Stroke Therapy through Motion-Based Games: A Case Study

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In the United States alone, more than five million people are living with long term motor impairments caused by a stroke. Recently, video games with affordable motion-based input devices have been proposed as a part of therapy to help people recover lost range of motion and motor control. While researchers have demonstrated the potential utility of therapeutic games through controlled studies, relatively little work has explored their long-term home-based use. We conducted a six-week home study with a 62-year-old woman who was seventeen years post-stroke. She played therapeutic games for approximately one hour a day, five days a week. Over the six weeks, she recovered significant motor abilities, which is unexpected given the time since her stroke. We explore detecting such improvements early, using game logs for daily measurements of motor ability to complement the standard measurements that are taken less often. Through observations and interviews, we present lessons learned about the barriers and opportunities that arise from long-term home-based use of therapeutic games.

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1. INTRODUCTION

In the United States, approximately 795,000 people have a stroke every year [Lloyd-Jones et al. 2010]. There are currently around 6.4 million people living with stroke [Lloyd-Jones et al. 2010], many of whom are affected by various cognitive and motor limitations. About 80% of people who survive a stroke experience motor impairments. One such impairment is hemiparesis: a partial paralysis of one side of the body [Langhorne et al. 2009]. Hemiparesis usually causes chronic disability in the upper extremities (arms) more than the lower extremities (legs). People with hemiparesis experience limitations in fine motor control, strength, and range of motion. These deficits can dramatically limit a person's ability to live independently, participate in leisure and social activities, return to productive work, and perform daily tasks

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such as dressing and bathing [Gabriele and Renate 1487; Lai et al. 2002; Wagner et al. 2007].

Participating in occupational therapy can help people with stroke overcome the limitations they experience. Research suggests that repetitive exercises can provide the brain with sufficient stimuli to remodel itself and provide better motor control [Kleim et al. 2003]. Experiments with animal models suggest that several hundred daily repetitions may be required to make progress towards recovery and that it is possible to return to motion levels that are close to normal [Selzer 2006]. However, the number of exercises in a therapy session is typically far fewer [Lang et al. 2007]. In order to overcome this limitation in therapy, therapists frequently prescribe home exercises as a part of outpatient therapy. However, one study indicates that only 31% of people with stroke perform these exercises as recommended [Shaughnessy et al. 2006], which can lead to an incomplete recovery [Lotze and Cohen 2006]. People who do not complete home exercises as recommended often cite slow progress and lack of motivation as impediments [Lloyd-Jones et al. 2010]. Recovery usually happens in plateaus, and it is easy to lose faith in exercises after observing no improvement for a long time. Therefore, finding motivating and effective ways to encourage people with hemiparesis to perform therapeutic exercises at home is crucial in helping them achieve a more complete recovery, where they regain lost motor control and become more independent.

Video games with motion-based input devices may provide a motivating way to help people with hemiparesis complete therapeutic exercises at home. Motion-based games could potentially become an alternative way to complete prescribed home exercises and help to increase the likelihood that the client will perform therapeutic exercises at home as required. Some research has demonstrated a potential for game-based therapy to help people with hemiparesis regain lost motor control [Bach-y-Rita et al. 2002; Deutsch et al. 2001]. However, most of the work in this area focuses on laboratory studies or short-term evaluations. Relatively little work has explored the potential barriers and opportunities that can arise when deploying motion-based therapy games at home.

There are challenges in using stroke rehabilitation games at home. First, the user population is quite different than regular computer users and game players. Many potential therapeutic game users have motor deficits and will need to interact with the games using the limited motion that they have. In addition, they are likely to be elderly and may be less comfortable using computers. Therefore, the software and the process should be designed to address human factors appropriately. To identify potential issues and start addressing them, it is necessary to observe the use of such game systems in the context in which they would be used in real life by therapists and clients at the clinic, and by clients at home. Through organizing studies that mimic such usage, we can begin to develop an understanding of the needs of the users of home-based game rehabilitation systems. Currently there are no such studies related to stroke rehabilitation.

This work attempts to take the first steps towards understanding the human factors related to game-based stroke rehabilitation at home. We describe a case study in which one woman with hemiparesis, who was seventeen years post-stroke, played therapeutic games at home over a six week period. In weekly meetings, she was supervised by an occupational therapy researcher in a manner similar to an outpatient therapy setting. Based on her experiences, we present barriers and opportunities that can guide the design of therapeutic game systems for home use.

We measured her motion abilities with standard motion measurements used in occupational therapy and complemented them with measurements using data from recorded game sessions. While the primary goal of this work was to explore how one person with hemiparesis integrated game-based therapy into her life, she did experience improvements in motor control over the six weeks. This is particularly surprising for a person who is seventeen years post-stroke. Considering her situation, the motor improvements were dramatic and resulted in changes that positively impacted her daily life. While the standard motion assessments that we used also suggested some improvement, they did not fully reflect the dramatic changes that she experienced. In addition, it was not feasible to have these assessments frequent enough to detect improvements soon after they developed. To complement such shortcomings of the standard measures, we explored measurements based on game logs that the system recorded throughout the study. Based on our analysis of the game logs, we propose techniques for evaluating motion improvements through game-based data. For our participant, these analyses suggest improvements in range of motion, motion precision, and motion smoothness. To further enhance the effectiveness of game performance to assess motor capabilities, we propose guidelines for game design for motion assessment.

In our recent work, we reported the initial findings of our case study [Alankus et al. 2010b]. We extend that work in this article by providing additional insights about the participant's experience and further analysis on the data that we collected.

1.1 Related Work

In order to successfully enable stroke rehabilitation through games at home, it is necessary to both enable rehabilitation through motion-based games, and to address the unique needs of individuals with stroke. In addition, game systems should monitor users' motion abilities and detect when improvements occur in an unsupervised home setting.

Existing research tends to focus on only one of these issues in isolation from the others. One group of studies explores how to make rehabilitation through games possible. While a few of these studies briefly touch on user-centric issues, these issues are not a focus. A second group of studies has focused on identifying the daily life needs of people with stroke at home. A final group of studies focuses on using data from motion sensors to automatically assess participants' motion abilities that are otherwise collected by therapists in lengthy sessions. In our work we sought to address all three issues in order to take a step towards enabling long-term home use of game-based rehabilitation for stroke.

1.1.1 Enabling Rehabilitation through Motion Games. Initially, studies focused on enabling game-based rehabilitation through custom or expensive input devices. Since these devices make widespread home adoption difficult, researchers have explored using affordable end-user input devices. The success of these initial pilot studies with games using these devices has led researchers to start designing games that specifically target stroke rehabilitation.

Custom or Expensive Input Devices. A number of researchers have either designed or adopted existing motion-sensing technology and explored its use in motor rehabilitation for conditions including stroke and cerebral palsy.

Bach-y-Rita et al. [2002] created custom mechanical input devices to be used with therapeutic arm exercises and enabled stroke survivors to play the Pong game while exercising. These input devices consisted of sliding levers that detected linear motion in one direction only. This limits the kinds of exercises that can be used within games and addresses the needs of a relatively small subpopulation of stroke survivors. The study took place in a clinical setting because the bulky nature and cost of the custom input devices prevented home adoption. The study found functional improvements in arm motion (e.g., ability to extend the wrist, use silverware, play volleyball with a balloon, dress/undress, reach out and grasp/release objects).

Broeren et al. [2008a] created a haptic stereovision immersive workbench and designed custom games to be played through grasping and moving a stylus. They used this system in clinical trials at an activity center for stroke survivors and reported motor improvements in arm motion related to manual ability, executive function, attention, and movement quality [Broeren et al. 2008b]. However, their device also limited the kind of exercises that could be used—the user needed to have sufficient motion to grasp the stylus and move it around in large arm motions. This excluded users without the required hand and arm motion, including the participant in our study.

Other researchers have focused on using sensing gloves for hand rehabilitation of people with cerebral palsy and stroke. While some of the studies addressing cerebral palsy took place at the homes of participants, the studies targeting stroke took place in the clinic. Adamovich et al. [2011] used a CyberGlove and a Rutgers Master II-ND haptic glove as input devices for hand rehabilitation with custom video games designed for stroke survivors. These games consisted of a 3D hand model that mimicked the user's motion. The user interacted with simple tasks on the screen, such as revealing an image or playing the piano. They conducted less than three weeks of training in the clinic with eight subjects. Using standard tests to measure success in functional tasks and assessing motion quality through kinematic data, they observed improvements in the users' hand motions (e.g., increased force and displacement of fingers, faster lifting of objects on a table). The same system has also been used for hand rehabilitation of people with cerebral palsy in long-term studies at the homes of participants. Golomb et al. [2009, 2010] conducted two long-term home-based studies on adolescents with cerebral palsy. They observed improvements in standard tests related to hand movement (e.g., grip testing and tests on functional tasks such as lifting light and heavy objects). To overcome issues related to home use, the researchers trained the parents of adolescent users to actively supervise the use of the game system at home. While these studies show promise, the use of a sensing glove limits their use to hand exercises only. This excludes stroke survivors who cannot use their affected hands, including the participant in our study. In addition, while parents of the adolescents with cerebral palsy helped resolve issues related to home use, it may not be practical to expect such close supervision when the system would be used by stroke survivors who do not enjoy the close attention of a parent or a caregiver.

Researchers have also used custom devices with games for the rehabilitation of lower extremities. Deutsch et al. [2001] used the Rutgers Ankle haptic interface to enable games to be played using the ankle and reported improvements in motion measurements (excursion and torque). They also ran usability studies on a version for telerehabilitation [Deutsch et al. 2011].

Affordable Input Devices. Although the studies mentioned in the previous section were successful in clinical and pilot trials, the input devices that they used were either expensive or custom-made. Considering that many stroke survivors suffer economic difficulties because they may not have jobs, the high cost associated with such devices is a barrier that prevents them from being adapted for widespread home use. While some custom devices for stroke rehabilitation could become cheaper if mass produced, the limited market for such niche products may limit the potential for sensors specifically for therapeutic use. If existing consumer input devices can be adapted for use in stroke rehabilitation, this may make motion-game-based therapy accessible to a broader audience.

Deutsch et al. [2008] used the commercially available Wii sports game system for rehabilitation of cerebral palsy in a school-based setting. They demonstrated the feasibility of the system and reported some improvements (increased walking distance, improvements in visual-perceptual processing, and postural control). Similarly, Flynn et al. [2007] used the commercially available Sony Playstation 2 EyeToy games at a stroke survivor's home and reported improvements after four and a half weeks of use (increase in perceiving motion of own body parts, improved balance). While participants in these studies made gains, the researchers acknowledged that the games were not designed for people with motion deficits and their use came with major limitations. They found that the games excluded many users with disabilities because they required a full range of motion. In addition, the motions in these games were not necessarily the kinds of motions that are required for rehabilitation.

To evaluate the use of motion games with a broader group of individuals with hemiparesis, other researchers have investigated the use of consumer input devices with custom games. Decker et al. [2009] demonstrated using the IR camera of a Wii remote to capture wrist motions. They suggested that this technique be used in stroke rehabilitation, but did not evaluate it with persons with stroke. Alankus et al. [2010a] used the accelerometers of Wii remotes to detect exercise motions by attaching the remotes to users' body parts. They created custom games, and tested them with people who had strokes. Alankus et al. [2010a] and Burke et al. [2009] used Web cameras with custom games, and tested them with people who had hemiparesis because of strokes but had some motion in their upper limbs. Burke et al. demonstrated that these games could be used at home by testing them at three individuals' homes and observing them playing in single user sessions. However, they did not test long-term and unsupervised use. Reinkensmeyer et al. [2002] used a joystick through a telerehabilitation system to sense therapeutic motions that drove simple web-based games. They reported increased elbow flexion/extension ability, but noted that the use of a joystick was limiting in terms of the therapeutic exercises that it allows.

The majority of existing research that we reviewed focuses purely on enabling the use of games in therapeutic exercise. However, research related to users' experiences with therapeutic games and their use in a home environment is also necessary to enable large-scale use of games in a therapeutic context. The cerebral palsy studies of Golomb et al. [2009, 2010] using sensing gloves were long-term and home-based; however, their main focus was the therapeutic effectiveness of the games rather than users' long-term interactions with them.

Designing Games for Stroke Rehabilitation. Recently, some researchers have started to focus on designing games based on the requirements of stroke rehabilitation. Goude et al. [2007] identified issues related to stroke (e.g., learned nonuse) and sought to address them with game elements (e.g., target distribution). Using their haptic stereovision immersive workbench as the hardware, they stressed these elements in simple games including Archery, Bingo, Memory, Simon, Space Tennis and Fish Tank [Broeren et al. 2008a]. While they used these games in clinical trials, they have not studied the effectiveness of these games from a user-centric point of view. In addition, they have not evaluated the home use of these games because the virtual reality hardware is not appropriate for the home. Another group of researchers, Burke et al. [2009], adopted principles from game design theory and used them as a guide in the development of games for stroke rehabilitation. They developed three games: Rabbit Chase, Bubble Trouble, and Arrow Attack. To demonstrate that the games could be played at home, they took the system to three individuals' homes and observed them playing in single-user sessions. Therefore, they have not had a chance to evaluate long-term unsupervised home use of these games. Alankus et al. [2010a] identified important game attributes based on limitations related to stroke and sought to sample the design space of games according to those attributes. Similar to previous researchers, they evaluated their games in short user sessions. While the body of research that we reviewed studied game design as an important part of user interaction, they have not addressed users' needs in long-term home-based use.

1.1.2 Studying the Needs of People with Stroke at Home. Another group of related work has developed guidelines for home-based stroke rehabilitation through user-centric techniques. Egglestone et al. [2009] organized workshops with therapists and people who had strokes to facilitate discussion with simple prototypes that could identify insights, issues and challenges in creating a home-based stroke rehabilitation system. They found that designs should, (1) consider the wider social context of strokes, (2) have the ability to be personalized for each stroke survivor, (3) manage when and how long the users should be engaged with them, and (4) sense improvements to provide appropriate feedback to users. Axelrod et al. [2009] took an iterative participatory design approach and studied the home environments of people with stroke to identify requirements for home-based stroke rehabilitation. They found that their participants lived in houses that are not ideal for their condition, and technology can help with their everyday activities. They also argued that new technologies should fit into these homes, as well as into people's lives and expectations. They noted that issues of ergonomics, robustness, usability, personalization and aesthetics must be addressed. Fitzpatrick et al. [2010] shared the insights and challenges that they identified in developing home-based technologies for stroke rehabilitation. They found that the users of such systems included caregivers and relatives in addition to the people with stroke. They reported that lack of autonomy and motivation are likely to be obstacles for technological solutions. Finally, they noted that use of prototypes may come with limitations and may not fully meet the expectations of therapists and clients.

This body of work suggests guidelines for designing new technologies for stroke survivors and identifies research challenges in this area. However, the research in this area did not explore home-based studies of new technology for stroke. In response, Balaam et al. [2010] implemented a prototype of a chess game with a tangible interface. Their case study shed light on how the user perceived and interacted with the prototype. They found that there is a fundamental tension between "designing for rehabilitation and designing for the user." While their prototype uncovered interesting challenges, they did not test its long-term usage.

While these user-centric studies were invaluable in learning more about users with stroke and their home environments, there is little research addressing longer-term use of rehabilitation game systems. We currently lack a user-centric understanding of how stroke survivors interact with customized home-based game systems over time. It is crucial to develop this understanding to create effective therapeutic game systems for long-term use. Our case study attempts to bridge the gap between, (1) research focusing on effective therapy through games, and (2) research focusing on understanding and addressing the needs of people with stroke at home.

1.1.3 Using Exercise Logs for Motion Assessment. While we did not begin this work with the intention of exploring new ways to measure the progress of rehabilitation game players, we observed in our case study that standard motion assessments used in therapeutic practice may not fully capture improvements as players recover. Other researchers have noted the same problem in the contexts of robotic rehabilitation [Hu et al. 2009] and studying the biomechanics of reaching [McCrea et al. 2002]. In this article, we also explore how to design games to maximize their utility in capturing player progress. In this section, we review the literature on motion assessment.

Researchers have used motion capture data from exercises for motion assessment [Shurtleff et al. 2009; Wagner et al. 2007]. Such kinematic data contains precise positions of limbs through motions in time. In comparison, the data supplied by the Wii remotes and Web cameras that we use in our study is less descriptive and less straightforward to use for a motion assessment technique. Zheng et al. [2005] surveyed a number of input devices used for various measurements of stroke survivors' movements. As they report, accelerometers have been mainly used for overall measurements such as energy expenditure, task classification, and counting, rather than more precise measurements related to motion trajectories. In addition, raw accelerometer data has also been used to predict clinical scores [Hester et al. 2006; Patel et al. 2010]. These studies employed statistical and data mining techniques to predict the clinical score values for standard tests that otherwise require therapists to spend hours to conduct. However, they did not use accelerometers to assess quality of exercise motions.

In addition, data related to game play has not been used along with data from input devices in the calculation of motion assessments. Data from games can reflect the person's intent, whereas data from sensors reflect the person's actual motions. They can be used together to calculate how successful the users were at their intents, which can provide a measure of their competencies in their motions. Games have the potential to provide a unique opportunity by making both intent and motion available for measurement of a user's motion abilities. In our work we take the first steps toward utilizing this potential that games provide.

2. GOALS

Researchers have proposed that using home-based games played with simple input devices may help to improve rehabilitation outcomes following a stroke. Although research has demonstrated that motion-based games show promise in rehabilitation, little research has explored the long-term home-based use of therapeutic games. We aim to take the current state of knowledge one step further by verifying the long-term home use of games for stroke rehabilitation, identifying related issues and proposing ways of addressing them. Specifically, our goals are as follows.

- Testing the home use of motion-based games using Wii remotes and Web cameras as a part of outpatient therapy;
- identifying issues that can occur when games are used as a part of outpatient therapy;
- understanding the needs of people with hemiparesis related to long-term home-use of therapeutic games;
- finding ways of addressing the identified issues and needs;
- exploring the use of game-related measurements to further aid the therapy process by complementing infrequent standard motion assessments.

We conducted a case study to make progress toward these goals. We present the details of this study in the following sections.

3. METHOD

We recruited one participant with hemiparesis and conducted a case study in which she played stroke rehabilitation games at home for six weeks and met with the occupational therapy researcher weekly. We organized our case study in a way that mimics regular outpatient therapy practice by holding weekly meetings similar to outpatient therapy and by replacing prescribed home exercises with games. To measure progress in her motor abilities over the course of the study, we held three motion assessment sessions. In the following sections we present the details of our case study.

3.1 Participant

We recruited a seventeen-year post-stroke, 62 year-old female with hemiparesis. We refer to her using the pseudonym "Marie" to protect her identity. In the years following her stroke, she has experienced some recovery through outpatient therapy as well as her own efforts.

3.1.1 History of Stroke and Initial Therapy. Prior to her stroke, Marie worked as a landscape designer for a plant nursery. She lost her job following her stroke. Marie's stroke affected her speech, memory, ability to write, and resulted in left hemiparesis (her nondominant side). She received hospital care for three months, and participated in intensive inpatient therapy for a month and a half during her time in the hospital. The inpatient therapy sought to improve her balance and reaching abilities. While her balance improved, her reaching did not, potentially because hemiparesis made the reaching exercises difficult to perform effectively.

She was discharged from the hospital roughly three months after her stroke. Doctors told her not to expect improvements to occur beyond the initial three month period immediately following her stroke. After leaving the hospital, she completed an additional month of outpatient therapy focusing on socialization and reintegration to home life through practicing simple daily tasks. She practiced completing these daily tasks using only her right (unaffected) arm.

3.1.2 Recovery on Her Own. Once at home, Marie worked to regain some of the abilities that she had lost and adapted new approaches to tasks that she could no longer perform. She initially focused on enhancing her memory through trying to remember facts about people she knew and improving her handwriting through copying recipes. She learned to perform many two-handed tasks in new ways using only her right arm. Her ability to speak improved over time. However, she still struggles with multitasking. As a result, she does not drive and relies on others for transportation.

She participated in stroke support groups for the first ten years after her stroke. These groups provided an opportunity to socialize with other people who had experienced a stroke. Through these meetings, she gained a better awareness of her condition and an awareness of her situation relative to others.

3.1.3 Later Therapy. Ten to eleven years after her stroke, Marie broke her right (unaffected) arm. In response, she began outpatient therapy with the goal of learning to use her left (affected) arm for daily tasks. As her left arm did not improve since her stroke, she found this impossible. Her therapist recommended home exercises consisting of ten to twenty daily left arm motions. She completed the exercises as directed for the duration of rehabilitation, but did not notice any improvements.

3.1.4 Present Day. Over the years Marie adapted a peaceful lifestyle. She lives with her husband and their adult son. She stays at home most days. Her hobbies include meal planning, cross-stitching, cooking, reading, doing puzzles, and playing games similar to puzzles. Today, she has no apparent cognitive or speech deficits resulting from the stroke, although she still chooses not to drive because she finds it difficult to multitask and worries that her reaction times are not fast enough to enable her to react to changing traffic conditions safely. She is comfortable using computers and the Internet. She reported using the computer daily for tasks ranging from online banking to playing solitaire.

Before the study began she had limited upper extremity motion on her left side. She typically rested her left arm against her body with her elbow bent at just less than ninety degrees and her thumb and fingers in a fist. She could raise her arm just above shoulder level, but she could not keep it there.

Marie was not participating in any rehabilitation when she began the home study. This was one of the reasons that we chose her, because we did not want to interfere with the best practices of current therapy approaches and wanted to avoid risking the recovery process of our participant. We first wanted to verify the feasibility of using games with someone without the expectation of motor improvements. Likewise, she stated that she was interested in participating because she believed that it would be fun and challenging. Neither she nor we expected to see motor improvements.

3.2 Game Infrastructure

We developed a game infrastructure by improving the capabilities and usability of the game system described in Alankus et al. [2010a] so that our participant could independently play games at home, and the occupational therapy researcher could manage and monitor the process. We chose games that were appropriate both for therapeutic exercises as well as her taste and provided the necessary hardware that she could set up and use independently at home.

3.2.1 Game Software. Using the information we collected about our participant (biography, likes and dislikes, motion abilities, etc.), we selected and customized three motion-based video games developed for use in stroke rehabilitation [Alankus et al. 2010a]: Helicopter, Pong, and Baseball Catch. In Helicopter, the player controls the elevation of a helicopter that constantly flies forward, while trying to collect fuel cells and avoid buildings (see Figure 1). In Pong, the player controls a vertical paddle and tries to keep a ball from going past it. The computer controls a paddle on the other side of the screen to counter the ball back. In Baseball Catch, the player controls the position of a baseball glove on the screen and tries to catch the baseballs thrown towards the screen by computer controlled characters (see Figure 1). The target location for the catcher's mitt is marked with an "X" on the screen. Occasionally, pitchers throw basketballs that the player needs to avoid.

The primary reason for choosing this set of games was that they were appropriate for the kinds of exercises that our participant needed to perform. The occupational therapy researcher chose a set of exercises based on the needs of our participant identified in the initial interview. Then she chose the games so that they provided physical and motor challenges similar to those she would suggest in standard occupational therapy care following a stroke. The elbow and shoulder exercises required games that could be played with 1D vertical motion. Among such games, we chose Pong because our participant was an avid ping pong player before her stroke. On the other hand, we chose Helicopter primarily because it provided predictable repetitive exercises and because she did not dislike this theme. Similarly, Baseball Catch was the best choice for exercising using reaching motions in 2D. Even though she did not play sports in her youth, we used it because she did not dislike the theme. Initially we were curious about her enjoyment of this game and it later turned out to be her favorite (see Section 6.3.1).

To enable our participant to play each game, the computer science researcher customized them for use with the therapist-chosen exercises. The occupational therapy researcher then adjusted the game settings to customize the difficulty for the participant. For the Helicopter game, the therapist can adjust the game speeds, target spawn rates, and average building heights and widths for Helicopter. For the Baseball game, the therapist can set the type of ball trail, adjust the target locations, and the rates at which basketballs appeared. For the Pong game, the therapist can set the paddle sizes (smaller paddles require additional motion accuracy). After watching the participant play each game, the occupational therapy researcher adjusted these settings so

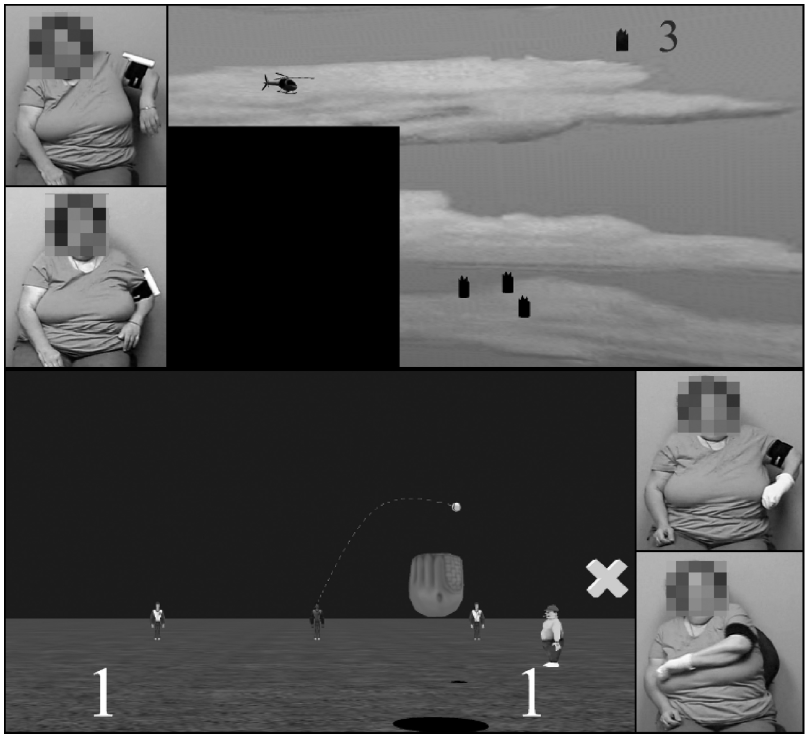

Fig. 1. Marie playing Helicopter by raising and lowering her arm to fly over buildings and collect fuel cells (top) and Baseball Catch by moving her hand in space to catch baseballs and avoid basketballs (bottom).

that the games were appropriately challenging. The concept of appropriate challenge is common to both therapy and game design disciplines. To avoid frustration or boredom, the game must provide enough challenge to the player while still remaining at a level that is achievable. Similarly, in occupational therapy, the clinician must design activities and exercises that are neither too easy nor too hard for the participant, and adjust the parameters at every meeting to address the therapeutic needs of the client. For the games, this was a subjective iterative process in which the occupational therapy researcher judged whether the exercises were frequent enough compared to therapeutic motions she would prescribe otherwise and gauged how difficult the game actions would be for the participant. She also consulted the participant on whether she was comfortable with the current settings.

To enable our participant to play the games, we created a simple game launcher (see Figure 2). The participant interacted with the launcher using a mouse with her right (unaffected) hand. When the mouse hovered over a game, the launcher played a video clip of the game and a video clip demonstrating the prescribed motion that she should perform in order to play that game. We describe the motions that she used to play each game in Section 3.3.2.

3.2.2 Hardware. We provided our participant a laptop computer with the game software preloaded, two Wii remotes, and a Web camera. The Wii remotes measured the tilt angle of her arm, so we also gave her arm straps that she could put on herself. She attached the Wii remotes to the straps to play the Wii-remote-based games (Helicopter

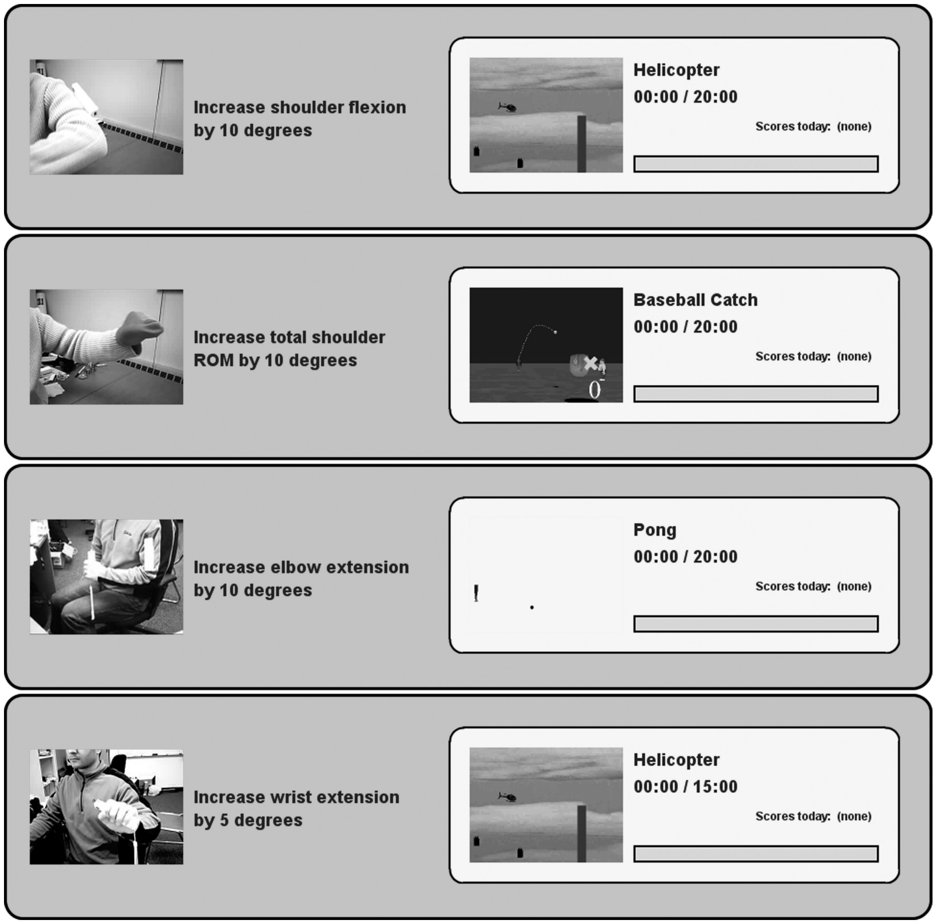

Fig. 2. The game menu in the launcher program used to start and play the games.

and Pong). The Web camera games used a simple color tracker [Alankus et al. 2010a]. She placed a brightly colored sock over her hand while playing Baseball Catch.

3.3 Home Play

Before beginning the home study, we introduced our participant to the process necessary to set up and play the games, and the daily game play program that she was expected to follow. We outline them in the following.

3.3.1 Game Setup. At home, the participant selected the game and exercise from a menu in the game launcher. The launcher then guided her through setting up and calibrating the appropriate motion sensing device using a wizard style interface.

To calibrate her range of motion for each game, the game launcher asked the participant to perform a few example motions as described in Alankus et al. [2010a]. These motions consisted of demonstrating the minimum and maximum points of her motion range. In the next step, the launcher asked her to touch targets representing the extremes of her motion range. This step helps ensure that she does not calibrate with a motion range that she cannot readily achieve and prevents cases in which the game would expect her to move outside of her effective range. This process took approximately one minute for each game.

3.3.2 Games. The participant exercised with the three games described in Section 3.2.1: Helicopter, Pong, and Baseball Catch.

She played Helicopter in two sessions using two different exercises: raising her arm to the side (shoulder abduction/adduction) and bending her wrist up and down (wrist flexion/extension). With the arm raising exercise in Helicopter (shoulder), she attached a Wii remote to her upper arm and controlled the motion of the helicopter by raising and lowering her arm (see Figure 1). The wrist exercise in Helicopter (wrist) required her to hold a Wii remote and bend her wrist up and down.

In Pong, she bent and straightened her elbow (elbow flexion/extension) to control the position of the paddle on the screen. This required her to use two Wii remotes: one strapped to her upper arm and one held in her hand. The use of two Wii remotes enabled us to isolate the motion of her elbow.

She played Baseball Catch by moving her hand in space. She placed the brightly colored sock on her left hand and moved her arm around in all directions (see Figure 1). While the first three games focus on the motions of single muscle groups, Baseball Catch required her to coordinate the behavior of multiple joints.

All games included scores that reflected her success related to game mechanics. While playing the games, she could view her total and target game play durations as well as her score. The system notified her when she completed the assigned time for a particular game and provided her with the option to continue.

3.3.3 Daily Program. The occupational therapy researcher also recommended a daily program of game play. The program initially required her to play each of the three games for twenty minutes a day, five days a week (totaling one hour per day). After the second week of the home study, the occupational therapy researcher added a fourth game (Helicopter using the wrist) and recommended that she play for fifteen minutes daily, increasing the total amount of game-play time to 75 minutes. We told her that she could complete her game play either as a single session or as multiple sessions spread throughout the day.

3.4 Weekly Meetings

In typical outpatient therapy, it is common to have weekly meetings between the client and the therapist in a clinical environment. During these meetings, the therapist and client discuss the client's home activities and exercises during the week. We closely mimicked this practice because we anticipate video games being used in an outpatient context.

Our participant came to the clinic every Friday for a weekly meeting. She brought the laptop with the motion games as well as the peripheral hardware necessary to play the games. During these meetings, we downloaded the game usage data and interviewed her (see Section 4.2). When necessary, we asked her to play the games to better understand her interactions with them. At the conclusion of the meetings, the occupational therapy researcher adjusted the difficulty settings for each game. The computer science researcher identified bug fixes and game or interface changes that could improve her experience. We implemented some changes immediately and others at a subsequent meeting.

3.5 Motion Assessment Sessions

Throughout the study, we conducted three motion assessment sessions to evaluate the participant's motion using standard therapeutic measures. We describe the details of these measures in Section 4.3. These sessions took place before the home study and during the third and sixth weeks of the study in order to evenly sample the total duration.

4. DATA

Throughout the study, we collected several types of qualitative and quantitative data: participant notes, interview data, motion assessment data, and game logs.

4.1 Participant Notes

After playing each game, our participant recorded personal notes that she shared with us during weekly meetings. These notes included her attitudes towards the games, her physical condition after playing, and any technical issues that arose.

4.2 Interview Data

To learn more about our participant's experiences, we conducted semistructured interviews before the home study, weekly over the course of the home study, and after the home study concluded.

At the prestudy interview, we focused on her interests, likes and dislikes, as well as her tentative goals for the six-week intervention. Throughout the study, we conducted semistructured interviews in the weekly meetings in the lab. In these meetings we discussed her experiences playing the games and technical issues that arose. During week three, she started to notice changes in her functional abilities, which we then discussed.

At the completion of the study, we conducted an in-depth interview to better understand our participant's full history with stroke and therapy, her experiences throughout the home study, and her suggestions for improving therapeutic games in the future.

4.3 Motion Assessment Data

To measure changes in the participant's range of functional performance and range of motion in her arm, we used two standard measures in occupational therapy: the Action Research Arm Test (ARAT) and the Reaching Performance Scale (RPS).

The ARAT is a standard test that measures upper extremity function [Yozbatiran et al. 2008]. The test requires the participant to carry out simple tasks including grasping, lifting, and placing standard objects, as well as functional tasks such as pouring water from one glass to another. A therapist scores the ARAT from 0 (paralysis) to 59 (full use) based on task completion and motion naturalness.

Although the ARAT gives a good picture of upper extremity function, it is still a measure based on the rating of an outside observer. To obtain more precise and detailed results, we used a marker-based optical motion capture system for an active range of motion assessment and the RPS [Levin et al. 2004; Shurtleff et al. 2009]. The RPS requires the participant to reach a number of targets. While sitting on a bench, the participant brings each arm directly in front of her to shoulder height or lower. The researcher places a small sphere on a tripod as the target at that height and distance. During the test, the participant reaches forward for the target 3 times. Then the target is moved 15cm forward. The participant reaches forward for the target again. The researcher repeats the test for both arms forward and to the side. Using the recorded motion capture data we can accurately measure joint angles throughout the motion and compare how her motions have changed between two sessions.

4.4 Game Logs

While RPS and ARAT can capture motion characteristics at specific points during the recovery process, they provide little insight into the progression of motor control over time. Rather than limiting motion assessments to data collected during a visit at the clinic, we can use the game system to log the user's motions that were detected by the input devices and used to play the games. Since they are recorded during regular game sessions, using game logs does not require additional work for the therapist or the client. Additionally, the high number of repetitions may make in-game measurements less susceptible to day-to-day variations. Therefore, we explored the use of game logs as a source of supplementary measurement.

The system recorded enough information during game play to fully recreate the game sessions. We logged the game data in two separate forms: game input logs and game event logs. We had to omit a small amount of this data due to technical issues.

4.4.1 Game Input Logs. The input subsystem logged game inputs that contained the stream of data generated by the input devices, independent of the game mechanics. It also contained data about how the input device was calibrated. For Wii remotes, the calibration data included the 3D axis of rotation and minimum and maximum angles. For the Web camera, the calibration data contained the width and height of the image region that was used to play the game.

4.4.2 Game Event Logs. The scene graph subsystem logged game events that contained the stream of 3D positions and orientations of the models in the scene, which represent the full visual state of the game at a given moment in time. In addition, it contained time and durations of game sessions as well as game scores.

We implemented the replay of game events in order to review the game play later. This way we could watch our participant's game sessions in the weekly meetings, monitor her game play, and provide suggestions. In addition, we combined motion data from game inputs and game events to extract high-level quantitative data about her motion during the game sessions.

4.4.3 Omitted Log Data. Due to a software bug, we were not able to collect game event logs for the first week. Additionally, our participant was supposed to catch baseballs and avoid basketballs in the Baseball Catch game. Unfortunately, the game event logs for the second week did not distinguish between them. Consequently, we could not use them in calculations related to target locations. As a result of this data loss, we did not have an accurate history of targets that the participant was attempting to reach in the first week for Helicopter (shoulder) and Pong, and the first two weeks for Baseball Catch. This prevented us from calculating motion precision for the affected weeks. Consequently, the graphs in Figure 5 are missing the first week for Helicopter (shoulder) and Pong, and the first two weeks for Baseball Catch. However, the game input logs were intact for each game, which enabled us to use them for all the weeks of the study (Figure 3 and Figure 7).

In addition, we omitted game sessions that were less than one minute long. Based on our observations, the participant was not engaged in game play during these subminute sessions, possibly due to technical issues. We included all other log data in our analysis.

5. RESULTS

Over the course of six weeks, the participant played the games largely as directed with occasional deviations (see Table I). Note that she started to play Helicopter (wrist) on week 3 (see Section 3.3.3). We assessed our participant's motor abilities using

Table I. Game Play Statistics

	Helicopter Shoulder	**Helicopter Wrist**	**Pong**	**Baseball Catch**
Week	*mins/day req: 20*	*mins/day req: 15*	*mins/day req: 20*	*mins/day req: 20*
1	20:12	–	19:52	15:17
2	22:15	–	20:12	23:02
3	21:08	13:32	20:38	20:10
4	19:31	15:13	20:07	20:33
5	20:15	15:08	20:08	20:14
6	20:11	14:54	21:30	21:05

Table II. Range of Motion Results (in Degrees, * Indicates Significant Difference)

	Baseline Avg (deg) +/- 2 St. Dev.	**3 Weeks** Trials 1, 2, 3 (deg)	**6 Weeks** Trials 1, 2, 3 (deg)
Humerothoracic elevation	27.07 +/- 3.31	33.38* 31.43* 31.85*	24.91 26.37 27.64
Humeral internal/ external rotation	20.43 +/- 1.62	17.95 19.73 19.11	31.68* 32.03* 33.84*

standard therapeutic measures as well as measures derived from our game logs: number of repetitions, range of motion, motion precision, and motion smoothness. In addition, we tracked her progress qualitatively through interviews in the weekly meetings.

While we did not expect our participant to experience functional improvements, over the course of the study she noticed improvements in her ability to use her affected arm in everyday tasks. These qualitative improvements are supported by the quantitative data that we collected. In the following sections, we present the details of these two types of quantitative results, followed by the qualitative results of our study.

5.1 Standard Therapeutic Measures

We used ARAT and RPS (see Section 4.3) for standard measurements of her motion before the first week, after the third week, and after the sixth week of the study. In RPS, using the two standard deviation band test for single subject analysis [Ottenbacher 1986], our participant showed two statistically significant improvements over her baseline performance (see Table II). We measured both changes during the forward extended reach task on the RPS.

(1) Three weeks into the home study, she could raise her shoulder higher to the side (an increased left humerothoracic elevation range). This difference did not persist at six weeks.
(2) At six weeks, she had a larger shoulder rotation range (increased humeral internal/external range).

Additionally, in ARAT, she was able to complete a water pouring task that she could not do before week six. This increased her ARAT score from six (baseline) to eight (six weeks).

Improvements in range of motion and motor control are most common among people who have had a stroke recently (within a year). To see a motor improvement in a participant who is seventeen years post stroke is very rare [Jørgensen et al. 1995].

5.2 Measurements from Game Logs

Through watching the replays of game logs we estimated the number of repetitions that she performed every day. In addition, by analyzing the logs, we explored three different aspects of motor control: range of motion, motion precision, and motion smoothness. Each of these plays a critical role in functional use of the arm.

5.2.1 Number of Repetitions. Research based on human and animal studies suggests a high number of repetitions for therapeutic exercises to have the best impact on stroke survivors' motions. Therefore we counted the number of repetitions that our participant performed daily. We did this by replaying game sessions and counting them visually as the player moves on the screen. Since the games provided nearly the same amount of exercise every day and the exact value of the number of repetitions is not critically important, we counted game sessions from one day and used it as an estimate of the number of repetitions she performed daily. For this we used day 33, which is the last day in which she played each game in single sessions. The repetition counts are 308 for Helicopter (shoulder), 131 for Helicopter (wrist), 222 for Pong and 157 for Baseball Catch. In total, she performed 818 repetitions in one day.

The number of repetitions that our participant performed daily is closer to that of animal studies (in the order of hundreds) [Selzer 2006], rather than studies on humans (in the order of tens) [Lang et al. 2007]. Prior studies of stroke recovery in animal models suggest that hundreds of daily repetitions are required to make progress towards recovery of motion abilities [Selzer 2006]. We believe that the high number of repetitions that our participant performed helped her to experience motion improvements, in a way that is similar to those observed in animal studies.

5.2.2 Range of Motion. Range of motion is a fundamental measurement of motion ability and is reduced as a result of Hemiparesis. This prevents people from carrying out everyday tasks such as reaching for objects in the environment. As people recover from Hemiparesis, their range of motion is expected to increase [Kamper et al. 2002].

We evaluated the changes in range of motion over the course of the study by examining the calibration data for the Wii remotes. Before every game session, the calibration system required the participant to demonstrate the minimum and maximum ends of her range of motion. The games use this range of motion measurement in order to ensure that targets are challenging but achievable. For games with the Wii Remotes, this process also provides direct measurements of range of motion.

We did not use the Web camera calibration data in estimating range of motion. The Web camera calibration data contains a rectangular subarea of the camera's output image representing the places that the participant can reach. However, this value depends on the location of the camera and the way in which it is positioned relative to the participant.

Figure 3 shows graphs of the participant's daily range of motion from the Wii remote data and a least squares fit line for the data. These graphs suggest a gradual increase in her range of motion. Based on the least squares fit, her shoulder range of motion increased from roughly 20 to 35 degrees over the course of the study, while her wrist range of motion increased from roughly 15 to 30 degrees. However, her elbow range of motion remained fairly stable. One potential explanation for the lack of improvement in her elbow range is that Pong, on average, may have required fewer repetitions. Players have to move to return the ball and can rest for a few seconds while the ball crosses the screen and is returned by the computer player.

It is also important to note that there are significant variations in range of motion from day to day. This result is similar to the home-based study with smart glove inputs of Golomb et al. [2010]. These variations are also consistent with our participant's

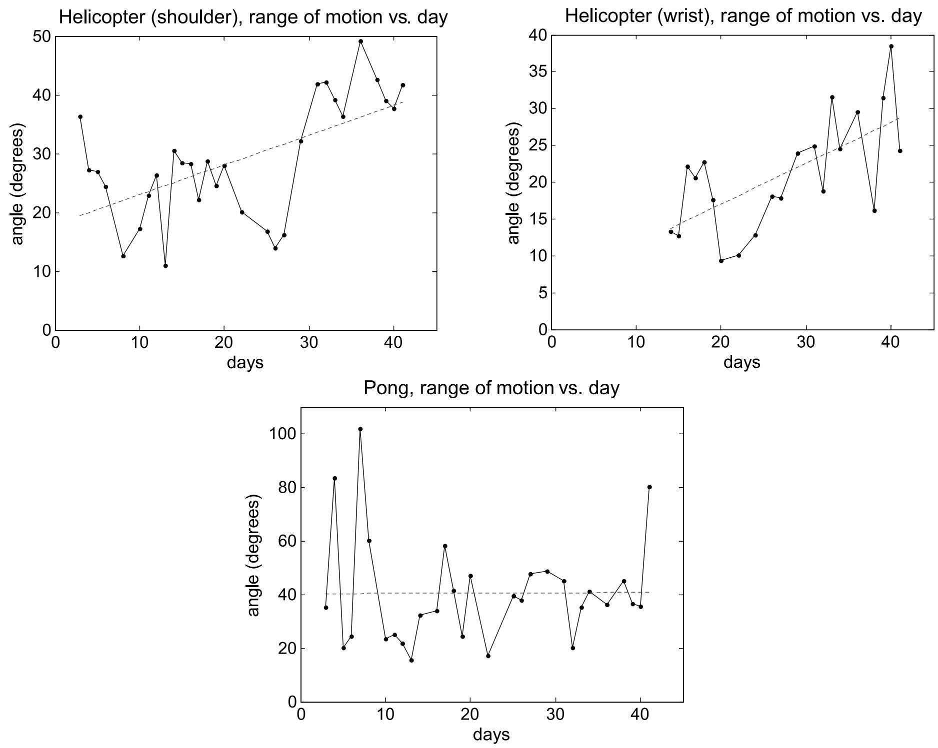

Fig. 3. Range of motion vs. day plots for the games played with the Wii remote. Least squares fit line is represented by the dashed line in the figures. An increase in angle indicates improvement in range of motion.

perception that on some days she found it much easier to move her affected arm than other days.

5.2.3 Motion Precision. To successfully complete functional tasks in daily life, people recovering from stroke need to increase the precision of their motions [Kamper et al. 2002]. An increase in precision helps them prevent unnecessary deviations from their planned trajectories and reach their targets quickly. In addition, it helps them prevent making unnecessary motions when they want to keep their arms fixed at a certain location.

Success in all games required our participant to reach target locations. In Helicopter, she needed to move to the altitude of the next fuel cell in order to collect it. In Baseball Catch, she needed to move to the target location indicated by an "X" in order to catch the baseball. In Pong, she tracked the vertical location of the ball in order to return it to the other side of the screen. With increased precision, we expect a reduction in how much the participant deviates from target locations during game play. We characterize this deviation by examining the cumulative error while moving towards, and anticipating, game targets.

We observed that our participant aimed to reach the anticipated target positions quickly and waited there for the target to arrive, rather than waiting to move until the target got closer. Additionally, in Pong, rather than geometrically estimating where the ball would land, she chose to track the vertical position of the ball with her paddle. We sought to quantify her success in these behaviors as our measurement of motion

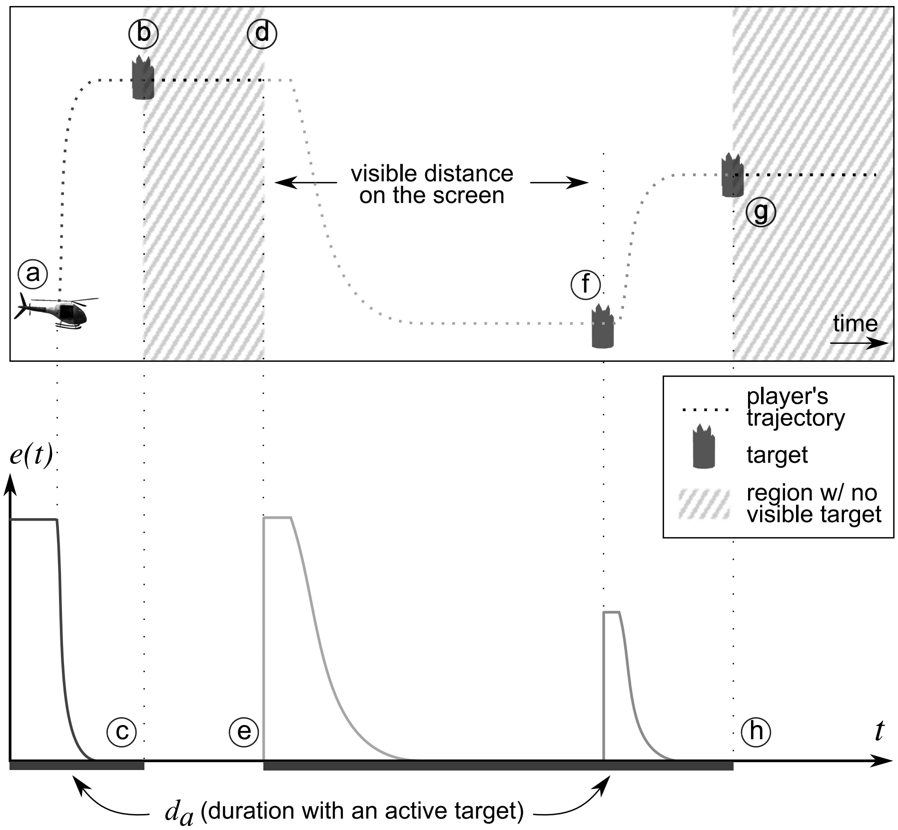

Fig. 4. Calculation of target error. Top: sample game trajectory of the Helicopter game in which the user controls the helicopter's vertical position while the helicopter advances to the right. Bottom: the corresponding target error function $e(t)$, which is the vertical distance between the helicopter and the next target.

precision. Note that this may not generalize to other users with different behaviors. Especially, users with a high degree of motion control may have different strategies (e.g. waiting till the last moment before moving to the target positions or predicting where the ball would land in Pong). For such cases, measurements that are appropriate for observed user behavior should be devised.

We define the cumulative target error as the sum of the player's distance to the anticipated target position over time (see Figure 4). Precise motions tend to minimize this error. We normalize the cumulative error by the total time that the target is available on the screen (d_a) to calculate the average target error. This provides a measure of how quickly and accurately the user reached the targets in the game.

We visualize the calculation of this error in Figure 4 with an example. Player (a) starts moving towards the target (b), which brings the error to zero (c). Since there is no immediate target within the visible distance until (d), the time between (c) and (e) is excluded. When the player arrives at (d), the target at (f) becomes visible on the screen and error becomes nonzero again. After the player collects the target (f), target (g) immediately becomes the next target since it's within the visible distance. Collecting (g) brings the error back to zero (h). We calculate the average target error by integrating the function $e(t)$ and dividing it by d_a.

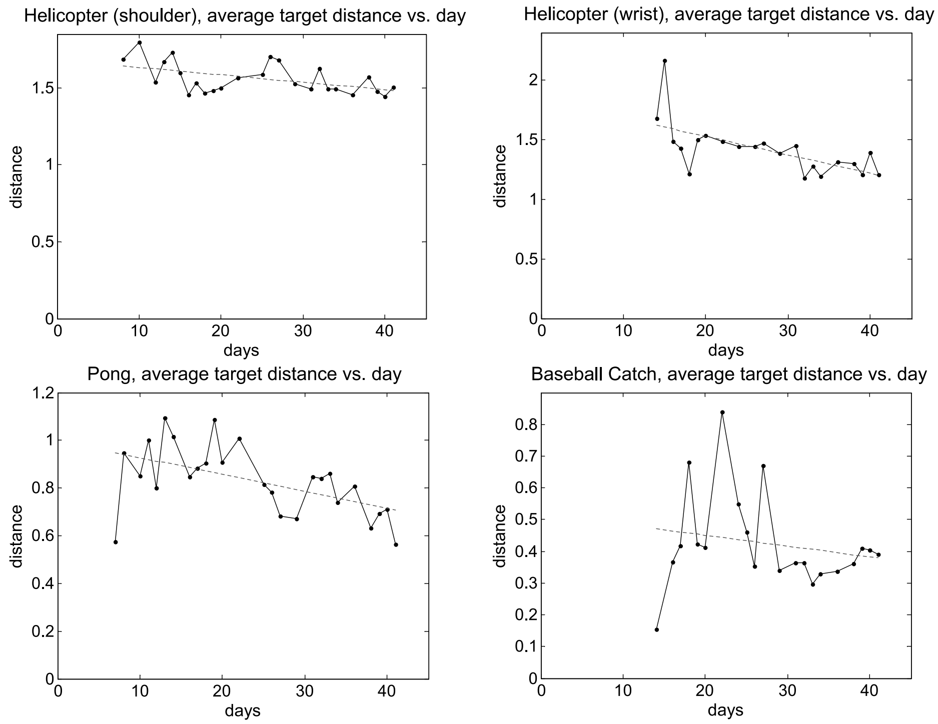

Fig. 5. Average target error vs. day plots for each game. A decrease in distance indicates improvement in motion precision.

Note that this measurement does not take obstacles (buildings) into account. While the tops of the buildings contain targets, after those targets are collected there is a short period of time in which the user cannot move towards the next target because the corner of the building is in the way. While this is a limitation, it does not invalidate the use of this measurement to compare two game sessions because both sessions are affected in a similar fashion.

We present the results of average target error per day in Figure 5. Note that the first week of Helicopter (shoulder) and Pong, as well as the first two weeks of Baseball Catch, are missing because of the software bug explained in Section 4.4. The least squares approximation lines suggest a decreasing trend in the average target distance. This corresponds to an increase in precision at reaching targets over the course of the study.

It is interesting to note that there is more variation in the motion precision data for Baseball Catch and Pong than for the Helicopter game (both shoulder and wrist). One potential explanation for this result is that the average duration that a target appears on screen in Helicopter (shoulder) and Helicopter (wrist) were shorter than that of Pong and Baseball Catch (0.97s and 1.38s vs. 4.15s and 3.54s). Therefore, in Pong and Baseball Catch, there was more time to prepare per target, and it was easier to choose a less efficient motion to reach that target.

5.2.4 Motion Smoothness. Stroke survivors with hemiparesis tend to have less control over their motion. Their motions appear as ataxic, jerky movements, and are expected to become smoother as they improve. The smoothness, or increased control of movement, is an expected outcome of interventions that target motor control abilities

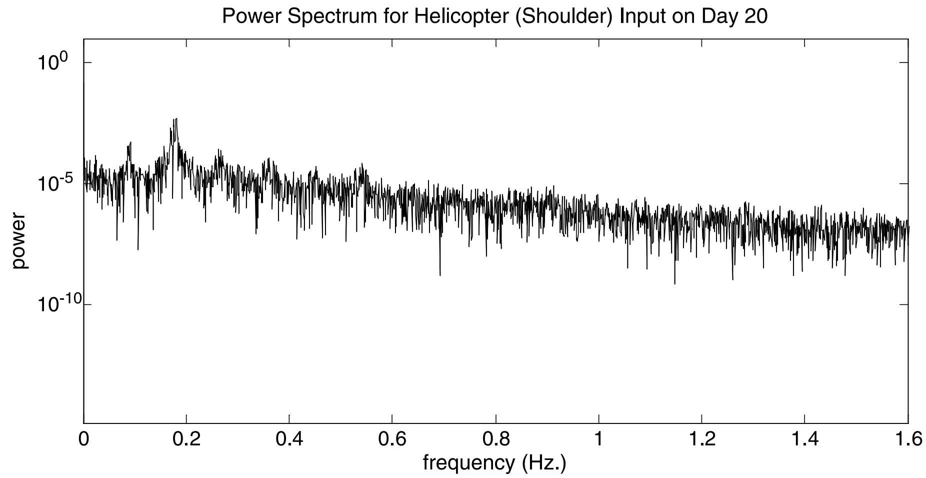

Fig. 6. Power spectrum of sample Helicopter (shoulder) session indicating that the signal is dominated by a motion with a frequency around 0.17 Hz. This corresponds to a movement that repeats every 5.9 seconds (flying over buildings).

[Rohrer et al. 2002]. By having smoother, more controlled movements, stroke survivors are able to interact with their environment in a more efficient and less taxing way.

Note that motion precision and motion smoothness measure different aspects of the level of control people have over their motions. Motion precision measures how successful people are at reaching their target locations, whereas motion smoothness measures the quality of trajectories while performing motions.

To quantify smoothness, we conducted a Fourier analysis on the input signal from the Wii remotes. Fourier analysis enables us to measure the frequencies of the components that make up the signal. Components with lower frequencies correspond to the larger motions necessary to play the game. Components with higher frequencies correspond to faster motions, effectively representing "shakiness" (e.g., tremor) in the input signal. Ideally, motion improvement should be accompanied by a shift from high frequency components towards low frequency components in the power spectrum, which indicates that the motions are becoming smoother.

Figure 6 displays a sample power spectrum of the input to the Helicopter game. The peak around 0.17 Hz corresponds to raising the arm up to fly over the buildings that appear approximately every 5.9 seconds. The shakiness in the input signal manifests itself as higher-frequency components in the power spectrum. To quantify this, we sum the values with frequencies above 1Hz, which correspond to signals with periods less than a second. Such rapid motions are not necessary to succeed in the games and are most likely the result of tremor in the participant's motion. We normalize this value by the duration of the session and the strength of the signal to enable a fair comparison between inputs from game sessions with different characteristics. This value gave us a measure of the occurrence of high frequency components in the signal, providing an estimate of smoothness for each game session. Figure 7 includes the plots of this tremor index for each game.

While tremor plots have a decreasing trend, they include a lot of variation, which warrants further investigation. We observed that the first three high peaks in Pong correlate with shorter game play sessions. This may suggest that the participant struggled to perform the needed motions on those days, and opted to stop early. On the other hand, the peaks in Helicopter (wrist) do not correlate with duration. Of the four,

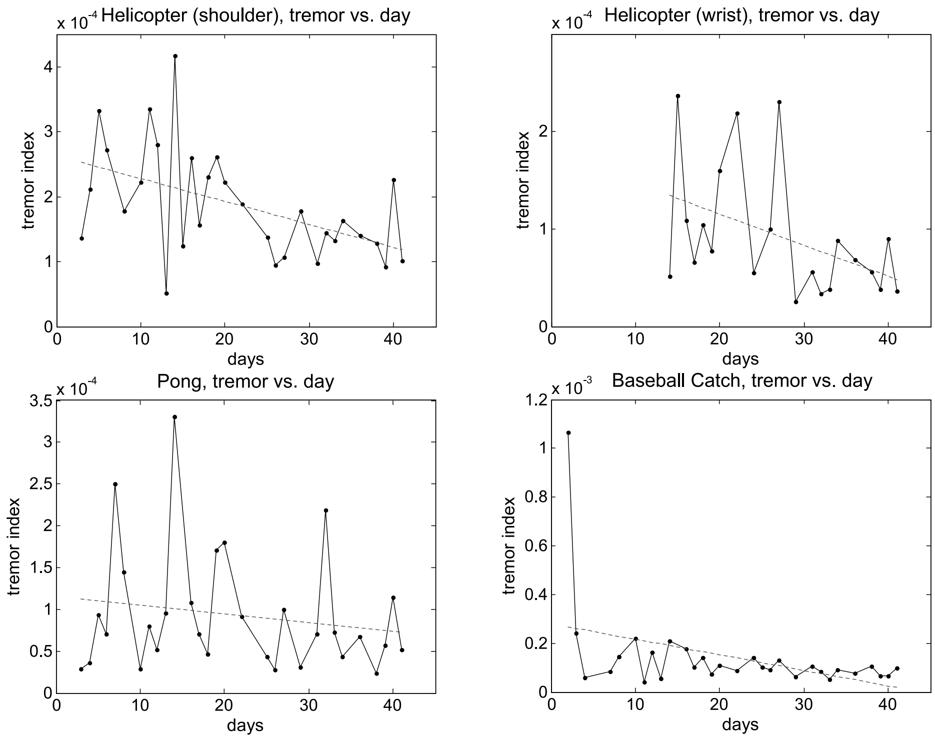

Fig. 7. Tremor vs. day plots for games played with Wii remotes. A decrease in tremor indicates improvement in motion smoothness.

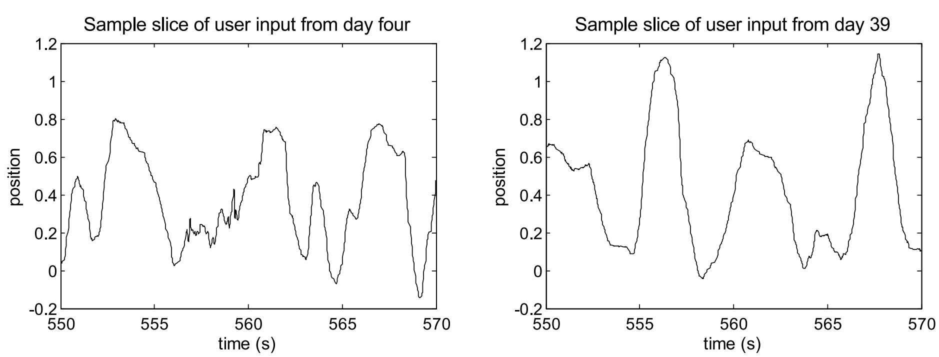

Fig. 8. Sample slices of user input for an early and a later session of Helicopter (shoulder). The session on day 39 has visibly less noise.

Helicopter (shoulder) seems to have the most substantial decrease in the overall tremor. A closer look at sample input trajectories for earlier and later sessions supports this observation with earlier signals having more noise than later sessions (Figure 8). Note that given the day-to-day variations, it would be wrong to draw conclusions solely from looking at slices from two sessions. Nevertheless, we selected two slices of user input that are subjectively representative of our participant's motion early and late in the case study to provide further insight into the changes in smoothness over time.

5.3 Qualitative Results

The quantitative results that we presented suggest that the participant's motor abilities improved over the course of the home study. Perhaps more importantly, she was able to translate these improvements into increased success at motor tasks in her day-to-day life. In addition, she was more active in discovering new abilities towards the end of the study.

5.3.1 Acquired Abilities. During the early weeks of the study, our participant reported that as she played the games, she found it easier to move her affected arm. Gradually, she began to report a larger range of motion and increased feelings of control. Toward the end of the study she enjoyed demonstrating the new ways she was able to move her arm. These increased motor capabilities translated into a number of improvements in her ability to perform daily tasks.

She discovered her first new ability in the kitchen. During the third week of the home study, she was getting out a crockpot from the cupboard using her right arm. She noticed that the power cord was in the way and planned to knock it away using her left arm in a flailing motion. However, when she reached for the cord, she discovered that she was able to grasp the cord with two fingers and she "moved the cord where [she] wanted to." This task, she stated, would have been impossible for her a month earlier.

Since her stroke, Marie has been unable to raise her left arm in order to wash underneath it. For the last seventeen years, she has either propped her arm on a surface or asked her husband to hold it up for her so that she could bathe. During week five, she discovered that she could raise her arm and hold it steady, enabling her to easily wash underneath it.

Over the course of the home study, she reported being able to do the following.

— Move objects around on a counter;
— catch a falling toothbrush;
— catch herself against a wall;
— adjust the bedcovers;
— hold a can opener at an angle for washing;
— hold dishes in place while she washed them;
— grasp a towel and dry her hands;
— unlatch and open doors.

While many of these tasks seem simple, they represent important changes for Marie. "I am so much happier to be able to use a towel like a grown up person instead of wadding it up on the floor [to be able to dry my hands]."

5.3.2 Active Discovery of New Abilities. At first our participant discovered her new abilities serendipitously. Once she recognized changes in motion capabilities, she began to actively look for new tasks she could perform. Since she had lived with hemiparesis for seventeen years, the initial physical improvements were unexpected for her. She realized during week two that there was some change in her motions. However, it took her about a week to find the first practical use for this change. It is important to remember that our participant has had very limited use of her affected arm since her stroke. In seventeen years, she has adapted the ways in which she performs daily tasks to account for her limited motion. She had to go out of her comfort zone every time she used her new motion abilities in everyday tasks. However, once she realized that she was able to carry out daily tasks differently, she started actively searching for new tasks in which she could use her affected arm: "I find more movement on my shoulder, wrist, and fingers. I think I can envision more things to do now." Each discovery of a new task she could perform using her affected arm served to increase her motivation and spurred more experimentation. This created a feedback loop that made her proactive about looking for new motion abilities, even ones she did not expect to find: "I think none of the games made me move my arm sideways but I can sort of do it now." She also looked for possibilities related to everyday tasks: "With all these games, I found that I can move objects around me to places that I want. I couldn't do that before. I find this very satisfying." She attributed these improvements to changes in her brain brought about by games: "I feel as though my brain is processing and relearning certain movements again."

5.4 Source of Improvements

Because the most dramatic improvements came in Marie's daily life, it is natural to question whether these changes are the results of, (1) an increase in motor skills, or (2) an increase in her willingness to attempt to use her affected arm. We believe that the answer is a combination of the two.

The early functional improvements that she noticed were accidental discoveries of improvements in tasks that she was already able to do, but in limited ways. In one, she intended to knock a cord away as she normally would, and instead found that she could now control it. In another, she raised her arm in the shower as she would every time she bathes, and found that she was able to hold it up for the first time in seventeen years. Because she discovered new capabilities in activities that she performs frequently, we believe these capabilities are due to changes in her motor abilities.

However, it is also clear that discovering motor improvements made her more open to attempting to use her affected arm during tasks that arise in her daily life. In many ways this is as much a victory as the motor improvements. To continue to improve, research suggests she needs to practice using her affected arm to complete a variety of tasks. Her openness to trying tasks that she is not sure she can complete provides the kind of context in which she might continue to improve further.

6. LESSONS LEARNED

Over the course of the home study, we identified several potential barriers and opportunities related to therapy game design, infrastructure, player motivation, and emotional opportunities.

6.1 Designing to Maximize the Utility of Game Log Data

Game logs present a rich opportunity to analyze motion characteristics and improvements. In contrast to traditional therapeutic measures such ARAT and RPS, game logs can capture large numbers of repetitions over a long period. Due to the diversity of data collected, the patterns in game logs may be less susceptible to daily variations in motor ability. However, the design of games and calibration systems can influence the quality of the data collected for assessment purposes.

6.1.1 Ensure Players can Identify Poor Calibrations. Noise in motion signals caused by poor color calibration was one of the issues that reduced the utility of Baseball Catch log data. At the beginning of each game play session, the participant completed a calibration process in approximately one minute. The purpose of the calibration process was to ensure an appropriate level of challenge. It required the participant to demonstrate her range of motion and verify that she could in fact reach targets within that range. In addition, the Web camera calibration required her to identify the color that the game should track, typically the color of a sock placed over her hand. She recalibrated if she noticed a problem with the calibration, typically when the range was too easy or too challenging. However, with the Web camera, the color calibration process created the potential for a poor calibration that she sometimes did not recognize. Specifically, poor color calibrations could cause shaking in the algorithm's position estimate from frame to frame. Since she could still readily play the game with a poor calibration, she did not see this as a problem. Unfortunately, while the position shaking did not create game play problems, it did add a significant source of noise to the recorded motion. This made it difficult to extract meaningful information from the motion trajectory.

To enable analysis of motion characteristics from game data, it is important that the calibration process identifies and helps players to minimize all sources of potential noise. Even calibrations that players perceive as acceptable may have noise levels that are high enough to threaten the utility of the recorded data.

6.1.2 Incentivizing Predictable Motions in Games. Another issue that reduced the utility of log data was that at times it was not possible to predict what the participant's intended motions were. When we measured motion precision with average target error (Figure 5), we noticed that Pong and Baseball Catch had significantly more variation than the two Helicopter games. As both Pong and Helicopter were played using Wii remotes, calibration issues do not explain this variation. One potential explanation is that the Helicopter game encouraged the player to move continuously by rarely leaving her without a target to catch or an obstacle to avoid. On average, the player needed to fly over a building every six seconds. In addition, several fuel cells appeared above each building and in the spaces between buildings. Without giving her much opportunity to wander around or rest, the game made her motions predictable. This reduced the uncertainty that would go into calculation of target error and increased the reliability of the motion precision measure. However, in Pong and Baseball Catch, she had time to take a break and rest between targets. More importantly, the following duration in which the target was moving towards the player was longer, which provided an opportunity to extend her break. As a consequence, this reduced the reliability of the motion precision measure by incorrectly increasing the target error.

In order to extract the most accurate information from game logs, it is important to be able to predict the player's goals and the intended motion, so that we can compare it with the actual motion to assess its quality. By extension, when designing games for use either partially or wholly as motion assessments, it is important to ensure that the player always has a predictable goal. Incorporating explicit rest periods may still be of value, but the opportunity for implicit rest periods should be avoided.

6.2 Infrastructure

The infrastructure surrounding therapeutic games plays a critical role in ensuring the accessibility and utility of therapy activity. Our participant encountered infrastructure problems such as the game not detecting that her effective motion range has changed and other technical issues related to the hardware and the software. Such problems might have slowed or halted progress in a less supportive environment.

6.2.1 Continue to Adjust Calibrations Based on Game Play. Motion calibration plays an important role in ensuring that games are therapeutically useful [Alankus et al. 2010a]. Previous research suggests that calibrating through example motions can capture the player's range [Alankus et al. 2010a]. Over the six weeks, we observed two barriers that led the participant to tend towards a narrower range of motion: failure to calibrate correctly and changes in her motion range during the game.

The calibration protocol, as stated earlier, incorporated two basic steps: capture and verification. This process helped the participant to determine if she had set too aggressive a range, but failed to help her understand if she set too conservative a range. Therefore, it was possible for the motion range that she used for calibration to be smaller than her actual motion range. Additionally, when she began her daily game play sessions, she reported that her arm often felt stiff. As she continued to play, the muscles in her arm would loosen, sometimes making a greater range of motion possible. In analyzing the log data, we identified sessions in which she moved beyond her calibrated range, either due to an overly conservative calibration or due to her muscles loosening through game play. It may be necessary to continue to detect and update the calibration over time in order to keep players moving through their full available range of motion.

To address both of these issues, we envision the need for an adaptive calibration mechanism in which the system detects the player's current range of motion from the motion data and adapts to it. However, it needs to be carefully designed to avoid ranges that are too small. For example, the game could include occasional bonus items that are outside of the player's current reaching range to encourage the player to move further.

6.2.2 Provide Environmental Troubleshooting Support. It is natural to expect that troubleshooting tools will need to be present in a home-based therapy system. However, our experience in this study suggests that troubleshooting tools will need to detect and help players address problems that extend beyond the domain of the games themselves.

Our participant had access to much more technical support than one might expect a typical therapeutic game player to have. She is married to an engineer and her adult son is very comfortable with computers. Additionally, we asked about and tried to assist with technical issues during our weekly meetings over the course of the six weeks. Still, she was initially afraid that she would break the game laptop, Web camera, or Wii remotes; an attitude that is likely to be fairly common in our target audience.

Over the course of the study, our participant encountered a range of technical problems including needing additional lighting to aid the Web camera, objects that occluded the Web camera's view of her, a Wii remote running out of batteries, and needing to reboot the laptop after the games repeatedly failed to run. Many of these represent problems with the player's environment more than problems with the software. Through their own technical knowledge and consultation with us during weekly meetings, she and her family were able to address all of the issues that occurred. However, it is unrealistic to expect players to diagnose and fix these problems.

6.3 Motivation

Few people perform therapeutic exercises at home as directed because they find home-based therapy boring [Shaughnessy et al. 2006]. The video game-based approach seeks to increase people's willingness to perform therapeutic exercises at home. Our participant felt that without the game context she would have done fewer exercises. Her experiences over the course of the home study suggest potential techniques to further enhance the motivational power of therapeutic games. These include choosing game themes carefully, providing motivation early, supporting personal goals, and emphasizing success.

6.3.1 Prestroke Activity-Themed Games may Negatively Impact Motivation. Many people with hemiparesis are no longer able to pursue activities that they enjoyed prior to their stroke. In response, researchers have suggested that leveraging enjoyable prestroke activities may provide a motivating context for therapy [Balaam et al. 2010]. However, for our participant, we found that the opposite was true.

She learned to play ping-pong as a child and recalled being a strong player. Despite the obvious relation to an activity that she used to enjoy, Pong was her least favorite game. When we asked for further explanation, she told us that playing Pong was a constant reminder that she can no longer play ping-pong. Rather than providing additional motivation, leveraging an activity that she used to enjoy provided constant discouragement.

In contrast, her favorite game was Baseball Catch. She spoke about how she never played ball games as a child, and catching a ball is an unfamiliar activity to her. As she gained skills in moving her arm to catch the game-world baseballs, she started to imagine being a baseball player. We were surprised when she told us that playing Baseball Catch increased her interest in watching baseball games on television. The simple mechanics of trying to move the glove to catch one baseball after another provided a way for her to connect with the experience of playing baseball.

6.3.2 Early Motivation is Critical. Our participant started playing the stroke therapy games because it was something to do. She had little or no expectation of improvement: “I like to play games, it sounded like fun to do it. I didn’t have anything else I needed to be doing. That’s all I expected. I didn’t expect any improvement.” For the first three weeks, she played primarily for fun.

Around week three, she began to notice functional improvements in her daily life. She stated that she was able to move her affected arm more quickly and accurately, changes that enabled her to use it more regularly. These changes helped her to feel and be more independent, or in her words feel “more like a big girl.” Although the game therapy case study started as something to do, the dynamic changed once she began to see changes in her abilities and she was no longer playing for just fun and challenge. Her motivation level increased dramatically once she realized that she was improving.

The potential for rapid motor improvements creates interesting design challenges that will require significant study. For our participant, the early period required the motivation to come primarily from the games themselves. As she began to see improvements, her motivation shifted: she wanted to improve. She never expected an improvement in the beginning, however others may have a stronger motivation to improve earlier. If such players do not see improvement quickly, that may increase the burden on the therapeutic games to provide motivation for them to keep going.

6.3.3 Support Personal Goals. While our participant noticed functional improvements relatively quickly, she still had a strong desire to set and achieve goals within the games. While playing the Helicopter game, she created challenges for herself. Initially, these included basic attributes like not hitting any buildings or getting all of the special fuel cells towards the top of the screen. She formulated more complex goals later in the study. For example, she noticed that she had difficulty lowering her arm in a quick, controlled way. To address this, she began attempting to collect fuel cells that were close the ground and right next to a building. To get them, she needed to fly over the building and then quickly drop down to the height of the cell.

Supporting players in making and evaluating their success at achieving personal goals may help maintain motivation as well as give players a greater sense of control in the rehabilitation process. Future games could enable players to track their performance on these goals either within the game or using minigames for testing purposes.

6.3.4 Help Players See Successes. Progress in stroke recovery is often hard to perceive. While people with hemiparesis might be gradually increasing their range of motion, they may be unaware of the increased range until they can perform a new task in life. One of the most persistent requests from our participant was for additional feedback from the games. She wanted the games to “make me feel good” by pointing out when she had increased her range of motion or completed a task more quickly. In addition to supporting personal goals, reporting the improvements that we can easily detect may help players tell the difference between slow progress and stagnation.

The participant began to track some of these statistics herself, reporting accomplishments such as playing for extra time of ”never hitting a building” in the Helicopter game at our weekly meetings. Certainly, capturing game statistics like targets captured and obstacles avoided can play this role. However, based on analysis of the game logs, we may be able to help her see fundamental progress earlier. It is interesting to note that before she reported her first improvements at the end of week three, we could detect motor precision improvements using the game logs. After the second week, her average target error for Helicopter (shoulder) was already in a noticeable decreasing trend (see Figure 5). By the end of week three (the first week of Helicopter with her wrist), the target error in Helicopter (wrist) showed a decreasing trend. These types of indicators may provide a valuable source of motivation, particularly in the period before players begin to notice improvements in their daily lives. These indicators can be powerful motivators when coupled with games that were designed for measurement, as described in Section 6.1.

6.4 Addressing Emotional Opportunities

In our conversations with our participant, we noted some deeply felt emotional themes: a desire for independence, gratitude for life, social isolation, and frustration. Building games that address these emotions may provide additional opportunities to enhance motivation.

6.4.1 Independence. Following her stroke, Marie lost a lot of her independence. Although she found ways to adapt some tasks (e.g., chopping vegetables with a “chopper” rather than a knife), she is dependent on others for many of the tasks she encounters. She equates her life following stroke with a return to early childhood. “When I first had my stroke, I felt like a 2 year old. I had to learn things like walking, from scratch. Now [at the end of the home study] I feel like I’m 3 or 4. Now I feel like I’m getting to be a grownup again and it feels good. Now I’m perceiving what’s possible.”

She shared one perceived possibility during our poststudy interview: to use these games to address her own goals. To enable the broadest use of individual games, we have created an underlying framework that affords the opportunity to use a single game with multiple therapeutic motions and custom difficulty settings. Over the course of the home study, we used this framework to make changes appropriate for her. By the end of the home study, she had started to consider using games to achieve her own goals. One such goal was to be able to move her thumb independently, after noticing that she could move it more than before through holding on to the Wii remote while playing. Around the time that she noticed the possibility of using motion improvements in daily tasks (week 3), she mentioned that her reaching motions were not precise enough and that she wanted to improve that. In later weeks she demonstrated to us during our weekly meeting that her precision had improved by moving her hand in space in purposeful motions and reaching objects around her. In the exit interview, she told us that she missed swinging her arms when she walks. She then brainstormed some ways in which she could rehearse arm swinging using games.

Although swinging her arms while walking is a relatively simple desire, one of the underlying themes in our interviews is her desire to feel greater control over her recovery and greater competence in life.

We see two ways to leverage this desire for control.

(1) The games provided starting points for imagination. This was most evident with Baseball Catch, which prompted her to think about what it might be like to be a baseball player. Through imagination, games may provide another way to address independence. She depends on other people in much of her daily life. Games in which she has to help or rescue other characters may provide an emotional break from the state of dependency that she is in.
(2) She wanted to use motion games to accomplish her own goals in terms of the types of motions that she wanted to improve in. While this may not be appropriate for people with significant cognitive losses, the ability to propose new game setups may give people greater feeling of control throughout recovery. Further, since only 30% of people who survive a stroke participate in outpatient therapy, interfaces that enable individuals to independently tailor games may provide opportunities for recovery to those without access to therapy.

The possibility of putting the participant in a position to lead and shape the therapy process can be very empowering. The feelings of responsibility may ignite high levels of engagement on the part of the participants and the choice of exercises may help them reach their goals faster, given that they would make appropriate choices. However, it is far from certain that participants would be successful in leading their own therapy process. The therapists we have spoken with are skeptical of this approach, in part because they believe that participant-driven therapy would be less effective than standard practice. While the appropriate mechanisms for player involvement in therapy design are unclear, we think this is an important space to explore. Even if players ultimately do not directly dictate their therapeutic directions, their ideas about their goals and how to address them in a game context could prove a valuable tool for increasing the communication between therapists and clients and clients' sense of ownership of their own recovery.

6.4.2 Gratitude. Like many people who experienced a stroke, our participant took part in several support groups for the first ten years following her stroke. For her, one of the concrete benefits of participating in these groups was the realization that things could be much worse. "I saw that people were going downhill and losing their jobs, and I thought, God, how lucky am I?" Through observing and interacting with other people who survived a stroke, she reflected on the positive things remaining in her life.

The things that individual people are grateful for are likely to vary widely. However, employing elements within games that serve as reminders of positive aspects of life may be valuable. Marie is particularly grateful for the love and support that she receives from family members. Games might be able to remind her of her connection with her family through simple strategies like including family members as avatars or incorporating game objects that represent positive memories with a family member.

6.4.3 Social Isolation. While Marie and her husband have adapted their own home, physical challenges often prevent her from visiting friends. On one visit to a friend's house, she was unable to reach the bathroom because her friend had put a tarp over the floor to protect it from her dog. Experiences like this one have made her more hesitant to leave her home.

As a result of undesirable experiences outside her home, she spends a lot of time at home, typically by herself. This brings a sense of isolation and a desire to interact more with other people. She especially enjoyed talking to other people with stroke, knowing that she was not the only one going through the problems related to stroke.

When we discussed the possibility of an online game scoreboard in which she can compare her scores to other players with stroke, she liked the idea first. Then, she changed her mind, fearing that she would perform worse than others. Even though she did not like the idea of being compared to other stroke survivors via game scores, she thought she would like it if she knew that other people were also playing the games. We believe that creating an online platform in which people with stroke can socialize and play together can be a great opportunity to motivate people to exercise and feel better. However, special care should be taken so that it does not become discouraging for them. People may start with the expectation that they will perform worse than others, and may quit once they verify this belief. One approach could be to focus on positives rather than negatives, and to promote collaboration rather than competition. Networked games that enable them to collaboratively play a game and interact with each other may help lessen social isolation following a stroke.

6.4.4 Frustration. For our participant, tasks that were simple before her stroke can now represent a significant challenge: "A simple task of chopping an onion is a half an hour project for me." And, when things do not go as planned, she gets frustrated. In some cases, this can lead her to want to "throw the computer out the window."

She found one way to channel some of her frustration through the games. When talking about collecting fuel cells in the helicopter game she told us "I knew that they were supposed to be fuel cells, but I liked to pretend like I was blowing them up." Well designed games may be able to provide a cathartic release for some of the frustration that people with hemiparesis feel.

7. LIMITATIONS AND DISCUSSION

While our study contributes new findings to our knowledge on using games for stroke rehabilitation, it also comes with a number of limitations. We review these limitations in the following and discuss possible ways of addressing them.

7.1 Number of Participants

The primary limitation in our study is the focus on a single participant. Stroke survivors are a very diverse group with different backgrounds and disability levels. In particular, while our participant had significant motion deficits, she does not have significant cognitive, language, memory, or speech disabilities as a result of her stroke. These other kinds of deficits following a stroke are common and may require additional support from the games and game systems. Larger studies that include a variety of demographics and post-stroke disabilities could help to expand the design guidelines for effective stroke games and ensure that we can create therapeutic games that are effective for the diverse audience of people with stroke.

7.2 Target Audience

In this study, we focused on a participant who is already seventeen years post-stroke. The prevailing wisdom in medicine is that most motor recovery happens early, typically within the first year. Any recovery at seventeen years post-stroke is surprising. Because the recovery from stroke has profound impacts on a person's life, we felt that it was important to perform early tests on people no longer participating in stroke rehabilitation to avoid any potentially negative impacts on the current best practices in therapeutic treatments following a stroke. Nonetheless, our findings show promise. We expect that motion-game-based rehabilitation may have the potential for much greater impact for people who have had a recent stroke. However, more research is necessary to strengthen the preliminary data before trying this experimental approach in place of the established therapeutic treatments.

To ensure that game-based therapy can be integrated into clinical practice, we followed a structure similar to clinical therapy, including weekly meetings with a therapist and additional, unsupervised exercise at home. This structure limited our direct observations of the participant's interactions with the game system at home. Although we collected other kinds of data (e.g., journals and interviews), we may have missed important aspects of the participant's experiences at home. Further, while our meeting structures were similar to therapeutic practice, they may not have captured all aspects of therapeutic practice.

7.3 Study Duration

Typically, therapy participants will experience periods of improvement followed by plateaus. At six weeks while playing an hour a day, our participant appeared to still be improving. While the six week period was sufficient to demonstrate the potential for improvement by playing motion-based games at home, more studies will be necessary to determine the appropriate dosing requirements.

Six weeks was an appropriate duration for studying the needs of a participant using a home-based game system for stroke rehabilitation. However, a question that is left unanswered is whether additional sessions would continue to improve functionality. Note that according to current knowledge based on therapy without video games [Jørgensen et al. 1995], the initial expectation in our study was that the participant would not experience any improvement. Our results may mean that this existing knowledge does not necessarily extend to high-repetition therapy with video games. Animal models suggest that through daily exercise with high numbers of repetitions it is possible to get close to normal in time. Perhaps high-repetition exercises with video games should be compared to animal models with a similar number of repetitions, rather than human studies with much fewer repetitions. Our study has shown promise in this regard for one participant. More, and longer-term, tests are necessary in order to find out whether this is the case.

7.4 Stability of Motor Improvements

We observed that improvement in some range of motion measurements did not persist at six weeks. The fact that some apparent improvements did not persist naturally leads to the question of whether or not the other improvements are real improvements. One potential explanation for the apparent loss of improvement at six weeks is the daily variation in motor capabilities. Perhaps more importantly, our participant regained the ability to perform a variety of tasks that occur in her daily life. While measuring range of motion and precision provide a convenient way to quantify progress, the true goal of post-stroke therapy is to help participants regain the ability to use their affected arms in a purposeful way. However, the need to understand and reliably quantify progress remains an important challenge.

8. FUTURE WORK

Our work uncovers a number of directions for future research. In our study it became evident that it may be possible to enable participants to have a more active role in the rehabilitation process. In addition, we observed that there are more opportunities for addressing the personal situations of users than what we envisioned. We outline these directions in the following.

8.1 Empowering Clients in Therapy should be Explored

In our study it was evident that our participant wanted to have a more active role in shaping the rehabilitation process and its content than what was expected of her. We envision two related possibilities: independent therapy with minimal burden on therapists and participatory therapy in which the client takes an active role in shaping the content and process of rehabilitation. We outline these two possibilities in the following.

Most medical insurers limit the amount of therapy a person can receive following a stroke. However, as our research suggests, it is possible for people with stroke to continue to improve, even long after a stroke. A key challenge in the design of systems for independent therapy will be ensuring that users select appropriate therapy goals. Studying the therapist-participant dynamics in outpatient therapy and their interaction with the game system may enable us to create systems that can mimic the role of the therapist after the participant has quit outpatient therapy. We do not expect such systems to outperform therapists—the expertise of therapists as well as the feelings of responsibility that they inspire in participants may be irreplaceable. However, independent therapy systems may offer an opportunity for improvement to people who do not have access to supervised therapy.

In an outpatient therapy context, enabling clients to shape the therapy process may provide a greater sense of empowerment through the process of therapy. While we expect that therapists will ultimately make therapeutic decisions, providing players with a way to capture their goals and ideas about how to implement them may help to facilitate communication between the therapist and client. Future research should explore how to help therapeutic game players capture their ideas for utilizing games to meet their personal goals. Therapists might address these goals during meetings in the clinic. While this kind of communication may not be appropriate for all persons with stroke, even in cases where the client cannot contribute effectively to treatment goals and decisions, clients may feel a greater sense of participation through contributing to the selection and shaping of game content.

8.2 Addressing Personal Situation should be Studied Further

Our efforts at addressing our participant's personal situation focused on shaping the study using the experience and the domain knowledge of the occupational therapy researcher. The kind of exercises chosen, the daily exercise schedule, the game settings that are adjusted weekly and the choice of game themes all aimed to address her personal situation. However, more can be done in this regard.

Through a participatory iterative design process, future game systems should be developed to better address the personal situation of the participant. We envision two ways in which future systems can address this: designing better feedback systems that address and encourage motion improvements and finding ways of integrating games into everyday routines of users.

One of the recurring themes in our study was that our participant wanted more information about how well she was doing. Future systems can address this in more detail by providing elaborate feedback mechanisms that focus on presenting an overall picture of the participant's state in a way that focuses on the positive aspects in order to avoid discouragement. For example, when the system detects that the participant is improving in a certain motion, it can inform and congratulate the user, bring up an interactive assessment screen to verify this detection, and show the user the extent of the improvement compared to previous assessments. Ultimately, the goal of therapy is to improve players' ability to perform tasks in daily life. While our participant actively explored tasks that arose in her daily life to find improvements, other persons with stroke may not be as aggressive in searching for newly accessible tasks. To help players translate improvements in the game context into their daily lives, game systems might also suggest everyday tasks for the user to try, in which the detected motion improvement can make a difference.

Another potential issue is the integration of games in the everyday routines of users. In our study, it was relatively easy for us to incorporate playing games to our participant's everyday routine. She was already a computer user and had a family that could help her to troubleshoot computer problems. If she had not spent time playing the games, she would be using the computer anyway for playing Solitaire, for example. However, integrating games into lives of people who do not regularly use computers or who have difficulty remembering to perform home exercises because of cognitive disabilities can be more challenging. In such cases, the design of the game system setup and troubleshooting support will be particularly important. Additionally, game systems may need to provide support for reminders and short sessions spread throughout the day.

8.3 Designing Motion-Assessing Games

As we and others have noted, the standard motion assessment instruments like the RPS and ARAT tests may not have the fidelity necessary to capture changing motion-performance details. Further, the approach of performing these assessments at specific intervals throughout an intervention is susceptible to the day-to-day variations in motion characteristics. The performance information collected by motion-based games has the potential to track recovery in greater detail and be less susceptible to daily variations. In our case study, we observed the play habits of our participant and used them to develop techniques for extracting her range of motion, precision, and motion smoothness. However, these metrics work in part due to the game designs and in part due to the ways in which our participant played. In addition, future games should make a greater effort to fully separate measurements of motion improvements from other potential factors (e.g., cognitive improvements and increased familiarity with games). Designing games such that they yield reliable motion performance data for all players is an important avenue for future research.

8.4 Relating Game Therapeutic Motions to Traditional Therapeutic Motions

The motions within a therapy game may not be directly comparably to typical motions within a clinical therapy session. In a clinical therapy session, the client typically performs motions that span the full motion range. In contrast, a motion in a game context may sometimes require that a user move through a part of their range. More research is necessary to determine how to reliably compare the amount of therapy delivered through a motion-based game versus a more traditional therapy context.

9. CONCLUSION

Seventeen years after a stroke, it is rare for someone to make significant progress in recovering range of motion and motor control. Nevertheless, through playing motion-based rehabilitation games for approximately an hour a day, the participant improved in both range and quality of motion. Further, she has been able to translate her motion gains into functional improvements that impact her daily life.

Recent research on stroke recovery in animal models suggests that hundreds of daily repetitions are necessary to help the brain recover from a stroke. Our case study demonstrates the viability of using home-based therapeutic video games in a similar way, through enabling approximately 800 daily repetitions. Over the course of the home study, the participant's motor abilities improved, as measured both through standard therapeutic assessments and through the quantitative data collected in our game logs. Those game logs show promise as a source for more detailed motor assessments. We proposed techniques for measuring motion precision, motion smoothness, and range of motion, as well as ways to enhance game designs to improve the data collected for the purpose of analysis. In addition, by focusing on our participant's experiences while playing the games, our case study uncovers potential issues, addresses them, and suggests future approaches for developing therapeutic games that are motivating and that increase the therapeutic value of in-game motions.

While the results of this case study are promising, the study included only a single participant. More research is necessary to reinforce these findings. Additionally, while the hardware necessary to enable home use of therapeutic games is affordable, the cost associated with developing custom games represents a barrier to the widespread use of games in stroke rehabilitation. Authoring environments that support the process of creating and customizing therapeutic games may help to enable more widespread use of games in stroke therapy.

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