Development of Recovery Rapids - A Game for Cost Effective Stroke Therapy

David Maung[1] Roger Crawfis[1] Lynne V. Gauthier[2] Lise Worthen-Chaudhari[2] Linda P. Lowes[3]
Alex Borstad[2] Ryan J. McPherson[4] Jacob Grealy[1] Josh Adams[1]

[1]The Ohio State University
CSE Department
395 Dreese Laboratories
2015 Neil Avenue
Columbus, OH 43210-1277

[2]The Ohio State University
Dept. of Physical Medicine and Rehabilitation
390 W 9th Avenue
Columbus, OH 43210

[3]Nationwide Children's Hospital
700 Children's Drive
Columbus, OH 43205

[4]The Ohio State University
ECE Department
205 Dreese Laboratories
2015 Neil Avenue

ABSTRACT
Here we discuss the development of a rehabilitation game that targets the upper extremity. Our target is an in-home implementation of Constraint-Induced Movement Therapy (CI Therapy), the current gold standard. Evidence based medicine supports the use of CI Therapy, but the widespread application of the treatment is hindered by the cost and accessibility as well as insurance reimbursement. The factors are driving the need for an affordable, accessible and effective alternative. Individuals with stroke and therapist stakeholders indicated that the following elements were required for effective "gamification" of CI therapy: intuitive game mechanics, proximal and distal motor practice, customization to the user, and the core components of CI therapy. These design considerations are present throughout every aspect of game design from scene selection through gameplay goals and gameplay mechanics. We discuss those decisions in game design including selection of game platform and interface devices, content generation, and game mechanics. We report on feedback regarding feasibility and acceptance and preliminary evidence of treatment efficacy.

General Terms
Design.

Keywords
Therapy, Kinect, Serious Games, Hemiparesis, Stroke

1. INTRODUCTION
The majority of United States citizens with diminished hand and arm function have inadequate access to long-term rehabilitation care. Stroke, the leading cause of hemiparesis, affects arm-hand function in about 350,000 people per year [10, 13]. Hemiparesis can additionally result from other neurological events including traumatic brain injury, multiple sclerosis, cerebral palsy, spinal cord injury, and surgical resection. If clinical practice guidelines [14] were followed, the majority of individuals would be expected to receive at least some outpatient rehabilitation [15], yet only 30.7% received this care. Amongst those who do receive outpatient rehabilitation services, most do not receive evidence-based treatments [16]. One particularly striking example of the dissociation between the scientific rehabilitation literature and clinical practice is the limited clinical dissemination of constraint-induced movement therapy (CI Therapy). CI therapy has been shown to provide improvements in paretic arm function and frequency of use [16], and to promote structural and functional brain plasticity [4]. Over the past 20 years since it was first described in the literature, more empirical support for its efficacy has been generated than for any other upper extremity intervention. Although it can be successfully implemented in up to 75% of stroke patients who exhibit residual hand/arm dysfunction, fewer than 1% of stroke survivors have access to this treatment. CI therapy is unavailable to most stroke survivors due to its cost, travel/scheduling demands, and dearth of trained providers.

To overcome these accessibility challenges, our team is developing a game using the Microsoft Kinect and XNA game studio environment that is designed to provide CI Therapy in the home setting. To the best of our knowledge, this is the first attempt to create a stand-alone home-based rehabilitation program for upper extremity hemiparesis **based on an empirically-validated treatment**. Although a few avatar-based virtual reality games and programs [5] have been designed for rehabilitation, they have not promoted critical motor learning elements, such as intensity of practice and carry-over of therapy gains to daily activities, that are being implemented here and have typically been of low complexity (prompting the person to reach out and touch virtual objects in repetitive patterns). Furthermore, other robotic technologies offered to facilitate delivery of motor rehabilitation have been criticized for not incorporating critical motor learning elements or delivering empirically-validated treatments [2]. Existing upper extremity stroke rehabilitation technologies may supplement therapy effectively, but are thus unlikely to be successful stand-alone interventions that can be implemented in a home setting. In keeping with the delivery schedule for CI therapy employed in the EXCITE trial [18], game content is being designed to support three hours of gameplay per day for ten consecutive weekdays.

This paper discusses how the team incorporated the requirements of CI Therapy and feedback from the target audience into game design and implementation.

2. REQUIREMENTS FOR GAMIFIED CI THERAPY

The overarching requirements of this game design are founded in the empirical basis of CI therapy. Critical elements of this protocol are massed motor practice and the "transfer package" - a number of behavioral techniques that *facilitate transfer of therapeutic gains to everyday activities*. It is through this combination of activity-based medicine and behavioral techniques that CI Therapy enables the patient to overcome a conditioned suppression of movement (e.g., learned nonuse) characteristic of chronic hemiparesis. [19,20] Transfer package techniques include a behavioral contract, daily monitoring of use of the more affected arm for everyday activities [via daily administration of the Motor Activity Log (MAL)] and guided problem-solving to overcome perceived barriers to using the extremity.

Effective video-game delivery of CI therapy required the following six game design considerations: 1) support play time of three hours daily for 10 consecutive days, 2) be sufficiently motivating to encourage the user to perform repetitive challenging therapeutic movements, 3) incorporate elements of the "transfer package" to encourage the user to increase use of the more affected upper extremity for daily activities. These include automated administration of the Motor Activity Log (MAL) with problem-solving via branching logic from user responses and encouraging the user to wear a restraint mitt on his/her less affected arm during daily life outside of the game. 4) adjust the difficulty and type of motor practice based on an individual's therapy needs, 5) adjust difficulty as a user's motor function improves (shaping/ leveling up), and 6) aesthetically appeal to the target audience, primarily older adults over the age of 50 who have had a stroke or children with hemiplegia, with little video game experience. These 2 dichotomous populations made choosing an engaging environment challenging. Surveys of potential adult consumers revealed heterogeneous desired aesthetics, yet the majority of stakeholders desired aquatic elements (e.g., lake, ocean, stream, underwater). Acceptance by pediatric healthcare necessitated that violence in the game is avoided. Every aspect of the game reflects these requirements. Using the Microsoft Kinect, our team developed a game that delivers the critical components of CI therapy, based on the aforementioned considerations, which is described in detail in the Game Mechanics and MAL sections below.

3. ASSESSMENT

One unique element to our design and development process is that success is defined by clinical outcomes. Design assessment therefore incorporates validated outcome measures from the field of rehabilitation medicine. These assessments are administered both before (pre-test) and after (post-test) a prescribed duration of game play (30 hours over 10 weekdays) to quantify the ability of the game to enhance rehabilitation compliance and improve motor function.

Outcomes measured include the following: time the game was played (logged within the game), total number of gestures performed for each type of gesture (logged within the game), time the constraint mitt was used (measured by the instrumented mitt and logged through the game), and standardized tests of movement (e.g., Wolf Motor Function test).

4. TARGET AUDIENCE

In the video game arena our target audience of people with chronic hemiparesis is unique for several reasons. First, they are often from an older demographic that is not accustomed to video games. Second, they often have other cognitive difficulties resulting from neurological injury. Third, nearly 75% of people who experience stroke are over 65 years of age. Finally, they are highly motivated to recover function in their hand or arm. This equates to the following design considerations: 1) this audience may be less able to tolerate in-game errors, poor instructions, and difficult user interfaces, 2) they will be more motivated to continue playing a game that they perceive as beneficial to their motor function, with less regard for aesthetics.

5. PLATFORM

Our team sought a low cost, commercially available platform with a modern natural user interface device that facilitates registration of skeletal joints and movement kinematics. We selected the Microsoft Kinect for Windows. Our current systems are quad-core Intel i5-3450 processors running at 3.1 GHz with 8Gb RAM and NVidia GeForce GT 640 graphics cards

A camera-based controller was chosen to ensure that the participants were being compliant with the therapy. The use of the Kinect was a key decision in designing the game. Using an off-the-shelf skeleton tracking system freed up substantial developer time.

5.1 Mitt

One component of CI therapy is a thick padded restraint mitt that, by constraining the less affected arm, encourages use of the more affected side for daily activities. Constraint is prescribed for 90% of waking hours during the 10 treatment days. See figure 1. In clinic-based CI Therapy, mitt time would be logged and reported to the therapist daily. The team desired an objective method of

Figure 1. Mitt with timer.

quantifying mitt use to verify compliance with this portion of the therapy and therefore designed an instrumented mitt. A standard Posey® mitt was enhanced with a digital timer, electronic switch, and LCD display to display wear time. At the beginning of each game session, the player is asked to input the mitt time and is reinforced with bonus points based on the time entered.

5.2 Glove

Important components of the rehabilitation program include training supination and distal motor function (i.e., hand). The Microsoft Kinect was unable to accurately identify some of the skeletal motions associated with reaching and grasping – specifically Kinect could not recognize wrist supination/pronation nor individual finger flexion/extension motions. To resolve these issues, our team developed a glove with axial accelerometers mounted on the back of the hand to determine orientation and flex sensors mounted to the thumb and fingers to provide measurements of flexion and extension. See figure 2. The aforementioned sensors were integrated into an open-palmed glove design for easier application in the presence of spasticity. A microcontroller unit with Bluetooth capability is attached to the glove and worn around the forearm in a flexible sleeve. The glove communicates serially with the therapy system via Bluetooth and continuously outputs accelerometer and flex sensor data. This data is used in conjunction with the Kinect skeletal data in recognizing therapeutic gestures [6].

6. GAME MECHANICS

One effective method of approaching game design is to examine a game from the perspective of its mechanics, their interactions, and their effect on the game state [11]. We considered all three of these elements to produce this gamified version of CI therapy. With regard to game state, in many games the most important state, or the ultimate goal, is the win state. Our desire to have a less stressful, more relaxing play style, and to accommodate repetitive play guided us toward a game in which the user completes laps on a game circuit for a score. The ultimate goal is therefore to compete against one's own previous scores, thus providing feedback on improvement. Score is based on successfully performing in-game activities (each of which requires exercise of a therapeutic gesture) and lap completion time. In this way, the score is reflective of the amount and quality of therapy performed. A time-based bonus encourages achieving more gestures per unit time.

Because this gamified therapy focuses only on movement of the upper body, the game was designed to be performed seated, both for safety and accessibility (for individuals with limited mobility).

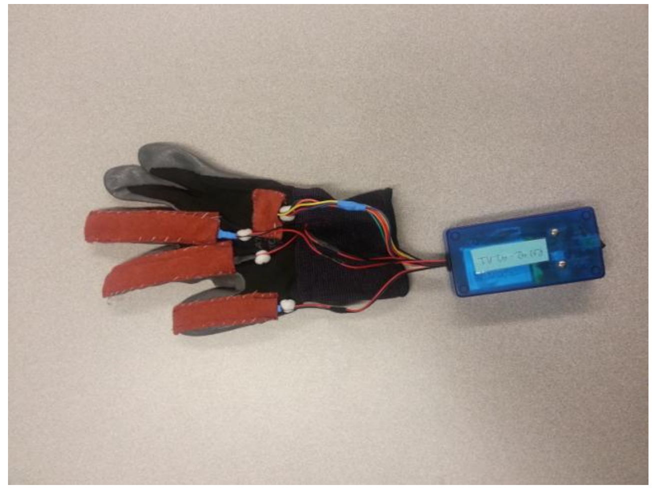

Figure 2. Glove

Qualitative data from stakeholder interviews revealed the importance of a game aesthetic that incorporated water. For these reasons, we chose the protagonist to be an individual paddling downriver in a kayak. We balanced the need for variety, which is important to maintain engagement, with the need for familiarity, which was important for patients with post-stroke cognitive deficits, by sequencing through two scenes in a continuous loop. The game environment consists of an outdoor river valley in a natural setting, followed by an underground maze with a semi-industrial theme as shown in figures 3 and 4. Each continuous lap takes about 30 minutes to navigate through. To add additional diversity, each lap the maze and river valley are procedurally generated and the outdoor ecology changes by retexturing the plants and landscape.

Due to our target audience, player control is not high fidelity. (Most of our users would be unable to navigate a boat down-river using a standard third person controller.) We use therapeutic gestures to trigger mechanics which control navigation. One mechanic moves the boat downriver a unit distance, one moves the boat to the right, and one moves the boat to the left. Also, due to this navigation mechanism, we decided on discrete lanes of travel in the river. The kayak may travel in the center, left or right lane.

Many game mechanics were tailored to therapy goals such as range of motion per joint, interjoint coordination, and smoothness of movement performance. The movements used to achieve these goals were permutations of reaching and grasping. Mechanics were further reduced to target motion at the skeletal joints involved in reaching and grasping, such as the shoulder, elbow, wrist, fingers and thumb.

Gestures coded to encourage reaching of the paretic arm included the following: rowing (from forward of the torso to behind the

Figure 3. Outdoor Gameplay

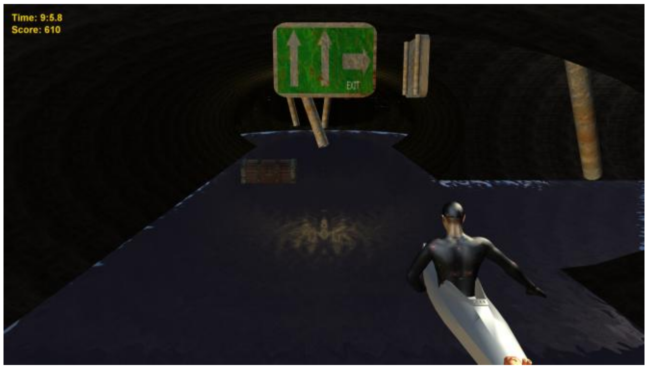

Figure 4. Underground Gameplay

torso), reaching across the midline of the body, and reaching laterally to the paretic side. These gestures were attached to the rowing, move right, and move left mechanics, respectively. One particularly difficult reaching motion for persons with stroke is to reach above the head. A gesture requiring overhead motion was attached to the Bats mechanic described below. Here are many of the mechanics that were designed specifically to promote desired therapy movements:

- Rowing. The player must complete a row gesture to make the boat travel down-river
- Avoid Barriers. Barriers are placed along the river path, blocking 1 or 2 lanes at a time. These barriers require the player to perform the move-right or move-left gesture to successfully navigate the river. If the player runs into a barrier, the boat stops and a small negative value is added to the score.
- Rapids. In rapids, the boat automatically moves downriver at higher speed than in rowing sections, allowing the user to focus on the gestures for moving the kayak from side to side, while making it more challenging to avoid barriers.
- Fishing. The fishing section is indicated by jumping fish and the avatar's use of a fishing net. The player gestures to scoop the net through the water to attempt to catch fish. Each successful scoop yields a 50% probability of catching a fish.

Figure 5. Fishing. Not all fish are equally rewarding!

- Parachutes. Parachutes yielding survival supplies fall from the sky over the river. The user must perform a gesture to catch the parachute and receive a reward – currently extending the arm forward and performing supination.

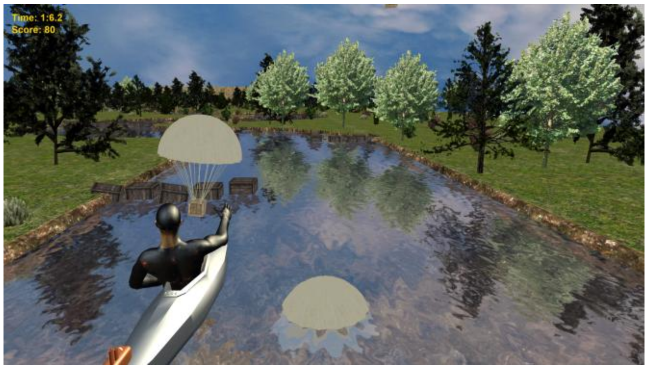

Figure 6. Attempting to catch a parachute.

- Bottles. The river is littered with plastic (2 liter) bottles. The player must perform a gesture to retrieve the bottle from the water and receive a reward.

Figure 7. Pulling bottles from the river.

- Maze navigation. The lanes in the maze control the direction of the boat as indicated by signs on the ceiling of the tunnel. The user must perform the left and right gestures to position the kayak in the desired lane to navigate the maze.
- Pipes. Dangerous pipes hang down from the ceiling inside the maze as shown in figure 4. The player must perform a gesture to avoid the pipes or use the left/right gestures to navigate to a lane that does not contain a pipe.
- Chests. Treasure chests are found within the maze. See figure 4. The user must navigate to the correct lane to run into a chest to receive its reward. Chests encourage exploration of the maze for increased score at the expense of time.

Figure 8. Swatting bats to move forward.

- Bats. Bats are located in dead ends throughout the maze. If the player runs into bats, the bats harass the player and stop forward motion. The player must perform a gesture to shoo away the bats and continue through the maze.
- Picking fruits. Picking fruits involves both a targeted reaching and grasp/release. While travelling downriver, bushes indicate the location of fruit-picking. When the player reaches the bushes, the game changes to a scene which provides a hand cursor and a set of fruits on background bushes. See figure 9. The player must move the cursor over each fruit target and perform a gesture (closing and opening the hand) to pick and release as many fruits as possible within a 2 minute time frame.

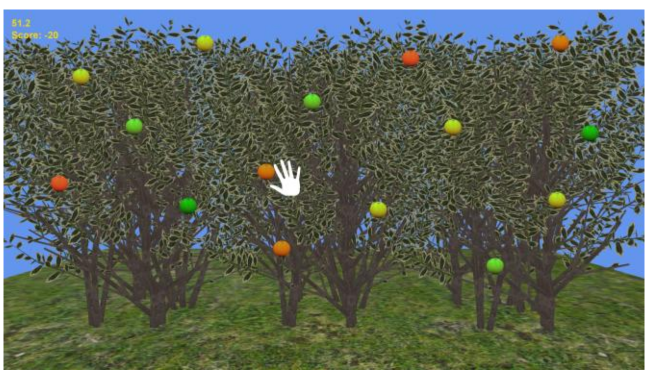

Figure 9. Fruit picking mini-game. The player moves the hand cursor over a fruit and closes his/her hand to pick the fruit.

Because the goal of the game is to increase mobility and function of the arm and hand, a change in performance during the course of game play is expected and desired. Therapeutic goals were promoted over time by leveling up the kinematic-based game mechanic triggers to require increasingly more challenging movements to be performed. For instance, range of motion required to trigger a game mechanic might be increased over time as might duration of hold at the reach/grasp end point.

7. TRANSFER PACKAGE

The transfer package is a number of behavioral techniques that facilitate transfer of therapeutic gains to everyday activities. Those portions of the transfer package which are implemented in game are the daily monitoring of the use of the affected arm in everyday activities through the MAL and problem solving. The MAL implementation in-game consists of a series of 26 questions asked during the course of 6 hours of gameplay. At the end of one lap of the content, a number of MAL questions are administered such that the total number of questions asked per day is 13 or greater. Each question asks the individual to rate his/her ability performing a daily task such as turning on/off a light switch on a 5 point scale. Video queues are given to help establish a common rating scale. If the individual had the opportunity to perform such a task, but did not, problem solving is performed via branching logic from user responses. In this way, a user selects a technique that may assist him/her in accomplishing a task in the future. MAL results are logged and performance gains can be measured over the course of treatment.

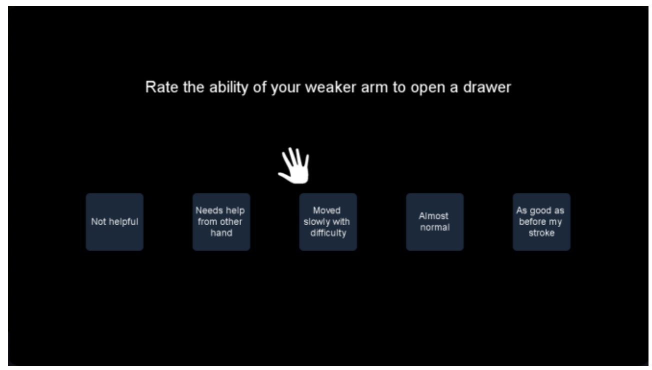

Figure 10. Motor Activity Log. Here the user is asked to rate his/her ability to open a drawer.

8. IMPLEMENTATION DETAILS

A therapy centric focus was used throughout the implementation. Our team addressed several issues in attempting to implement the game. Herein are some of the major implementation decisions relevant to creating a game for CI therapy.

Developing artistic content for 30 hours of gameplay was not feasible given limited development resources. Procedural content therefore provided a feasible alternative. Procedural content is used in creation of the outdoor river valley scene; the indoor maze scene; the placement of trees, barriers, pipes, and chests, and the creation of interesting boulders.

8.1 Procedural River

Our team produced two methods of generating a river. In the first case, the path of the river was modeled as a periodic function and specified based on its Fourier coefficients. This produced a believable river path through the valley, but it was not easy to control the direction of the river at the beginning and end when joining the outdoor river with the underground waterway. In the second method, the river was built from tiles, each containing a segment of river. When constructing seamless tilings to create a believable terrain, it is necessary to make sure adjoining edges match. Seamless tilings with textures was described in [9] and our method for 2D height maps is analogous, with the addition of criteria for the river. Adjoining tiles were constructed such that the river crossed the boundary smoothly and the first and last tiles were designed such that the river meets the underground pathway. Tiles allowed us to customize therapy to the individual user by allowing the user/therapist to select the frequency with which various game mechanics occur (each associated with particular motor movements). Therapists specify the number of river tiles and the therapy to be performed on each tile using an XML configuration file.

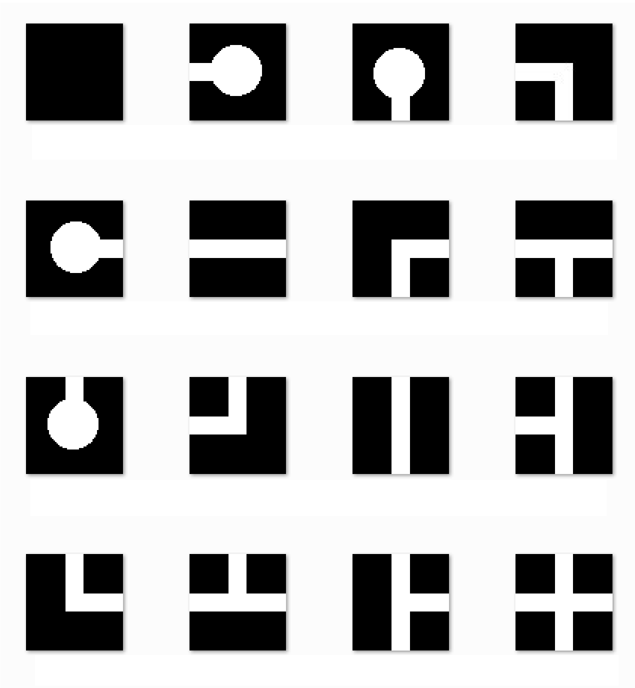

Figure 11. Maze tiles. These 16 tiles represent all possible combinations of open or closed pathways along each edge of the tile. A maze is randomly constructed from placing these tiles into a tiling such that the edges are consistent.

8.2 Procedural Maze

The maze is stored as a 2D grid of integers where each integer is a tile index and defines how the maze crosses each edge of the tile. All possible tiles are shown in figure 11. The maze is initially seeded with a set of random integer indices in each grid cell by choosing a random state for each cell edge as open or closed. All boundary edges are initialized as closed. The entrance to the maze is then placed in the upper left-hand corner and the exit is placed at the bottom right-hand corner. The maze at this stage may be disconnected. Maze components are joined by randomly adding maze segments until all components are joined. Maze difficulty was tuned based on play testing, and a maze size of 5 x 5 was found to provide sufficient challenge and interest.

8.3 Tree Placement

Trees are placed using a Poisson point distribution with a given radius r. We use a quick Poisson distribution algorithm which takes a given number of trees n and a radius r and a max fail value of m. If a new point is not able to be found in m iterations, r is modified to be r/2. Trees are further constrained so as not to fall within the river path.

8.4 Barrier Placement

As the boat travels down river, the user may travel in one of three lanes: center, left of center, and right of center. Barriers are placed throughout the river path, requiring the use of the move left and move right game mechanics, which are attached to therapeutic gestures, to avoid the obstacles.

Barriers are placed procedurally along the river path traversing from the start of the canyon to the end of the canyon. Barriers block one or more lanes of travel down river. The set of possible barriers is shown in Table 1. The placement of a new barrier is based on the previous barrier as shown in Table 2. Barrier placement is designed to require movement to the left and right while navigating the river.

Table 1. List of barrier types and which lanes of travel are blocked in the river.

Barrier Type	Lane is Blocked?		
	Left	Center	Right
1	Y	N	N
2	Y	Y	N
3	N	Y	N
4	N	Y	Y
5	N	N	Y
6	Y	N	Y

Table 2. List of possible barriers that can follow a given barrier. Using this table, a player is encouraged to make a move each time a new barrier is reached.

Barrier Type	Choices allowed for next barrier
1	2, 3, or 4
2	4 or 5
3	1,2, 4, 5, or 6
4	1 or 2
5	2,3 or 4
6	2,3, or 4

8.5 Pipes and Chests

Pipes and chests are placed in the maze on a per tile basis. Given r pipes and s chests per tile, a random location is chosen along the path in the current tile for each pipe and chest. Due to therapist and patient feedback, we avoid placing chests in intersections, as this created a conflict between the lane in which the player wants to travel to make the appropriate turn in the intersection and the lane required to retrieve the chest.

8.6 Procedural Boulders

Believable rock formations are formed by applying functional operations on a regular unit sphere mesh. Each operation perturbs the vertices of the mesh. These operations are random displacement, subdivide, extrude to sphere, random slice, and smooth. A rock is defined as a set of operations $O = \{ o_1, o_2, \ldots, o_n\}$, where o_i indicates a specific operation from the above list. Several rocks are constructed at load time using a fixed random seed and used throughout the game.

8.7 Logging

The following items are logged during play:

- Session start time.
- Skeletal data.
- Each gesture state completed.

- Each completed gesture.
- Mitt total time.
- Answers to MAL questions.

9. RESULTS

During initial game development, feedback from more than 30 individuals with stroke representing multiple socioeconomic, cultural, and ethnic backgrounds revealed widespread acceptance of virtual reality gaming as a method of rehabilitation irrespective of age, technological expertise, ethnicity, or cultural background.

Pilot data from 4 participants with chronic stroke who completed the in-home intervention demonstrated preliminary feasibility and efficacy of the therapist-as-consultant video-game model of CI therapy delivery. Rehabilitation outcomes/measures were positive and will be reported in detail in a subsequent manuscript. Benchmarks of feasibility were demonstrated, including acceptance of the game, compliance with the intervention, therapist ability to support the intervention and participant safety. All participants learned to access the game and completed the 10-day intervention. Therapists were able to support participants and progress the intervention via 4, 1 to 1.5 hour visits across the 10-day intervention. One participant developed mild shoulder pain on day four of playing. The consulting therapist modified game parameters and the participant successfully completed the intervention without pain, playing for a total of 33 hours in 10 days. No participants experienced an adverse event during the intervention.

On average, participants played the game for 21.9 hours (range 11.2 to 33.1) during the 10-day intervention. They achieved an average of 1,600 therapeutic movements (gestures) recognized per hour of game play. This is much higher than the number of movements achieved in traditional CI therapy, 110 per hour on average in our laboratory.

Participants' subjective comments suggest that they felt the intervention was effective. Despite having no experience with video games, they felt comfortable playing the game, and were able to operate the game independently. All participants reported increased strength and endurance of the arm and hand. Three of four participants reported that they also experienced improved control of the arm and hand. Although the intervention focused on the upper extremity, two participants reported that they experienced improved gait following the intervention. This could be attributable to improvements in trunk control facilitated by across body movements. All participants perceived that they were using their arm more functionally and with greater frequency following the intervention and all expressed a desire to continue playing the game after completion of the study.

10. ACKNOWLEDGEMENTS

In addition to the authors, a number of students have contributed to the Recovery Rapids game during the course of their education at The Ohio State University. These include Kala Phillips, Yinxuan Shi, Juan Roman, Jana Jaffe, Dan Bibyk, Wesley Stover, Kyle Donovan, Tristan Reichardt, Evan DeLaubenfels, and Rengao Zhou. This work was supported by the Patient-Centered Outcomes Research Institute (PCORI) grant and UL1TR001070 from the National Center For Advancing Translational Sciences. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Center For Advancing Translational Sciences or the National Institutes of Health..

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