Application—Full Text View*. Accessed: Nov. 14. 2017. [Online]. Available: https://clinicaltrials.gov/ct2/show/NCT02706912

[2] E. Benjamin *et al.*, "Heart disease and stroke statistics—2017 update: A report from the american heart association," *Circulation*, vol. 135, no. 10, pp. e146–e603, Mar. 2017.

[3] C. Russo and R. Andrews, "Hospital stays for stroke and other cerebrovascular diseases, 2005: Statistical brief #51," in *Healthcare Cost and Utilization Project (HCUP) Statistical Briefs*. Rockville, MD, USA: Agency Healthcare Res. Quality, 2008.

[4] G. Kwakkel, B. Kollen, J. van der Grond, and A. Prevo, "Probability of regaining dexterity in the flaccid upper limb: Impact of severity of paresis and time since onset in acute stroke," *Stroke*, vol. 34, no. 9, pp. 2181–2186, 2003.

[5] D. Mozaffarian *et al.*, "Heart disease and stroke statistics-2016 update: A report from the american heart association," *Circulation*, vol. 133, pp. e38–360, 2016.

[6] J. A. Stevens and M. E. P. Stoy, "Using motor imagery in the rehabilitation of hemiparesis," *Arch. Phys. Med. Rehabil.*, vol. 84, pp. 1090–1092, Jul. 2003.

[7] M. Hallett, "Plasticity of the human motor cortex and recovery from stroke," *Brain Res. Rev.*, vol. 36, nos. 2–3, pp. 169–174, Oct. 2001.

[8] R. J. Nudo, "Adaptive plasticity in motor cortex: Implications for rehabilitation after brain injury," *J. Rehabil. Med.*, vol. 41, pp. 7–10, May 2003.

[9] P. S. Lum, S. Mulroy, R. L. Amdur, P. Requejo, B. I. Prilutsky, and A. W. Dromerick, "Gains in upper extremity function after stroke via recovery or compensation: Potential differential effects on amount of real-world limb use," *Topics Stroke Rehabil.*, vol. 16, no. 4, pp. 237–253, 2009.

[10] J. Tretriluxana, N. Runnarong, S. Tretriluxana, N. Prayoonwiwat, R. Vachalathiti, and C. Winstein, "Feasibility investigation of the accelerated skill acquisition program (ASAP): Insights into reach-to-grasp coordination of individuals with postacute stroke," *Topics Stroke Rehabil.*, vol. 20, no. 2, pp. 151–160, 2013.

[11] H. K. Kristensen, D. Persson, C. Nygren, M. Boll, and P. Matzen, "Evaluation of evidence within occupational therapy in stroke rehabilitation," *Scandanavian J. Occupational Therapy*, vol. 18, no. 1, pp. 11–25, 2011.

[12] L. Legg *et al.*, "Occupational therapy for patients with problems in personal activities of daily living after stroke: Systematic review of randomised trials," *Brit. Med. J.*, vol. 335, pp. 922–925, Nov. 2007.

[13] P. Allain *et al.*, "Detecting everyday action deficits in Alzheimer's disease using a nonimmersive virtual reality kitchen," *J. Int. Neuropsychol. Soc.*, vol. 20, no. 5, pp. 468–477, 2014.

[14] T. Yamaguchi, D. Foloppe, P. Richard, E. Richard, and P. Allain, "A dual-modal virtual reality kitchen for (re)learning of everyday cooking activities in Alzheimer's disease," *Presence*, vol. 21, pp. 43–57, May 2012.

[15] L. Zhang, B. C. Abreu, G. S. Seale, B. Masel, C. H. Christiansen, and K. J. Ottenbacher, "A virtual reality environment for evaluation of a daily living skill in brain injury rehabilitation: Reliability and validity," *Arch. Phys. Med. Rehabil.*, vol. 84, no. 8, pp. 1118–1124, 2003.

[16] N. Katz, H. Ring, Y. Naveh, R. Kizony, U. Feintuch, and P. L. Weiss, "Interactive virtual environment training for safe street crossing of right hemisphere stroke patients with unilateral spatial neglect," *Disability Rehabil.*, vol. 27, no. 20, pp. 1235–1244, 2005.

[17] Y. S. Lam, D. W. K. Man, S. F. Tam, and P. L. Weiss, "Virtual reality training for stroke rehabilitation," *NeuroRehabilitation*, vol. 21, no. 3, pp. 245–253, 2006.

[18] A. Turolla *et al.*, "Virtual reality for the rehabilitation of the upper limb motor function after stroke: A prospective controlled trial," *J. Neuroeng. Rehabil.*, vol. 10, p. 85, Aug. 2013.

[19] P. Kiper, M. Agostini, C. Luque-Moreno, P. Tonin, and A. Turolla, "Reinforced feedback in virtual environment for rehabilitation of upper extremity dysfunction after stroke: Preliminary data from a randomized controlled trial," *BioMed Res. Int.*, vol. 2014, Mar. 2014, Art. no. 752128.

[20] J. S. Kwon, M. J. Park, I. J. Yoon, and S. H. Park, "Effects of virtual reality on upper extremity function and activities of daily living performance in acute stroke: A double-blind randomized clinical trial," *Neurorehabilitation*, vol. 31, no. 4, pp. 379–385, 2012.

[21] S. Jang *et al.*, "Cortical reorganization and associated functional motor recovery after virtual reality in patients with chronic stroke: An experimenter-blind preliminary study," *Arch. Phys. Med. Rehabil.*, vol. 86, pp. 2218–2223, Nov. 2005.

[22] K. Laver, S. George, S. Thomas, J. Deutsch, and M. Crotty, "Virtual reality for stroke rehabilitation," *Cochrane Database Syst Rev.*, no. 2, Art. no. CD008349, 2015.

[23] G. Saposnik and M. Levin, "Virtual reality in stroke rehabilitation: A meta-analysis and implications for clinicians," *Stroke*, vol. 42, no. 5, pp. 1380–1386, 2011.

[24] J. H. Shin *et al.*, "Effects of virtual reality-based rehabilitation on distal upper extremity function and health-related quality of life: A single-blinded, randomized controlled trial," *J. Neuroeng. Rehabil.*, vol. 13, p. 17, Feb. 2016.

[25] R. J. Adams, M. D. Lichter, E. T. Krepkovich, A. Ellington, M. White, and P. T. Diamond, "Assessing upper extremity motor function in practice of virtual activities of daily living," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 23, no. 2, pp. 287–296, Mar. 2015.

[26] A. Ellington, R. Adams, M. White, and P. Diamond, "Behavioral Intention to Use a Virtual Instrumental Activities of Daily Living System Among People With Stroke," *Amer. J. Occupational Therapy*, vol. 69, no. 3, pp. 1–8, 2015.

[27] M. Lowenthal, *Lives in Distress*. New York, NY, USA: Basic Books, 1964.

[28] M. P. Lawton and E. M. Brody, "Assessment of older people: Self-maintaining and instrumental activities of daily living," *Gerontologist*, vol. 9, no. 3, pp. 179–186, 1969.

[29] *Occupational Therapy Practice Framework: Domain and Process*, 3rd ed. American Occupational Therapy Association, Bethesda, MD, USA, 2014.

[30] A. R. Fugl-Meyer, L. Jääskö, I. Leyman, S. Olsson, and S. Steglind, "The post-stroke hemiplegic patient. I. A method for evaluation of physical performance," *Scandinavian J. Rehabil. Med.*, vol. 7, no. 1, pp. 13–31, 1975.

[31] S. L. Wolf, P. A. Catlin, M. Ellis, A. L. Archer, B. Morgan, and A. Piacentino, "Assessing wolf motor function test as outcome measure for research in patients after stroke," *Stroke*, vol. 32, no. 7, pp. 1635–1639, 2001.

[32] S. J. Page, G. D. Fulk, and P. Boyne, "Clinically important differences for the upper-extremity Fugl-Meyer Scale in people with minimal to moderate impairment due to chronic stroke," *Phys. Therapy*, vol. 92, no. 6, pp. 791–798, 2012.

[33] K. Lin, Y. Hsieh, C. Wu, C. Chen, Y. Jang, and J. Liu, "Minimal detectable change and clinically important difference of the wolf motor function test in stroke patients," *Neurorehabil. Neural Repair*, vol. 23, no. 5, pp. 429–434, 2009.

[34] J. Kim, C. Chung, S. Nakamura, S. Palmisano, and S. Khuu, "The oculus rift: A cost-effective tool for studying visual-vestibular interactions in self-motion perception," *Frontiers Psychol.*, vol. 6, p. 248, Mar. 2015.

[35] B. E. Riecke and J. D. Jordan, "Comparing the effectiveness of different displays in enhancing illusions of self-movement (vection)," *Frontiers Psychol.*, vol. 6, p. 713, Jun. 2015.

[36] F. Rowe, "Visual perceptual consequences of stroke," *Strabismus*, vol. 17, no. 1, pp. 24–28, 2009.

[37] J. M. Veerbeek *et al.*, "What is the evidence for physical therapy poststroke? A systematic review and meta-analysis," *PLoS ONE*, vol. 9, no. 2, p. e87987, 2014.

[38] D. Rand, N. Givon, H. Weingarden, A. Nota, and G. Zeilig, "Eliciting upper extremity purposeful movements using video games: A comparison with traditional therapy for stroke rehabilitation," *Neurorehabil. Neural Repair*, vol. 28, no. 8, pp. 733–739, 2014.

[39] F. Wittman *et al.*, "Self-directed arm therapy at home after stroke with a sensor-based virtual reality training system," *J. Neuroeng. Rehabil.*, vol. 13, p. 75, Aug. 2016.

[40] C. Lang *et al.*, "Observation of amounts of movement practice provided during stroke rehabilitation," *Arch. Phys. Med. Rehabil.*, vol. 90, no. 10, pp. 1692–1698, 2009.

[41] C. Dohle, J. Püllen, A. Nakaten, J. Küst, C. Rietz, and H. Karbe, "Mirror therapy promotes recovery from severe hemiparesis: A randomized controlled trial," *Neurorehabil. Neural Repair*, vol. 23, no. 3, pp. 209–217, Oct. 2008, doi: 10.1177/1545968308324786.

[42] S. Page, J. Szaflarski, J. Eliassen, H. Pan, and S. Cramer, "Cortical plasticity following motor skill learning during mental practice in stroke.," *Neurorehabil. Neural Repair*, vol. 23, no. 4, pp. 382–388, 2009.

[43] G. F. Clark and M. J. Youngstrom, "Guidelines for documentation of occupational therapy," *Amer. J. Occupational Therapy*, vol. 62, no. 6, pp. 684–690, 2008.