THESIS

THE USE OF MOTION-TRACKING GAMES FOR REHABILITATION OF THE PARETIC UPPER EXTREMITY IN INDIVIDUALS WITH STROKE

Submitted by

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ABSTRACT

THE USE OF MOTION-TRACKING GAMES FOR REHABILITATION OF THE PARETIC UPPER EXTREMITY IN INDIVIDUALS WITH STROKE.

BACKGROUND: In the United States someone experiences a stroke, or cerebrovascular accident, every 45 seconds. Stroke is the leading cause of disability in the United States, which underscores the importance of access to efficacious and feasible rehabilitation treatment. Researchers have estimated that 77% of survivors experience upper extremity weakness, or paresis after stroke. When this weakness affects one side of the body, it is known as hemiparesis. Overall, a large volume of therapy is required to produce the neuroplastic changes that lead to meaningful recovery post-stroke, but with the constraints of conventional, “hands-on” approaches, a system is needed that allows for convenient, at-home practice with remote supervision and feedback of a therapist. Over the last 30 years, treatments have emerged through scientific advances, which integrate the principles provided by conventional therapy treatment using computer technology. These treatments allow for repetitive action-based, at-home practice. METHOD: Four participants who have experienced stroke were recruited from the northern Colorado community. The materials used for the study include the suite of web-based games, a commercially available Leap Motion sensor, a custom stand designed to hold the sensor, and a laptop computer. To use the game, participants moved their hand underneath the motion sensor which interacts with the games on the computer screen. The researchers adjusted the difficulty, time, and sensitivity of the games depending on the movement capacity of the participant. The intervention sessions took place over five consecutive days, except for one participant who used the system in his home over ten consecutive weekdays. The participants were assessed using the Wolf Motor Function Test (WMFT), the Fugl-Meyer Assessment-Upper Extremity Test (FMA-UE), and the "Quality of Movement" scale of the Motor Activity Log (MAL-QOM). The baseline and post-intervention scores on the WFMT-Timed, the WMFT-FA, the MAL-QOM and the FMA were analyzed using Wilcoxon's Signed-Rank Test. RESULTS: The mean scores in all measures of motor performance moved in the direction of improvement, though none were shown to be statistically significant. The intervention was overall well-tolerated by the participants, with no adverse effects reported. DISCUSSION: The primary aims of the study were to investigate the efficacy and feasibility of an at-home, motion-tracking rehabilitation gaming system (GATOR) for increasing users' real-world use of their paretic upper extremity. Future research on this system with increased length of treatment in the home of the participant is needed to further evaluate the use of this system as a rehabilitation technology for the increased use of the stroke-affected arm.

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Introduction

In the United States someone experiences a stroke, or cerebrovascular accident, every 45 seconds (American Heart Association, 2014). While the 85% overall survival rate is encouraging, this means there are over 7,000,000 survivors of stroke living with the lifelong challenges that recovery brings. Stroke is also the leading cause of disability in the United States, which underscores the importance of access to efficacious and feasible rehabilitation treatment (American Heart Association, 2014). Researchers have estimated that 77% of survivors experience UE weakness, or paresis, after stroke (Lawrence et al., 2001). When this weakness affects one side of the body, it is known as hemiparesis. Hemiparesis is a common consequence of stroke resulting from damage to brain regions responsible for voluntary movement. Hemiparesis interferes with a person's independence and ability to participate in activities of daily living (ADL), such as self-care and functional mobility. Due to the debilitating nature of this impairment, rehabilitation that focuses on regaining functional use of the affected upper extremity is vital (National Stroke Association, 2006).

Recovery from stroke can be a long process that typically begins in the acute care hospital and continues into outpatient treatment after the survivor has returned home. Patients normally experience a limited amount of time with therapists relative to the amount of therapy that is needed to make a substantial recovery, due to restrictions in time, financial resources and insurance benefits (Alamri, Cha, & El Saddik, 2010). Therapists often prescribe home exercise programs, but the barriers to success of these programs are extensive. Jurkiewicz, Marzoloni, and Oh (2011) have detailed specific obstacles to home-exercise plan adherence, with patients citing motivation deficits, lack of enjoyment and lack of perceived benefit as hindrances to participation. Additionally, poor adherence to home exercise programs has been cited as a contributing factor to post-stroke disability. In order for a home-based rehabilitation program to be successful, there must be five components:

1. A personally meaningful task (Crosbie, McNeill, Burke, & McDonough, 2009)

2. Repetitive functional movement (Casserly & Baer, 2014; Crosbie, et al., 2009)

3. A clearly defined, achievable goal (Davis, 2006; Maclean, Wolfe, Pound & Rudd, 2002)

4. Ability to receive feedback (Kitago & Krakauer, 2013) and increased difficulty of challenges (Casserly & Baer, 2014; Davis, 2006)

5. A motivating factor (Casserly & Baer, 2014; Maclean, et al. 2002).

Some examples of post-stroke rehabilitation interventions that address these five components using computer technology are virtual reality-based (VR) therapy, augmented reality-based (AR) therapy, and commercial off-the-shelf (COTS) gaming systems. The motor-based rehabilitation system, known as GATOR (Games and Assistive Technologies fOr Rehabilitation), in the present research incorporates features of VR, AR, and COTS and tailors these features for individual participants. The GATOR project was developed by Colorado State University researchers Dr. Sudeep Pasricha and Dr. Matthew Malcolm with the aim to deliver high-quality and engaging therapy to persons who have experienced UE limitations after stroke. The opportunities and limitations of VR, AR, COTS, and the GATOR system will be discussed along with implications for future research.

Literature regarding the dose-response nature of therapy has concluded that more therapy and more intensive therapy are associated with greater recovery of motor deficits. Moreover, there does not appear to be a ceiling effect for intensity of therapy (Norouzi-Gheidari, Archambault, & Fung, 2012). Overall, a large volume of therapy is required to produce the neuroplastic changes that lead to meaningful recovery post-stroke (Lohse, Lang, & Boyd, 2014), but with the constraints of conventional therapy and "hands-on" approaches, there needs to exist a system which allows for convenient, at-home practice with remote supervision and feedback of a therapist.

There is currently a large body of work concerning stroke rehabilitation and occupational therapy with interventions falling into two categories: conventional and emerging. Conventional occupational therapy rehabilitation for stroke includes strength and balance exercise, manual dexterity training, functional task and ADL practice, and stretching and weight-bearing of the affected extremity (Wang, Zhao, Zhu, Li, & Meng, 2011; Davis, 2006). In recent years, technologically-based treatments for motor recovery after stroke, including VR, AR, COTS, and the GATOR system, have emerged through scientific advances, which integrate the principles provided by conventional therapy treatment using computer technology. These treatments, especially the GATOR system, allow for repetitive, action-based, at-home practice, which have the potential to fulfill the five components of a successful at-home rehabilitation program. Therefore, the aim of this study is to assess the efficacy and feasibility of the GATOR games system, a motion-tracking based rehabilitation tool for the remediation of UE impairments in individuals with stroke.

Virtual reality

Virtual reality systems have the capacity to transform traditional rehabilitation into fun, motivating exercises that encourage patient participation and have been shown to increase motor function following stroke. VR-based rehabilitation is computer-based, interactive, and multi-sensory, using dedicated computer software that can be experienced through a human-machine interface (Laver, George, Ratcliffe, & Crotty, 2011; Lucca, 2009). These simulated, interactive environments can contribute to functional rearrangement of the damaged motor cortex and relearning of motor skills following stroke (Lucca, 2009; Turolla, et al., 2013).

Although there is great potential for the use of VR in stroke rehabilitation, there is a paucity of research that conclusively points to the feasibility of using this method in clinical settings or at home. These technologies are typically too expensive, complex and require a good deal of expertise to use, which has diminished the extent of VR's clinical application. While the VR technologies appear to fulfill the requirements of a successful rehabilitation program by supplying a personally meaningful task, repetitive functional movement, a clearly defined, achievable goal, ability to receive feedback, a motivating factor, and the "just-right challenge", the cost, availability, and usability of these systems needs to be improved (Casserly & Baer, 2014; Laver, George, Ratcliffe, & Crotty, 2011).

Augmented reality

In contrast to VR, AR technology enables real-world objects to blend with virtual scenes with the use of motion tracking technology, or fiducial-marker recognition. For this reason, AR technology is in between the virtual world, where interaction with objects is simulated, and the real-world, where interaction with objects is intuitive and natural (Alamri, Cha, & El Saddik, 2010). AR applications for rehabilitation came about because VR, while shown to have some use in rehabilitation, is cost-prohibitive and complicated, with limited access and in-home utility (Alamri, Cha, & El Saddik, 2010).

AR-based therapies can overcome several barriers of conventional therapy. For example, sustaining motivation during treatment has traditionally been a barrier for patients in recovery. These technologies have been shown to sustain motivation and engagement in therapy sessions by allowing the user to experience real force while practicing (Alamri, Cha, and El-Saddik, 2009). [M1] They are also highly adaptable to individual treatment programs and allow progress to be measured via the instrument. Augmented reality technologies also allow for focused practice that incorporates the principles of motor learning: repetitive, functional, and task-related practice of UE movement. (Alamri, Cha, & El Saddik, 2009; Kitago & Krakauer, 2013). A recent case study used AR mirror therapy to “replace” the stroke-injured arm with an image of a healthy arm during rehabilitation exercises. Following the intervention, scores on the Fugl-Meyer Assessment were significantly improved for the AR group over the control (Assis, Corrêa, Martins, Pedrozo, & Lopes, 2014). Initial work using AR as a therapy tool for upper extremity rehabilitation after neurological injury shows promise, however, there are a very small number of studies using this treatment, and no commercially available systems.

Commercial off-the-shelf gaming consoles

Commercial off-the-shelf (COTS) gaming technology, for example the Nintendo Wii or the Microsoft Kinect, has been gaining ground in recent years as cost-effective and fun way to involve stroke patients in rehabilitation (Celinder & Peoples, 2012; Casserly & Baer, 2014). A systematic review cites eight articles that use COTS as a therapy tool and found, overall, COTS gaming technology had a positive effect on UE function of participants with stroke (Casserly & Baer, 2014). Though studies using this technology are few in number, the preliminary results show promise that this tool can provide improved physical outcomes and increased quality of life for stroke patients (Casserly & Baer, 2014; Choi, et al., 2014). The Nintendo Wii uses a hand-held controller to engage the user with games such as tennis, golf, and boxing, through a motion sensor located on the console. The games often require total body movement, which allows the user to simulate real-world activities in a fun and safe environment. The intervention is well tolerated by people with stroke due to the engagement with other patients and therapists and variety it adds to daily routines (Celinder & Peoples, 2012). The COTS gaming intervention does provide several key components of successful rehabilitation: motivation through performance feedback, continuous challenge, personal meaning, and repetitive goal-oriented practice (reach, grasp, manipulate, and release).

There are limitations to using a COTS device, however. The feedback provided is based on the movement of healthy individuals, and some movements used during gameplay are compensatory, not adaptive (Choi, et al., 2014). For example, a person who does not have adequate shoulder flexion may instead elevate the trapezius and use momentum to propel the controller forward. Additionally, a recent study including several participants in a rehabilitation hospital setting reported feeling defeated by the level of physicality required to participate in the games (Celinder & Peoples, 2014). Using these gaming systems, specifically the Nintendo Wii, involves complex motor coordination. Participants need to be able to hold the controller, press a button, and reach simultaneously (Celinder & Peoples, 2012). While the COTS gaming systems are showing promise by aiding in the recovery of UE range of motion, grip strength, dexterity, and motor function, evidence showing carryover to increased UE functionality is limited (Pietrzak, Cotea, & Pullman, 2014). Many questions remain concerning the efficacy of using COTS in stroke rehabilitation, largely the problems of individualizing the experience for each participant and the practicality and safety of using the system at home (Joo, et al., 2010). In summary, despite the advantages of COTS gaming for rehabilitation after stroke, the systems are limited in being able to provide therapy-specific feedback, individualized intervention, and a program for persons with little available UE movement.

GATOR gaming system

The present study puts forth a motion-tracking rehabilitation system that advances virtual technologies by providing individually tailored rehabilitation programs, motivational and engaging games that encourage functional movements in an easy-to-use system. The GATOR system was developed by researchers Malcolm and Pasricha of Colorado State University (CSU) with the aim of providing low-cost, convenient, and engaging therapy in the homes of individuals with a stroke-affected upper limb. The GATOR system has the potential to be cost-effective because it is built around off-the-shelf components and web-based games. The participant needs only to have a personal computer, a LEAPmotion sensor ($79.99), a custom stand (approximately $50.00), and access to the web-based games (price undetermined). The system can be set up in the participant's home and monitored remotely by trained therapists. The GATOR system can address the five components of a successful therapy regimen by allowing for participation in a meaningful task, repetitive, functional activity, motivational feedback, graded difficulty of challenges, and remote supervision of skilled therapists. This system also provides access to increased practice time and individualized treatment which can be used in the participant's home. . The games require that participants use visual scanning and a range of UE movements to interact with the computer screen and rely on the remotely located therapist to monitor progress and provide guidance. This system will allow stroke survivors to participate in intensive, goal-oriented, and motivational therapy at home with a high-speed internet connection.

Methodology

Participants

Four participants were recruited from the northern Colorado community through a previously established network of therapists who commonly work with this population, flyers placed at local rehabilitation hospitals, and a database of past research participants. Once contacted, participants were screened for the following inclusion criteria: 1) must be stroke patients in the sub-acute to chronic stage of recovery, at least one month post-stroke 2) must have a motor deficit that affects the UE 3) in the affected UE, participants must have some voluntary movement such that they are able to lift the arm onto the table and slide the arm to reach all quadrants of a 24 by 18 inch square 4) participants must score higher than 24 on the Mini-Mental Status Exam (Folstein, Folstein, & McHugh, 1975) 5) be at least 18 years of age 6) be able to tolerate a one-hour therapy session per day. Characteristics of each participant are displayed in Table 1 below. All participants were scheduled for the five-day intervention except for AR01, who participated in the ten-day intervention. The original intent of the study was to test the system in the homes of participants, however, due to technical issues, the intervention was moved to the Assistive Technology Resource Center at CSU Informed consent was obtained for each participant and all protocols were reviewed and approved by the CSU Institutional Review Board.

Table 1

Participant Characteristics

Participant ID	Age	Gender	Time Since Stroke (years, months)	Side of Lesion	Type of Stroke
AR 01	65	M	6,0	R	Ischemic
AR 02	67	F	6,9	R	Ischemic
AR 03	65	M	5,6	L	Ischemic
AR 04	71	F	11,5	L	Ischemic

Materials

The materials used for the study include the suite of games developed by the Pasricha and Malcolm laboratories at CSU. In addition to the games, a commercially available Leap Motion sensor, a custom stand designed to hold the sensor, a mat, and a laptop computer were included. To use the game, participants move their hand underneath the motion sensor, which is connected to the laptop computer via a USB cable. . There are twelve web-based games which were accessed and adjusted by the researchers who were also able to grade the difficulty of the games and see time and usage data. Therefore, participants were able to use this system in their home on a laptop, and performance and setting data can be remotely monitored by the researchers.

The GATOR games suite consists of twelve games: Water Drops, Meteors, Maze, Whack-a-mole, Pirates Cove, Gestures, Breakout, LeapPong, Alien Invaders, Fruit Viking, Dolphin Run, and LeapFrog. These games can be accessed by the participants and therapists through the CSU GATOR games dashboard, a custom-designed interface that set up for each user. Generally speaking, participants use arm and hand movement to control an on-screen effector which will be used to either strike a target or avoid an obstacle. For example, in the Water Drops game, the participant uses his or her hand via the motion sensor to move a cup along the bottom of the computer screen, which is used to catch the virtual drops of water. The researchers were able to adjust the difficulty, play time, and sensitivity of the games depending on the movement capacity of the participant. The sensitivity is a correlation between movement in real life and movement on the screen and is displayed as a ratio. The higher the sensitivity, the less real-life movement is needed relative to on-screen movement. This is useful for participants with little movement capability of the affected UE. Each of these games elicits different UE movements of the user, including flexion and extension of the elbow, and shoulder flexion, pronation and supination of the wrist in gravity eliminated planes and against gravity. In addition, some games require quick, accurate movements, while others require slow, controlled movements.

Study Design

The present study used a within-subjects, pretest-posttest design with descriptive data included. The intervention sessions were located in the Assistive Technology Resource Center (ATRC) in Colorado State University's Occupational Therapy Department over five consecutive days, except for one participant who used the system in his home over ten consecutive weekdays. For the five-day intervention, the first session consists of participant training on the games, practice time, and problem solving, followed by an hour of game play. Sessions two through five consist of one hour of game play, with researcher adjustments to sensitivity, pattern, and level of difficulty. At the ATRC, participants had the benefit of access to height-adjustable tables and ergonomic chairs, which allowed for optimum comfort and positioning. For the ten-day intervention, session one occurred in the laboratory, where introduction to the system and set up occurred. Sessions three through ten occurred in the home of the participant, with the intervention taking place each of the following weekdays. Each day of the intervention, the participant logged onto the dashboard and played the games for two 30-minute sessions with at least 15 minutes in between. On days three, five, and eight, the researcher called the participant to discuss any issues and provid problem-solving assistance. Additionally, the researcher was able to make adjustments to the game play remotely. The first participant used the system in his home because it was originally intended to be an in-home rehabilitation tool. However, after encountering technical difficulties, the system was moved to the laboratory for closer monitoring.

Assessment Measures

The participants were assessed in the areas of UE motor capacity using the Wolf Motor Function Test (WFMT), motor system recovery using the Fugl-Meyer Assessment-Upper Extremity Test (FMA-UE), and ability to perform common daily activities using the "Quality of Movement" scale of the Motor Activity Log (MAL-QOM). Together, these assessments form a complete picture of function and quality of movement for the affected UE. The baseline and post-intervention scores on the WFMT-Timed, the WMFT-FA, the MAL-QOM and the FMA were analyzed using the Wilcoxon Signed-Rank Test, a non-parametric test for paired samples. The Wilcoxon Signed-Rank Test was used because the sample size was too small to assume normal distribution of scores. Each assessment was administered at baseline and post-intervention.

Wolf Motor Function Test. The WMFT was designed to assess the movement capability of persons affected by moderate to severe motor deficits of the UE. The test consists of a variety of strength and functional tasks, each of which have positioning and timing requirements. Each task is scored two ways: performance time (Timed) and functional ability (FA) (Taub, Morris, & Crago, 2011). In order to capture the performance time scores, the researcher uses a stopwatch to measure the amount of time needed to complete each task. Therefore, a lower score on the post-intervention assessment is considered an improvement. The participant is videotaped completing each of the tasks and the researcher watches the video and assigns a FA score ranging from 0 (does not attempt with UE being tested) to 5 (Does; movement appears to be normal) (Taub, Morris, & Crago, 2011). For the performance time subtest, a maximum time allowed to perform each task is two minutes, or 120 seconds. When a participant is unable to perform the task, a score of 121 is assigned, meaning they took more than two minutes. For this reason, median must be used to measure central tendency. In contrast, the FA score is most accurately analyzed using the mean. The WMFT is shown to have good reliability and validity for both the Timed and FA tests. Research shows internal consistency reliability for overall test is 92.4%. Also, test-retest reliability was shown to be 0.90 for the timed test and 0.95 for the FA test (Wolf, et al., 2001). Inter-rater reliability was found to range from 0.97-0.99. Further, the WMFT has been found to have adequate concurrent validity with the FMA ($r = -0.57$) and was able to distinguish between clinical and non-clinical populations ($p < 0.0006$) (Wolf, et al., 2001).

Fugl-Meyer Assessment-Upper Extremity. The FMA is used to assess sensorimotor recovery in post-stroke patients using four domains: motor function, balance, sensation, and joint function. For this study, the UE motor function portion (FMA-UE) was used to test the movement, coordination and reflexes of the shoulder, elbow, forearm, wrist, and hand. The results are a cumulative numerical score comprised of the ordinal ratings 0=cannot perform, 1= performs partially, and 2=performs fully, with a maximum score of 66 (Fugl-Meyer, Jaasko, Leyman, Olsson, & Steglind, 1975). The FMA was shown to have good internal consistency reliability (92.4%) (Wolf, et al., 2001) and inter-rater reliability (0.99) (Sulllivan, et al., 2011).

Motor Activity Log. In addition to the motor performance tests, the researchers also evaluated the participant's ability to perform common daily activities, like opening a drawer and drying hands, by using the MAL. The MAL is an instrument that uses structured interview to obtain information from the participant regarding how often (Amount of Use) or how well (Quality of Movement) the affected UE is used during the specified functional activities (Taub, McCulloch, Uswatte, & Morris, 2011). For the present study, the Quality of Movement scale (MAL-QOM) was used to gather self-perceptions of participant's UE use by means of a scale which ranges from 0 (my weaker arm was not used at all for that activity) to 5 (my ability to use the weaker arm for that activity was as good as before the injury) (Taub, McCulloch, Uswatte, & Morris, 2011). The average of all ratings is then computed at baseline and post-intervention. The MAL is shown to be a reliable and valid measure of post-stroke arm use in everyday tasks. The QOM scale was shown to have high internal consistency reliability (0.91) and both scales together have good concurrent validity with the Action Research Arm Test (0.63) (Van der Lee, Beckerman, Knol, De Vet, & Bouter, 2004).

Table 2

Scores for the FMA-UE, WMFT-Timed, WMFT-FA, and MAL-QOM at baseline and post-intervention.

	Baseline		Post-intervention		Statistical Analysis		
Assessment	*M*	±SD	*M*	±SD	Critical value	*p* value	Change in scores (%)
FMA-UE (66)[a,b]	42	9.42	44	9.63	-1.51	0.131	4.76
WMFT-Timed (seconds)[b]	9.62	11.1	6.75	7.58	-1.46	0.212	-29.83[c]
WMFT-FA (0-5)[b]	2.67	0.57	2.86	0.71	-1.46	0.144	7.12
MAL-QOM (0-5)[b]	1.94	1.15	2.01	0.96	-3.65	0.715	3.61

[a]High score on the Fugl-Meyer Assessment
[b]Statistic used was Wilcoxon's Signed-rank Sum Test
[c]decrease in scores indicates faster performance time

Results

Motor-based Data

The results of the statistical analysis are displayed below in Table 2. Post-intervention scores all measures of motor performance trended toward improvement, though none were shown to be statistically significant at $\alpha=0.05$ level. Individual participant scores for each assessment are displayed following Participant Data as Figures 1-4.

Participant Data

The intervention was overall well-tolerated by the participants. During each session, the researcher would check in with participants to determine if they were experiencing any fatigue or pain following the intervention. There were no reports of adverse effects. The following section describes experiences using the GATOR system for each individual participant.

Participant 01. AR01experienced a R-sided ischemic stroke but has since gained significant movement in his L arm and hand and was the least functionally impaired of the group according to our measures. He lives on a small farm with cows, chickens, and large gardens and owns a landscaping business with his sons. He does not use a computer regularly, but is able to type using his unaffected arm. AR01 experienced difficulty logging into the system and would need several tries to type the user name and login correctly. Once in the system, he had little difficulty navigating the dashboard and using the games. He was the only participant to use the system in his home**,** and valued being able to have the convenience of at-home rehabilitation. Participant AR01 performed tasks on the WFMT-Timed with a median speed of 2.47 seconds at baseline and 2.56 seconds post-intervention. His WMFT-FA score increased 0.2 points from 3.33 to 3.53. He also increased 3 points on the FMA-UE from 55 to 58, but decreased 0.02 points on the MAL-QOM from 2.88 to 2.86. Overall, Participant AR01's scores remained fairly stable on all measures, except for the 3 point increase on the FMA-UE, which translates to a 5.5% gain.

Participant 02. AR02 experienced a R-sided ischemic stroke which she reports prevented her from “walking and talking at the same time” in the beginning. She remains very impaired in her L arm and hand, but is computer-savvy. AR02 is retired and lives far away from family members, so she uses her computer every day as a way to keep in touch with loved ones. She was very receptive to the technology and found the games to be enjoyable and challenging, commenting, “by the tiniest movement of my hand or my fingers, I can achieve something on that screen… that’s a big win-win”. AR02 would sometimes use an upturned coffee mug or baby powder to help her hand slide more easily on the mat. The most difficult game for her to play was “Dolphin Run”, which requires the user to complete shoulder flexion against gravity for several minutes in order to propel a dolphin through water and avoid obstacles. Her favorite game was “LeapPong”, commenting “this is the one where I get aggressive!” Similar to the Atari version, the GATORgames version uses elbow flexion and extension to move a paddle vertically along the screen. AR02 would sometimes use compensatory movements, such as trunk flexion, to move the paddle, and would be reminded to still her trunk and use her forearm.

Participant AR02 performed tasks on the WFMT-Timed with a median speed of 25.97 seconds at baseline and 18.06 seconds post-intervention, decreasing by 7.91 seconds. Her WMFT-FA score increased 0.13 points from 2.07 to 2.2. She also increased 3 points on the FMA-UE from 33 to 36, and increased on the MAL-QOM 0.3 points from 0.94 to 1.24. Overall, Participant AR02’s scores increased on all measures, with the most marked increases on the WMFT-Timed and the FMA-UE, where she saw gains of 30% and 9% respectively.

Participant 03. AR03 experienced a L-sided ischemic stroke, which included the cerebellum and brainstem. He presents with ataxia, which affects both R and L body, diplopia and dysarthria, making him a unique participant in this study. Prior to this intervention, he never used a computer for any task. In spite of this, he performed remarkably well and enjoyed the challenge and success of using this system. Due to his significant dysarthria, he spoke only when directly addressed, but following the sessions, his wife commented "he was so talkative on the way home, it's good to see him like that". During his sessions, he wore an eye patch to combat diplopia. AR03 excelled at games like "Meteors", which would allow him to make sweeping gestures using abduction and adduction of the shoulder to collect stars along the bottom of the screen, but struggled during the "Maze" game, which required slow, controlled movement along a set path. During these periods of extreme concentration, AR03's ataxic movement would lighten. Participant AR03 performed tasks on the WFMT-Timed with a median speed of 7.11 seconds at baseline and 4.05 seconds post-intervention, decreasing by 3.06 seconds. His WMFT-FA score decreased 0.07 points from 2.36 to 2.29. He also decreased 1 points on the FMA-UE from 42 to 41, but increased on the MAL-QOM 0.15 points from 0.96 at baseline to 1.11. Overall, Participant AR03's scores remained fairly stable on all measures, except for the 3.06 second time decrease on the WMFT-Timed, which translates to a 43.5% gain.

Participant 04. AR04 experienced a L-sided ischemic stroke which has challenged her UE movement and coordination, especially in her hand. In the beginning, she would become frustrated easily and make fun of herself when she did not excel at a game. During an early session, she commented that music helps her "concentrate and move better". In prior sessions, the laboratory was kept quiet to minimize distraction, however, when we introduced music during the intervention, she visibly relaxed and could reach a "flow" state. She wore a custom splint during the sessions to keep her fingers and thumb from contracting into a fist. The sensors have difficulty picking up a fisted hand because it uses the thumb as a principal marker for location. AR04, like others, struggled with the against-gravity shoulder flexion required when playing "Dolphin Run", but excelled at "LeapFrog", which moved a frog up lily pads using adduction and abduction of the shoulder joint.

Participant AR04 performed tasks on the WFMT-Timed with a median speed of 2.91 seconds at baseline and 2.33 seconds post-intervention, decreasing by 0.58 seconds. Her WMFT-FA score increased 0.47 points from 2.93 to 3.4. She also increased 3 points on the FMA-UE from 38 to 41, but decreased on the MAL-QOM 0.19 points from 3.00 at baseline to 2.81. Overall, Participant AR04's scores remained fairly stable on all measures, except for the 3 point increase on the FMA-UE, which translates to a 7.9% gain.

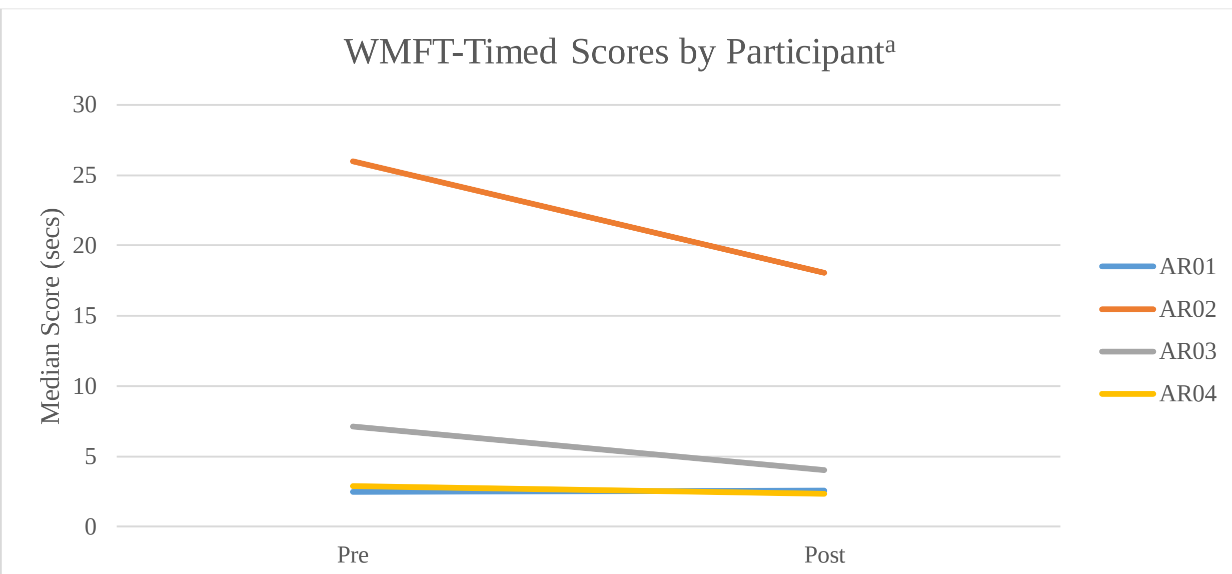

Figure 1

[a]decreased scores on the WMFT-Timed test show improvement

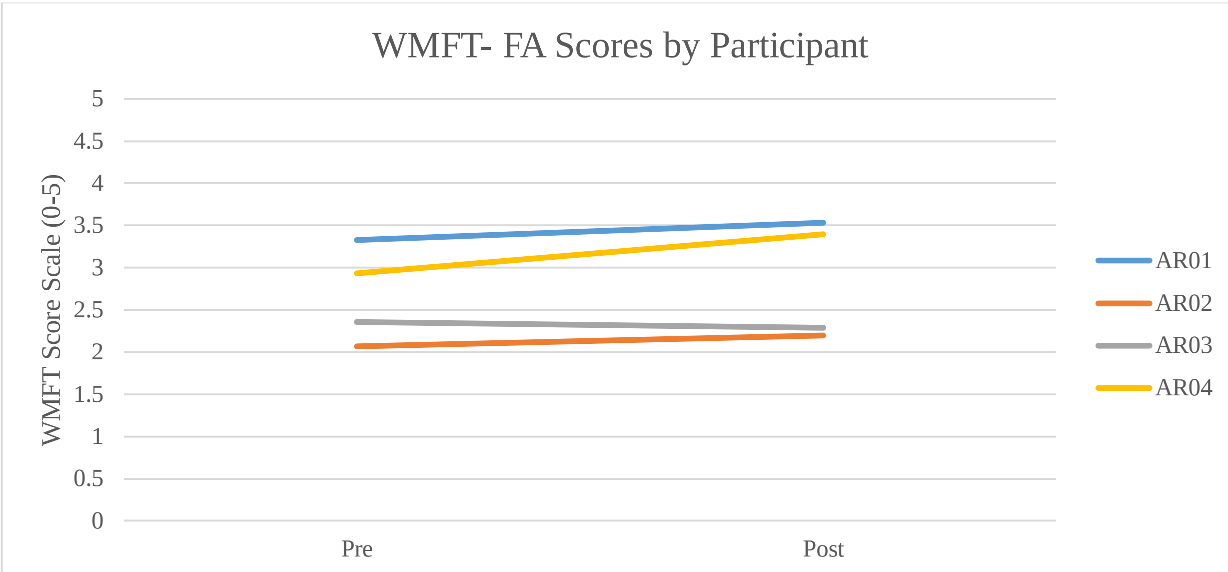

Figure 2

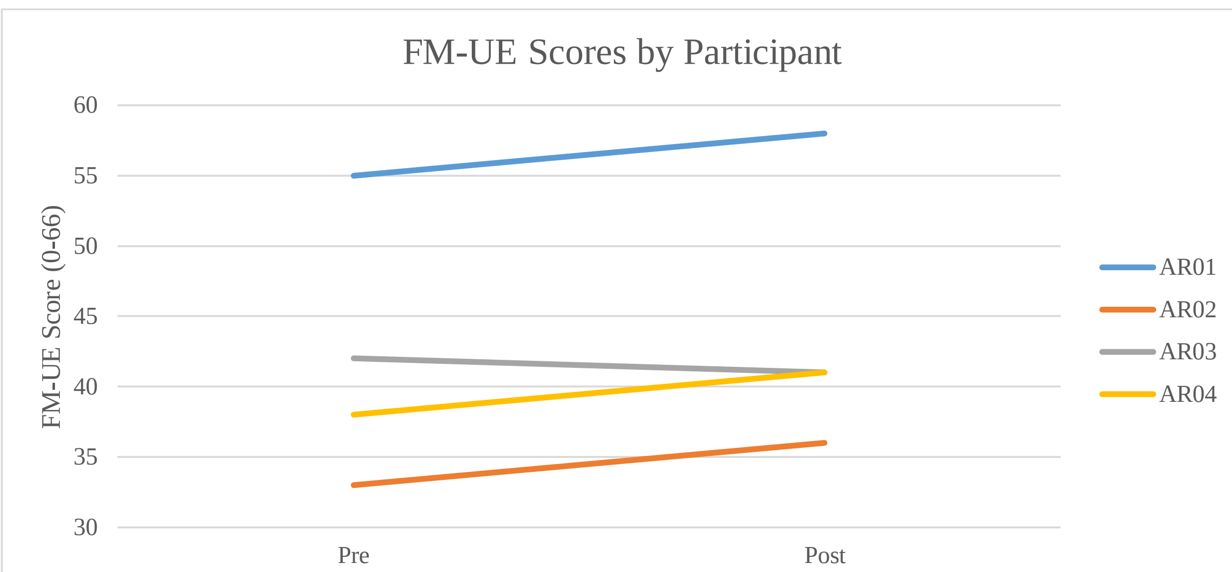

Figure 3

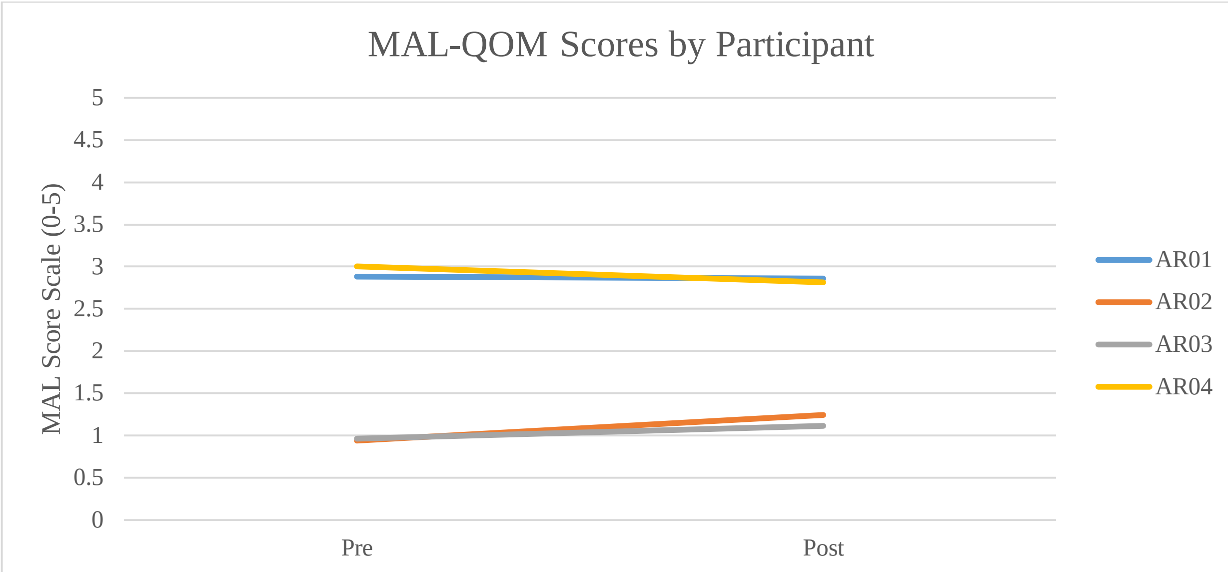
MAL-QOM Scores by Participant
MAL Score Scale (0-5)
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Pre
Post
AR01
AR02
AR03
AR04

Figure 4

Discussion

Study Aims

The primary aims of the study were to investigate the efficacy and feasibility of an at-home rehabilitation system which uses motion-tracking technology to allow the user to interact with a suite of internet-based games, which in turn, would increase users' real-world use of their paretic upper extremity. The combined participant's results show numbers that trend in the direction of improvement, however, they were not found to be statistically significant at $\alpha=0.05$ level. The strengths and limitations of the present study and comparisons with extant literature are discussed below.

Strengths and limitations

The strengths of our methods and materials are many, including: 1) The GATOR games dashboard was developed and dedicated specifically for use as an UE stroke rehabilitation tool with required movements reinforcing functional UE actions and therapist access to monitor usage data and adjust the parameters of the games to find the "just-right challenge". The introduction of these properties increase the success of the intervention over COTS gaming consoles. 2) Participants were limited to one hour of use per day, and were encouraged to discontinue usage of the GATOR system if persistent pain occurs. 3) Researchers frequently checked in with participants, either in person or by phone, to assess fatigue, pain, and satisfaction with the system. Overall, these practices ensured participants feel supported and motivated to continue participation in our study.

In addition to the many strengths of the present study, there are several potential limitations to consider. 1) The small sample size of the study limits the statistical power 2) We began the intervention in the home of participant 01, but were unable to continue the remaining interventions in that manner due to complex technical issues. The games are internet-based, so a high-speed internet connection is vital. While the participant had high-speed internet, the service was inconsistent and made transmission of information and game play unpredictable. In addition, the system was still in its early stages and the program was undergoing many updates. Despite this, participant AR01 was able to log all of his hours. However, the research team decided to move the study to the laboratory to provide a more tightly controlled environment with computer engineering students present to provide troubleshooting assistance. 3) We introduced a novel approach to rehabilitation, which makes assessment of potential risks and benefits difficult. We based our expectations regarding possible outcomes and risks on similar research on UE stroke rehabilitation that has been conducted in the past. We have also used empirical data to inform decision-making and method development. No adverse effects were reported. 4) There was no standard algorithm which would inform the researcher when it was time to advance the participant to the next level of difficulty (i.e. easy to medium). Therefore, it was left up to the discretion of the researcher who would make judgements based upon clinical observations and feedback of the participant. This was a logically-based and effective decision-making process, but could be standardized for future experiments. 5) The shortness of the study (either five or ten intervention days) could potentially have detracted from positive outcomes that could be associated with continued involvement in a rehabilitation program. However, previous research of this kind shows that significant gains can be made in a short amount of time (Casserly & Baer, 2014). Future research on this system may include the added benefit of increased treatment time. Nevertheless, each of the limitations provided potentially offers valuable information for the introduction of future studies and further development of the GATOR games system.

Comparison with Extant Research

The research field of the use of computer technology in UE stroke rehabilitation is fairly nascent. As of the time of this writing, there are few high-quality research studies comparing the use of computer technologies in stroke rehabilitation to conventional therapy (either physical or occupational). One such study was conducted by Choi and colleagues (2014) at the Jeju National Hospital and the Kwandong University College of Medicine, both of South Korea. The study used a randomized, controlled design to compare the use of gaming-based VR movement therapy (VR) with conventional occupational therapy (OT) in individuals with sub-acute stroke. The intervention period for this study was 4 weeks, wherein participants played the Nintendo Wii 30 minutes per day, 5 days per week. At the conclusion of the study, improved scores were shown for the VR group over the OT group for the FMA-UE, the Box and Block Test, and the manual function test. It is worth noting, however, that scores on the Korean version of the Modified Barthel Index did not improve in either group, and grip strength improved in the OT group only (Choi, et al., 2014).

There are important similarities and differences between the present study and Choi and colleagues' work. First, Choi and colleagues (2014) used the Nintendo Wii, a COTS system designed for healthy individuals. The researchers found some participants would use compensatory movements to play the game when accessing the desired movement was difficult or impossible. This was also found to be true with the GATOR system, especially the use of trunk flexion to replace forearm extension. In contrast to the present study, the intervention population was sub-acute stroke patients, where the GATOR project examined participants in the chronic stage of recovery (mean time since stroke= 7.5 years). Some of the improvement in the Choi and colleagues (2014) study could be attributed to spontaneous recovery, whereas any improvement in the present research can be assumed to be due to the intervention. Also, no participants were receiving any outside therapy. Additionally, the Choi and colleagues (2014) study used a 4 week intervention period, where participants benefitted from 20 sessions of game play. The present study used a much shorter intervention period (5 days), so future research on this system would benefit from extended participation.

Conclusion

In conclusion, the GATOR games system is shown to be an enjoyable way to engage the paretic UE of persons who have experienced stroke. This project is part of the emerging practice area of technology-based at-home rehabilitation options. . In consideration of the aforementioned necessary components of a successful home rehabilitation program, the GATOR system fulfills 1) repetitive, functional movement, 2) ability to receive feedback and increasing difficulty of challenges, and 3) a motivating factor. The system has the potential to be personally meaningful if the user values game play as a form of therapeutic engagement. However, feedback from participants indicates that the system does not fulfill the need for a clearly defined, achievable goal. Many of the games do not have a defined end-point or advanced levels. Further, there are several games wherein the participant collects coins or stars, but these tokens are not assigned a value or "cashed in". The addition of these expansions to the existing games would increase the therapeutic value exponentially.

While the technology is still evolving, there is need for further research of the GATOR games system. This system has the potential to provide a much-needed service to persons who do not have access to traditional rehabilitation due to financial limitations, insurance limitations, or location. While the motor-based data was not statistically significant, the trend toward improvements in scores demonstrate that the GATOR games system shows promise as a rehabilitation tool. Similar studies have shown significant improvements when more than 15 therapy hours were provided (Laver, George, Thomas, Deutsch, & Crotty, 2015) Future research on this system should include increased length of treatment and should occur in the home of participants in order to fully and accurately evaluate the use of this system as an in-home rehabilitation technology for the increased use of the paretic UE.

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Supplementaries

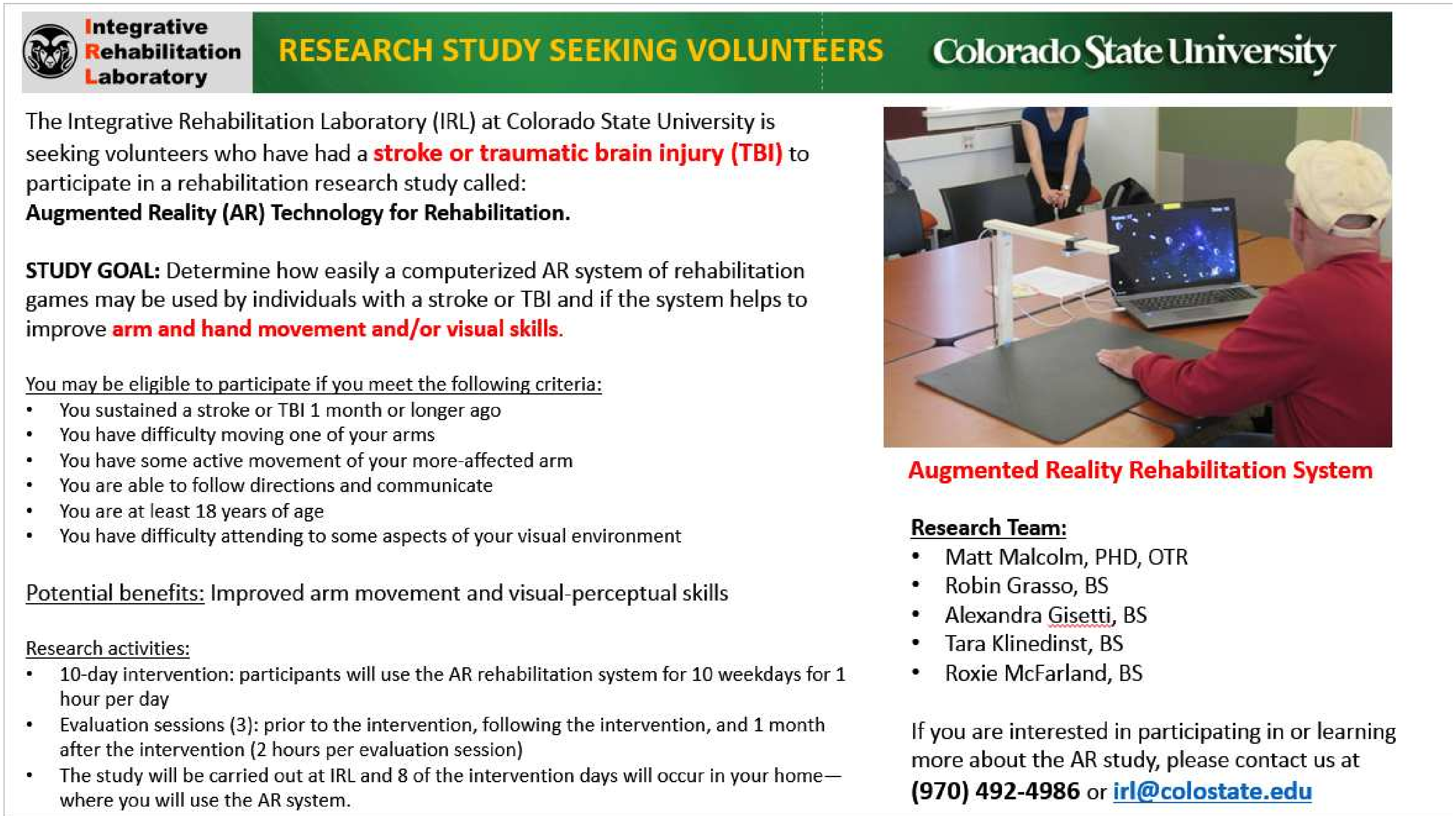

Figure S1: AR Study Flyer

Supplementaries

Figure S2: Components of the system

Supplementaries

Figure S3: Participant using the system

Supplementaries

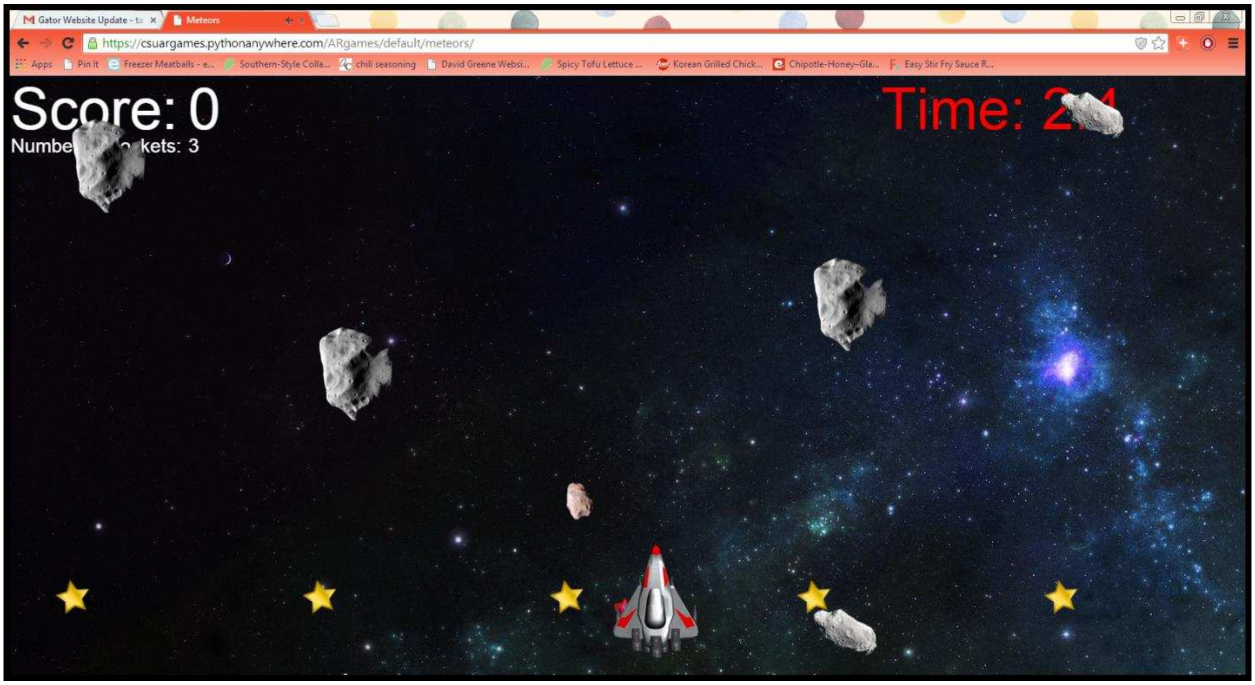

Figure S4: Screenshot of “Meteors” game

Supplementaries

WMFT
Functional Ability Scale

0 – Does not attempt with upper extremity (UE) being tested.

1 –UE being tested does not participate functionally; however, attempt is made to use the UE. In unilateral tasks the UE not being tested may be used to move the UE being tested.

2 – Does, but requires assistance of the UE not being tested for minor readjustments or change of position, or requires more than two attempts to complete, or accomplishes very slowly. In bilateral tasks the UE being tested may serve only as a helper.

3 – Does, but movement is influenced to some degree by synergy or is performed slowly or with effort.

4 – Does; movement is close to normal *, but slightly slower; may lack precision, fine coordination or fluidity.

5 – Does; movement appears to be normal *.

(*) For the determination of normal, the less-involved UE can be utilized as an available index for comparison, with pre-morbid UE dominance taken into consideration.

Supplementaries

Subject Code: Testing Date: Tester:

MOTOR FUNCTION (in sitting)			
TEST	ITEM	SCORE	SCORING CRITERIA
14. Reflexes	Biceps	a.	0-No reflex activity can be elicited 2-Reflex activity can be elicited
	Triceps	b.	
15. Flexor Synergy	Elevation	a.	0-Cannot be performed at all 1-Performed partly 2-Performed faultlessly
	Shoulder retraction	b.	
	Abduction (at least 90^0)	c.	
	External rotation	d.	
	Elbow flexion	e.	
	Forearm supination	f.	
16. Extensor Synergy	Shoulder add./int. rot.	a.	0-Cannot be performed at all 1-Performed partly 2-Performed faultlessly
	Elbow extension	b.	
	Forearm pronation	c.	
17. Movement combining synergies	Hand to lumbar spine	a.	1-No specific action performed 2-Hand must pass anterior superior iliac spine 2-Performed faultlessly
	Shoulder flexion to 90^0, elbow at 0^0	b.	1-Arm is immediately abducted, or elbow flexes at start of motion 2-Abduction or elbow flexion occurs in later phase of motion 3-Performed faultlessly
	Pronation/supination of forearm with elbow at 90^0 & shoulder at 0^0	c.	1-Correct position of shoulder and elbow cannot be attained, and/or pronation or supination cannot be performed at all 2-Active pronation or supination can be performed even within a limited range of motion, and at the same time the shoulder and elbow are correctly positioned 3-Complete pronation and supination with correct positions at elbow and shoulder
18.Movement out of synergy	Shoulder abduction to 90^0, elbow at 0^0, and forearm pro- nated	a.	1-Initial elbow flexion occurs, or any deviation from pronated forearm occurs 2-Motion can be performed partly, or, if during motion, elbow is flexed, or forearm cannot be kept in pronation 3-Performed faultlessly
	Shoulder flexion 90-180^0, elbow at 0^0, and forearm in mid-position	b.	1-Initial flexion of elbow or shoulder abduction occurs 2-Elbow flexion or shoulder abduction occurs during shoulder flexion 3- Performed faultlessly

Supplementaries

Subject Code: Testing Date: Tester:

MOTOR FUNCTION (continued)			
TEST	ITEM	SCORE	SCORING CRITERIA
18.Movement out of synergy	Pronation/supination of forearm, elbow at 0^0 and shoulder between 30-90^0 of flexion	c.	1-Supination and pronation cannot be performed at all, or elbow and shoulder positions cannot be attained 2-Elbow and shoulder properly positioned and pronation and supination performed in a limited range 3-Performed faultlessly
19. Normal reflex activity (This stage is only included if the patient attains a score of 6 in stage V)	Biceps and/or finger flexors and triceps		1-At least 2 of the 3 phasic reflexes are markedly hyperactive 2-One reflex is markedly hyperactive, or at least 2 reflexes are lively 3-No more than one reflex is lively and none are hyperactive
20. Wrist	Stability, elbow at 90^0, shoulder at 0^0	a.	1-Patient cannot dorsiflex wrist to required 15^0 2-Dorsiflexion is accomplished, but no resistance is taken 3-Position can be maintained with some (slight) resistance
	Flexion/extension, elbow at 90^0, shoulder at 0^0	b.	1-Volitional movement does not occur 2-Patient cannot activley move the wrist joint throughout the total range of motion 3-Faultless, smooth movement
	Stability, elbow at 0^0, shoulder at 30^0	c.	1-Patient cannot dorsiflex wrist to required 15^0 2-Dorsiflexion is accomplished, but no resistance is taken 3-Position can be maintained with some (slight) resistance
	Flexion/extension, elbow at 0^0, shoulder at 30^0	d.	1-Volitional movement does not occur 2-Patient cannot activley move the wrist joint throughout the total range of motion 3-Faultless, smooth movement
	Circumduction	e.	1-Cannot be performed 2-Jerky motion or incomplete circumduction 2-Complete motion with smoothness
21. Hand	Finger mass flexion	a.	1-No flexion occurs 2-Some flexion, but not full motion 3-Complete active flexion (compared with unaffected hand)

Supplementaries

Subject Code: Testing Date: Tester:

TEST	ITEM	SCORE	SCORING CRITERIA
21. Hand	Finger mass extension	b.	1-No extension occurs 2-Patient can release an active mass flexion grasp 2-Full active extension
	Grasp I - MCP joints extended and proximal & distal IP joints are flexed; grasp is tested against resistance	c.	0-Required position cannot be acquired 1-Grasp is weak 2-Grasp can be maintained against relatively great resistance
	Grasp II - Patient is instructed to adduct thumb, with a scrap of paper interposed, all other joints at 0^0	d.	1-Function cannot be performed 2-Scrap of paper interposed between the thumb and index finger can be kept in place, but not against a slight tug 3-Paper is held firmly against a tug
	Grasp III - Patient opposes thumb pad against the pad of index finger, with a pencil interposed	e.	1-Function cannot be performed 2-Pencil interposed between the thumb and index finger can be kept in place, but not against a slight tug 3-Pencil is held firmly against a tug
	Grasp IV - The patient should grasp a can by opposing the volar surfaces of the 1st and 2nd digits	f.	0-Function cannot be performed 1-A can interposed between the thumb and index finger can be kept in place, but not against a slight tug 2-Can is held firmly against a tug
	Grasp V - The patient grasps a tennis ball with a spherical grip or is instructed to place his/her fingers in a position with abduction position of the thumb and abduction flexion of the 2nd, 3rd, 4th & 5th fingers	g.	0-Function cannot be performed 1-A tennis ball can be kept in place with a spherical grasp but not against a slight tug 2-Tennis ball is held firmly against a tug
22.Coordination/ Speed- Finger to nose (5 repetitions in rapid succession while patient is blindfolded	Tremor	a.	0-Marked tremor 1-Slight tremor 2-No tremor
	Dysmetria	b.	0-Pronounced or unsystematic dysmetria 1-Slight or systematic dysmetria 2- No dysmetria
	Speed	c.	0-Activity is more than 6 seconds longer than unaffected hand 1-(2-5) seconds longer than unaffected hand 2-Less than 2 seconds difference

23. Total Motor Score:________________

Supplementaries

Study:

MOTOR ACTIVITY LOG

Pre-test / Post-test (circle one)

Subject code: _________ / Date:________________ / Tester:___________

		How Well	Comments include comment if no rating given
1	Flip Light Switch		
2	Opening Drawer		
3	Remove Item Clothing from Drawer		
4	Pick up Phone		
5	Wiping Counter		
6	Use hand when getting out of car		
7	Opening Refrigerator		
8	Turning Doorknob		
9	TV Remote		
10	Washing Hands		
11	Turn on/off Water		
12	Drying Hands		
13	Put Socks On		
14	Take Socks Off		
15	Put Shoes On		
16	Take Shoes Off		
17	Get up from Chair		
18	Pull Chair Out		
19	Pull Chair In		
20	Pick up Glass		
21	Brush Teeth		
22	Put on Makeup/ Shaving Cream		
23	Use Key to unlock door		
24	Write		
25	Carry Object		
26	Use Fork		
27	Use Comb		
28	Pick up Cup by Handle		
29	Button shirt		
30	Eating finger food		
	Average		average (sum / number of items completed)

Codes for recording "no" responses:

1. "I used the unaffected arm entirely." (assign "0")
2. "Someone else did it for me." (assign "0")
3. "I never do that activity, with or without help from someone else because it is impossible." For example, combing hair for people who are bald. (assign "NA" and drop from list of items).
4. "I sometimes do that activity, but did not have the opportunity since the last time I answered these questions." (carry-over last assigned number for that activity).
5. Non -dominant hand hemiparesis. (assign "NA" and drop from list of items.)

Version 1, 10/30/14
Created by Matt Malcolm, PHD, OTR

Supplementaries

How Well Scale

0 - My weaker arm was not used at all for that activity **(of no use).**

.5

1 - My weaker arm was moved during that activity but was not helpful **(very poor).**

1.5

2 - My weaker arm was of some use during that activity but needed some help from the stronger arm or moved very slowly or with difficulty **(poor).**

2.5

3 - My weaker arm was used for that activity but movements were slow or were made with only some effort **(fair).**

3.5

4 - The movements made by my weaker arm for that activity were almost normal but not quite as fast or accurate as normal **(almost normal).**

4.5

5 - My ability to use the weaker arm for that activity was as good as before the injury **(normal).**