

Towards Customizable Games for Stroke Rehabilitation

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ABSTRACT

Stroke is the leading cause of long term disability among adults in industrialized nations. The partial paralysis that stroke patients often experience can make independent living difficult or impossible. Research suggests that many of these patients could recover by performing hundreds of daily repetitions of motions with their affected limbs. Yet, only 31% of patients perform the exercises recommended by their therapists. Home-based stroke rehabilitation games may help motivate stroke patients to perform the necessary exercises to recover. In this paper, we describe a formative study in which we designed and user tested stroke rehabilitation games with both stroke patients and therapists. We describe the lessons we learned about what makes games useful from a therapeutic point of view.

Author Keywords

stroke rehabilitation, video games, design

ACM Classification Keywords

H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

General Terms

Human Factors, Design

INTRODUCTION

Stroke is the most common cause of long term disability among adults in industrialized nations [26]. Stroke survivors experience a broad range of problems that can impact their cognitive, visual, and motor systems. Some studies suggest that up to 80% of survivors experience significant motor impairment, which can make living independently and returning to the work force difficult and in many cases impossible [26]. Research in animal models suggests that with intensive therapy (repeating individual motions hundreds of times per day), animals that

experience strokes can recover a significant amount of their lost motor control [22]. Similarly, recent guidelines for treatment of human patients recommend high-intensity, repetitive motions while keeping patients informed about their progress [18]. Unfortunately, typical sessions with therapists include a relatively small number of motions [17]. To experience significant recovery, stroke patients must perform a substantial number of daily exercises at home. While therapists prescribe a home exercise regimen for most patients, a study indicates only 31% of patients actually perform these exercises as recommended [23].

Home based stroke rehabilitation games have the potential to help patients in recovering from a stroke. By decreasing monotony of hundreds of repeated motions and providing performance feedback, games may increase both the quality and quantity of patients' home therapy. Our long term goal is to create a game authoring system in which therapists can create or customize games for use by individual patients. To have the greatest impact, these games must:

1. Ensure that patients are correctly performing useful therapy motions
2. Provide a motivating context for therapy

In this paper, we describe initial work in designing and user testing a series of games to help patients regain use of their stroke-affected arm. In collaboration with an occupational therapist, we identified four stroke patients spanning a wide range of motor disability levels. We used an iterative design process to build and user test games that could be productively used by patients at many stages in recovery. We present a description of the games and game infrastructure that we built as well as the lessons learned about how to ensure that stroke games can be productively used by patients and can be adapted to each patient's needs.

BACKGROUND ON STROKE

A stroke usually occurs when a blood clot stops the flow of blood to a portion of the brain. Within minutes, brain cells lacking blood begin to die. Depending on the location and extent of brain tissue damage, patients who survive a stroke are likely to suffer cognitive, visual and motor losses.

Cognitively, stroke survivors may lose both memory and speech, losses that can substantially affect a stroke survivor's interaction with the world [7]. Some stroke patients experience unilateral neglect in which they no

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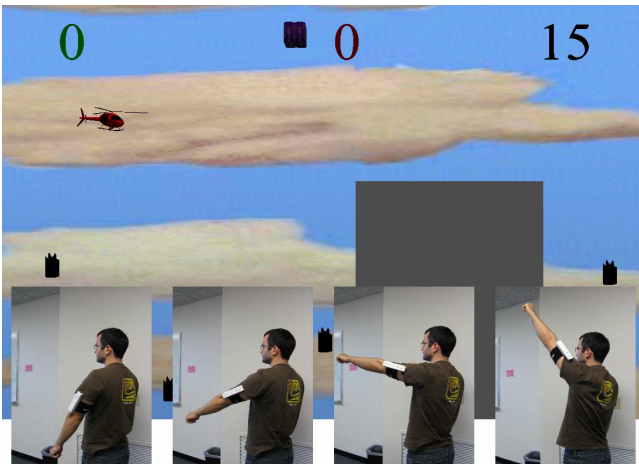


Figure 1. A subject playing the Helicopter game using a Wii remote strapped to the upper arm detecting shoulder flexion.

longer perceive one side of their visual field [22]. Motor problems, such as paralysis or weakness on one side of their bodies are also common [26]. The loss of control over one leg can make walking difficult or impossible [26]. The inability to use one arm can limit the stroke patients' ability to perform activities of daily living such as bathing, dressing, and feeding themselves [26]. All of these barriers can make it difficult for stroke survivors to live independently or return to the workforce.

Stroke Therapy

Physical and occupational therapy help reverse disabilities caused by stroke. By encouraging the use of the affected parts of the body through exercise, the patient can slowly relearn the ability to use them again. This is a very demanding process that can require hundreds of repeated motions every day to make progress towards recovery [16]. Current research suggests that stroke patients recover lost function in three ways: overcoming learned non-use, learning to use existing redundant neural pathways that do not include damaged brain tissue, and the development of new neural pathways through brain plasticity [22].

Recovering stroke patients typically participate in some form of therapy program which often consists of the patient performing repeated motions under the supervision of a therapist in a one-on-one session [18]. Exercises include active exercises in which the patient repeats one basic motion many times, and purposeful exercises in which the patient carries out simulations of everyday tasks that require a combination of motions. Motion abilities gained are initially hard to control, and require less effort in time. The goal is to get the patients to move their affected limbs as easily as they move their unaffected limbs. Studies have shown that increasing the amount of such exercise results in better recovery [16].

Our correspondence with occupational therapists showed that therapy on the lower extremity (i.e. legs) is the primary concern in early inpatient stroke therapy in order to enable mobility of the patient. Recovery of the upper extremity

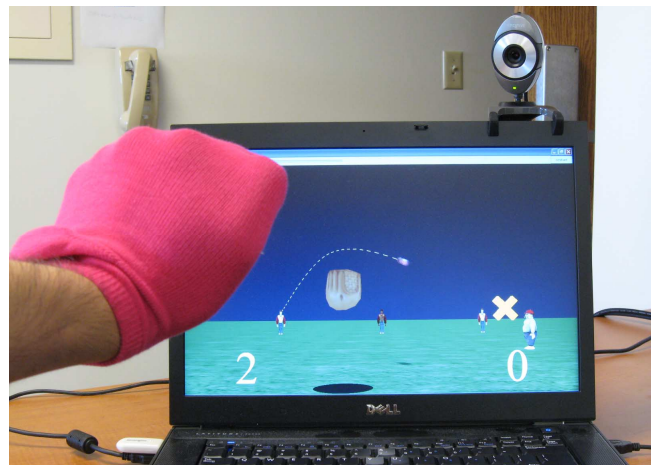


Figure 2. A subject using a colored sock and webcam color detection to play the Baseball Catch game.

(i.e. arms) has a slower progression and is usually gained through outpatient and home therapy [19]. Patients with upper extremity paralysis typically regain motion starting from their shoulder. Over time, they may gradually regain motion in the elbow, wrist, and, finally, the hand. Because of limitations on therapy, patients must do much of the work necessary to recover arm function at home, underscoring the need for home-based technologies that can both help and motivate patients to perform therapeutic exercises.

RELATED WORK

A number of research projects have explored how to use games to help patients recover following a stroke. An analysis of the properties of virtual reality and gaming in the context of the needs of stroke patients suggests that this is an important area to explore [20].

In the therapy community, some research has examined the potential of existing commercial games for stroke rehabilitation. Existing console games with motion-based input devices, such as the Playstation 2 EyeToy [11] and Wii Sports [9], have been used in stroke therapy studies. While these games are promising for patients in the later stages of recovery, they were designed for users with a full range of motion. Consequently, they cannot be used by the majority of patients recovering from a stroke [9,11].

In order to reach stroke patients in earlier stages of recovery, researchers have developed their own games. Colombo et al. created a simple game in which the patient tried to move a colored circle from an initial position to a goal position using a robotic device designed for arm rehabilitation [8]. Huber et al. [13] and Jack et al. [14] developed haptic glove based games in which users scare away butterflies, play the piano, and squeeze virtual pistons to improve the player's finger flexion and extension. Broeren et al. created several games for use with a pen-like haptic device that patients could position in 3D [3]. Burke et al. built two webcam color tracked games similar to whack-a mole [5]. In addition, they created a physics-based

orange catching game and a whack-a-mouse game, both controlled with magnetic sensors and a vibraphone game which used a Wii remote as a pointing device [5]. Yeh et al. developed a series of games involving manipulating objects in a 3D world [28]. Sanchez et al. developed training exercises modeled on everyday tasks [21]. Chen et al. created a dynamic decision network for audio-visual feedback for arm reaching motions [6].

Recently, researchers have begun to think about what properties are desirable in stroke rehabilitation games. Jung et al. stressed identification of the target audience, visibility and feedback as three important human factors for stroke rehabilitation games [15]. Burke et al. proposed meaningful play and challenge as relevant game design principles [4,5]. Goude et al. analyzed the potential of different game elements in addressing common problems among stroke patients [12]. They developed and user tested a number of successful games with these elements [3]. Flores et al. expanded the work in [12] and identified game design criteria that stem from stroke rehabilitation and elderly entertainment [10]. In addition they analyzed a number of games based on those criteria.

In this work, we take a step towards supporting game use throughout the recovery process. Rather than selecting a narrow range of disability, we focus on building games that can be adapted for use by patients in different levels of recovery. By working closely with therapists and stroke patients with a range of motor abilities, we have developed a series of games and an infrastructure that enables the tailoring of games for individual patients.

METHOD

To date, relatively little work has explored the question of how to design games specifically for the purpose of rehabilitation. To begin to develop an understanding of the requirements for therapeutic games, we conducted an exploratory study. Specifically, we were interested in the following questions:

1. What supports are necessary to adapt games to make them playable by individual users with different kinds of brain injuries and different levels of recovery?
2. How do we ensure that games are valuable from a therapeutic context?

To answer these questions, we used an iterative approach in which we developed and user tested a game system with several games that we designed to cover the space of arm motions. Four stroke patients participated in our tests and we met with each participant once for one to two hours. During the sessions, we selected games that we thought should be playable for each participant given their ability to control the motion of their upper extremity. We adapted the games as much as possible to the participants' available motions and cognitive skills, and observed them as they played. When possible, a therapist also attended these sessions to evaluate the games from a therapeutic point of

view. After each game, we briefly discussed its strengths and weaknesses as well as its applicability to stroke recovery. During these sessions, we identified barriers to stroke patients playing rehabilitation games as well as requirements on games from a stroke therapy perspective. In subsequent iterations, we adapted existing games to solve the identified problems and developed additional games to more fully explore the space of stroke rehabilitation games.

In the following sections, we present details of our game system, the participants, the games, and lessons learned about developing games for stroke therapy. We conclude with a discussion of findings and suggestions for future work.

HARDWARE AND SOFTWARE

In this section we describe the design decisions made in selecting the hardware and software.

Input Devices Used

We strove to choose devices inexpensive enough to make home use feasible, but technologically advanced enough to detect motions typically prescribed by therapists (see section below, Targeted Motions). Another concern was ease of use by patients. To facilitate these goals, we chose two inexpensive, commercially available devices: the Nintendo Wii remote and the webcam.

Wii Remotes

Wii remotes are inexpensive wireless input devices that include an accelerometer and an infrared camera. Although made for the Nintendo Wii console, PC-compatible software exists (we use the free Java-based WiiRemoteJ library [1]). The three-axis accelerometer senses acceleration that is dominated by gravity in simple motions. We use a lowpass filter to obtain an "up" vector, representing the tilt of the remote [27]. However, the accelerometer cannot detect rotation around the vertical axis and is not sufficient to detect displacement. Using the "up" vector, we use the remote as a free joystick for 2D input as well as for tracking the angle of motion in a vertical plane for 1D input. Due to the limited field of view, we found the infrared camera was not suitable for tracking larger motions often required in therapy.

To enable detection of a variety of different arm motions and to accommodate patients with limited hand mobility, we used Velcro to attach the Wii remotes to sweatbands or wrist braces worn on patients' arms and torsos (see Figure 1). While this was adequate for our initial prototype, our tests showed that a more dependable solution is necessary for robust home use.

In order to ensure that patients used the correct muscle groups to perform the motions, we developed a way to detect compensatory motions. By attaching additional Wii remotes to the body parts that were supposed to remain

| Motion | Sensing |
|---|--|
| Shoulder abduction and adduction | Detection: Wii remote on the upper arm Compensation: Wii remote on the torso |
| Shoulder flexion and extension | Detection: Wii remote on the upper arm Compensation: Wii remote on the torso |
| Shoulder internal/external rotation | Detection: Webcam, tracking the hand |
| Elbow flexion and extension | Detection: Wii remote on the forearm Compensation: Wii remote on the upper arm |
| Wrist rotation (pronation and supination) | Detection: Wii remote on the hand, held or strapped Compensation: Wii remote on the forearm |
| Wrist flexion and extension | Detection: Wii remote on the hand, held or strapped while palm facing up or down Compensation: Wii remote to the forearm, Wii remote in the hand can detect changes in palm |
| Hand and finger flexion and extension | Detection: Webcam, with colored ball on finger Compensation: Webcam, with a point in the forearm, occlusion is possible |
| Grasp, move, and release | Detection: Webcam, by handling a prop Compensation: Webcam, with a point in torso |
| Reaching | Detection: Webcam, with a gloved hand Compensation: Webcam, with a point in torso |

Table 1. Detection of basic arm motions commonly used in stroke rehabilitation exercises.

stationary, we could detect when motions were performed using the targeted muscle groups.

Webcams

We built a simple color tracking implementation to track the positions of multiple colorful objects worn or held by the user (see Figure 2). The implementation involves the user marking an initial rectangle surrounding the colored object to be tracked in the camera image. We then use a hill-climbing algorithm to find a lower and upper threshold for each channel in the hue-saturation-value color space to separate the color of the object from the rest of the colors in the scene.

At runtime, we use these thresholds to determine the pixels that are likely to belong to the object, and track the center of this pixel cloud as the object location. This works well for well-lit settings and for objects with distinct colors.

Targeted Motions

When properly used, our system can cover a wide range of exercises for stroke therapy. Table 1 lists some fundamental motions and the input devices that accommodate them. We identified these “building blocks” of exercises from literature as those used by therapists for the recovery of arm motion [18,22,26]. In the table, we provide the way that the

input devices should be used for detecting these motions and detecting and filtering out compensatory motions.

Note that, in many cases, multiple methods for identifying the same motions exist. For example, webcams can be used for almost all of the motions. However, we use Wii remotes for individual muscles because of their increased accuracy.

To make games that can be played with more than one type of exercise motion, we classify the inputs generated by the input devices into input types, represented by dimension and orientation. A more general classification scheme can be found in [24]. We use the Wii remote to generate 1D vertical input when attached to a body part such as the upper arm and moved in a vertical plane, 1D horizontal input when attached to a body part such as the wrist that is rotated around a horizontal axis and 2D input when used like a free joystick. We use the webcam to generate 1D horizontal, 1D vertical and 2D inputs by calibrating it accordingly. Every motion in Table 1 provides one of these input types. Similarly, each game that we build expects one of these input types for each of its players. As long as the input device and the muscle motion it was used with can provide the input type that a game expects, they can be used to play the game. This architecture enables games to be used for multiple different exercises.

Software

We developed our games in Java, using the LookingGlass [2] code base that includes a library of 3D models with a scene graph data structure for easy creation and manipulation of 3D scenes.

PARTICIPANTS

We worked with an occupational therapist to select four participants so that they represent a wide range of stroke patients. We describe each of the participants in ascending order of their range of upper extremity motion. All of our participants were female and had participated in some therapy program designed to assist them in recovering from stroke. We have assigned each participant a pseudonym to protect her identity.

Anne’s stroke left her unable to walk and largely paralyzed on the left side of her body. She has a limited ability to move her shoulder with a throw-like gesture and no control of her elbow, wrist, or hand. If she does a throwing gesture with her shoulder to raise her upper arm, she can hold her arm a few inches in front of her torso for a couple of seconds. Anne is fully dependent on her husband for her care. She described with apparent frustration watching hours of Home and Garden television to pass the time. She talked about wanting the “miracle pill” that would give her back control of her body. While Anne could chat knowledgeably about the latest news reports, she sometimes started to do a task (e.g. filling out the consent form or playing a game), and then seemed to forget about the task and started an unrelated conversation



Figure 3. Frog Simon game: The patient remembers and repeats tunes.

Barbara had her stroke 16 years ago and has recovered enough to be able to walk around independently, although she wears a leg brace. She has a little bit of use of her affected arm. She can raise her shoulder such that her arm is approximately parallel with the floor. Barbara can move her elbow and rotate her wrist a little bit, but without much control. She also had the ability to position her shoulder somewhat more precisely. While Barbara has a little bit more motion in her upper extremity, she does not use her affected arm for day to day tasks and she finds that she gets tired easily when she tries to use her affected arm.

Carol had her stroke 8 years ago, but has seen the greatest recovery in the last year during which she participated in an experimental treatment. She is also an active participant in a stroke survivor support group. Carol can walk but has a condition called left-neglect in which she will often fail to perceive objects (moving or not) on her left side. As a result, she does not drive. Carol can reliably move her shoulder and elbow, but without a lot of precision. When standing she has a wide range of motion, although she cannot fully raise her arm over her head. She has some movement in her hand, but her fingers will often close tightly, sometimes painfully, and involuntarily around objects that she is holding. In response, she prefers not to hold objects in her hand. While Carol does not have full use of her affected arm, she does use it in daily tasks such as carrying or holding an object by pressing it against her side.

Of all of our participants, Diane has the most use of her upper extremity, despite the fact that only two years have elapsed since her stroke. She uses her affected arm fluidly enough that one of the researchers present at the session had to ask which side was affected by her stroke. Diane has nearly full normal motion of her shoulder and elbow. She still has some difficulty with her wrist and hand. She particularly mentioned struggles with writing. Diane is also the only one of our participants who has returned to full time work. She relies on her husband for transportation as she cannot drive. But, in all other ways she is able to care for herself. Diane described taking a very aggressive approach to recovering from her stroke. She identified an experimental study in which she wanted to participate and

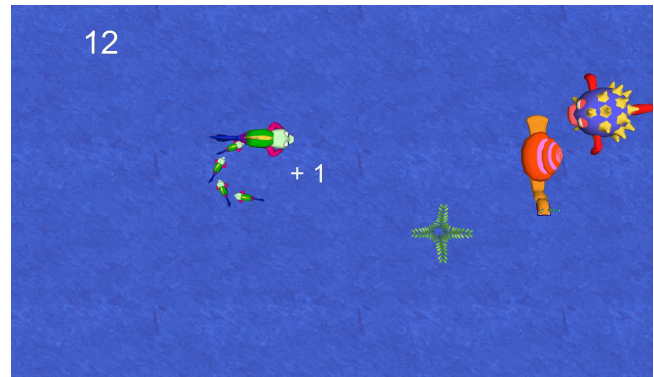


Figure 4. Under the Sea game: The patient controls the snail to protect the mother fish and the babies.

continued therapy until she met the inclusion criteria for the experimental study, which consequently helped her a lot.

GAMES DEVELOPED

In our study, we wanted to explore the space of games that can be used for stroke rehabilitation. As a result of our brainstorming sessions with therapists, we identified three attributes in this space: social context, type of motion required, and cognitive challenge. We explain why we chose these attributes below and identify them in the descriptions of individual games.

Social context. For a typical stroke patient, it can be difficult to find a companion to play with every day; however, multi-player games can provide extra motivation compared to single-player games. Multi-player games can be competitive or collaborative. Beating the opponent in competitive games can be very motivating; however, patients would need to have a clear advantage in the game considering their condition. In contrast, collaborative games can provide a friendlier game play and can improve the social bond between players. We provide a computer player for some multi-player games so that patients can also play them by themselves.

Motion type. The exercise motion can either be focused on a single muscle motion such as elbow flexion, or can require a combination of multiple muscles such as reaching, both of which are important. This choice depends on the required input type determined by the spatial structure of the game. 1D vertical and horizontal inputs are useful for measuring simple muscle motions and 2D inputs are useful for purposeful and coordinated motions using multiple muscles. Apart from the input type, characteristics of motions that the game expects affects the exercise that the patient experiences. The games may expect basic motions such as hitting an object, or may require more accurate inputs and be more challenging.

Cognitive challenge. Because many stroke patients have cognitive issues caused by their stroke, the degree of cognitive challenge is an important factor while designing games. Games can either be simple to understand and play, or they can require challenges such as recognizing and

remembering different objects, which can be difficult for some patients and fun and useful for others.

Games

When designing our games, we aimed to sample this space of possible design decisions. With an iterative approach, we developed, tested and improved the following games:

Frog Simon is a single-player game that requires an accurate 2D input, and provides a level of challenge on memory. This game is a variation of the handheld game Simon. The player controls a flower in the center of the screen, surrounded by four frogs as in Figure 3. The player uses a 2D input to touch the frogs in order to recreate tunes that they played. We found that this combination of a difficult physical challenge with a difficult cognitive challenge was impractical for most stroke patients.

Dirt Race is a two-player collaborative game that requires a basic 1D input for the stroke patient, and is simple to play. A truck is driving through a locust swarm in a village. The stroke patient controls a hand-operated windshield wiper to clear off the bugs for the other player to safely steer the car. The goal is to have the patient do the repetitive exercise over and over without much cognitive challenge. One patient played this game for 15 minutes.

Baseball Catch is a single-player game that requires an accurate 2D input, and provides some cognitive challenge in terms of differentiating between types of balls and following the trajectory of a ball in 3D. Three baseball players throw either a baseball or a basketball, targeting random positions on the screen. The player controls a baseball glove to catch the baseballs and avoid basketballs. Markers for the ball trajectory and target can be turned on to make it easier. This game is best played with the webcam and uses coordinated motions of the whole arm for reaching to random locations. Three patients played this game for an average of 25 minutes. Initially, the webcam motion range was hard-coded in the game and therapists were critical of it because it was not suitable for motion ranges of different patients. As a result, we enabled calibration of the input range with the webcam and found that this enabled making use of the whole motion range of users.

Catch the Kitty is a two-player competitive game that requires accurate horizontal 1D inputs, and provides some cognitive challenge in terms of quickly differentiating between different pets. Various animals fall from above and the players move horizontally along the bottom of the screen. Each tries to catch the pet type that is assigned to her or the shared pet type and score higher than the other. We developed this as a simple game to test whether patients could readily translate vertical motion to a horizontal change in the game. We found that patients were not comfortable with it unless the 1D input they used was horizontal displacement. Four patients played this game for an average of 20 minutes with Wii remotes, and could not

succeed because the Wii remote could not provide horizontal 1D inputs using a displacement motion.

Under the Sea is a two-player collaborative game that requires a somewhat basic vertical 1D input, and is easy to play. As in Figure 4, the mother fish and its trailing babies are controlled by one player with a 2D input to collect and eat ferns to get points. Meanwhile, a hungry predator (Spiky) stalks the fish, coming from off screen to the right to eat one of the babies. The stroke patient controls the snail, moving vertically across the right side of the screen to prevent spiky from reaching them. In this collaborative game, the stroke patient is the protector of the fish family and needs to do a somewhat basic repetition every time they come under attack. This game included appealing audio and visuals and was popular among the patients. Three patients successfully played this game for an average of 25 minutes.

Pong is a two-player competitive game that requires accurate vertical 1D inputs and provides some cognitive challenge in terms of following the ball trajectory. This is a remake of the classic game in which players control vertically moving paddles on each side of the screen, trying to keep the bouncing ball in the field. Even though we can adjust the ball speed towards either way and change paddle and ball sizes in difficulty settings, we found competitive scoring to be discouraging for patients and awkward for their caregivers. Competing against someone with a clear disability creates a difficult social situation. Alternatively we created a cooperative “rally” mode, in which one central score tracks how many times the ball was hit in a row, and another shared score keeps the longest streak. This created a more enjoyable experience for everyone. Three patients successfully played this game for an average of 20 minutes.

Frogger began as a single-player game that initially required accurate 2D input and provided cognitive challenge in terms of avoiding cars on a road. Similar to the classical game, the objective is to help the frog cross a busy highway with cars moving horizontally across the screen. We found that it was difficult for some patients to coordinate lane hopping and moving side to side, therefore we created a collaborative two-player version in which the stroke patient makes the frog hop to the next lane using a basic vertical 1D input and the other player moves the frog along the lane. We observed that this version worked better by providing ease of play. Further, this required the players to communicate to achieve a shared goal. Two patients played this game for an average of 15 minutes.

Helicopter is a single-player game that requires accurate vertical 1D input and is cognitively easy. As shown in Figure 1, there is a helicopter flying in front of a horizontally scrolling background. The player controls it vertically with a 1D input to avoid hitting the buildings and to collect fuel cells in the air. Between buildings, fuel cells appear close to the ground, which encourages the patient to move to the bottom end of the motion range. Larger fuel cells appear on top of the screen above buildings. Two



Figure 5. Detecting elbow flexion and extension with Wii remotes. The Wii remote on the upper arm detects and cancels out the compensation by the rest of the body.

players successfully played this game for an average of 25 minutes. This game is unique among our games in the sense that the patient is encouraged to perform full repetitions more than anything else. We developed this game to answer the following question: *is it better for the motion to be driven by random events in the game or should the game events be driven by the requirements of exercise?* The former has the risk of not being as helpful from a therapeutic point of view, while the latter has the risk of being too predictive and boring. In our limited tests, boredom was not a problem and the patient felt like the game was actually helping her. However, in longer tests such as home use, this question should be brought up again. We predict that the answer is somewhere in between to ensure the balance between fun and exercise, and hope to find ways of quantifying it.

Garden is a single-player game that requires accurate 2D input and provides a simple cognitive task of differentiating between weeds and flowers. The objective of this game is to clear a garden of weeds while preserving the flowers. With the webcam, we track a colored glove that controls a virtual robot arm and a beanbag that controls a dynamite in the game. While wearing the glove, the user grabs the beanbag (in the game, the robot arm lifts the dynamite). The player wants to drop the dynamite on a weed and then push a handle to the left of the screen to make the dynamite explode, which decimates the crop nearest to it. This game was inspired by our conversation with a therapist who believed strongly that the most important goal of rehabilitation was to encourage purposeful motions which are necessary for activities of daily living. Therefore, in this game, we tried to replicate similar motions and use them in the context of a game.

LESSONS LEARNED

Through user testing our games, we learned a number of lessons that are detailed below.

Making games playable for a broad range of stroke patients

Assume no use of hands

Of all the participants, only Diane could hold a Wii remote comfortably. Anne and Barbara had very little control over their fingers. Carol experienced involuntary finger clenching that led to discomfort. To enable the use of the Wii remote for these participants, we used Velcro to attach it to sports bands and wrist wraps placed on the participants' arms, as in Figure 5. We used a ping pong ball "ring" that slid over participants' fingers, or we made them wear a colored sock on their hands to enable the use of the webcam.

Simple games should support multiple methods of user input

Early in recovery a user may need to focus on increasing shoulder range of motion. For this situation, playing games like pong and the helicopter game can help users to practice simply moving their shoulder. Later in recovery, the user might play the same basic games but control them by grasping and lifting an object. By building games with flexible input methods, we can enable therapists to use them for different purposes over the course of recovery.

To enable therapists to use a given game for multiple purposes, we built an abstraction layer between games and input devices, as explained in the section Targeted Motions. This abstraction enables therapists to select the physical motions to be used to play each game based on the needs of the patient. To enable customization, we provide a calibration module that defines the mapping from the output of the device to the input that the game receives. This is useful for capturing the patient's range of motion and mapping it to the game's input range. The input can also exceed the calibrated range, which is useful when encouraging users to extend their range of motion.

Calibrate through example motions

Unlike users of typical commercial motion based games, our user base has specific and restricted ranges of motion. In addition, therapists want the patients to use their entire range of motion and sometimes to extend it. Initially, we captured motion ranges by asking the user to demonstrate their limits while we press a button. However, Anne could only move her arm in a jerky movement and could not hold it high long enough. Later we changed our system to accept example motions, so that the user could move her arm a couple of times, and we automatically identify the motion range. We observed that this made the process easier.

Direct and natural mappings are necessary

Even with immediate and continuous feedback, most of our users struggled to understand indirect motion mappings. For example, even when explained, three of our four users struggled with using vertical motion (raising and lowering their arm) to control the horizontal position of the character. Even a mapping in which rotating the wrist right and left causing a game character to move horizontally, was

confusing for users. We do not know whether these difficulties are attributable to lack of familiarity with video games or some cognitive issue resulting from the stroke. Of our four participants, only Diane seemed to exhibit no difficulties with understanding indirect motion mappings. Diane is younger than the other participants and played arcade style games as a young adult.

Ensuring that games are valuable from a therapeutic perspective

Ensure that users' motions cover their full range

Games that encourage patients to move through and extend beyond their full motion range have the greatest potential value. Unlike typical games which use random or physics-based targets, therapeutic games should bias target placement to encourage movement through the user's full range. For example, we provide an option in pong to slightly curve the ball to bias it towards the top and the bottom of the screen.

Placing some targets slightly outside of the user's calibrated range can help expand the user's range. For example, in the helicopter game, a bonus fuel package will occasionally appear above the tops of the buildings, at a height that is just outside of the user's current reaching range to encourage range expansion.

Detect compensatory motion

Patients often compensate for limited motion in an affected joint by moving other parts of their body, often without being aware of it. For example, Carol used her legs to rotate the office chair while playing Baseball Catch and was able to move the baseball glove without moving her arm. It is important to address such compensatory motions because otherwise the player can play the game without carrying out the repeated motions that are the goal of the game.

In order to address this problem, we eliminated environmental factors, such as rotating office chairs, which encourage compensatory motion. In addition, we attached additional Wii remotes to the user's body to detect and filter out compensatory motion. For example, in exercises that focus on elbow motion, we place Wii remotes on both the upper and lower arm to ensure that the game can only be played by changing the elbow angle, eliminating compensation through the shoulder (see Figure 5).

Allow coordinated motions

While patients in early stages of recovery may not be able to perform actions involving the coordinated motion of their shoulder, elbow, wrist, and hand, such motions are vital for patients hoping to perform activities of daily living. Purposeful exercises, including tasks that require grasping, moving and releasing objects, are particularly valuable for this purpose. The garden game utilizes these motions as users picking up a bean bag, moving it such that it is over a virtual "weed", and then releasing the bean bag. This type of game would be inappropriate for stroke patients with

little mobility, but is crucial for patients in later stages of recovery, hoping to restore coordinated motions.

Let therapists determine difficulty

The physical and cognitive abilities of stroke patients vary widely and patients undergoing therapy regain mobility in different ways at different rates. To create a challenging but playable game system for this diverse group, we found it necessary to create customizable difficulty settings to be adjusted to each patient's abilities. By creating individual difficulty profiles, therapists can also enable patients to work towards different goals. A patient can use one configuration to improve motion range and another to improve precision. We envision the therapist setting up difficulty profiles during a session with the patient, which can later be used when the patient plays the games at home.

Making games fun and challenging

Audio and visuals are important

Stroke patients tend to be older than typical gaming audiences. Like Flores et al [10], we found it necessary to pay careful attention to issues of size and contrast. Anne sometimes struggled to maintain focus during game play. However, when she played Under the Sea, she maintained attention, which she attributed to the colorful scenes and sound effects. While she was able to maintain focus better with this game, she sometimes struggled to notice when she was supposed to act. We have since added "danger" sound effects to try to draw the player's attention when necessary.

Automatic difficulty adjustments provide adequate challenge

In some games, we realized that once the patient got used to the game play, it could get boring unless we manually increased difficulty. To address this issue, we created automatic settings which gradually changed difficulty with the player's successes or failures based on a set of base difficulty values provided by the therapist. We observed that this enabled less boredom and provided challenge, which is consistent with the concept of flow [25].

Non-Player Characters (NPCs) and Storylines are intriguing

Initially, we spent little time developing storylines for the games. However, we observed that patients spoke about the game characters imaginatively. For example, users mentioned enjoying how baby fish followed their mother in Under the Sea, took the responsibility for protecting them and tried hard to save them from the spiky fish. When playing Baseball Catch, Carol was interested in interacting with the commentator and said she wanted to "kick him" as he reported missed balls. We believe that more opportunities to interact with NPCs and more developed storylines beyond regular game dynamics may provide a deeper sense of engagement with the game.

DISCUSSION AND FUTURE WORK

We have presented a number of guidelines that can help ensure that therapists can use games to elicit motions that

are useful in a therapeutic context. The number of tests that we were able to do with the patients was limited and our findings should be taken as suggestive rather than conclusive. Nevertheless, the therapists that attended the tests found that the games did motivate the patients and that they used the kind of motions that are required for their home exercises. Furthermore, these tests resulted in invaluable lessons on how to design a game system for stroke therapy. In order to collect more data and reason about whether the games motivated the patients to exercise and contributed to their recovery, we are planning to deploy the games at the home computers of a number of patients. We are hoping to use game logs and therapist evaluations in order to observe the effects of games in their recovery.

We believe that many of the lessons learned can also be useful for other patient groups that could benefit from exercising. However, additional work by therapists is necessary to ensure that games are useful and not harmful, such as avoiding exacerbation of physical injuries.

The ability to enable therapists to customize games such that they are useful for individual patients at a wide range of ability levels is crucial for the long term success of home-based stroke therapy games, but it is not enough. We believe that there are two primary areas of remaining work to enable therapeutic use of stroke rehabilitation games: 1) interfaces for therapists and patients and 2) a model of how to build motivating stroke rehabilitation games.

Interfaces for Therapists and Patients

At present, the team that created the games must still be around to assist with customization of games. Ideally, therapists should do this independently in the clinic. In addition to an interface for therapists, patients will also need a home interface and the ability to independently set up the Wii remotes and web cameras necessary to play each game. We are currently working with our colleagues in occupational therapy to design braces with which the patients can put on the Wii remotes using their unaffected arm. With this, we hope to evaluate our system in an outpatient stroke therapy context in the near future.

Motivating Stroke Rehabilitation Games

Although we made some strides towards understanding how to make games that encourage patients to perform therapeutically useful motions, we have not fully explored how to ensure that they will find the games motivating. In this work, our interactions with the patients focused primarily on their ability to understand and effectively play the games that we created. However, we also observed that some patients were motivated more than others. Two of the patients that participated in our studies, Anne and Carol, commented that they would like to be able to take the games home to play. Diane, when asked by her husband whether she would play the games at home stated that she would prefer to use them in sessions with her therapist. However, she felt that knowing that her therapist could

monitor her home game play would encourage her to play at home, too. In some ways the differing levels of interest that Anne, Carol and Diane showed in playing our existing games may be a reflection of their situations. Anne and Carol are essentially home bound. Activities that help them to pass time are appealing, particularly if they have some potential value. Diane, on the other hand, has returned to full time work and prefers to relax when she is home.

As we move forward in trying to develop games that can motivate patients recovering from stroke, we believe that there are ways in which rehabilitation games can tap into deep motivations. We are particularly interested in two opportunities in this space: 1) games that can help patients recovering from stroke to connect in meaningful ways with collocated friends and family members and 2) games that help stroke patients to feel a sense of social connectedness when they are alone.

Connecting with Friends and Family Members

Relatively few stroke patients who experience paralysis are able to live independently. Anne seemed to feel an acute sense of social isolation. She described spending hours watching Home and Garden Television. Yet, when she played Under the Sea, she began to talk about potentially playing games with her grandson as a way of furthering her connection with him. Thus, incorporating roles for family members and using therapeutic games to help stroke patients connect with their families presents a strong potential motivation.

Games may also help stroke patients and their caregivers feel a greater sense of connection as peers. Three of our four participants had very involved husbands who served as their primary caregivers, which is by its nature a very unequal relationship: one person is dependent on the other. Perhaps rehabilitation games, in addition to motivating patients to exercise, can also provide a context in which stroke patients and caregivers collaborate as equals. Several of our games were intended to be two-player games, some competitive and some collaborative. Our user tests did not include friends or family members of stroke patients, so often a researcher filled in as player two when necessary. While we included different difficulty controls for healthy and recovering players in the competitive games, we found the notion of competing against someone who is struggling to control their arm uncomfortable. Moving forward, we believe that collaborative games hold more potential as stroke rehabilitation games.

Increasing Social Connectedness

Three of our four users described spending a lot of time alone as a result of having spouses who are working full time. Games that provide a sense of social connectedness, perhaps with other post-stroke patients may help decrease their sense of isolation while motivating them to exercise.

We believe that games designed for rehabilitation at home have the potential to help stroke patients regain lost motion.

Understanding the social context that stroke patients find themselves in may help identify opportunities for rehabilitation games to tap into deep motivations.

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