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Motion-Based Video Games for Stroke Rehabilitation with Reduced Compensatory Motions

Gazihan Alankus
Washington University in St. Louis

WASHINGTON UNIVERSITY IN ST. LOUIS
School of Engineering and Applied Science
Department of Computer Science and Engineering

Dissertation Examination Committee:
Caitlin Kelleher, Chair
Jack Engsberg
Chris Gill
Cindy Grimm
Robert Pless
Gruia-Catalin Roman

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by

Gazihan Alankus

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ABSTRACT OF THE DISSERTATION

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Stroke is the leading cause of long-term disability among adults in industrialized nations, with 80% of people who survive strokes experiencing motor disabilities. Recovery requires daily exercise with a high number of repetitions, often without therapist supervision. Motion-based video games can help motivate people with stroke to perform the necessary exercises to recover. We explore the design space of video games for stroke rehabilitation using Wii remotes and webcams as input devices, and share the lessons we learned about what makes games therapeutically useful. We demonstrate the feasibility of using games for home-based stroke therapy with a six-week case study. We show that exercise with games can help recovery even 17 years after the stroke, and share the lessons that we learned for game systems to be used at home as a part of outpatient therapy. As a major issue with home-based therapy, we identify that unsupervised exercises lead to compensatory motions that can impede recovery and create new health issues. We reliably detect torso compensation in shoulder exercises using a custom harness, and develop a game that meaningfully uses both exercise and compensation as inputs. We provide in-game feedback that reduces compensation in a number of ways. We evaluate alternative ways for reducing compensation in controlled experiments and show that using techniques from operant conditioning are effective in significantly reducing compensatory behavior compared to existing approaches.

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Chapter 1

Introduction

In the United States, approximately 795,000 people have a stroke every year and there are currently around 7 million people living with stroke [100]. Stroke survivors experience a broad range of problems that can impact their cognitive, visual, and motor systems. 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 [70]. Hemiparesis usually causes chronic disability in the upper extremities (i.e., arms) more than the lower extremities (i.e., 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 such as dressing and bathing [41, 68, 117]. Intense daily therapy with high number of repetitions can help recovery of motor abilities [70], however most stroke survivors do not have access to such therapy and as a result do not recover. One possible solution is to create automated home-based systems that enable daily therapeutic exercises and help stroke survivors achieve the necessary amount of repetitions required for recovery. In this work, we present the studies that we conducted to work towards a home-based video game system for stroke survivors that aims to enable necessary therapeutic exercises.

1.1 Background on Stroke

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

Cognitively, stroke survivors may lose both memory and speech, losses that can substantially affect a stroke survivor's interaction with the world [18]. Some stroke patients experience unilateral neglect in which they no longer perceive one side of their visual field [103]. Motor problems, such as paralysis or weakness on one side of their bodies (hemiparesis) are also common [119]. The loss of control over one leg can make walking difficult or impossible [119]. The inability to use one arm can limit the stroke patients' ability to perform activities of daily living such as bathing, dressing, and feeding themselves [119]. All of these barriers can make it difficult for stroke survivors to live independently or return to the workforce.

1.2 Stroke Therapy

Physical and occupational therapy help reverse disabilities caused by stroke. By encouraging the use of the affected parts of the body through exercise, the patient can slowly relearn the ability to use them again. Recovery occurs through overcoming learned non-use, learning to use existing redundant neural pathways that do not include damaged brain tissue, and the development of new neural pathways through brain plasticity [103]. This is a very demanding process that can require hundreds of repeated motions every day to make progress towards recovery [67]. Therapy with repetitive exercises can provide the brain with sufficient stimuli to remodel itself and provide better motor control [65]. However, research suggests that most stroke survivors do not perform sufficient repetitions to make progress towards recovery and that most stroke survivors need to exercise by themselves at home to achieve enough repetitions [104].

Recovering stroke patients typically participate in some form of therapy program which often consists of the patient performing repeated motions under the supervision of a therapist in a one-on-one session [70]. Exercises include active exercises in which the patient repeats one basic motion many times, and purposeful exercises in which the patient carries out simulations of everyday tasks that require a combination of motions. During the recovery process, newly gained motion abilities are initially hard to control, and require less effort in time. The goal is to get the patients to move their affected limbs as easily as they move their unaffected limbs. In early inpatient stroke therapy, recovering motion in the lower extremity (i.e. legs) is the primary concern in order to enable mobility of the patient. Recovery of the upper extremity (i.e. arms) has a slower progression and is usually gained through outpatient and home therapy after the patient is discharged [71]. Patients with upper extremity paralysis typically regain motion starting from their shoulder. Over time, they may gradually regain motion in the elbow, wrist, and, finally, the hand [103].

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 [103]. Similarly, recent guidelines for treatment of human patients recommend high-intensity, repetitive motions while keeping patients informed about their progress [70]. A survey reveals that only 30.7% of stroke survivors participate in outpatient therapy [124]. Those that participate in outpatient therapy typically have therapy sessions only once a week and the number of exercises in a typical therapy session is far fewer than what research suggests (i.e., tens instead of hundreds) [69]. Therefore, most stroke survivors perform very little or no therapeutic exercises, compared to the required hundreds of daily repetitions needed to progress towards recovery.

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 [104] which can lead to an incomplete recovery [76]. People who do not complete home exercises as recommended often cite slow progress and lack of motivation as impediments [124].

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.

1.3 Video Games for Stroke Rehabilitation

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 for completing prescribed home exercises and help to increase the likelihood that the client will perform therapeutic exercises at home as required. By decreasing the monotony of hundreds of repeated motions and providing performance feedback, games may increase both the quality and quantity of patients' home therapy. Some research has demonstrated a potential for game-based therapy to help people with hemiparesis regain lost motor control [7, 33]. 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 developing games for stroke to be used at home. These challenges are related to the unusual nature of the target audience and the context that games will be used. The target user population is unusual compared to regular computer and computer games users. Although stroke survivors are a diverse population, most have a combination of motor, cognitive and visual deficits that make it difficult to interact with computers. Stroke survivors are also likely to be elderly and not comfortable with computers. The second major challenge is related to the context that a game system would be used. Games need to be used at home by stroke survivors without supervision. This introduces extra challenges in the design of the software. The software needs to be easy to use and should actively troubleshoot things that may go wrong. In addition, it should lead and motivate the user to participate in exercise and should not assume that the user is always motivated to play. The unusual and diverse nature of the user base may require these systems to be designed in similarly unusual ways.

To identify potential issues and start addressing them, it is necessary to observe the use of games and game systems in the context that they would be used in real life: by therapists and clients at the clinic, and by clients at home. In our work, we mainly focus on stroke survivors as our main target audience and also include therapists for completeness. Currently, very few researchers have considered developing games that address the unique needs of stroke survivors and making them suitable for stroke survivors with different situations. 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.

1.4 Approach

Our main goal in this work is to improve the current knowledge required for a successful home-based rehabilitation system. We did this by working towards verifying the hypothesis that people recovering from stroke can and will perform therapeutically effective exercises with motion-based video games, at home and daily. We approached this by first demonstrating that games and affordable game systems can be designed for effective stroke rehabilitation. Then, we demonstrated that stroke survivors would play therapeutic games at home, daily and benefit from them. Finally, we showed that games can be designed for therapeutically correct exercise by reducing compensatory motions.

1.5 Contributions

In this work we extend the current knowledge about using games for home-based stroke rehabilitation that targets the upper extremities. We worked with occupational therapists and stroke survivors and conducted a number of formative studies, followed by a summative study. Specifically, our contributions are:

- Finding ways of using affordable end-user devices for sensing therapeutic exercises and using them as game inputs
- Exploring a portion of the design space of games for stroke rehabilitation
- Developing a video game system and conducting a home-based case study to test the feasibility of including games in current outpatient therapy practice
- Exploring ways of using video games as tools for assessing motion ability levels
- Identifying compensatory motions as one of the major issues that reduce the quality of exercise performed using game-based stroke rehabilitation
- Finding ways of detecting torso motions during shoulder exercises using affordable end-user devices
- Developing a game that can detect and apply corrections for compensatory motions
- Comparing different approaches to reduce compensation in controlled experiments as a summative study

We believe that our contributions advance the current knowledge on games for therapy and provide valuable lessons for future developers of therapeutic games.

1.6 Executive Summary

Developing games for rehabilitation can be a novel challenge for most game developers. In our studies we developed and used games for motor rehabilitation of stroke survivors and learned lessons that may help other developers and researchers. In the next section, we present the guidelines that we identified on how to develop therapeutic games. We follow this with strategies for making games more effective therapeutically.

1.6.1 Developing Therapeutic Games

Developing games for stroke rehabilitation can be different than developing games for other purposes in a number of ways. In the following sections we list some of the requirements that we identified in our studies. First, it is necessary to enable the use of therapeutic exercise motions for intuitive interactions with the computer. In addition, it is necessary to design games to be appropriate for the diverse nature (disability levels, personal situations, tastes, etc.) of the stroke survivor audience. To better address their unique situations, it is also necessary to customize games for each user. By addressing these requirements, we may develop games that stroke survivors will enjoy while performing therapeutic exercises.

1.6.1.1 Enabling Interactions with Therapeutic Exercises

Before starting to develop a game, we need to ensure that we can detect therapeutic exercises and reflect them on the screen in an intuitive way. We first need to choose and adapt input devices that are suitable for home use and can be used to detect therapeutic exercises. We then need to use them to create on-screen interactions with the therapeutic exercises. These interactions can later be used as starting points for games.

Enabling therapeutic exercises is the main goal of games for stroke therapy. Therefore, we need to enable the use of therapeutic motions as inputs to the computer. This requires finding motion-based input devices that are appropriate for the context and the target audience. In our studies we targeted wide-spread home use, therefore we chose affordable input devices. To enable stroke survivors to use the devices during therapeutic exercise, we did not assume that they can hold the devices in their affected hands and identified practical ways of attaching the devices on their arms. We used easy-to-attach straps to ensure that they can set up the system at home by themselves.

Current technologies for motion sensing all have limitations in their sensing abilities. It is important to ensure that these limitations do not interfere with the accurate detection of therapeutic motions. For example, accelerometers alone cannot detect rotational motions around the vertical axis and vision-based systems have limitations in detecting precise motions, especially motions of a single joint. To cover therapeutic exercises used for stroke, we should ensure that we can detect both simple muscle motions and coordinated motions involving multiple muscles. It is necessary to identify input devices that are the most suitable for each type of therapeutic exercise, using multiple kinds of devices if necessary.

While a few of the stroke survivors had experiences with computer games, most did not. As a first step for creating games using the detected motions, we mapped users' motions to the motions of on-screen avatars. We observed that many had difficulty in understanding non-direct mappings. For example, users found it confusing when the avatar moved horizontally in response to their vertical exercise motions. We created simple on-screen interactions with direct and natural motion mappings and used them as starting points for games.

1.6.1.2 Designing Games for Stroke Survivors

While simple visual interactions enable exercising with a computer, games can provide purpose and motivation that they may lack. We can start with such visual interactions and use principles from game design to create games (e.g., Pong game using a vertical motion mapping). However, there are things that we may need to do differently to address the stroke survivor audience. Stroke survivors have unique combinations of disabilities depending on the parts of the brain that are affected. Together with differences in personal situations and tastes, this makes stroke survivors a diverse audience. Therefore, we need to design a variety of games that can address this diversity. Here we share our observations on how to design games with respect to (1) users' social situations and (2) users' levels of motion ability.

An important factor in stroke survivors' lives is their social situations. Some users live by themselves while others live with their families and caregivers. Regardless of their social situations, most users can make use of single-player games. If the user has friends and family members that would be interested in playing games with them, including them with multiplayer games that they can play together would be very useful. We observed that having stroke survivors play with healthy people creates an unbalanced situation and requires multiplayer games to be collaborative rather than competitive.

The level of motion ability is another source of diversity among stroke survivors. Some users have severe motor disabilities and can only perform very simple motions, while others have better motion abilities but lack precision. Motion abilities also improve over the course of recovery. Early on, users may only need to practice simple motions, and it is important to help them redevelop their range and precision as they recover their motions further. Games should be designed to address different levels of motion ability and users should be provided with a suite of games that target the motion skills that are appropriate for their current recovery level.

1.6.1.3 Customizing Games for Stroke Survivors

Creating a suite of games may help address different stroke survivors. However, each stroke survivor has a unique condition and using games that are not specifically designed for them leaves room for improvement. Therefore, to maximize the effectiveness of games, we need to customize them for each user. In our studies we achieved customization by having a therapist and a programmer work together to reprogram games for users. Here we present our main approaches for customizing games: further adjusting along the design dimensions, customizing for users' tastes and avoiding themes about pre-stroke activities.

The unique conditions of stroke survivors make it likely that a game chosen from a suite of games will not be perfectly appropriate for a user. To customize games for stroke survivors, one of the strategies that we used was to adjust games further on the main design dimensions (e.g., increase the expected motion precision, create multiplayer version, simplify cognitive expectations, etc.). In an iterative fashion, the therapist identified the need for such customizations and the programmer implemented them. With a small amount of effort, these adjustments made games more appropriate for users.

Another potential problem is that games may not cater to the tastes of users. Therefore, we customized games' themes and visuals according to users' likes and dislikes. For example, we replaced cats in one of the games with dogs, and observed that this resulted in a much more positive attitude towards the game for a user who disliked cats. We observed that such customizations according to users' choices caused them to feel a personal connection with games.

We also observed that taste may not always be the dominant factor for a user to enjoy playing a game. Conversely, themes that users like may not be good candidates for games if they are related to users' pre-stroke activities. Using themes related to activities that users used to take part in before their stroke was demotivating because it reminded them that they cannot participate in these abilities anymore. Rather, we observed that using themes that are new to them was motivating.

1.6.2 Making Games Effective Therapeutically

We observed that therapeutic effectiveness is another important requirement for stroke games that may not be fully realized without extra effort. We identified guidelines for modifying existing games to increase their therapeutic effectiveness. In addition, we found that games can be designed specifically to fulfill important therapeutic concerns, such as exercises with reduced compensatory motions.

1.6.2.1 Increasing Therapeutic Effectiveness

Having a therapist be the judge and improving games using her suggestions resulted in games that are more effective therapeutically. During this process we learned that (1) games should be appropriately challenging, (2) users should use their whole motion range while playing the games, and (3) games should encourage users to perform exercise motions correctly to be more beneficial therapeutically.

We observed that games should challenge users appropriately not only to provide enjoyment but also to be useful therapeutically. Therefore, we customized games to provide appropriate challenge by adjusting various parameters about games that determine challenge (e.g., sizes of objects, speeds, etc.). We observed that in time users' abilities in games improved because of learning and motor improvements, and it was necessary to readjust challenge often. Rather than having the programmer change them every time, we provided the therapist with an interface to easily modify the related game options. Furthermore, we noticed that warm-up and fatigue required these parameters to change during game sessions and developed automatic in-game difficulty adjustments that adjust parameters depending on measured skill. This helped ensure games to continuously provide appropriate challenge.

We learned that for increased therapeutic effectiveness, users should exercise repetitively using their whole motion ranges for therapeutic exercises. As a first step, we ensured that we map the user's whole motion range to the on-screen range. We achieved this using a pre-game calibration session that collects the user's motion range. However, we observed that users' motion ranges may change during the game, and adjusted the expected range automatically by targeting fixed success ratios at the edge of the motion range. While this provided the game with the ability to use the whole motion range, it was not sufficient unless the game mechanics required the use of the whole range. We enabled this by modifying games to expect repetitive motions in which the user traverses the whole range.

Another factor that reduces the therapeutic effectiveness of exercises is performing the exercises incorrectly. To counter this, we modified games so that success in games depends on correct exercises. For example, an issue that we observed was that users tended to "throw" their arms to easily reach heights that are otherwise difficult for them. We prevented this in games by expecting users to stay at a difficult pose for a duration that requires the use of controlled motions.

1.6.2.2 Creating Games That Reduce Compensatory Motions

We observed that users tended to move other muscles and joints to compensate for their lack of motion in some exercises without being aware of it. This is a major problem in unsupervised therapy and currently the only feasible solution is to have therapists supervise the exercises. Although games can be modified to increase their therapeutic effectiveness, addressing the issue of compensatory motions required games to be designed specifically for this purpose. We designed a game that can detect, use and reduce compensatory motions of the torso during shoulder exercises.

To use compensatory motions, first we had to detect them. We used another input device to detect the torso orientation. Using two devices, we calculated exercise and compensation signals to be used in games. We calculated the compensation signal by calculating the user's pose relative to a default pose. Changes to the way the user is seated resulted in changes to this default pose, to which our input algorithm had to adapt. Another issue was that in response to efforts to reduce compensation, users tended to change compensatory behavior in ways that were not detected. For example, when a user realized that she was not supposed to compensate by leaning backwards, she started to lean to the side. Therefore, the input algorithm should be able to detect multiple types of compensation.

Another challenge was designing a game that uses both exercise and compensation signals. We found that simply ignoring the compensation signal and ensuring that compensation does not help users in the game was not sufficient to change users' compensatory behavior. Therefore, we had the game react to compensation in an intuitive way. We mapped the vertical exercise motion to the vertical location of a flying avatar, and mapped the compensatory motion to its orientation. As a result, the avatar moved vertically with exercise motions and tilted with compensatory motions. We observed that since users performed exercise and compensation at the same time, they may confuse the effects of the two in the game. We resolved such issues with tutorials and extra informative feedback.

Providing intuitive feedback for exercise and compensation did not cause a significant reduction in compensatory motions. Therefore, we enhanced our game using principles from operant conditioning. To reduce users' compensatory motions, we created incentives for low compensation and disincentives for high compensation. We created pleasant feedback for incentives (i.e., smiley face, green color, shooting stars and happy sounds) and unpleasant feedback for disincentives (i.e., sad face, red color and unhappy sounds). We found that this strategy based on operant conditioning significantly reduced compensatory motions.

We highlighted some of our research findings that may help other researchers and developers create therapeutic games. While our findings were in the context of stroke rehabilitation, we believe that a number of our findings can be useful for games for other types of rehabilitation, or games for purposes other than rehabilitation. We hope that researchers and developers can make use of our findings to create successful home-based game rehabilitation systems in the future.

The rest of this document is organized as follows. Chapter 2 presents how we use affordable input devices to detect therapeutic exercises. Chapter 3 introduces our summative study in which we explored the design space of video games to be used for stroke rehabilitation. In Chapter 4 we present the home-based case study using our video-game system, with our findings and improvements. In Chapter 5 we identify compensatory motions as one of the major weaknesses of game-based stroke rehabilitation and in Chapter 6 we design and verify a harness that we developed for detecting compensatory motions of the torso. Chapter 7 includes the design of a video game that includes compensatory motions as one of its core elements. In Chapter 8 we modify this game so that it changes users' behaviors to reduce the amount of compensation that they perform. We create different versions of the game based on what we learned and compare them in a summative study in Chapter 9. We conclude our work in Chapter 10 with a discussion related to our findings and possible future directions of research that our work uncovers.

Chapter 2

Detecting Therapeutic Exercises

To enable people with stroke to play video games using therapeutic exercises, we first need a way to detect the exercise motions. We need to detect them continuously and at interactive rates so that the user can immediately observe the results of his or her motions and use them to interact with a game. We strove to choose devices inexpensive enough to make home use feasible, but technologically advanced enough to detect motions typically prescribed by therapists. Another concern was ease of use by patients. To facilitate these goals, we chose two inexpensive, commercially available devices: the Nintendo Wii remote and the webcam.

The upper body exercises used in occupational therapy practice are either simple motions of isolated joints, or more complicated task-based motions that require the coordinated motions of multiple joints. Simple motions of joints are preferred when motion abilities are very low in early stages of recovery. Task-based motions that require coordination of multiple joints are more useful in the later stages of recovery in which the person with stroke works to regain premorbid motion abilities [119]. We target both simple and complex exercises using the upper body for a good coverage over possible therapeutic exercises.

The question that we answer in this chapter is how to utilize Wii remotes and webcams to detect therapeutic exercises used in stroke rehabilitation. To answer this, we conducted a formative study in which we developed methods for detecting therapeutic exercises with Wii remotes and webcams. We found ways for detecting nine main types of therapeutic exercises, and improved our methods through calibrating using example motions.

2.1 Related Work

Here, we review the existing literature of computer-aided stroke rehabilitation systems with respect to the input devices they use for detecting therapeutic exercise. The input device is the most important hardware part of a motor rehabilitation system because such a system is required to detect the physical exercises necessary for therapy, and sometimes actively help the user performing these exercises. Usually it is the most customized hardware part of the system, and sometimes specifically built for this purpose. In this regard, the kind of input device used is a major factor that may determine whether a computer-aided stroke rehabilitation system can go beyond a prototype, can be used in clinical settings, or can be used by patients at home.

We categorize the input devices previously used for stroke rehabilitation into robotic devices, haptic devices and passive input devices.

2.1.1 Robotic Devices

Since motor rehabilitation is inherently a physical activity, robot-based active systems consisting of physical sensors and actuators can be suitable for use. Robotic systems have the potential to accurately sense the patient's motion and effectively constrain it into certain trajectories. They can also mimic the role of the therapist by physically helping the patient with the exercises and even performing the entire exercise motion for the purpose of passive exercises and stretching.

Robotic systems have been considered for use in exercises for motor rehabilitation of stroke survivors since early 90's [116]. Various robotic systems have been developed and tested for this purpose. Among these are MIT-MANUS [66], MIME [78], ARM Guide [95], Gentle/S [77], T-WREX [102] and other simpler robots [23]. These systems have been tested with stroke survivors for their therapeutic use. Most of them were used in ongoing rehabilitation sessions with a number of people with stroke in a clinical setting and were shown to be effective. In some studies they were even shown to outperform regular therapy practices [78].

Although robotic systems have a strong potential to be used in motor rehabilitation, there are a number of obstacles that prevent robots from being widely used at patients' homes. Most robotic systems are usually custom-built and their cost may make it difficult to adopt for most stroke survivors. Also, robots are usually bulky and using them often requires technical assistance. Such issues may make them poor candidates for widespread home use. Another concern is that in case of software or hardware failures, the robot may move the patient's limbs with excessive speed or distance, which may be dangerous for the user. This can be a major issue especially when the patient is exercising without supervision. One noteworthy effort is the use of passive brake-actuated manipulators that are "inherently safe" [30]. However, the design of such manipulators is difficult, and the passivity constraints prevent them from being controlled to follow arbitrary trajectories. An attempt to avert this is using visual distortion to trick the patient to cooperate [29]. However, building robotic rehabilitation systems that do not have the risk of hurting users is still an open area of research.

2.1.2 Haptic Devices

Haptic devices are active physical input devices similar to robots, whereas their main purpose is to provide accurate force feedback in user interaction to "feel" virtual objects or forces. They typically can exert a small amount of force (1-2 lbs) [87, 92], which is enough for providing feedback, but usually insufficient for moving limbs for passive exercises. The way they are used in rehabilitation is to precisely sense patient exercises and provide force feedback to help patients build strength and develop their senses of touch and kinesthesia [108].

In the literature, haptic devices vary from sophisticated 3D haptic input devices to devices that simply vibrate. The high-fidelity devices contain a moving piece that can be held by the user to freely interact with a 3D virtual world with high degrees of freedom. Simpler devices with force feedback, such as joysticks and steering wheels, provide a more basic form of interaction. Physical feedback in terms of simple vibration has also been classified as haptic cues, which can be useful in rehabilitation [74].

A number of existing general-purpose haptic devices have been used for stroke rehabilitation. High-fidelity 3D haptic devices such as PHANTOM [92] and Novint Falcon [87] were used for arm exercises and the Stewart platform [33] was used for leg exercises. In general, such studies report positive patient experience and recovery of motions [12]. Simpler devices such as force-feedback joysticks [96, 108, 125] and steering wheels [58] have also been shown to be useful. One downside of these devices is that they usually come with motion restrictions that the subject has to conform to. Another is that subjects need to be able to grasp haptic devices with their hands. Not all stroke survivors have this ability, which limits the target audience.

Among other haptic devices are force-feedback gloves that can provide haptic interaction at every finger. Studies have used Rutgers Master II-ND [81], CyberGrasp [126] and CyberGlove [1], and demonstrated that force feedback provided by these gloves were very useful in hand motion recovery [56].

2.1.3 Passive Input Devices

Unlike active devices such as robotic and haptic devices, there are many motion-based input devices that do not provide force feedback and simply sense the motion of the user. The therapy that patients receive with such devices is similar to regular unassisted exercises that they would perform. For unassisted therapy to be effective, the patient needs to be able to complete at least a portion of the exercise motions [78]. Together with a display device, passive input devices can be used to interact with virtual scenes that provide motivation and structure for exercise.

Passive input devices that have been used for stroke rehabilitation range from precise motion capture equipment to simple switches. Chen et al. [16] used a state-of-the-art motion capture setup for detecting arm motions. While such equipment provides precise sensing, they are usually too expensive. Miaw et al. [82] developed a custom motion capture device for the same purpose as a cheaper solution that has not yet been used for stroke rehabilitation. Murgia et al. [84] and Attygalle et al. [5] used the IR cameras of multiple Nintendo Wii Remotes for an affordable motion capture setup; however, the low field-of-view of these cameras restricts the kind of exercises that can be done.

Motion-detecting sensors such as accelerometers [32, 34, 42, 120], magnetic sensors [53, 60, 93, 115] and "inertial sensors" that contain accelerometers and gyroscopes [85, 99, 129, 131] have been used as passive input devices to track the state of the patients' limbs. Such devices provide effective ways of tracking the user's motions and provide the user with the necessary freedom to exercise. However, they are usually part of custom devices that may not be affordable for wide spread home use. Wii remotes, however, are end-user devices that are affordable and contain accelerometers for simple motion sensing. They have been used with existing commercial games [32, 34] and very simple custom games [42] with the goal of stroke rehabilitation. However, their full potential with games specifically developed for stroke rehabilitation is yet to be achieved. Recently, we have used the accelerometers of Nintendo Wii remotes by attaching them to users' arms [3] and demonstrated that they are useful for detecting many of the fundamental motions used in stroke therapy sessions.

Vision-based systems with cameras have also been used as input devices for stroke rehabilitation. A notable example is the IREX system [127], which merges the subject's video image inside a virtual world on screen in which the subject can interact with the environment while watching him or herself. However, this requires a green screen setup, which is not convenient for home use. A simpler alternative is the use of Sony Playstation II EyeToy [39, 94], which can be used in a home setting, but is less accurate and bound to the commercial games that are developed for it. PC webcams are an alternative and have been used by Burke et al. [15] via color detection. Recently, we also used webcams in a similar fashion as alternative input devices for the games that we have developed [3]. The difference between our work and that of Burke et al. is that in their games they superimpose the simple game graphics on the webcam image and use fixed target positions. This requires the camera angle and the subject position to be very precise. Therefore, if the camera is not positioned properly, it can be too easy or too hard—even sometimes impossible—to reach to the targets. This is likely to happen when used in a home setting, and in such cases the therapeutic value of the exercises would be less than ideal. In contrast, our games are independent of the webcam video. We provide range calibration that enables mapping of the available motion range from the webcam image to the full motion range of the game.

Another end-user passive motion-sensing device that holds great potential for use in detecting therapeutic exercises is the Kinect [64], which can be used for tracking users' skeletal postures and using them in games. Since it is a fairly new device, its potential in rehabilitation is yet to be verified. The official software for Kinect is designed to detect motions while standing up; sitting poses and unusual poses that stroke survivors can exercise in may require custom software to be developed. Another question to be answered about the use of Kinect is accuracy. One study that evaluated Kinect for rehabilitation reports that Kinect may provide "irregular performance on non-structured environments" [90] and combines it with the use of inertial sensors similar to Wii motion plus for increased tracking accuracy. Studies that quantify the accuracy of Kinect with various therapeutic exercises in a home context may identify its possible shortcomings. Should the accuracy be insufficient, further studies may find ways of increasing it and fulfilling the potential of Kinect for therapeutic exercises.

In addition to the devices we listed, sensing gloves [55, 83] have been used for rehabilitation and have been shown to improve patient motor abilities. Other devices include pressure sensors [9], pen devices [26], Nintendo Wii balance board [34, 109], sliding mechanical devices [7] and tangible interfaces in which patients do daily tasks with real objects and the switches that they are connected to provide input to the computer [52].

2.2 Affordable Motion-Sensing Devices

Our goal is to create a system that can be used at home by most of the people with hemiparesis caused by stroke. The goal of wide-spread home use creates additional requirements beyond a system that satisfies the therapeutic requirements. One such requirement is related to the cost of the system. Most people who survive a stroke may not be able to afford expensive treatments because of job loss and limitations in insurance plans [119]. Therefore, a system that targets wide-spread home use needs to be affordable. One way of satisfying this requirement is to use inexpensive end-user hardware. Even though past research has reported success with more expensive and special-purpose devices, we strove to use devices that most people with stroke are more likely to afford. We chose two such devices that are affordable and readily available in stores: Wii remotes and webcams.

Wii remotes are the motion-sensing controllers of the Nintendo Wii console [121]. Players of the console normally hold them in their hands and play games by moving them in space. In addition, there are plastic shells in shapes related to the game (e.g., tennis racket, sword, etc.) that the user can attach the Wii remote to and play the game by moving the shell around for a more realistic game experience. Similarly, there are arm straps that enable users to attach Wii remotes to their arms, making it unnecessary to hold the Wii remote in games that are played with arm motions. We take this approach, attaching Wii remotes to users' limbs to detect therapeutic exercise motions.

Webcams are simple and affordable cameras for PCs that are typically used for capturing video for online chat or recording personal videos in front of the computer. The high frame rate video that webcams provide enables tracking objects in the scene with simple computer vision techniques [13]. Similarly, we use a webcam to track colorful objects that move as a result of the users' exercise motions.

By using these affordable devices, we aim to keep the cost of our system within reasonable limits for most people with stroke.

2.3 Wii Remotes

We use Wii remotes for detecting simple exercise motions of isolated joints in a precise way. We find ways of using the motion sensors of the Wii remotes to detect therapeutic exercises with a standard PC. This way, we keep the system affordable as Wii remotes ($30) and Bluetooth dongles ($10) are low-cost hardware. They can be used with a standard PC, which may be purchased for a couple of hundred dollars if it is not already present at the home of the stroke survivor.

2.3.1 Preparing a Wii Remote for Use

To start using the Wii remote to detect motions, we first attach them to a user's limb. We used a couple of alternative ways to attach a Wii remote. We used Velcro to attach the Wii remote to sweatbands or wrist braces. Alternatively, we used commercial arm straps that are made to hold a Wii remote.

Even though Wii remotes are created to be used with the Wii console, it is possible to connect it to a PC using a Bluetooth dongle, and communicate with it using various libraries. We used WiiRemoteJ to use it in our games we developed in Java [122]. Unlike the Wii console, connecting a Wii remote to a PC requires action on the user's part. To connect to the Wii remote, our software first starts listening for Bluetooth connections. The user presses the 1 and 2 buttons on the Wii remote to get it to broadcast a connection request with the unique identifier of the Wii remote. The PC then establishes a Bluetooth connection with the Wii remote. The PC can request the Wii remote to continuously send readings of the motion sensors.

2.3.2 Detecting Motions with the Wii Remote

Wii remotes have two facilities that can be used for motion detection: an infrared (IR) camera and a three-axis accelerometer. The IR camera tracks up to four external IR light sources simultaneously to infer the motion of the Wii remote. In the Wii console, it is mainly used for precisely detecting locations on the screen that the Wii remote is pointed to, with the help of the "sensor bar" hardware that contains IR light sources. We found that the field-of-view of the IR camera was too narrow to detect large exercise motions that most therapeutic exercises require. Therefore we did not use the IR camera in our system.

We detect exercise motions by attaching Wii remotes to body parts (e.g., upper arm) and using accelerometer readings to sense the motion of the body part. The three-axis accelerometer supplies proper acceleration, i.e., acceleration relative to a reference frame in free fall [50]. Consequently, when the Wii remote is at rest, the accelerometer measures an acceleration vector with a magnitude that is equal to gravitational acceleration but is opposite in direction (upwards). If the Wii remote is linearly accelerating as a result of the user moving it, the accelerometer reading contains the instantaneous acceleration (i.e., change in velocity) plus the constant inverse gravitational acceleration (see Figure 2.1).

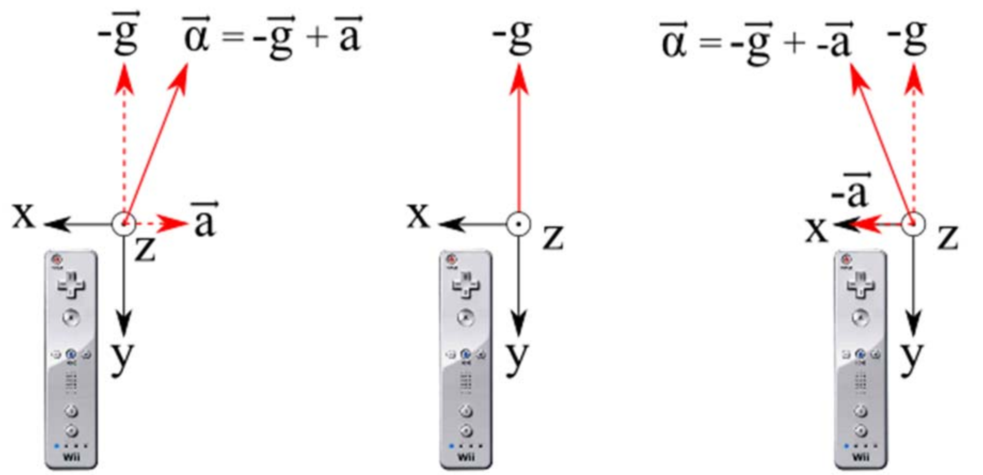

Figure 2.1. A Wii remote moving from left to right. Left: The Wii remote is accelerating towards the right, in which the accelerometer measures inverse gravity plus the acceleration. Center: The Wii remote is moving in constant speed with no instantaneous acceleration. Right: The Wii remote is decelerating.

In addition to instantaneous acceleration, rotation of the Wii remote also changes the accelerometer readings by changing the direction of gravity with respect to the Wii remote's coordinate frame (see Figure 2.2).

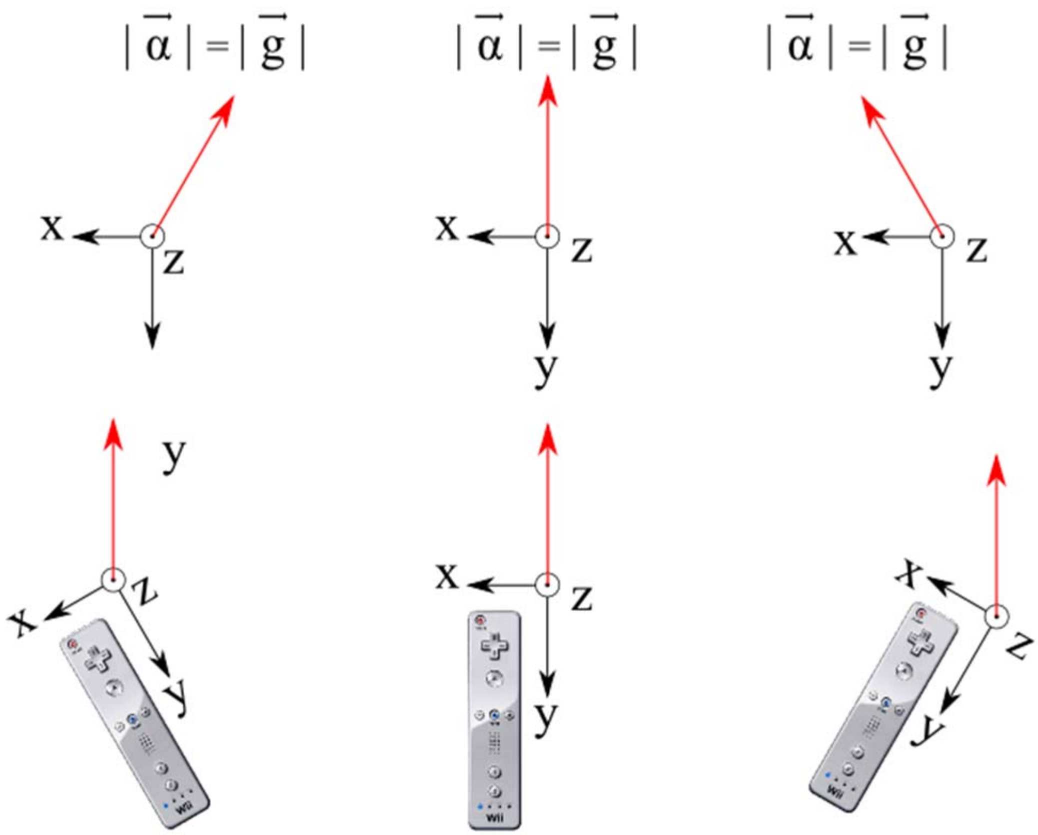

Figure 2.2. Stationary Wii remotes with different orientations. Left: Wii remote tilted to the left. Center: Wii remote straight. Right: Wii remote tilted to the right. Accelerators of each Wii remote measure an acceleration reading with the magnitude of gravity and that represent the orientation of the Wii remote with respect to the vertical axis.

As Figure 2.1 and Figure 2.2 demonstrate, accelerometer readings change direction both because of instantaneous acceleration and because of change in orientation. While the magnitude provides some information, the noisy nature of the accelerometer readings and the mixing of two motions make it ambiguous to decode the instantaneous acceleration. Even if we could decode it, using discrete-time acceleration samples to infer distance is prone to drift errors. Therefore, we cannot rely on the instantaneous acceleration. However, it is usually the case with human motions that the accelerometer readings are dominated by the reverse gravity rather than the instantaneous acceleration. This is especially true with people with motion limitations. Therefore, we can treat the instantaneous accelerations as noise, clean them away with a lowpass filter and approximately calculate the direction of the reverse gravity vector [120]. This gives us the orientation of the Wii remote with respect to the vertical axis.

$$\vec{v}_k = (1 - t)\vec{v}_{k-1} + t\vec{\alpha}$$

Where $\vec{v}_k$ is the current approximation and $\vec{v}_{k-1}$ is the previous approximation of the inverse gravity vector, $\vec{\alpha}$ is the accelerometer reading and t is the contribution of the new accelerometer reading, which is typically a low fraction (0.1).

Using this method, we approximately measure the direction of inverse gravity relative to the Wii remote, which represents how much it is tilted away from the vertical axis with respect to a reference orientation. Note that this is a two dimensional rotational entity representing roll and pitch, but not yaw (i.e., rotation around the vertical axis). This is because rotating the Wii remote around the vertical gravity axis does not change the gravity vector that the accelerometer measures (see Figure 2.3).

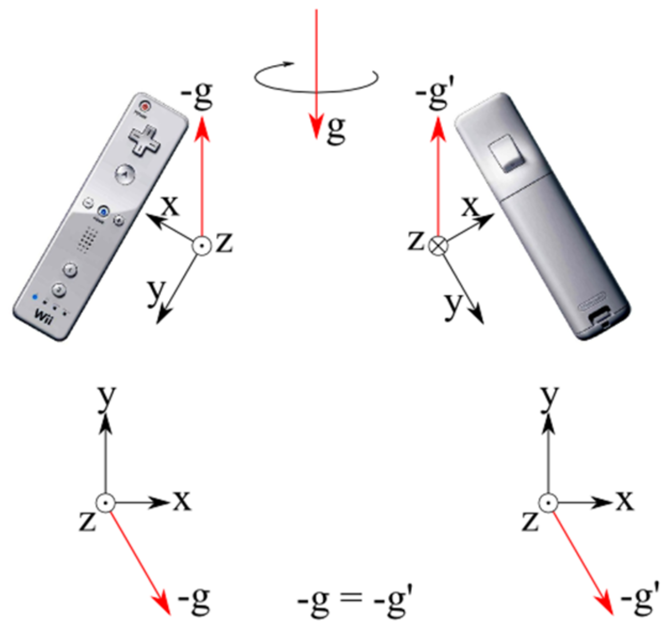

Figure 2.3. When a Wii remote is rotated around the vertical axis, the measured accelerometer value does not change.

Therefore, tracking the inverse gravity vector detects components of exercise motions that are rotations around a horizontal axis and ignores the components of exercise motions that are rotations around the vertical axis. For example, when holding the Wii remote upright and moving it like a joystick, we can detect its motions because tilting the Wii remote is rotating it around a horizontal axis. However, if we turn it around the vertical like a screwdriver, accelerometers cannot detect its motion because it is rotating around the vertical axis that is parallel to gravity. While this may eliminate some exercises, most exercises either have or can be modified to have a rotational component that is around a horizontal axis (see Section 2.6).

2.3.3 Therapeutic Exercises and Wii Remotes

With Wii remotes, we detect simple exercises of single joints in which the user repeats the same motion without changing the overall pose. We attach the Wii remote to the appropriate part of the arm that will move during the exercise. If the exercise motion is simple and inherently one dimensional, there is usually a fixed axis around which the detected gravity vector will rotate during exercise. We calculate the angle of rotation around the axis and use it as a scalar value that represents the progress of the exercise motion. If the exercise motion is two dimensional, we use two axes to measure two scalar values that represent the motion. To calculate these scalar exercise measurements, we first calibrate the device using sample exercise motions to identify some reference values.

2.3.3.1 Detecting 1D Exercises

Simple exercises that consist of a single motion can usually be represented as rotations of a limb around a fixed axis (e.g., bending and flexing the elbow). If the axis of rotation is close to a horizontal world axis, then we can use a Wii remote to detect it and convert it to a scalar value that represents the progress of the exercise motion. Figure 2.4 shows such an exercise motion in which the axis of rotation is towards the camera.

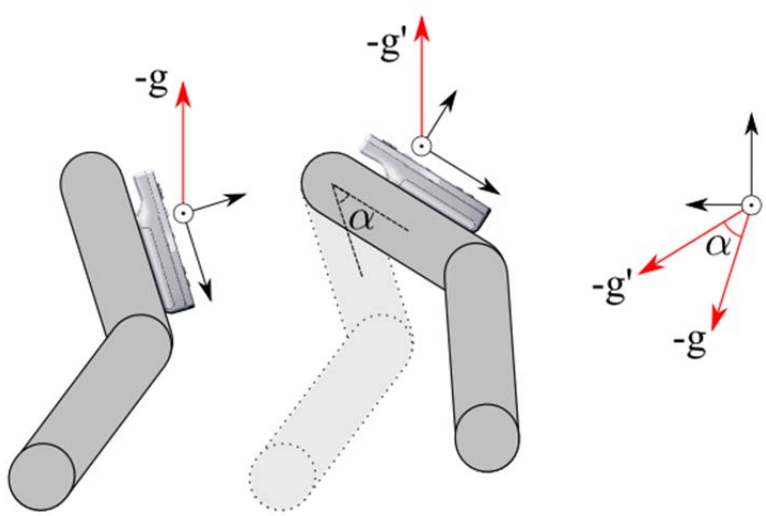

Figure 2.4. Simple exercise motion that is a rotation around a horizontal axis. The angle between the inverse gravity vectors in time reflects the progress in the exercise motion.

However, if the axis of rotation of the exercise motion is close to vertical, accelerometers cannot be used to detect the motion. Figure 2.5 shows such an exercise motion in which the axis of rotation is away from the camera.

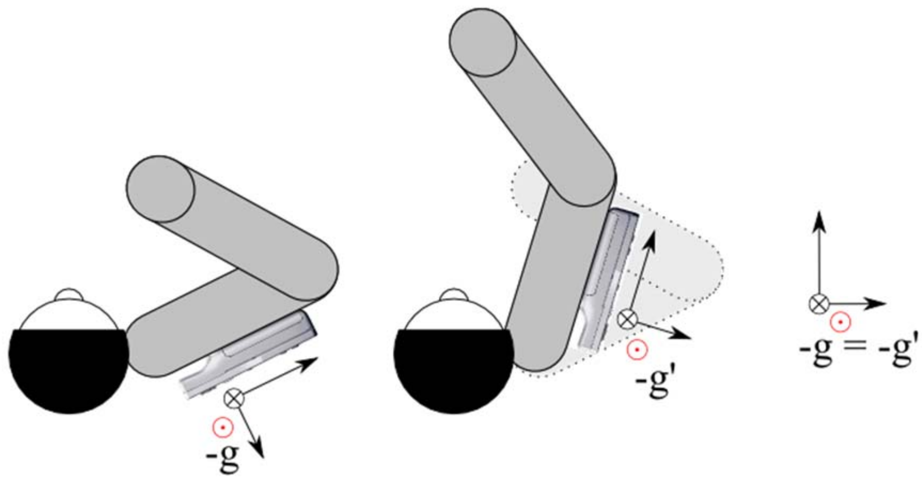

Figure 2.5. Exercises that rotate the Wii remote around the vertical axis cannot be detected using the accelerometer.

To map a simple exercise motion to a scalar value, we identify the axis of rotation and two extremes for the inverse gravity vector. We first explain how we collect these vectors, followed by how we use them to obtain a scalar value.

Calibration. To obtain the axis of rotation, maximum and minimum inverse gravity vectors, we created a calibration procedure in which the user performs sample motions by following on-screen instructions. First, the user performs the exercise motion a couple of times. Then, we use the sample motions to deduce a suitable axis that the inverse gravity vector rotates around (see Appendix A). Once we determine the axis, we map the exercise motion to the motion of an on-screen moving square. Next, the user demonstrates the two ends of his or her motion range. We project the inverse gravity vectors corresponding to the minimum and maximum of the motion range. We follow this with a verification step, in which the user moves the on-screen square to touch squares at the two extremes of the motion range.

During the game, we use these calibration vectors to convert the inverse gravity vector to a scalar. We do this by projecting the inverse gravity vector to the plane that is perpendicular to the axis and computing the angle that the projected vector $\vec{y}$ makes with the minimum vector $\vec{y}_{min}$ around the axis $\vec{a}$. As mapping circular rotation to linear values needs to have a discontinuous seam, we modify angles outside the motion range to explicitly arrange the seam to be far from the extremes and opposite to the middle of the range. We divide this angle value with the angle that the maximum vector makes with the minimum vector around the axis so that the minimum vector is mapped to 0 and the maximum vector is mapped to 1.

$$v = \frac{\alpha_{\vec{y}}}{\alpha_{\vec{y}_{\max}}}$$

$$\alpha_{y_{max}} = \alpha(\vec{y}_{min}, \vec{y}_{max}, \vec{a})$$

$$\alpha_y = \alpha(\vec{y}_{min}, \vec{y}, \vec{a}) - \begin{cases} 2\pi, & \alpha(\vec{y}_{min}, \vec{y}, \vec{a}) > \pi + \frac{\alpha_{\vec{y}_{max}}}{2} \\ 0, & otherwise \end{cases}$$

$$\alpha(\vec{p}, \vec{q}, \vec{a}) = arctan2\big((\vec{p} \times \vec{q}) \cdot \vec{a}, \vec{p} \cdot \vec{q}\big)$$

This way, when the user moves out of the region, the game receives continuous values and the user does not experience a jump as we hide the seam. Figure 2.6 summarizes this calculation.

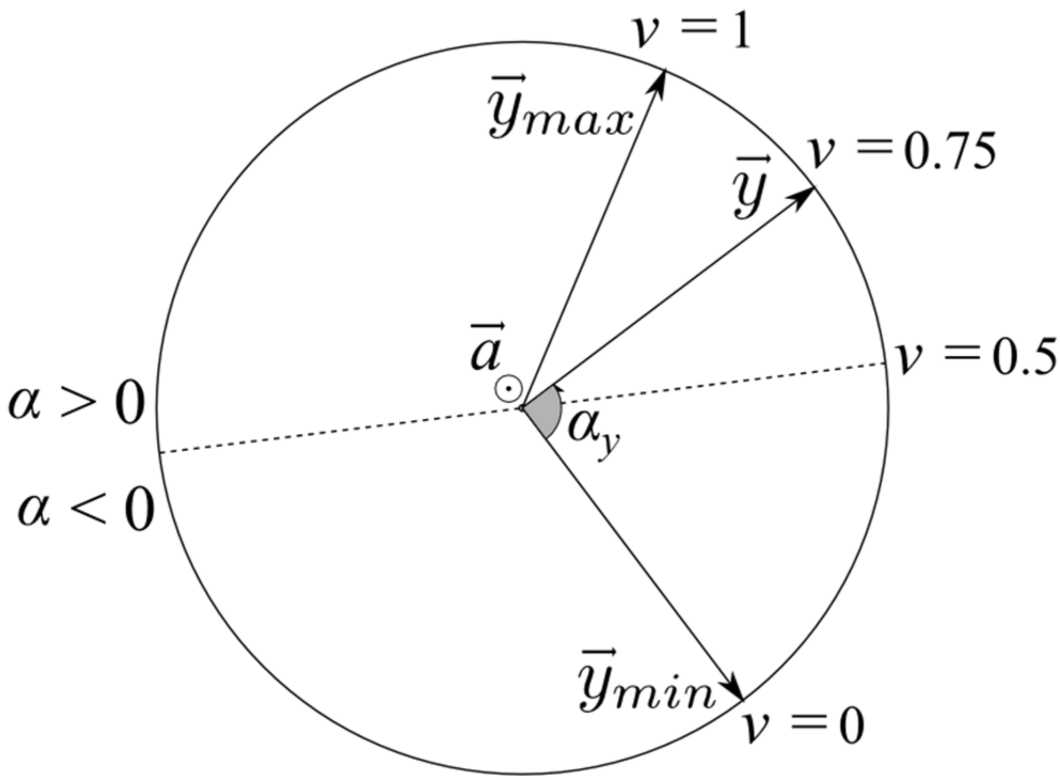

Figure 2.6. Converting the projected inverse gravity vector to a scalar.

2.3.3.2 Detecting 2D Exercises

In addition to 1D exercises in which the user repeatedly moves a limb the same way, there are therapeutic exercises in which the user can move a limb in more than one direction. For example, wrist rotation exercise requires a user to move the wrist in every direction. As the inverse gravity vector detected by the Wii remote accelerometer has two degrees of freedom, we can capture such exercise motions as 2D inputs to a game.

One option to handle such exercise motions is to extend our 1D calibration and calibrate the device similarly for the 2D exercises by capturing two axes of rotation. However, in our user tests we found that some users were having difficulty with operating the 1D calibration process and having a calibration process twice as complicated would not be practical. Therefore, we used a simpler way to calibrate and convert these motions to game inputs. Rather than using example motions to identify two rotation axes, we made an assumption on the default orientation of the Wii remote and how it would be moving during exercise. For example, with wrist rotation exercise, we assume that the user holds the Wii remote vertically in the hand with the buttons pointing towards him or her. This way we correctly map the directions of the inverse gravity vector in the Wii coordinates to the directions in the user's coordinates. We project this vector to the horizontal plane to find a direction and a magnitude that represents the state of the user's exercise (i.e., which direction and how much the remote is tilted). We use the magnitude of this projection and the direction (normalized) as separate inputs.

While this is convenient, it does bring limitations on how it can be used and require that the way the Wii remote is held needs to be hardcoded in the program (e.g., the user holding the Wii remote like a joystick). Conversely, calibrating 1D motions using example motions does not have this limitation and enables the user to attach the Wii remote to the limb in any orientation.

With this approach, we mainly tracked wrist motions in which the user either held the Wii remote like a joystick, or held it parallel to the ground with the back of the hand facing upwards. However, it can be modified to detect other motions, such as motions of the arm both forwards and to the side.

2.4 Webcam

We detect exercises with the webcam by visually tracking objects with distinct colors in the scene that move as a result of exercise motions. While this provides less precision compared to Wii remotes, tracking the end effector enables more complex motions that require the use of multiple joints in coordination.

2.4.1 Preparing the Webcam and Detecting Motions

We capture the webcam video in our Java games using JMF software [57]. We use a simple color tracking algorithm to track the location of the distinctly colored object in the scene. By following on-screen instructions, the user calibrates the color tracking algorithm to start tracking the distinctly colored object (e.g., sock, beanbag, etc.).

The PC displays the user's video, and a pre-defined rectangular region that is large enough to contain the whole object but not larger. The user moves the colorful object into the rectangle and presses a key. We take a picture from the video and find thresholds in HSV space that bound the colors inside the rectangle. Then, we refine the thresholds using a hill-climbing algorithm in a way that minimizes the number of pixels outside the rectangle that have colors between the thresholds, while ensuring that more than x% of the pixels inside the rectangle are within the thresholds. If there are no other objects in the scene with colors that are very close to the tracked object, the resulting thresholds approximately distinguish the pixels belonging to the object from the rest of the pixels in the picture (see Figure 2.7).

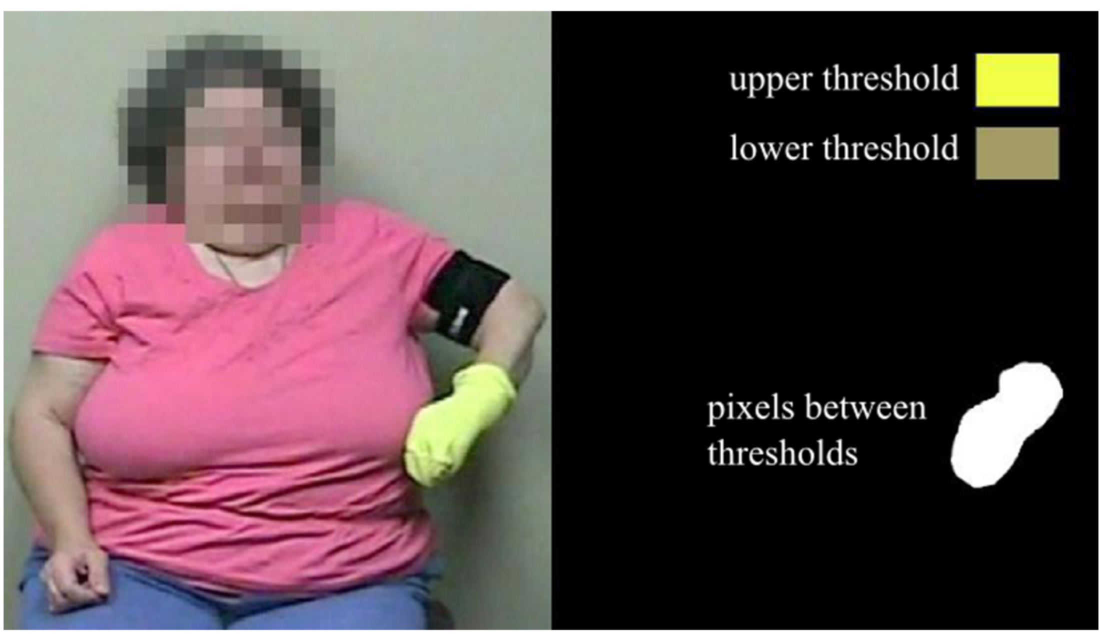

Figure 2.7. Segmenting the tracked object using HSV color thresholds.

By tracking the average position of the pixels between the identified thresholds, we track the approximate position of the tracked object in the webcam video.

2.4.2 Therapeutic Exercises and the Webcam

We track the colorful object in the video as a way to detect exercises. We do this by tracking colorful objects such as beanbags that users hold or socks that users put on their hands. This way we track exercises as a result of which the colorful object moves in the video. While this is a less-precise way to detect motions compared to Wii remotes, it enables us to track task-related exercises such as reaching to locations in space. These exercises require coordinated use of multiple joints and are difficult to track with Wii remotes.

After color calibration is complete, the user performs the exercise motions and demonstrates the extremes that the user is able to perform. For example, for a reaching exercise the user reaches up, down, left and right as far as possible. We identify the rectangle that the object stays within during these motions and map the location of the object in the video to 2D game input (see Figure 2.8).

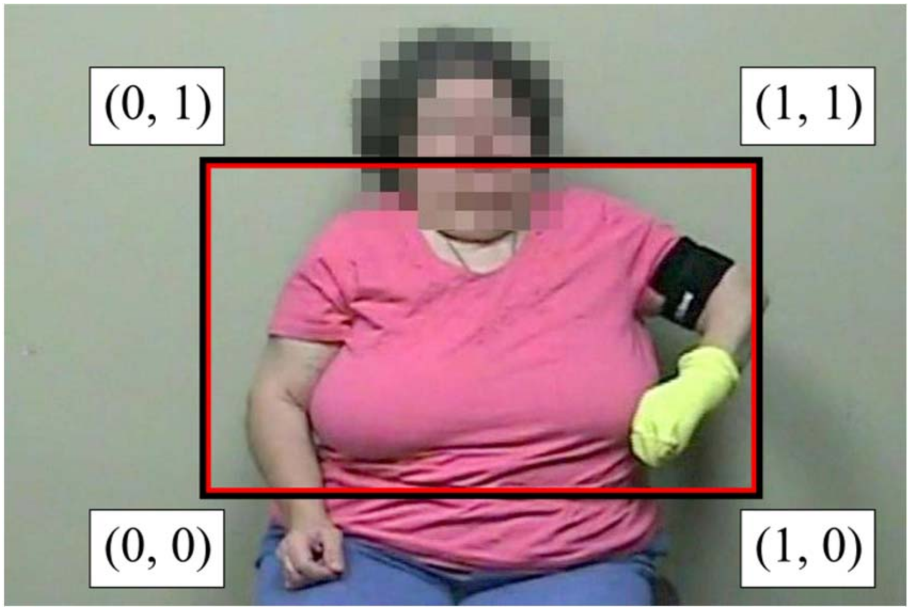

Figure 2.8. Mapping the locations of the colorful sock to 2D game input.

Through this mapping, the user can play a game that expects 2D positional input. We use colorful socks on hands for the player and colorful small beanbags for other in-game objects that the user interacts with as a part of the game. Through such interactions, we enable people with stroke to perform task-based exercises that consist of motions such as reaching, grasping and releasing while playing video games.

2.5 Addressing Compensation

In our user tests we found Wii remotes and webcams to be useful for detecting therapeutic exercise. However, we observed that as users became tired, they found it more difficult to move the joints and muscles that the exercise targeted. As a result, they started to use other joints and muscles to help ease the exercise motions. This is a common problem identified by therapists: when people with stroke perform exercise motions they tend to compensate with other joints [40]. When the exercises are supervised by a therapist, the therapist corrects such motions and encourages the use of the targeted joints and muscles. However, when users perform the exercises without supervision, compensation is usually inevitable. Compensating while playing video games at home may not be worse than unsupervised home exercises, however, we wanted to address compensation because the use of motion-sensing devices provided an opportunity to detect it.

We specifically look at compensation in an exercise in which it was especially detrimental: elbow flexion and extension exercise. In this exercise the user is expected to bend and flex the elbow. We detected this by attaching a Wii remote to the lower arm. However, the exercise motion was very difficult for some users and they moved their whole arm using their bodies and shoulders instead to get the same effect in the game (see Figure 2.9). This defeated the purpose of the exercise motion and had to be addressed.

Figure 2.9. Left: proper elbow exercise. Right: elbow exercise with compensation.

Since we only wanted the elbow exercises to affect gameplay, we wanted to find a way to detect only elbow motions and not the motions of the rest of the body that indirectly move the lower arm. Therefore, we attached another Wii remote to the upper arm to detect the motions coming from the rest of the body. We calibrated and detected the motions of the Wii remote in the upper arm similarly using example motions. We subtracted the angle computed for the upper arm from the angle computed for the lower arm to find the angle of the elbow exercise. We converted this angle difference to the game input.

Figure 2.10. Using a second Wii remote attached to the upper arm to detect and cancel out compensatory motions.

Using the difference angle caused the game to be affected by only the elbow motions and not the motions of the shoulder and the torso. Therefore, moving the shoulder and the torso had no major effect in the game and the user had to extend and flex the elbow in order to succeed in the game.

Attaching a Wii remote to the upper arm was convenient as we already had a way to attach Wii remotes to arms. However, detecting other forms of compensation was more difficult. For example, detecting torso compensation in shoulder exercises was not easy because reliably attaching a Wii remote to the torso proved to be a challenging task. Therefore we left addressing compensation in other exercises for future work.

2.6 Detecting Therapeutic Exercises with Wii Remotes and Webcams

In our user tests, we use simple and common therapeutic exercises to demonstrate that Wii remotes and webcams can be effectively used for detecting therapeutic exercises. With the Wii remote, we detected exercises of the shoulder, elbow and the wrist. With the webcam we detected exercises that consisted of reaching to locations in space, reaching to beanbags, grasping, moving and releasing them. In addition, we detected elbow exercise and its compensatory motions with Wii remotes and canceled out the compensation so that we use only the motions of the elbow.

In addition to the exercise motions that we used, we list most of the commonly used therapeutic exercises and suggest ways of using our system to detect them. We surveyed the literature for the fundamental exercises that are used as "building blocks" in therapeutic exercise plans [70, 103, 119]. We list these exercise motions in Table 2.1 along with their descriptions and our suggested way of sensing the exercise and compensation for each.

Table 2.1. Suggested ways of detecting basic arm motions commonly used in stroke rehabilitation exercises.

Motion	Description	Sensing
Shoulder abduction and adduction	Similar to a wing, moving the arm from the torso to an extended position to the side and back	Detection: Wii remote on the upper arm Compensation: Wii remote on the torso
Shoulder flexion and extension	Lifting and extending the arm forwards all the way and moving it all the way back in the opposite direction	Detection: Wii remote on the upper arm Compensation: Wii remote on the torso
Shoulder internal and external rotation	Similar to opening a door, moving hand towards and away from the other arm	Detection: Webcam, tracking the hand
Elbow flexion and extension	Using the elbow joint to move the hand closer and back	Detection: Wii remote on the forearm Compensation: Wii remote on the upper arm
Wrist rotation (pronation and supination)	Rotating the wrist similar to using a screwdriver, making the palm face down and up	Detection: Wii remote on the hand, held or strapped Compensation: Wii remote on the forearm
Wrist flexion and extension	Moving the hand up and down and rotating the wrist like changing gears on a bicycle or accelerating a motorcycle.	Detection: Wii remote on the hand, held or strapped while palm facing up or down Compensation: Wii remote to the forearm, Wii remote in the hand can detect changes in palm
Hand and finger flexion and extension	Closing and opening the hand	Detection: Webcam, with colored ball on finger Compensation: Webcam, with a point in the forearm, occlusion is possible
Grasp, move, and release	Grasping an ordinary object (such as a can or beanbag) and being able to handle and move it from one location to another	Detection: Webcam, with a prop that is handled by the user Compensation: Webcam, with a point in the torso
Reaching	Extending the arm to take the hand to locations in space with a combination of muscle motions	Detection: Webcam, with the hand using a glove Compensation: Webcam, with a point in the torso

To make games that can be played with more than one type of exercise motion, we classify the inputs generated by the input devices into input types, represented by dimension and orientation. A more general classification scheme can be found in [107]. We use the Wii remote to generate 1D vertical input when attached to a body part such as the upper arm and moved in a vertical plane, 1D horizontal input when attached to a body part such as the wrist that is rotated around a horizontal axis and 2D input when used like a free joystick. We use the webcam to generate 1D horizontal, 1D vertical and 2D inputs by calibrating it accordingly. Every motion in Table 2.1 provides one of these input types. Similarly, each game that we build expects one of these input types for each of its players. As long as the input device and the muscle motion it was used with can provide the input type that a game expects, they can be used to play the game. This architecture enables games to be used for multiple different exercises.

2.7 Conclusion

By finding ways for detecting therapeutic exercises using Wii remotes and webcams, and converting them to inputs suitable for games, we made it possible for games to be developed using exercise motions. We developed these techniques together with games that use them, and tested them together with stroke survivors. We present our efforts for developing the games as well as the user tests that we tested both games and motion detection techniques together in the next chapter.

Chapter 3

Developing Games for Stroke Rehabilitation

Motion-based games can be an effective alternative for people with stroke to perform therapeutic exercises at home. Games can provide the necessary motivation and structure to follow a home exercise program. In addition, by providing an engaging context, games can enable the high number of exercise repetitions necessary for motor recovery. One of our main goals is to enable the use of motion-based video games for stroke rehabilitation at home. As a first step, we identified ways of using two affordable input devices for detecting therapeutic exercises and converting the exercise motions into game inputs. While this covers most of the technical requirements for starting to develop video games for stroke rehabilitation, designing games specifically for people with stroke is a challenging and unusual task that requires further research.

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

3.1 Related Work

A number of research projects have explored how to use games to help patients recover following a stroke. An analysis of the properties of virtual reality and gaming in the context of the needs of stroke patients suggests that this is an important area to explore [98].

In the therapy community, some research has examined the potential of existing commercial games for stroke rehabilitation. Existing console games with motion-based input devices, such as the Playstation 2 EyeToy [39] and Wii Sports [32], have been used in stroke therapy studies. While these games are promising for patients in the later stages of recovery, they were designed for users with a full range of motion. Consequently, they cannot be used by the majority of patients recovering from a stroke [32, 39].

In order to reach stroke patients in earlier stages of recovery, researchers have developed their own games. Colombo et al. created a simple game in which the patient tried to move a colored circle from an initial position to a goal position using a robotic device designed for arm rehabilitation [23]. Huber et al. [55] and Jack et al. [56] developed haptic glove based games in which users scare away butterflies, play the piano, and squeeze virtual pistons to improve the player's finger flexion and extension. Broeren et al. created several games for use with a pen-like haptic device that patients could position in 3D [10]. Burke et al. built two webcam color tracked games similar to whack-a mole [14]. In addition, they created a physics-based orange catching game and a whack-a-mouse game, both controlled with magnetic sensors and a vibraphone game which used a Wii remote as a pointing device [14]. Yeh et al. developed a series of games involving manipulating objects in a 3D world [126]. Sanchez et al. developed training exercises modeled on everyday tasks [102]. Chen et al. created a dynamic decision network for audio-visual feedback for arm reaching motions [16].

Recently, researchers have begun to think about what properties are desirable in stroke rehabilitation games. Jung et al. stressed identification of the target audience, visibility and feedback as three important human factors for stroke rehabilitation games [60]. Burke et al. proposed meaningful play and challenge as relevant game design principles [13, 14]. Goude et al. analyzed the potential of different game elements in addressing common problems among stroke patients [46]. They developed and user tested a number of successful games with these elements [10]. Flores et al. expanded the work in [46] and identified game design criteria that stem from stroke rehabilitation and elderly entertainment [38]. In addition they analyzed a number of games based on those criteria.

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

3.2 Method

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

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

To answer these questions, we used an iterative approach in which we developed and user tested a game system with several games. We designed the games to cover the space of arm motions that we identified in Chapter 2. Four people with hemiparesis because of stroke participated in our tests and we met with each participant once for one to two hours. During the sessions, we selected games that we thought should be playable for each participant given their ability to control the motion of their upper extremity. We adapted the games as much as possible to the participants' available motions and cognitive skills, and observed them as they played. When possible, a therapist also attended these sessions to evaluate the games from a therapeutic point of view. After each game, we briefly discussed its strengths and weaknesses as well as its applicability to stroke recovery. During these sessions, we identified barriers to stroke patients playing rehabilitation games as well as requirements on games from a stroke therapy perspective. In subsequent iterations, we adapted existing games to solve the identified problems and developed additional games to more fully explore the space of stroke rehabilitation games.

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

3.3 Hardware and Software

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

3.3.1 Input Devices Used

We used Wii remotes and webcams for detecting therapeutic exercises, as we discussed in Chapter 2. We used them with a standard PC that conducted the required input processing and ran the games.

3.3.2 Software

We developed our games in Java, using the LookingGlass [75] code base that includes a library of 3D models with a scene graph data structure for easy creation and manipulation of 3D scenes.

3.4 Participants

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

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

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

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

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

3.5 Games Developed

In our study, we wanted to explore the space of games that can be used for stroke rehabilitation. We first identified the main attributes of games for stroke rehabilitation and then designed and developed a number of games to explore this space.

3.5.1 Game Attributes

As a result of our brainstorming sessions with therapists, we identified three attributes in this space: social context, type of motion required, and cognitive challenge. We explain why we chose these attributes below and identify them in the descriptions of individual games.

3.5.1.1 Social Context

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

3.5.1.2 Motion Type

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

3.5.1.3 Cognitive Challenge

Because many stroke patients have cognitive issues caused by their stroke, the degree of cognitive challenge is an important factor while designing games. Games can either be simple to understand and play, or they can require challenges such as recognizing and remembering different objects, which can be difficult for some patients and fun and useful for others.

3.5.2 Games

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

3.5.2.1 Frog Simon

Frog Simon (Figure 3.1.a) is a single-player game that requires an accurate 2D input, and provides a level of challenge on memory. This game is a variation of the handheld game Simon. The player controls a flower in the center of the screen, surrounded by four frogs. The player uses a 2D input to touch the frogs in order to recreate tunes that they played. We found that this combination of a difficult physical challenge with a difficult cognitive challenge was impractical for most stroke patients. One patient played this game for 10 minutes.

Figure 3.1. Four games that we developed. a. Frog Simon: the player remembers and repeats tunes. b. Dirt Race: The player controls the windshield wiper to clear off the bugs while the other player is driving the car. c. Baseball Catch: The player catches the balls thrown at the screen. d. Catch the Kitty: Players save the falling pets by catching them.

3.5.2.2 Dirt Race

Dirt Race (Figure 3.1.b) is a two-player collaborative game that requires a basic 1D input (e.g., shoulder abduction and adduction) for the stroke patient, and is simple to play. A truck is driving through a locust swarm in a village. The stroke patient controls a hand-operated windshield wiper to clear off the bugs for the other player to safely steer the car. The goal is to have the patient do the repetitive exercise over and over without much cognitive challenge. One patient played this game using shoulder abduction and adduction motion for 15 minutes. This duration was sufficient to observe that the user was performing therapeutic motions with the game.

3.5.2.3 Baseball Catch

Baseball Catch (Figure 3.1.c) is a single-player game that requires an accurate 2D input, and provides some cognitive challenge in terms of differentiating between types of balls and following the trajectory of a ball in 3D. Three baseball players throw either a baseball or a basketball, targeting random positions on the screen. The player controls a baseball glove to catch the baseballs and avoid basketballs. Markers for the ball trajectory and target can be turned on to make it easier. This game is best played with the webcam and uses coordinated motions of the whole arm for reaching to random locations. Three patients played this game for an average of 25 minutes. Initially, the webcam motion range was hard-coded in the game and therapists were critical of it because it was not suitable for motion ranges of different patients. As a result, we enabled calibration of the input range with the webcam and found that this enabled making use of the whole motion range of users.

3.5.2.4 Catch the Kitty

Catch the Kitty (Figure 3.1.d) is a two-player competitive game that requires accurate horizontal 1D inputs, and provides some cognitive challenge in terms of quickly differentiating between different pets. Various animals fall from above and the players move horizontally along the bottom of the screen. Each tries to catch the pet type that is assigned to her or the shared pet type and get the high score. We developed this as a simple game to test whether patients could readily translate vertical motion to a horizontal change in the game. We found that patients were not comfortable with it unless the 1D input they used was horizontal displacement. Four patients played this game for an average of 20 minutes with Wii remotes strapped on the upper and the lower arm, and could not succeed because the Wii remote could not provide horizontal 1D inputs using a displacement motion.

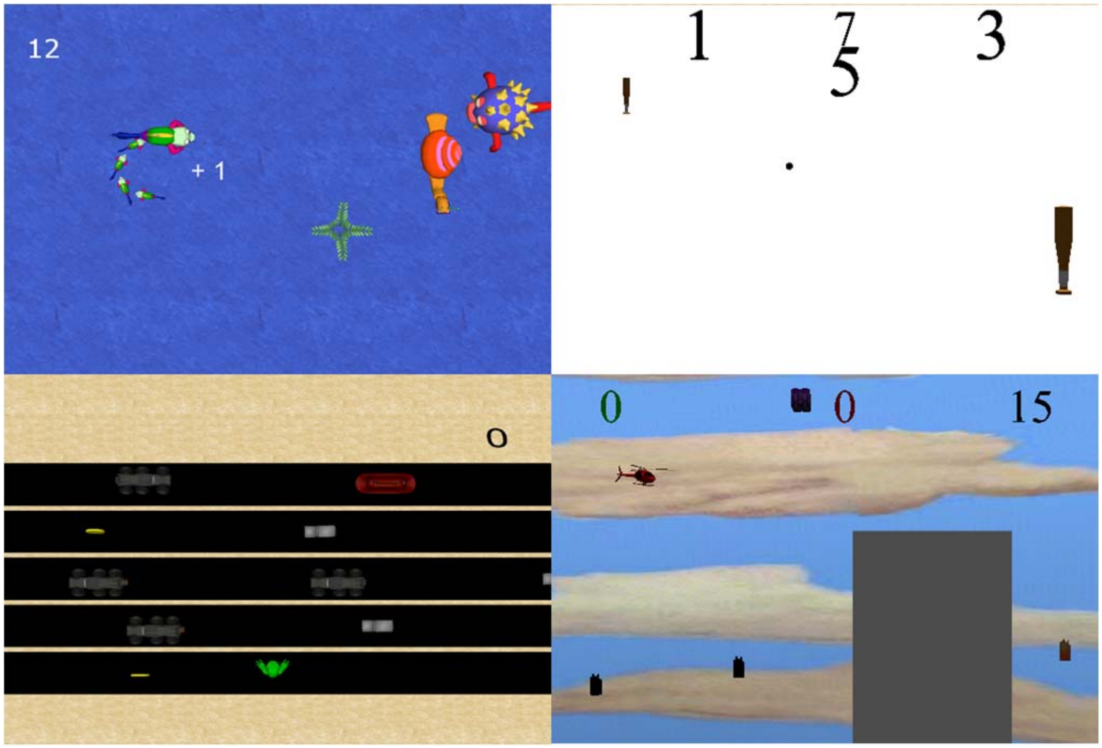

Figure 3.2. Four other games that we developed. a. Under the Sea: the player controls the snail to protect the fish family from the spiky fish. b. Pong: The player controls one of the paddles to counter the ball. c. Frogger: The player controls the frog to move it across the road. d. Helicopter: The player moves the helicopter vertically to collect fuel cells and avoid buildings.

3.5.2.5 Under the Sea

Under the Sea (Figure 3.2.a) is a two-player collaborative game that requires a somewhat basic vertical 1D input, and is easy to play. The mother fish and its trailing babies are controlled by one player with a 2D input to collect and eat ferns to get points. Meanwhile, a hungry predator (Spiky) stalks the fish, coming from off screen to the right to eat one of the babies. The stroke patient controls the snail, moving vertically across the right side of the screen to prevent Spiky from reaching the babies. In this collaborative game, the stroke patient is the protector of the fish family and needs to do a somewhat basic repetition every time they come under attack. This game included appealing audio and visuals and was popular among the patients. Three patients successfully played this game for an average of 25 minutes.

3.5.2.6 Pong

Pong (Figure 3.2.b) is a two-player competitive game that requires accurate vertical 1D inputs and provides some cognitive challenge in terms of following the ball trajectory. This is a remake of the classic game in which players control vertically moving paddles on each side of the screen, trying to keep the bouncing ball in the field. Even though we can adjust the ball speed separately towards each player, and change paddle and ball sizes in difficulty settings, we found competitive scoring to be discouraging for patients and awkward for their caregivers that were present at the sessions. Competing against someone with a clear disability creates a difficult social situation. Alternatively, we created a cooperative "rally" mode, in which one central score tracks how many times the ball was hit in a row, and another shared score keeps the longest streak. This created a more enjoyable experience for everyone. Three patients successfully played this game for an average of 20 minutes.

3.5.2.7 Frogger

Frogger (Figure 3.2.c) began as a single-player game that initially required accurate 2D input and provided cognitive challenge in terms of avoiding cars on a road. Similar to the classical game, the objective is to help the frog cross a busy highway with cars moving horizontally across the screen. We found that it was difficult for some patients to coordinate lane hopping and moving side to side, therefore we created a collaborative two-player version in which the stroke patient makes the frog hop to the next lane using a basic vertical 1D input and the other player moves the frog along the lane. We observed that this version worked better by providing ease of play. Further, this required the players to communicate to achieve a shared goal. Two patients played this game for an average of 15 minutes.

3.5.2.8 Helicopter

Helicopter (Figure 3.2.d) is a single-player game that requires accurate vertical 1D input and is cognitively easy. The game consists of a helicopter flying in front of a horizontally scrolling background. The player controls it vertically with a 1D input to avoid hitting the buildings and to collect fuel cells in the air. Between buildings, fuel cells appear close to the ground, which encourages the patient to move to the bottom end of the motion range. Larger fuel cells appear on top of the screen above buildings. Two players successfully played this game for an average of 25 minutes. This game is unique among our games in the sense that the patient is encouraged to perform full repetitions more than anything else. We developed this game to answer the following question: *is it better for the motion to be driven by random events in the game or should the game events be driven by the requirements of exercise?* The former has the risk of not being as helpful from a therapeutic point of view, while the latter has the risk of being too predictive and boring. In our limited tests, boredom was not a problem and the patient felt like the game was actually helping her. However, in longer tests such as home use, this question should be brought up again. We predict that the answer is somewhere in between to ensure the balance between fun and exercise, and hope to find ways of quantifying it.

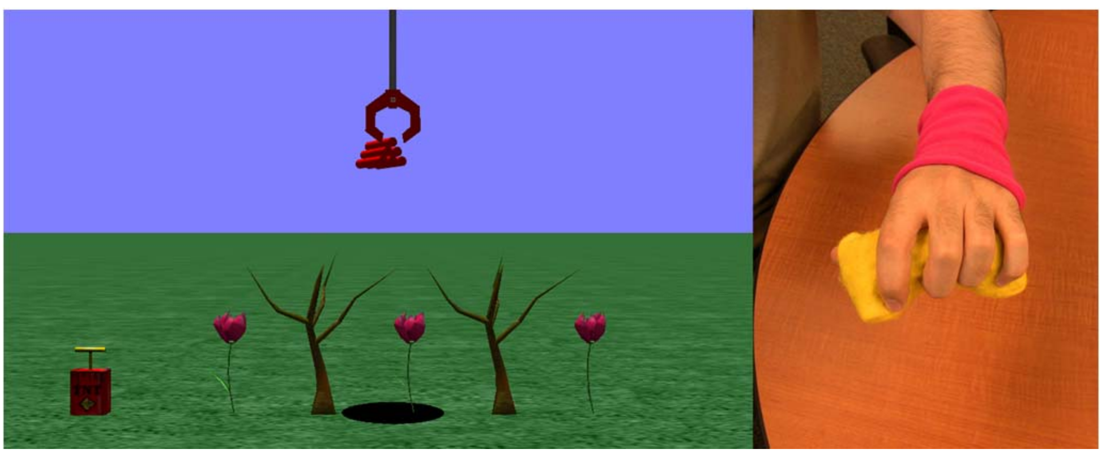

Figure 3.3. Garden: the player controls the robot arm and the beanbag controls the dynamite. The player tries to blow up the weeds growing in the rose garden.

3.5.2.9 Garden

Garden (Figure 3.3) is a single-player game that requires accurate 2D input and provides a simple cognitive task of differentiating between weeds and flowers. The objective of this game is to clear a garden of weeds while preserving the flowers. With the webcam, we track a colored glove that controls a virtual robot arm and a beanbag that controls a dynamite in the game. While wearing the glove, the user grabs the beanbag (in the game, the robot arm lifts the dynamite). The player wants to drop the dynamite on a weed and then push a handle to the left of the screen to make the dynamite explode, which decimates the crop nearest to it. This game was inspired by our conversation with a therapist after the user tests, who believed strongly that the most important goal of rehabilitation was to encourage purposeful motions which are necessary for activities of daily living. Therefore, in this game, we tried to replicate similar motions and use them in the context of a game.

3.5.3 Summary

Through our iterative design process, we developed the nine games to explore the interesting parts of the design space that we laid out in Section 3.5.1. The design of the games was mainly driven by the needs of users that we observed during user tests. As a secondary goal, we wanted to explore the space evenly. Figure 3.4 shows the games' representations in the design space.

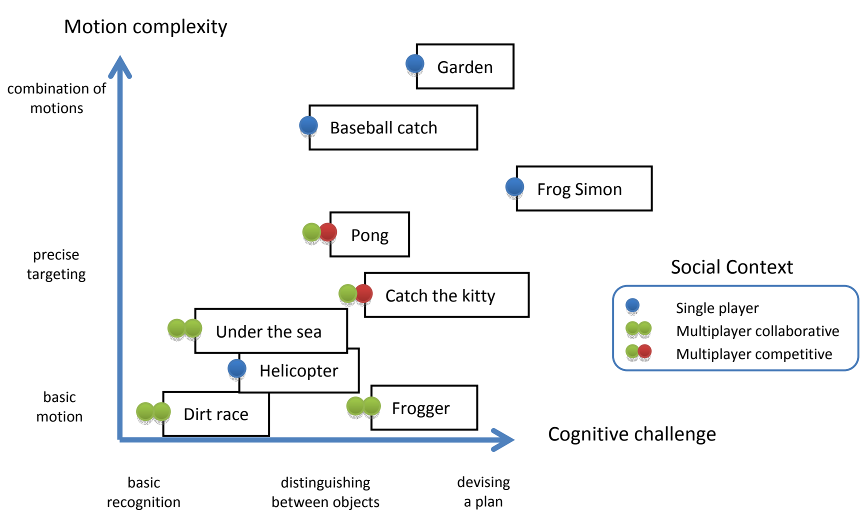

Figure 3.4. The nine games that we developed and their representations in the game design space.

We provided information about users' experiences while playing the games during user tests in Section 3.5.2. We summarize the durations of play in Table 3.1.

Table 3.1. Games, the number of players played them in user tests and the average duration that each user played.

Game Name	Number of Players	Average Duration (min)
Frog Simon	1	10
Dirt Race	1	15
Baseball Catch	3	25
Catch the Kitty	4	20
Under the Sea	3	25
Pong	3	20
Frogger	2	15
Helicopter	2	25

3.6 Lessons Learned

Through user testing our games, we learned a number of lessons related to (1) making games playable for a broad range of people with stroke, (2) ensuring that games are valuable from a therapeutic perspective and (3) making games fun and challenging.

3.6.1 Making Games Playable for a Broad Range of People with Stroke

3.6.1.1 Assume No Use of Hands

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

3.6.1.2 Simple Games Should Support Multiple Methods of User Input

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

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

3.6.1.3 Calibrate Through Example Motions

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

3.6.1.4 Direct and Natural Mappings Are Necessary

Even with immediate and continuous feedback, most of our users struggled to understand indirect motion mappings. For example, even when explained, three of our four users struggled with using vertical motion (raising and lowering their arm) to control the horizontal position of the character. Even a mapping in which rotating the wrist right and left causing a game character to move horizontally, was confusing for users. We do not know whether these difficulties are attributable to lack of familiarity with video games or some cognitive issue resulting from the stroke. Of our four participants, only Diane seemed to exhibit no difficulties with understanding indirect motion mappings. Diane is younger than the other participants and played arcade-style games as a young adult.

3.6.2 Ensuring That Games Are Valuable From a Therapeutic Perspective

3.6.2.1 Ensure That Users' Motions Cover Their Full Range

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

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

3.6.2.2 Detect Compensatory Motion

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

In order to address this problem, we eliminated environmental factors, such as rotating office chairs, which encourage compensatory motion. In addition, we attached additional Wii remotes to the user's body to detect and filter out compensatory motion. For example, in exercises that focus on elbow motion, we place Wii remotes on both the upper and lower arm to ensure that the game can only be played by changing the elbow angle, eliminating compensation through the shoulder (see Figure 2.10).

3.6.2.3 Allow Coordinated Motions

While patients in early stages of recovery may not be able to perform actions involving the coordinated motion of their shoulder, elbow, wrist, and hand, such motions are vital for patients hoping to perform activities of daily living. Purposeful exercises, including tasks that require grasping, moving and releasing objects, are particularly valuable for this purpose. The garden game utilizes these motions as users picking up a bean bag, moving it such that it is over a virtual "weed", and then releasing the bean bag (see Figure 3.3). This type of game would be inappropriate for stroke patients with little mobility, but is crucial for patients in later stages of recovery, hoping to restore coordinated motions.

3.6.2.4 Let Therapists Determine Difficulty

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

3.6.3 Making Games Fun and Challenging

3.6.3.1 Audio and Visuals Are Important

Stroke patients tend to be older than typical gaming audiences. Like Flores et al [38], we found it necessary to pay careful attention to issues of size and contrast. Anne sometimes struggled to maintain focus during game play. However, when she played Under the Sea, she maintained attention, which she attributed to the colorful scenes and sound effects. While she was able to maintain focus better with this game, she sometimes struggled to notice when she was supposed to act. We have since added "danger" sound effects to try to draw the player's attention when necessary.

3.6.3.2 Automatic Difficulty Adjustments Provide Adequate Challenge

In some games, we realized that once the patient got used to the game play, it could get boring unless we manually increased difficulty. To address this issue, we created automatic settings which gradually changed difficulty with the player's successes or failures based on a set of base difficulty values provided by the therapist. We observed that this resulted in less boredom and provided challenge, which is consistent with the concept of flow [110].

3.6.3.3 Non-Player Characters (NPCs) and Storylines Are Intriguing

Initially, we spent little time developing storylines for the games. However, we observed that patients spoke about the game characters imaginatively. For example, users mentioned enjoying how baby fish followed their mother in Under the Sea, took the responsibility for protecting them and tried hard to save them from the spiky fish.

When playing Baseball Catch, Carol was interested in interacting with the commentator and said she wanted to "kick him" as he reported missed balls. We believe that more opportunities to interact with NPCs and more developed storylines beyond regular game dynamics may provide a deeper sense of engagement with the game.

3.7 Discussion

We have presented a number of guidelines that can help ensure that therapists can use games to elicit motions that are useful in a therapeutic context. The number of tests that we were able to do with the patients was limited and our findings should be taken as suggestive rather than conclusive. Nevertheless, the therapists that attended the tests found that the games did motivate the patients and that they used the kind of motions that are required for their home exercises. Furthermore, these tests resulted in invaluable lessons on how to design a game system for stroke therapy.

A shortcoming of study is that our tests took place in the clinic. Although this was convenient and representative of regular meetings with therapists that people with stroke may have, it was not representative of the target context that games would eventually be useful in: the homes of participants. Participants would likely be in a very different situation when they use these games at home. In our tests we supervised the participants, whereas at home they would be by themselves or perhaps by family members to some extent. Participants were motivated to participate because we asked them to. Conversely, they would have to be motivated to play at home. In addition, their home environments may not be suitable for the activity. Since one of our main reasons behind exploring game-based rehabilitation was to enable people with stroke to perform therapeutic exercises at home, we need to understand the dynamics for when these games would be played at home. Therefore, one of the next research questions that we would like to tackle is: what are the supports that are necessary to enable and motivate people with stroke to play these games at home?

In addition, even though we enabled them to play games using therapeutic exercises, we do not know whether the motions that they perform while playing these games are actually useful for them. Although the therapists that supervised the sessions thought so, we would like to find out whether games are actually helpful, how we can make exercise through games be maximally useful and how we can integrate them in an actual therapy context.

Chapter 4

Using Games in Outpatient Therapy: A Case Study

As we demonstrated in Chapter 3, 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 for completing 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 [7, 33]. 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 games at home for stroke rehabilitation.

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 that 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. Prior to this work, there were 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 frequently enough to detect improvements soon after they came to be. 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.

4.1 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.

4.1.1 Enabling Rehabilitation through Motion Games

Initially, studies focused on enabling game-based rehabilitation through custom or expensive input devices. Since these devices make wide-spread 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.

4.1.1.1 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. 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, using silverware, playing volleyball with a balloon, dressing/undressing, reaching out and grasping/releasing objects) [7].

Broeren et al. created a haptic stereovision immersive workbench and designed custom games to be played through grasping and moving a stylus [10]. 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 [11]. 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. 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 [2]. 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 3 weeks of training in the clinic with 8 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. conducted two long-term home-based studies on adolescents with cerebral palsy [44, 45]. 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 that 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. used the Rutgers Ankle haptic interface to enable games to be played using the ankle and reported improvements in motion measurements (excursion and torque) [33]. They also ran usability studies on a version for telerehabilitation [31].

4.1.1.2 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 wide-spread 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. 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) [32]. Similarly, Flynn et al. 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) [39]. 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. 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 [28]. Alankus et al. used the accelerometers of Wii remotes to detect exercise motions by attaching the remotes to users' body parts [3]. They created custom games, and tested them with people who had strokes. Burke et al. and Alankus et al. 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 [3, 13]. Burke et al. demonstrated that these games could be used at home by testing them at three individuals' homes and observing them play in single user sessions. However, they did not test long-term and unsupervised use. Reinkensmeyer et al used a joystick through a telerehabilitation system to sense therapeutic motions that drove simple web-based games [96]. 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. 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.

4.1.1.3 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. identified issues related to stroke (e.g., learned nonuse) and sought to address them with game elements (e.g., target distribution) [46]. 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 [10]. 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 VR hardware is not appropriate for the home. Another group of researchers, Burke et al., adopted principles from game design theory and used them as a guide in the development of games for stroke rehabilitation [13]. 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 play in single user sessions. Therefore, they have not had a chance to evaluate long-term unsupervised home use of these games. Alankus et al. identified important game attributes based on limitations related to stroke and sought to sample the design space of games according to those attributes [3]. 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.

4.1.2 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. 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 [36]. 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. took an iterative participatory design approach and studied the home environments of people with stroke to identify requirements for home-based stroke rehabilitation [6]. 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. shared the insights and challenges that they identified in developing home-based technologies for stroke rehabilitation [37]. 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. implemented a prototype of a chess game with a tangible interface and their case study shed light on how the user perceived and interacted with the prototype [8]. 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.

4.1.3 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 [54] and studying the biomechanics of reaching [80]. In this paper, 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 [106, 118]. Such kinematic data contains precise positions of limbs through motions in time. In comparison, the data supplied by 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. surveyed a number of input devices used for various measurements of stroke survivors' movements [130]. 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 [51, 91]. 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 them. 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 motion. Games have the potential to provide a unique opportunity by making both intent and motion available for measurement of user's motion abilities. In our work we take the first steps toward utilizing this potential that games provide.

4.2 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:

- 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.

4.3 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 before, at the middle and at the end of the six-week period. In the following sections we present the details of our case study.

4.3.1 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.

4.3.1.1 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 non-dominant 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.

4.3.1.2 Recovery on Her Own

Once at home, Marie worked to regain some of the abilities that she 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.

4.3.1.3 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.

4.3.1.4 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.

4.3.2 Game Infrastructure

We developed a game infrastructure by improving the capabilities and usability of the game system described in [3] 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.

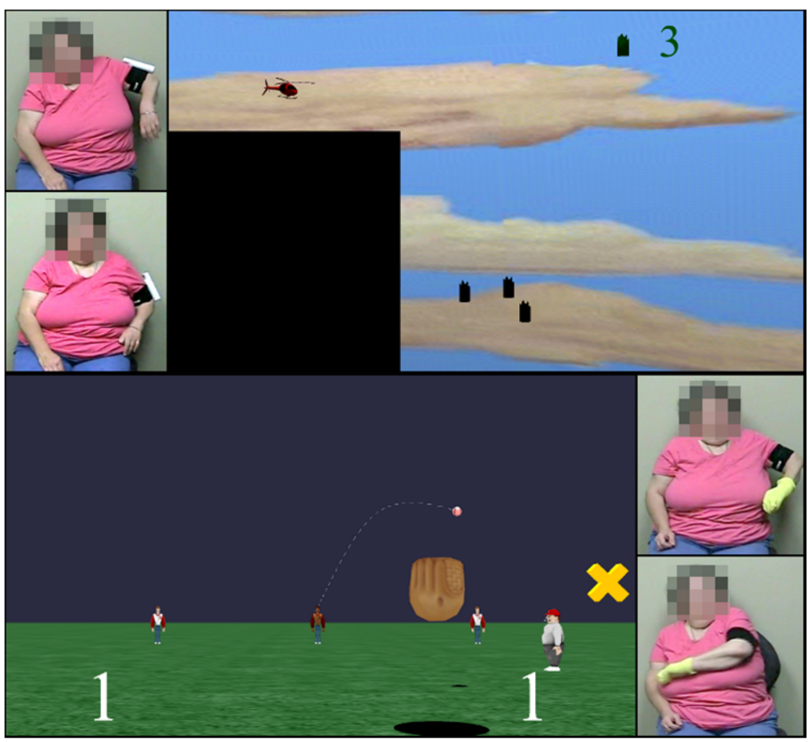

Figure 4.1. Marie playing Helicopter by raising and lowering her arm to fly over buildings and collect fuel cells (top) and Baseball Catch by moving her hand in space to catch baseballs and avoid basketballs (bottom).

4.3.2.1 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 (see Section 3.5.2): Helicopter, Pong, and Baseball Catch [3]. 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 4.1). 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 4.1). 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: elbow flexion and extension, arm reaching, shoulder abduction and adduction, and wrist flexion and extension motions. After choosing the exercise motions, 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 participant's background was another factor in the choice of the games. 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. We chose Helicopter as the other 1D vertical game, 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 4.6.3.1).

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, 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 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 4.2). 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 4.3.3.2.

Figure 4.2. The game menu in the launcher program used to start and play the games.

4.3.2.2 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 and Pong). The web camera games used a simple color tracker [3]. She placed a brightly colored sock over her hand while playing Baseball Catch.

4.3.3 Home Play

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

4.3.3.1 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 [3]. 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 prevent cases in which the game would expect her to move outside of her effective range. This process took approximately one minute for each game.

4.3.3.2 Games

The participant exercised with the three games described in Section 4.3.2.1: 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 4.1). 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 4.1). 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.

4.3.3.3 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. She tried both throughout the study.

4.3.4 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 4.4.2). 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.

4.3.5 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 4.4.3. 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.

4.4 Data

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

4.4.1 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.

4.4.2 Interview Data

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

At the pre-study 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 semi-structured 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.

4.4.3 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 [128]. 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 [72, 106]. 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.

4.4.4 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 users' 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 (see Section 4.4.4.3).

4.4.4.1 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.

4.4.4.2 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.

4.4.4.3 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 those weeks. Consequently, the graphs in Figure 4.5 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 (see Figure 4.3 and Figure 4.7).

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

4.5 Results

Over the course of six weeks, the participant played the games largely as directed with occasional deviations (see Table 4.1). Note that she started to play Helicopter (wrist) on week 3 (see Section 4.3.3.3). We assessed our participant's motor abilities using 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.

Table 4.1. 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

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

4.5.1 Standard Therapeutic Measurements

We used ARAT and RPS (see Section 4.4.3) 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 [89], our participant showed two statistically significant improvements over her baseline performance (see Table 4.2). 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 [59].

Table 4.2. 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*

4.5.2 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.

4.5.2.1 Number of Repetitions

Research based on human and animal studies suggest 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) [103] rather than studies on humans (in the order of tens) [69]. Prior studies of stroke recovery in animal models suggest that hundreds of daily repetitions are required to make progress towards recovery of motion abilities [103]. 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.

4.5.2.2 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 [61].

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 sub-area 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 4.3 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.

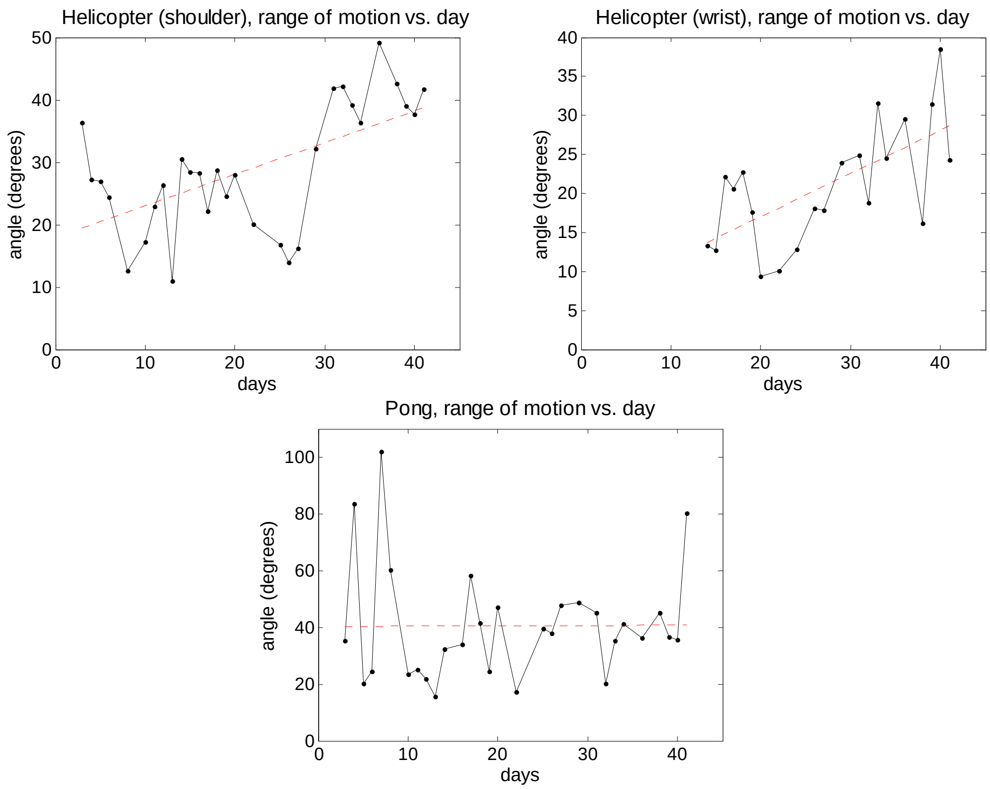

Figure 4.3. Range of motion vs. day plots for the games played with the Wii remote. Least squares fit line is represented by the dashed line in the figures. An increase in angle indicates improvement in range of motion.

It is also important to note that there are significant variations in range of motion from day to day. This result is similar to that of Golomb et al.'s home-based study with smart glove inputs [45]. These variations are also consistent with our participant's perception that on some days she finds it much easier to move her affected arm than other days.

4.5.2.3 Motion Precision

To successfully complete functional tasks in daily life, people recovering from stroke need to increase the precision of their motions [61]. 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 they deviate 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 gets 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 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.

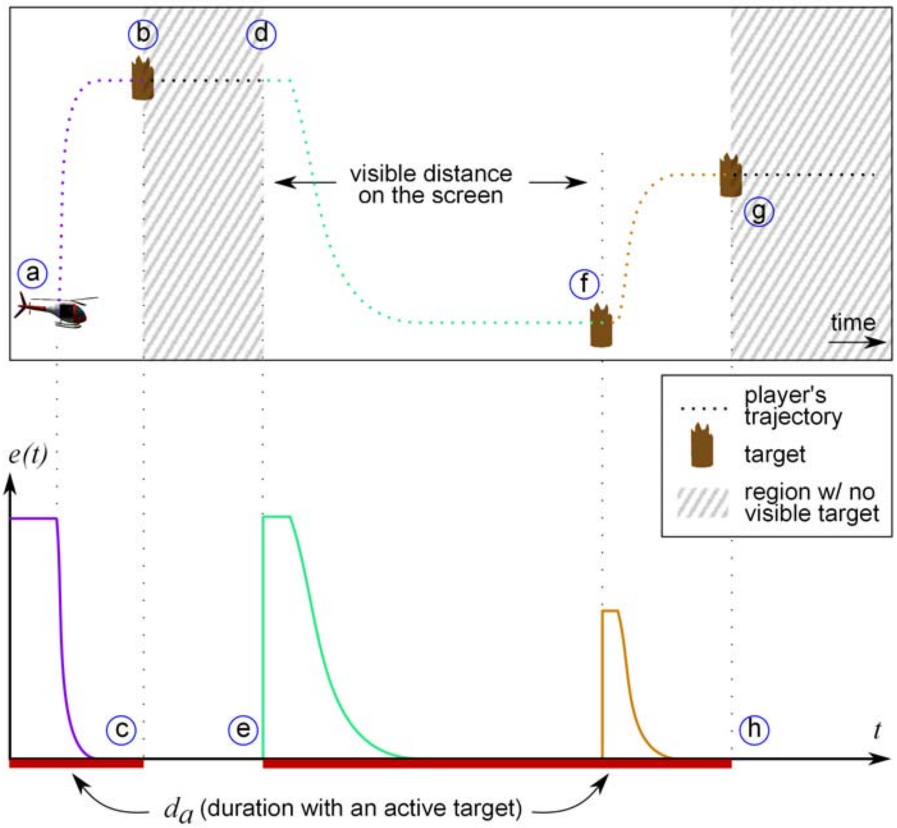

Figure 4.4. Calculation of target error. Top: sample game trajectory of the Helicopter game in which the user controls the helicopter's vertical position while the helicopter advances to the right. Bottom: the corresponding target error function *e(t)*, which is the vertical distance between the helicopter and the next target.

We define the cumulative target error as the sum of the player's distance to the anticipated target position over time (see Figure 4.4). 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 4.4 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.

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 4.5. 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 4.4.4. 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.

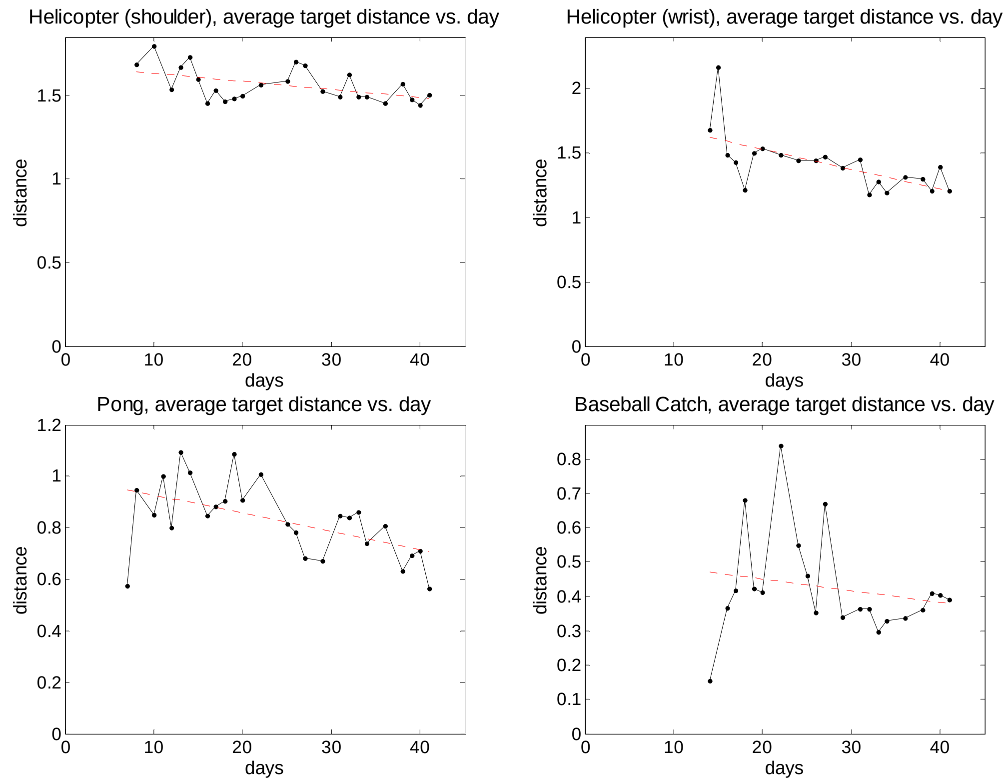

Figure 4.5. Average target error vs. day plots for each game. A decrease in distance indicates improvement in motion precision.

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.

4.5.2.4 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 [101]. 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.

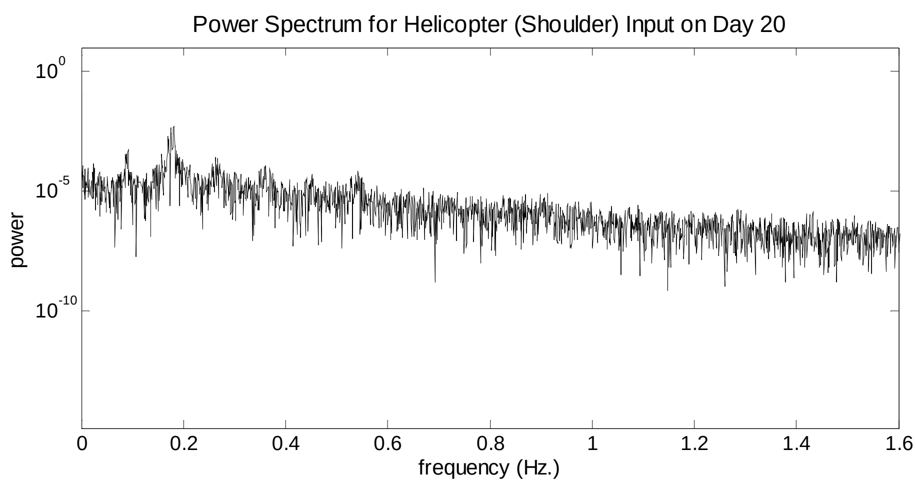

Figure 4.6. Power spectrum of sample Helicopter (shoulder) session indicating that the signal is dominated by a motion with a frequency around 0.17 Hz. This corresponds to a movement that repeats every 5.9 seconds (flying over buildings).

Figure 4.6 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 up 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 4.7 includes the plots of this tremor index for each game.

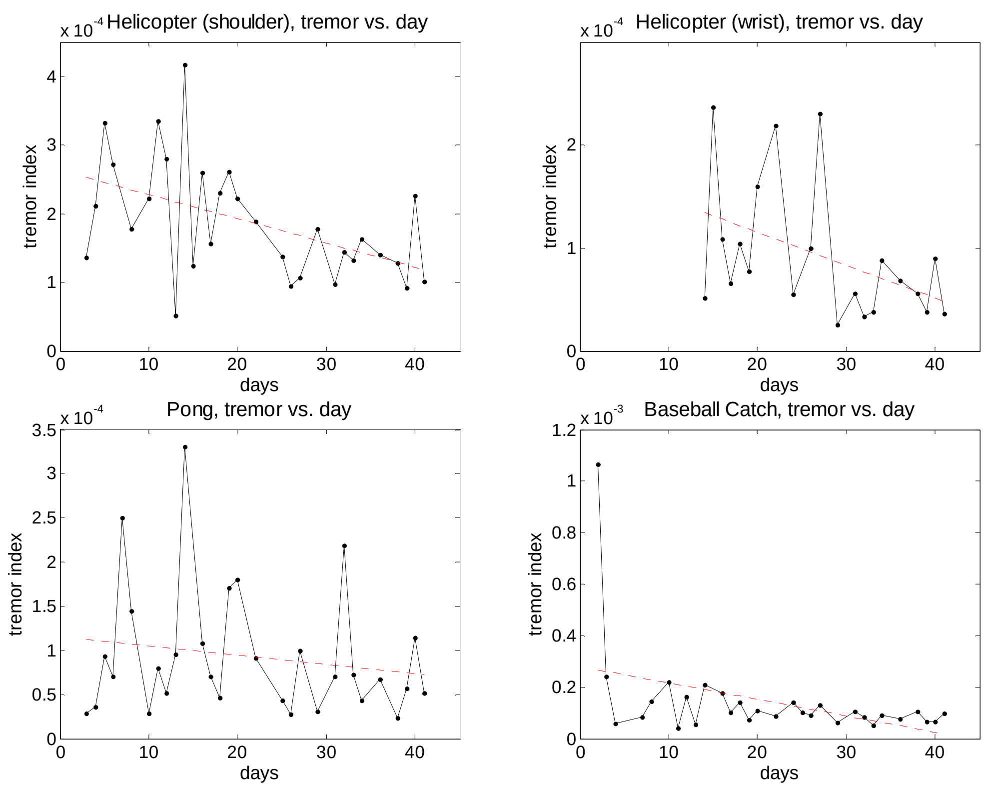

Figure 4.7. Tremor vs. day plots for games played with Wii remotes. A decrease in tremor indicates improvement in motion smoothness.

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, 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 4.8). 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.

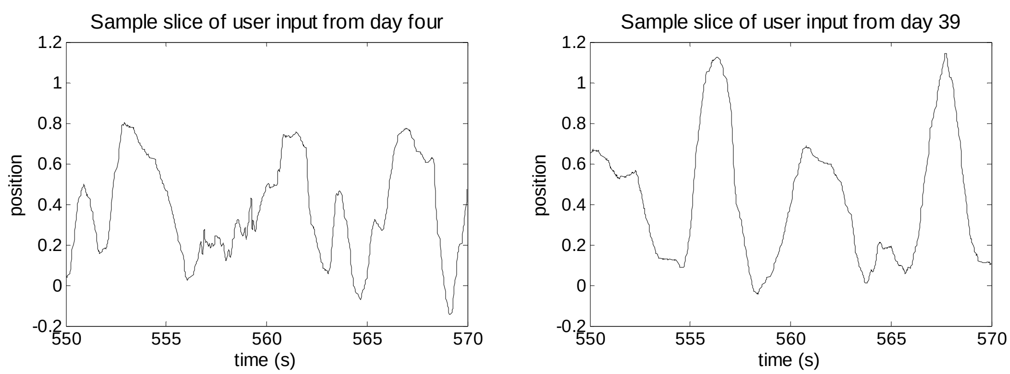

Figure 4.8. Sample slices of user input for an early and a later session of Helicopter (shoulder). The session on day 39 has visibly less noise.

4.5.3 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.

4.5.3.1 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 in. 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:

- 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]."

4.5.3.2 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 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."

4.5.4 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.

4.6 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.

4.6.1 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.

4.6.1.1 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 re-calibrated 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.

4.6.1.2 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 4.5), 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.

4.6.2 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.

4.6.2.1 Continue to Adjust Calibrations Based on Game Play

Motion calibration plays an important role in ensuring that games are therapeutically useful [3]. Previous research suggests that calibrating through example motions can capture the player's range [3]. 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 of a range, but failed to help her understand if she set too conservative of 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.

4.6.2.2 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.

4.6.3 Motivation

Few people perform therapeutic exercises at home as directed because they find home-based therapy boring [104]. 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.

4.6.3.1 Pre-Stroke 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 pre-stroke activities may provide a motivating context for therapy [8]. 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.

4.6.3.2 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 therapeutic games to provide motivation for them to keep going.

4.6.3.3 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 small mini-games for testing purposes.

4.6.3.4 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 4.5). 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 4.6.1.

4.6.4 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.

4.6.4.1 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 grown up again and it feels good. Now I'm perceiving what's possible."

She shared one perceived possibility during our post-study 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.

4.6.4.2 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 is 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.

4.6.4.3 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 it was not only her that was 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 at 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.

4.6.4.4 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.

4.7 Limitations

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 below and discuss possible ways of addressing them.

4.7.1 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.

4.7.2 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.

4.7.3 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 that is based on therapy without video games [59], 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 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 it is the case.

4.7.4 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 arm in a purposeful way. However, the need to understand and reliably quantify progress remains an important challenge.

4.7.5 Compensatory Motions

Perhaps one of the biggest limitations was that when unsupervised, our participant tended to use compensatory motions as she exercised, i.e., she used muscles and joints that were not part of the exercise to compensate for the lack of motion in the muscles and joints she was expected to use. We addressed this in elbow exercises by attaching another Wii remote on the upper arm to detect and remove compensatory motions. However, we could not find an easy solution to detect and remove compensation with the trunk in shoulder exercises. In addition, even though we were removing the compensatory motions from the exercise and making sure she was playing the game with her elbow, this was not stopping her from compensating. We were effectively using the elbow motion and ignoring the compensation.

We gave a presentation about our work to a group of therapists and doctors. The presentation contained general information about the study and contained videos of our participant exercising. Although the general feedback was that this was a much needed solution, one of the few issues that the audience agreed on was that the compensatory motions of our participant were harmful. Without finding a way to entice her to reduce the compensation she performed, the exercises she performed were bound to be less useful compared to exercise that she would perform with the supervision of a therapist.

4.8 Discussion

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.

Although we demonstrated that games can indeed be useful for people with stroke as a part of an outpatient therapy program, there were some significant shortcomings. While most issues can be overcome with further studies and trying to understand users better, we believe that the issue of using compensatory motions was one of the most significant as well as one of the most difficult issues. Therefore, we wanted to answer the research question: how can we detect torso compensation and develop games to cause it to be reduced? We deal with this issue in the following chapters.

Chapter 5

Compensation: A Major Issue in Unsupervised Therapy

Through our work in earlier chapters, we have demonstrated the possibility of using video games to enable and motivate people with hemiparesis to perform their therapeutic exercises at home, without supervision. Our short-term and long-term user tests uncovered various important considerations for the success of a therapeutic video game system for people with stroke. As a next step, we wanted to take our knowledge further by identifying major issues in our system and finding solutions to them. We conducted meetings with therapists and identified that compensation is a major issue not only with our system but with home-based therapy in general. Therefore we studied compensation further and found ways of addressing it through the rest of our work.

In the previous chapters, we presented our efforts on developing a video game system for stroke rehabilitation. We attempted to uncover what properties a game for stroke rehabilitation should have, how to address user-centric issues related to people with stroke playing video games and how to integrate a video game system in outpatient therapy practice. Our six-week home study demonstrated the viability of such a system and uncovered issues that may come up during home use. These encouraging results indicated the possibility that an affordable video game system for home-based stroke rehabilitation can be feasible.

To make further progress towards a game-based home rehabilitation system, we wanted to identify major issues with our current design and attempted to address them. We consulted with physical and occupational therapists, conducted group meetings and presented the details of our work as well as videos of our participant performing therapeutic exercises with our system. One point that therapists unanimously agreed in our meetings was that our participant was not always performing the exercise motions correctly. While performing the exercises, she tended to compensate for the lack of motion in one joint by moving another joint. For example, because of the difficulty in moving her shoulder, our participant was using her torso to help move her arm, which enabled her to succeed at the game. The therapists agreed that compensation is already a common issue with unsupervised exercises outside of games and should be addressed for better recovery. They also noted that therapists would look for evidence of compensation when they supervised therapy sessions and would provide feedback to prevent it. Unless our system is able to reduce compensation similarly, the exercise that it enables would be inferior to that of supervised therapy sessions. Therefore, we identified compensation to be a major issue with our system and wanted to address it properly.

Throughout the rest of this work, we attempt to address compensation by creating a home-based exercise system that targets correcting therapeutic exercises. In this chapter we present the problem of compensation and the state of the art for addressing it. In later chapters we present multiple studies in which we created and verified an accessory to detect compensation, designed a game that focuses on enabling corrections on the exercise motions, created different versions of it to observe effects of different design decisions and compared these game versions in within-subjects controlled experiments to observe their effectiveness in promoting correct exercises. We focus on shoulder exercises and torso compensation because they are one of the most common therapeutic exercises that a majority of people with stroke can perform.

5.1 Background

Therapeutic exercise is known to help stroke survivors with hemiparesis experience motion improvements [70]. In most cases, hemiparesis makes it difficult if not impossible to carry out exercises properly [70]. Using the correct joints and muscles in these exercises similar to a nondisabled person is important for experiencing proper motion improvements [40]. Therapists can help people with hemiparesis to correct their exercise motions. However, limitations on therapy resources require a typical stroke survivor to perform therapeutic exercises at home, often without the supervision of a therapist. They are likely to perform the therapeutic exercises incorrectly when they exercise by themselves [40]. In addition to basic home exercises, people may start using game-based systems in the near future that motivate them to exercise. However, research on such systems pays little attention to the correctness of the therapeutic exercises. As a result, when people with hemiparesis perform therapeutic exercises at home, they currently do not have a means of helping them perform the exercises correctly. Research suggests that this may prevent them from experiencing proper motion improvements [40]. In this work, we attempt to address this issue by developing the first game-based exercise system that is focused on correcting exercise motions to increase their therapeutic value.

5.2 Problem

As a part of therapy, stroke survivors with hemiparesis perform repetitive therapeutic exercises in order to improve their motion abilities. The way they perform these repetitive motions plays an important role on how the motion improvement will take place. The ideal case is to enable the type of recovery that will bring back their premorbid motion abilities (i.e., the way they used to move before their stroke). This requires performing repetitive exercises that are similar to their premorbid motions. However, the limited motion of people with hemiparesis forces them to use other muscles and joints to help and they tend to perform exercises using compensatory motions. If they exercise with compensatory motions, part of the long-term motion improvement takes place through learning to compensate better. This causes them to miss the opportunity to experience a more complete motor recovery [22]. Therefore, reducing compensation in therapeutic exercises is important for enabling better motion improvements in which stroke survivors may regain premorbid motion abilities.

5.3 Types and Levels of Motor Improvements after Stroke

Here we clarify the definitions used throughout this text that are related to motor improvements. According to Levin et al.'s classification [73], motor improvements after stroke happen in two ways: (a) recovery and (b) compensation. We explain these types of improvements in an abstract level. Improvement can be because of recovery, in which the person returns back to a premorbid state. Another type of improvement is through compensation, in which the person does not return back to a premorbid state, but adapts to the postmorbid state or substitutes other facilities in place of the lost ability [73]. In addition, Levin et al. examine improvement in three different levels pertaining to the nature of the change: improvement in (1) health condition, (2) bodily functions and (3) activity [73]. The abstract definitions of recovery and compensation become more concrete when they are considered in the context of one of these levels. Recovery and compensation mean different concepts when addressing these three different levels [73].

The health condition level refers to the changes in the brain. Recovery in this level means the restitution of damaged brain tissue, and compensation means motor map reorganization. While the healing of the whole damaged tissue is less common, the restitution in the neighboring areas can be sufficient to provide the person with recovery of lost motor abilities [73]. In contrast, compensation in this level refers to adaptation through substituting the role of the damaged brain region to other parts of the brain to control the body parts that used to be controlled by the damaged region. While this is a complex area of study, research using fMRI scans can shed light on the nature of improvement in the health condition level [17].

The bodily functions level refers to the elementary movement patterns such as flexing a muscle, moving a joint in a certain way, or coordinating multiple joints. This level is concerned with the quality of motions rather than fulfillment of tasks. Recovery in this level means that the person can perform the lost elementary movement patterns and move the body parts similar to the premorbid motions. Compensation in this level means adapting the motions to the motor limitations (e.g., using the shoulder more in arm motions), or making up for the lost motion by substituting other body parts that are not normally used for the task (e.g., moving the trunk to move the hand).

The activity level refers to the fulfillment of activities compared to how the person was able to perform them before the stroke. In this level, achieving the end goal of the activity is more important than the quality of motion in performing the activity. An example to compensation in this level is opening a bottle by holding it in place between the legs and opening the cap with one hand. Holding the bottle with one hand instead of the legs, and opening the cap with the other hand is considered recovery in this level.

Note that the same motion gain can be considered as different kinds of improvement in different levels. For example, if a patient can relearn to use a fork with his or her hand, but does it differently than a nondisabled person by using his or her shoulder more than before, we can classify his or her improvement as recovery in the activity level, compensation in the bodily functions level, and most likely compensation in the health condition level. To explain it further, he or she is considered to be recovered in the activity level because he or she is able to carry out the activity with the same end-effector similar to his or her premorbid days. He or she is compensating in the bodily functions level because he or she is using his or her shoulder excessively to make up for the limited arm motion. He or she is most likely compensating in the health condition level because he or she is most likely not using the part of his or her brain that he or she used to for this task before the stroke. Our focus in this work will be on the bodily functions level.

5.4 Therapy and Motor Improvement

The goal of motor rehabilitation is to improve motion through repetitive exercises, preferably through recovery rather than compensation. Since rehabilitation is fundamentally a behavioral intervention, it can directly address bodily functions and activity levels rather than the health condition level (i.e., changes in the brain). Typically, therapists direct clients to perform repetitive exercise motions in one-on-one sessions. Therapists correct the exercise motions that clients perform through providing feedback and physical assistance. These corrections can address motion quality (e.g., shoulder angle, the use of the body, etc.) to reduce compensation in the level of bodily functions. They can also address the task being performed (e.g., bringing the fork to the mouth) to reduce compensation in the activity level. This way therapists aim to entice the client to perform correct therapeutic exercises in order to enable recovery of bodily functions and activities.

In this work we are focused on motor rehabilitation and how to enable it with the use of a computerized system. Similar to motor rehabilitation with therapists, we target improvements in bodily functions and activities since they can be addressed in a behavioral way. Since improvements in bodily functions are usually reflected in improvements in related activities, our main focus is motion improvement in the level of bodily functions. We are not focused on the health condition level, since we are not dealing with the neurological aspects of recovery. Therefore, our definition of motor recovery and compensation rely on observable changes of the client's motion behavior. In the following sections, we clarify the definitions of motor recovery and compensation used in the rest of this document.

5.4.1 Motor Recovery

By "motor recovery" we refer to reacquisition of elemental motion patterns through change in bodily functions, which is the main reason for improvement in motion abilities. Through therapy exercises, stroke survivors may regain the ability to move their body parts in ways that are similar in quality to motions of nondisabled people. The underlying causes of motor recovery may include restitution of damaged neurological structures and reorganization of motor mapping of the brain. As a result of motor recovery, the person may regain functional abilities to use in everyday life. Regardless of its biological causes and behavioral effects, motor recovery in terms of reacquisition of elemental motion patterns is one of the main goals of motor rehabilitation following stroke. This motion reacquisition process is the kind of motor recovery that we are interested in.

5.4.2 Compensation

By "compensation" we refer to adaptation or substitution of bodily functions in place of ones that are lost. Hemiparesis caused by stroke limits the ability in bodily functions (e.g., flexing and extending the elbow). These limitations initially prevent completing tasks that depend on them (e.g., reaching for objects on a table). If the lost bodily functions are not restored, the person learns to circumvent them and achieves tasks differently. The new way of achieving the tasks may involve adaptation of remaining bodily functions (e.g. rotating the shoulder more to make up for the elbow while reaching) or substituting other bodily functions in place (e.g. reaching with the tip of the elbow rather than the hand). We refer to both of these behavior types as compensation.

Through learning to compensate, a person may achieve tasks that she could not achieve because of the lost bodily functions. For example, a stroke survivor who cannot extend his hand can use his elbow to turn the light on or off. He can also lean forwards with his body to reach for objects on the table. While compensation can help a person be successful at a task, it is generally undesirable because it can (1) limit motor recovery and (2) result in health complications in the long term.

Compensation can limit motor recovery, which usually happens through correct repetitive exercise [40]. By repeatedly performing the part of the motion that the person cannot complete, he or she gives the brain a chance to reorganize and relearn how to complete the motion again. Compensation provides an alternative way to complete the task, therefore the person stops attempting to complete the task the original way in which he or she is not able to. As a result, he or she loses the chance to relearn to complete the task the way he or she could before the stroke [20, 22, 40].

Another disadvantage of compensation is that it can cause long-term health problems. Most kinds of compensation promote the use of body parts in ways that are different than how a nondisabled person would move. Using body parts in such unnatural ways for a long time can create orthopedic problems such as reinforcing distorted joint positions, causing muscle shortening and reducing the range of joint motion [20]. Such problems usually come with pain and discomfort [73] which can reduce the quality of life for a stroke survivor.

Despite all these disadvantages, compensation may be acceptable for people with severe disabilities and without much hope for motor recovery [73]. However, for most other stroke survivors, compensation is undesirable. Therefore, the goal of rehabilitation is to minimize compensation and allow motor recovery to take place.

5.5 Addressing Compensation with Therapists

Traditionally, compensation has been addressed in motor rehabilitation with one-on-one sessions with a therapist [70]. In therapy sessions, therapists direct clients to perform therapeutic exercises and provide feedback to correct the compensatory motions. They can either physically correct the motions through moving the clients' limbs with their hands, or provide verbal feedback on how the client should be moving.

Without such feedback, the client is more likely to compensate as a result of exercise [22].

Note that therapists can provide two types of corrections. They can either provide feedback about the end result of the motions, i.e., knowledge of results (KR). Alternatively, they can provide feedback about the quality of the motion itself, i.e., knowledge of performance (KP). In a reaching task, an example to KR is "try to reach further" as it provides feedback about the end result of the motion. An example to KP is "extend your elbow more", as it provides feedback on the way the motion is performed. For nondisabled people, KR is more effective in motor learning. However, for people with hemiparesis, KP is shown to be more effective in motor recovery [19, 21]. Therefore, by providing feedback about the quality of the exercise motions, therapists can help clients reduce compensatory motions and make progress towards motor recovery.

5.6 Addressing Compensation without Therapists

Therapists can address compensation in one-on-one therapy sessions with clients. However, these sessions require time and effort on the part of therapists. Therapy resources are limited and are not sufficient for all stroke survivors. Therefore, most stroke survivors that have access to therapy receive it in the form of outpatient therapy, in which they only see the therapist once a week. In a typical outpatient therapy setting, the client and the therapist get together in the clinic for one-on-one weekly meetings. In these meetings, the client performs therapeutic exercises with the supervision of the therapist. However, motor recovery requires daily repetitive exercises [70]. Therefore, these weekly supervised exercises are not sufficient to make progress towards motor recovery. To overcome this limitation, the therapist prescribes a daily exercise regimen for the client to perform at home without supervision. Unlike the supervised exercises in the clinic, there is nothing that prevents the client from compensating in these unsupervised home exercises. Therefore, most of the exercises performed in outpatient therapy lack the feedback that would reduce compensation. Considering that people with hemiparesis are likely to compensate in the absence of feedback [22], addressing compensation in unsupervised home exercises is currently an important open problem.

In addition to classical outpatient therapy, there are other settings in which people with hemiparesis may perform therapeutic exercises without the supervision of a therapist. The advent of telerehabilitation [53] and rehabilitation with motion-based video games at home [3] promise that people with hemiparesis can exercise at home without the presence of a therapist. However, they either ignore the problem of compensation, or address it insufficiently. Similar to home exercises in outpatient therapy, addressing compensation using home exercise systems is also an important open problem.

5.6.1 Proposed Solutions

Addressing compensation in unsupervised exercises may help stroke survivors reduce the amount of compensation during exercise, and help them make progress toward motor recovery. Despite its importance in enabling motor recovery and eliminating long-term health issues, there is little research done on reduction of compensation in unsupervised exercises. Here we review the three studies that aim to address this issue. These studies are based on therapist feedback through telerehabilitation, physical trunk restraints and audio feedback driven by pressure sensors.

5.6.1.1 Reducing Compensation through Telerehabilitation

Telerehabilitation systems aim to enable therapists to supervise therapeutic exercises from a distance through the use of networked multimedia technology. There is research done on telerehabilitation systems that acknowledge the necessity to address compensation in exercise. A notable example is Holden et al.'s work, in which they used expensive motion capture equipment to detect exercise as well as trunk compensation to be reported to the therapist [53]. While this was effective, the use of expensive equipment poses a barrier to wide-spread home adoption. Another example is Lum et al., who delegated the responsibility of detecting compensation to a therapist [79]. The therapist remotely supervised the session through the videoconferencing equipment of the telerehabilitation device, and instructed the client when he or she used "obvious compensatory movement strategies" while completing exercise tasks. While this approach can also be effective, observation and feedback through a videoconferencing system may not be optimal.

While telerehabilitation enables home rehabilitation without the presence of a therapist, it requires the therapist to be on the line and to remotely supervise the session. It may be superior to in-person rehabilitation through eliminating the time, cost and inconvenience of transportation. However, it still requires the time and attention of the therapist to supervise the sessions remotely. Since therapy resources are limited, the person would have to perform at least some of the exercises without supervision and without feedback on compensation.

Further, observing and providing feedback on exercises through a videoconferencing system may be inferior to the in-person alternative. The therapist may not be able to observe all the details of the motion through the camera and may miss some compensatory motions. The expensive motion capture alternative resolves this issue by creating another one: the high expense of the system that would prevent wide-spread home adoption. In either case, the feedback that the therapist provides through videoconferencing equipment is likely to be inferior to the in-person alternative. When in-person, the therapist can touch and guide the body parts of the participant in order to provide most accurate and timely feedback. However, in videoconferencing, the feedback of the therapist is confined to the audio and video transmission, and is in the mercy of the client's attention—the client may sometimes ignore the feedback since there is no way of escalating to physical feedback.

Because of these issues, we believe that feedback through telerehabilitation is not a viable solution for reducing compensation in unsupervised home exercises unless it is improved in a way that does not require the therapist's constant attention and unless ways of improving detection and feedback mechanisms are invented that can replace the therapist in a cost-effective way.

5.6.1.2 Reducing Compensation through Trunk Restraints

A number of researchers addressed the need to reduce compensation using trunk restraints (i.e., strapping the trunk to a chair) to prevent trunk motion in arm exercises [73, 113, 123]. Levin et al. showed that using trunk restraints together with task-related training of the upper limb causes motor recovery by frequently providing the brain with somatosensory input that is close to motion patterns before the stroke [73]. They suggested that this technique be used in clinical practice to improve the effectiveness of reaching exercises. In a similar study, Thielman et al. compared trunks restraints to resistive exercise and showed that trunk restraints resulted in better motor recovery [113]. In addition, Woodbury et al. introduced trunk restraints into intensive task practice of constraint induced therapy and showed that it enabled motion recovery in terms of straighter reaching trajectories and less trunk movement [123]. In all these studies, exercises with trunk restraints were supervised by therapists. While using trunk restraints is shown to be effective, they have three potential issues: (1) so far trunk restraints have not been used in unsupervised exercises, (2) they address compensation of only trunk movements, and (3) they may not necessarily teach how to resist moving the trunk.

As we explained in Section 5.6, it is necessary to find ways of reducing compensation in unsupervised home exercises. However, the studies that use trunk restraints took place in a clinical environment and the participants performed the exercises under the supervision of a therapist [73, 113, 123]. We included them in our review because it may be possible to use trunk restraints in unsupervised home exercises in the future. However, more studies are necessary to determine whether this potential can be realized. While we acknowledge this future potential, we anticipate that ease of use and safety will need to be addressed. Without identifying and addressing the issues that may come up with home use, we believe that trunk restraints are currently not a viable option for reducing compensation in unsupervised home exercises.

Another disadvantage of trunk restraints is that they only address compensation using the trunk. There are therapeutic exercises that compel the use of body parts other than the trunk for compensation (e.g., compensation using the shoulder for elbow flexion/extension exercises). While restraints for other body parts may be designed, they may be less convenient compared to strapping the trunk to a chair. In addition, addressing different compensation motions would require different pieces of equipment, which may introduce additional inconveniences to the process.

The last potential disadvantage of using a trunk restraint is that it does not necessarily teach the person to prevent using the trunk. Using a trunk restraint enables the repetitive exercise of the arm motion without the use of the trunk as compensation and facilitates motor recovery of the arm independent from the trunk. Without the trunk restraint, this may not be possible in persons that are used to compensating with the trunk. However, even though the person experiences motor recovery in the arm during the training, she may still find it easier to use the trunk as compensation [112]. Therefore, finding other approaches that can teach not using the trunk may be more valuable.

Although trunk restraints are currently not a viable option for reducing compensation in unsupervised home exercises, further research may find ways of making them a viable option. However, we anticipate that the physical nature of the solution would maintain the concerns related to convenience, ease of use and safety.

5.6.1.3 Reducing Compensation through Auditory Feedback

The success of trunk restraints in improving the motor recovery of the arm and the limitations of using a trunk restraint has led Thielman to explore other alternative methods of reducing trunk compensation in arm exercises [112]. With the goal of both reducing trunk motions during exercise and teaching not to use the trunk for compensation, Thielman created a system that automatically provides feedback for compensation. He used a pressure sensor attached to the back of a chair to detect when the person uses the trunk in forward-reaching motions. When the trunk reduced the pressure on the back of the chair, an auditory signal warned the person to remind him or her not to compensate. He observed that this approach was at least as effective as using a trunk restraint. This system resulted in motor recovery that is similar to that of trunk restraints and especially resulted in better improvements in reaching to targets that are close to the person's body [112].

Thielman's work showed that using an auditory signal may be preferable to using trunk restraints in terms of enabling motor recovery without compensation. An added benefit of this is the potential to actively teach the person not to compensate. Areas of possible improvement are replacing the simple nature of the auditory signal with a more user-friendly and motivating form of feedback and using the same approach for other body parts.

In addition to providing equal or better motor recovery compared to trunk restraints, using an auditory signal has the added benefit of actively teaching the person not to compensate. When trunk restraints are used for preventing compensation, the person is physically prevented from moving the trunk. With the auditory feedback, the user cognitively decides not to move the trunk upon hearing the audio signal. This way, the user learns to prevent the trunk motion while performing arm exercises. Through internalizing this self-control mechanism, the person may recover motions in a way that is closer to ones before the stroke and may better avoid compensation in the long term [112].

One limitation of Thielman's study is that it only addressed a very specific type of compensatory motion: leaning forwards with the trunk in reaching exercises. While the main idea of the auditory feedback is generalizable, the way he detected compensation is specific to the motion used—the pressure sensor attached to the back of the chair can only detect the motion of the trunk away from it. Detecting other kinds of compensatory motions (e.g., compensation using the shoulder for elbow flexion/extension exercises) may not be as simple.

Another point that Thielman's study can be improved on is the nature of the feedback. The auditory signal provides a simple feedback that makes the users aware of compensation that they perform. We believe that more effective and motivating feedback strategies can be devised with the help of games.

Despite its limitations, the idea of automating both the detection of compensation and the provision of feedback can be a viable alternative for reducing compensation in unsupervised home exercises. In this work, our goal is to build on this idea and provide feedback that would reduce compensation in the context of unsupervised exercise with motion-based video games. At the same time, we would like to present the feedback in such a way that will not discourage the person from playing the game.

5.6.2 Discussion

Reducing compensation in unsupervised exercises is a very important requirement in stroke rehabilitation that has not received the necessary attention that it deserves. Without addressing it, unsupervised exercises are likely to increase compensation over time [22], prevent proper motor recovery [40] and create additional health issues [20].

Despite this important limitation, current outpatient therapy practice does not provide effective ways to reduce compensation in home exercises, which constitute most of the exercises that a person performs in outpatient therapy. This is a major issue that may prevent proper motor recovery for stroke survivors receiving outpatient therapy. A solution that helps reduce compensation in unsupervised exercises would be useful for millions of people with hemiparesis that need to perform home exercises [124].

In addition to current outpatient therapy practice, there are many systems that are proposed for home-based stroke rehabilitation. While they target changing the way outpatient therapy works and facilitating new ways of performing home exercises, they simply ignore the fundamental issue that people are likely to compensate without appropriate feedback. Therefore, these systems are bound to be suboptimal unless they adopt reducing compensation as one of their primary goals.

As reducing compensation is such a fundamental issue with the effectiveness of unsupervised exercises, both existing rehabilitation practice and new rehabilitation approaches require ways of addressing it. In this work we take a step towards providing a way for addressing compensation in game-based rehabilitation systems. We specifically focus on shoulder exercises and torso compensation because it is one of the most common therapeutic exercises that most people with stroke can perform. We present our efforts for addressing compensation with games in the rest of this document.

Chapter 6

Reliably Detecting Compensation with the Torso

As a first step in starting to design games and comparing them in terms of how much they reduce compensation, our goal was to ensure that we can reliably detect the exercise and compensation motions with Wii remotes. We designed and created a harness that can hold a Wii remote on a person's back, tested it with users and iteratively improved it. Then we verified the precision of motions detected using Wii remotes attached with the harness and an armband by comparing them to ground truth motion capture data. As a result of this process we created a way to detect shoulder exercise and trunk compensation using Wii remotes, and showed that the detection error is likely to be within reasonable bounds.

6.1 Requirements

To study reducing compensation during exercise with motion-based games, we chose to address trunk compensation in the context of shoulder exercises (see Figure 6.1). We wanted to detect the corresponding motions using Wii remotes so that we can use them in games. Additionally, we wanted to derive measurements from the detected motions precise enough to be used as data in comparative studies.

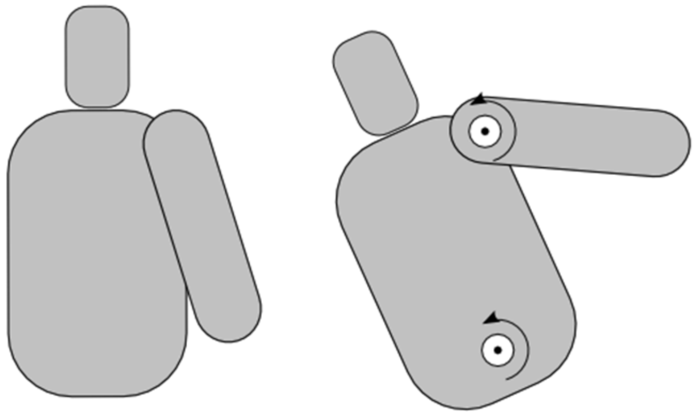

Figure 6.1. Shoulder abduction/adduction exercise rotates the upper arm around a horizontal axis. Using the torso to compensate would also rotate the torso around a horizontal axis. Therefore, they can both be detected using accelerometers.

6.1.1 Detect Shoulder Exercise and Trunk Compensation

People with stroke use different body parts for compensation in different therapeutic exercises. In this work, we decided to concentrate our efforts and address one type of exercise and compensation. We chose shoulder exercises and torso compensation because (1) detecting torso motions with a Wii remote is more challenging compared to detecting arm motions, (2) shoulder exercises are common therapeutic exercises that most people with hemiparesis can perform and benefit from.

While we successfully detected motions of the limbs by attaching Wii remotes to them in our previous work, we did not detect motions of the torso as we were not able to find an easy way to attach a Wii remote to it. Therefore, we decided to address compensation of the torso in this work, so that our findings can later be used with forms of compensation that are easier to detect.

In addition, we chose shoulder exercises because they are one of the most common therapeutic exercises. After hemiparesis because of stroke, people have more motion in parts of the body that are closer to their chests and less motion towards the tips of the limbs [103]. Throughout the recovery process, people typically first recover motion in the shoulder, followed by the elbow, the wrist and the fingers [103]. Therefore, shoulder exercises are among the most common therapeutic exercises that are used in stroke therapy and we chose to focus on them.

6.1.2 Reliably Measure Compensation

We want our exercise and compensation measurements to be more precise than what is sufficient to play a game, so that we can compare different techniques on how they affect compensation. In our work in the previous chapters, we observed that webcam color detection provided measurements that were sufficient to play a game, but they may not be sufficiently precise to be used as measurements. On the other hand, we observed that angle measurements that we extract from Wii remotes appeared precise enough for comparative measurements. Therefore, we use Wii remotes to measure compensation during exercise. This requires reliability in both the way we attach the Wii remotes and the algorithms that we use to extract measurements from them.

6.2 Preparation

We wanted to use the three-axis accelerometers of Wii remotes to detect shoulder abduction/adduction as exercises and torso bending as compensation. Initially, possible issues that we anticipated were limitations of accelerometers and difficulty in attaching Wii remotes to users' body parts.

6.2.1 Using Accelerometers for Shoulder Abduction/Adduction and Trunk Compensation

A limitation of accelerometers is that they cannot detect rotation around the vertical axis. However, the main components of shoulder abduction/adduction and the related compensation of the body are perpendicular to the vertical axis (see Figure 6.1).

Therefore, we found that this limitation of accelerometers did not prevent Wii remotes from being suitable for detecting these motions.

6.2.2 Attaching Wii Remotes

Another issue was attaching Wii remotes to the body parts to be tracked. We wanted the Wii remotes to closely track the motions of the body parts. To detect shoulder abduction/adduction exercise, we needed to attach a Wii remote to the upper arm, which we have done in our previous studies using armbands with success. However, detecting compensation in the form of bending the torso required attaching a Wii remote to the trunk of the person. We have not done this before and we anticipated it to be a challenging task.

We could not find any commercial solution for attaching a Wii remote to a person's torso, unlike the armbands that we used that were specifically designed to hold a Wii remote attached to one's arm. Therefore, we had to create a solution from scratch. This was a challenging task compared to attaching a remote to the arm. The arm is isolated from other body parts and their motions, it is mostly a rigid bone structure, arm widths are bounded in a certain range, usually there is light clothing on the arm and it is possible to roll up the sleeves if necessary. Most of these qualities are the opposite for the trunk. The trunk is confined between other limbs and is affected by their motions, it is composed of a number of bones that move relative to each other, trunk sizes vary greatly depending on one's body figure and people wear various kinds of clothes that may slide over the body as they move. Therefore a solution had to

- detect only motions of the body, should not detect motions of the shoulder and collar bone
- work with different body builds
- work with different kinds of clothes

According to these requirements, we designed a harness, improved it in an iterative design process through user tests and verified its detection of motions by comparing it to motion capture data.

6.3 Formative Study: Detecting Compensation

We wanted to ensure that we could reliably detect the exercise and compensation motions with Wii remotes. Therefore, we conducted an iterative, formative user study to develop and verify (1) a Wii remote harness that enables attaching a Wii remote to a participant's torso and (2) a compensation detection algorithm based on the accelerometer readings of Wii remotes attached to the participant's arm and torso. We developed the harness and the algorithm, tested it with users and iteratively improved it. Then, we verified the motions detected using Wii remotes by comparing them to motion capture data.

6.3.1 Participants

Three female Occupational Therapy (OT) doctoral students and four participants with stroke (three female, ages 55-60) participated in a series of single user study sessions.

6.3.2 Session Description

We conducted seven, 45 minute, single user sessions. After obtaining consent, we assisted the user in putting on two Wii remotes, one each on the upper arm and the torso. Next, we asked the participant to perform repeated shoulder abduction/adduction exercises to control an on-screen target that moves vertically with exercise and tilts with compensation to catch oncoming targets (see Figure 6.2). During the session, we adjusted the difficulty settings (motion range, target frequency and speed) in order to create an appropriate challenge level such that participants demonstrated some compensatory motion behavior without being asked to compensate.

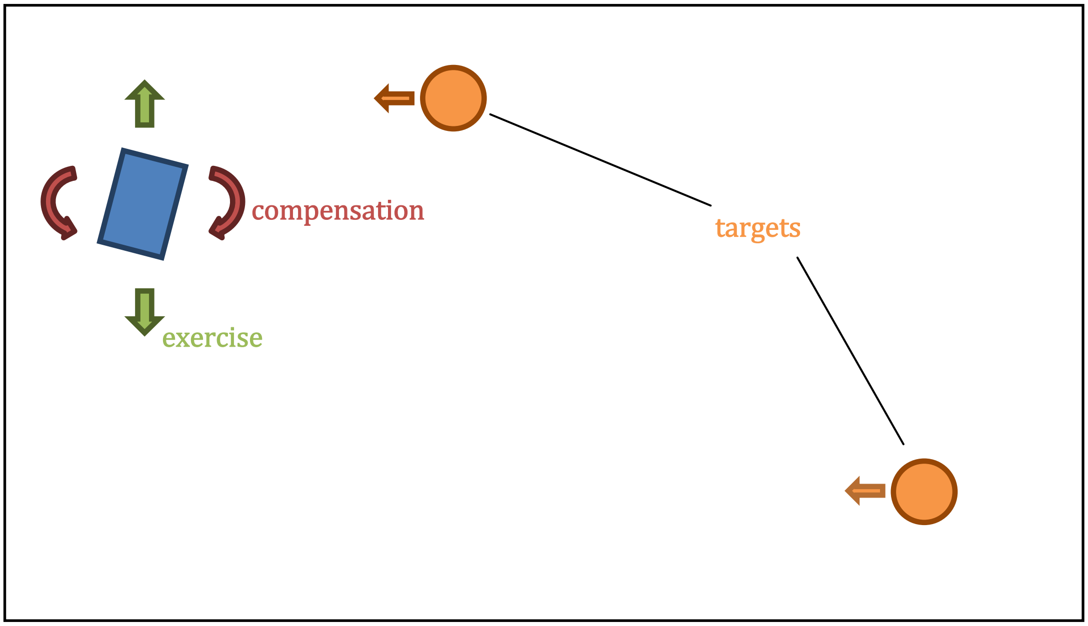

Figure 6.2. Representation of the visuals feedback during exercise sessions.

We created the harness using webbing, buckles, staples, and duct tape. First we designed and tested the harness and the motion detection algorithm with OT participants. In subsequent sessions, we worked with participants with stroke to further refine our harness design and algorithm.

After each session, we conducted a semi-structured interview to learn more about the experience of the participants. We asked questions about whether the harness was comfortable, ideas about improving the harness, ideas about improving the process, and what we can expect when we conduct user tests with stroke survivors. We used these answers to improve the harness. We also used these questions to improve our user test process as we anticipated conducting similar user test sessions in studies that would follow this one (e.g., formatively developing a game).

6.3.3 Data

We captured accelerometer data from the arm and torso Wii remotes, with which we computed exercise and compensation angles. We also recorded video of the participant's motion and reviewed the video and the recorded accelerometer data to identify issues with the harness and the algorithm.

6.3.4 Initial Design of the Harness

We wanted to design a harness that would hold a Wii remote attached horizontally to the trunk to track trunk motions. We considered different locations in the trunk and decided to attach the Wii remote on the middle-back. Then we designed and developed the harness so that it would hold a Wii remote there as the user performed shoulder abduction and adduction exercises.

6.3.4.1 Location of the Wii Remote

For the target location to track with the Wii remote we chose the back of the trunk, right below the scapula and on the lower half of the rib cage (see Figure 6.3). The reasons for choosing this location are: (1) the rib cage closely reflects the motion of the trunk, (2) the back of the body usually contains less fat compared to the front, (3) the lower half of the rib cage is less affected by the scapula and the muscles around it compared to the upper half.

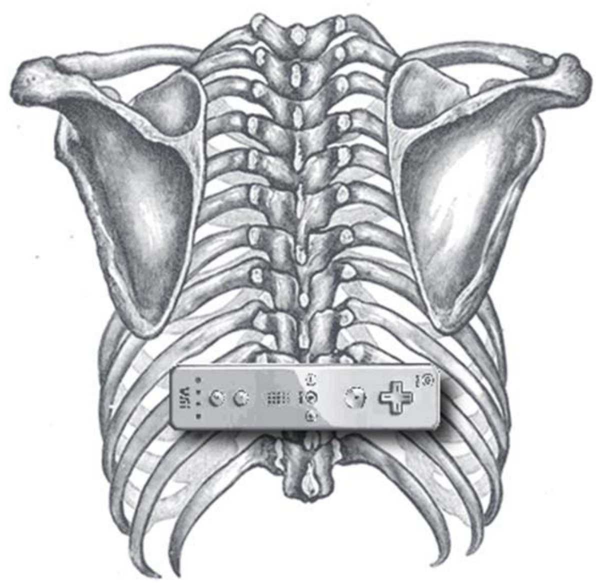

Figure 6.3. Approximate desired placement of a Wii remote for detecting torso motion.

6.3.4.2 The Harness

Our goal was to design the harness in a way that will keep the Wii remote on the lower back of the rib cage. We initially designed it similar to existing body harnesses used for various other activities (e.g., fall protection, scuba diving, etc.). We built a prototype using webbing straps as the main connecting material. We cut the webbing straps with scissors to appropriate lengths, connected them together with a stapler, and attached tension lock triglides so that the size of the harness could easily be adjusted. We included connections using plastic side-release buckles to make it easy to put on and take off the harness. When worn, the harness has a horizontal webbing strap across the lower half of the rib cage. We attached a Wii remote pocket to this strap so that it could hold the Wii remote on top of the lower rib cage (see Figure 6.5.a).

6.3.5 Initial Design of the Algorithm

Initially, we used a simple method for detecting motions of the Wii remotes. We used the approach in Section 2.3.3 for both Wii remotes and assumed that each Wii remote rotates around a fixed axis during exercise and compensation. We identified these axes and the default pose in a short calibration session using sample motions that the user performs. We used them later to calculate angles for the arm and the body. We used the body angle as compensation and the difference between the two angles as exercise. We divided them by their maximum values captured during calibration to convert them to normalized values. This simple algorithm was sufficient to reflect the angles detected by the Wii remotes. We improved it in Section 6.3.7.1 to correct issues and better match user expectations.

6.3.6 Lessons Learned

Over the course of the study, we learned several lessons about the design of the torso harness (see Figure 6.4) and the compensation detection algorithm.

Figure 6.4. The harness we designed to track the torso motion with a Wii remote. The pocket that holds the Wii remote is attached to the rectangular brown cardboard piece.

6.3.6.1 Attach the Harness around the Neck, Not the Shoulders

Initially, we designed a backpack-style harness with two straps going over the shoulders. However, we quickly realized that straps of such a harness rested on the clavicle, which moved with arm motions even though the trunk is not moving. This resulted in motion of the Wii remote that is held by the harness, and prevented detecting the trunk motion alone. We switched to a diagonal design so that the harness rests towards the neck and away from the shoulder to minimize the effect of arm motions on the harness (see

Figure 6.5). We covered the harness with soft cloth to prevent it from rubbing on and hurting the neck.

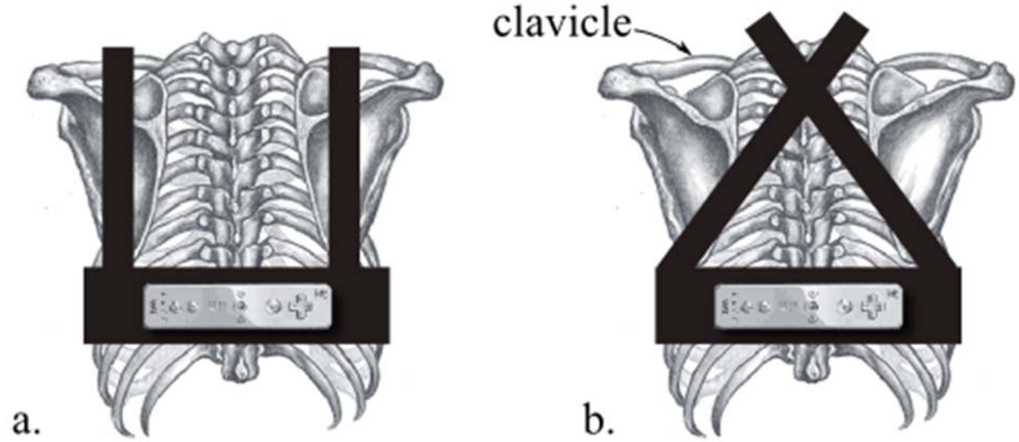

Figure 6.5. Wii remote harness with straight straps (left) vs. diagonal straps (right). Diagonal straps avoid motions of the clavicle from moving the Wii remote.

6.3.6.2 Stabilize the Wii Remote against the Back to Prevent Rolling

Initially, the Wii remote pocket that the Wii remote resided in was connected to a line of webbing. Since the webbing is soft and not rigid, this attachment sometimes allowed the Wii remote to roll against the user's spine. This resulted in false compensation readings. To prevent this, we fastened a piece of firm cardboard to the back of the Wii remote holder so that the Wii remote could not move without moving the cardboard with it (see Figure 6.4). The cardboard was wide and tall enough so that it would rest on the rib cage even when the harness would loosen a bit. This minimized the motion of the Wii remote independent from the trunk, and enabled reliable detection of the trunk motion.

6.3.6.3 Participants Do Not Always Compensate the Same Way

We originally assumed participants would always compensate in the same way. Specifically, we expected that participants' compensatory motions would manifest themselves as Wii remote rotations around a single, user-specific axis. Accordingly, we identified these axes in the calibration stage and used them to compute angles during gameplay. However, during user sessions we observed that as some users attempted to reduce the compensation feedback, they began to compensate around an axis that is perpendicular to the axis identified during calibration, which our original algorithm did not capture. For example, one user started out by leaning to the side to compensate. In time, she noticed that the game was not noticing when she leaned to the back. Gradually, she transitioned to leaning back which also made it easier for her to perform the exercise motions.

To prevent this, we modified the algorithm in Section 6.3.5 to calculate the angle between two free orientation vectors: a captured resting pose vector and the live vector of the Wii remote (i.e. the player's current torso orientation). We note that these two vectors alone do not tell us the direction of compensation (see Figure 6.6.b). To determine the compensation direction, we define tilting the body backwards and away from the player's affected arm as positive compensation (i.e. it decreases the motion's difficulty). Similarly we consider tilting the body forward and towards the affected arm to be negative compensation (see Figure 6.6.c).

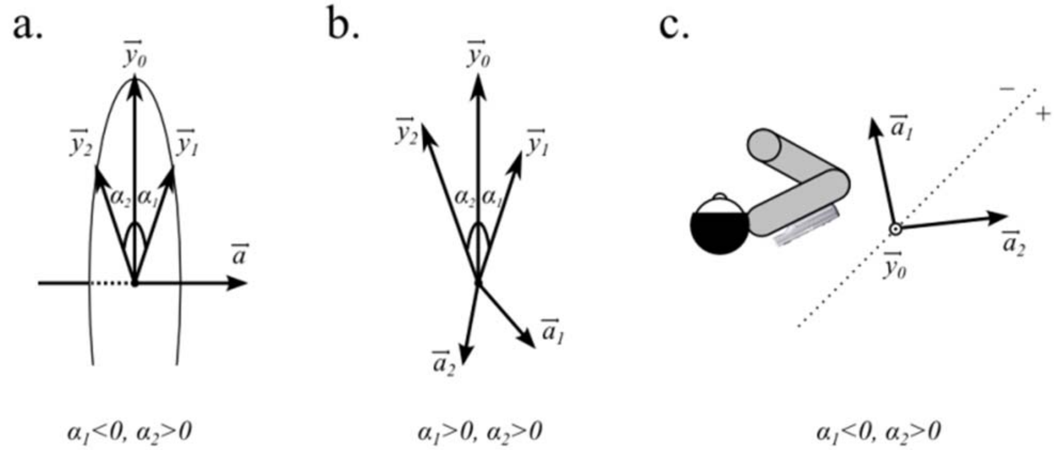

Figure 6.6. The evolution of compensation detection. A. Assuming a fixed axis enables calculating directional angles and setting the sign of angles using the right hand rule. B. Removing the axis assumption and using axes perpendicular to the current inverse gravity vector and the default one (y_0) makes all angles positive. C. Assuming that leaning back or towards the stationary arm is positive compensation enables us to set the sign of the calculated angle using the axis for the inverse gravity vector.

6.3.6.4 Players' Default Poses May Change Over Time

As playing time increased, we noticed that participants' resting pose vector sometimes changed, because either they shifted sitting positions or the harness slipped. This led to situations in which the participant was sitting straight but the game registered slight compensation.

To avoid this, we update the resting pose vector throughout each game session. We observed that when a player's arm is low, the player is likely to be at rest. During these times, we updated the resting pose vector using exponential smoothing with a low weight to slowly move the previous resting pose vector towards the captured vector. Over time, this converges to the participant's new resting pose.

6.3.7 Final Design

We shaped the harness and the algorithm throughout the formative study by improving it according to the issues that we found in our user tests. Figure 6.4 shows the final design of the harness that we built using material including webbing, staples, tape, cloth, cardboard, etc. The diagonal strap design helped avoid effects of arm motions, the cloth helped prevent the webbing from hurting the neck and the cardboard helped prevent the Wii remote from moving independently from the torso.

6.3.7.1 Final Algorithm

We also improved our algorithm and removed the assumption that compensation will always be the same way, so that we can detect compensation towards any direction. We also adjusted to the changes in default pose in time. The final algorithm works as follows: in the calibration stage, we ask the user to perform the exercise motions with and without using the trunk. Using the sample motions, we calculate the arm axis $\vec{a}$ the way we described in Section 2.3.3.1. For the body Wii remote attached to the torso, we only capture the default inverse gravity vector $\vec{y}^0_{body}$ detected when the user is at rest. After calibration is complete, we calculate the arm angle as described in Section 2.3.3.1. For a given vector $\vec{y}_{body}$ that the body Wii remote senses, we calculate the body angle α as follows:

$$\vec{a} = \hat{y}_{body} \times \hat{y}^0_{body}$$

$$\alpha = \begin{cases} \angle \hat{y}_{body}\hat{y}^0_{body} & \vec{a} \cdot \vec{a}_p \geq 0 \\ -\angle \hat{y}_{body}\hat{y}^0_{body} & otherwise \end{cases}$$

Where $\vec{a}_p$ is a vector towards the back-right of the user if the user is using the right arm to exercise (perpendicular to the dotted diagonal line in Figure 6.6.c). This way, the angle is positive when the user is performing compensation that would help the exercise and negative when the user is leaning in a way that would not help the exercise. We use this angle α as the compensation value. We subtract α from the arm angle θ to find the difference angle that represents the exercise angle. We divide it by the maximum arm angle calculated during calibration θ_{max} to get a normalized exercise value $v = \frac{\theta-\alpha}{\theta_{max}}$.

In addition, we assume that the user is not exercising when the arm angle θ is below the threshold θ_{ex} and update the default vector $\vec{y}^0_{body}$. At every frame,

$$\vec{y}^{0new}_{body} = \begin{cases} \vec{y}^0_{body} & \theta < \theta_{ex} \\ t\hat{y}^0_{body} + (1-t)\hat{y}_{body} & otherwise \end{cases}$$

$$\vec{y}^0_{body} \leftarrow \vec{y}^{0new}_{body}$$

The outputs of our algorithm are v that represents the normalized exercise value and α that represents the compensation angle.

6.4 Validation Study: Detecting Compensation

Although we were visually satisfied with the detected motions, we wanted to validate them by quantifying the error between the detected motions and the ground truth. This error would determine our level of confidence in the motion measurements and help us put the error into perspective by comparing it to other potential sources of noise.

To facilitate this we conducted two user studies. In the first study, we used motion capture data as the ground truth and used it to find the error in the motions detected by the Wii remotes. In the second study, we asked an occupational therapy student to perform the shoulder exercises by reaching to fixed heights indicated by a tripod. By asking her to repeat the exercises under different conditions and in different days, we obtained a consistency metric that we could compare to the error that we found in the first study. We validated the detected motions by showing that the error value of detection with the Wii remotes is smaller than the error value that represented the user's consistency.

6.4.1 Participants

Two female OT doctoral students participated in the study. We recruited Ots because their familiarity with persons with stroke allows them to simulate a wider variety of motions that people with stroke may perform. While the motion of an OT participant may not be the best representative sample of the general stroke survivor population, using an OT participant helped us to avoid the danger of recruiting a participant with stroke that is not representative of the general body of persons with stroke. In addition, the daily motion variation of OT participants is expected to be less than that of participants with stroke. This helped us to avoid the possibility of the participant's motions changing greatly between daily sessions and creating too loose of a reference for acceptable error.

6.4.2 Session Descriptions

We began each session by attaching Wii remotes to the arm and torso of a participant. The first participant also wore the reflective markers of a motion capture system (see Figure 6.7). Participants then performed ten repetitions of sixteen different shoulder abduction/adduction exercise sets (160 repetitions). Sessions took approximately 45 minutes.

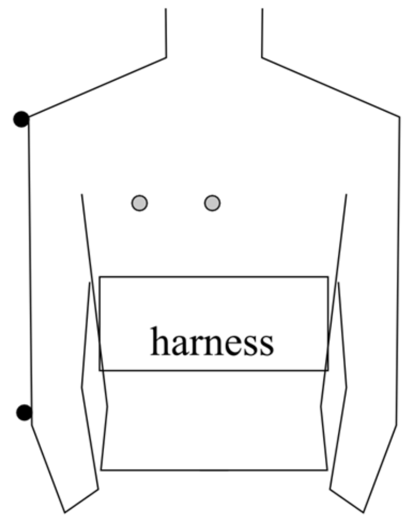

Figure 6.7. The reflective motion capture markers that we used to track the body angle (gray) and the arm angle (black), both in the coronal plane.

The sixteen exercise sets varied four types of reaching tasks with four types of visuals. Each task required participants to raise their elbow to a target. The four task types were: (1) reaching low targets, (2) reaching low targets with resistance (i.e., a Theraband attached to the arm), (3) reaching high targets, and (4) reaching high targets while trying not to move the body at all. The four types of visuals were: (a) no visual feedback, (b) a physical tripod to display the target height during exercise, (c) a graphical balloon moving on a monitor, and (d) the same graphical balloon that rotated with participants' torso compensation. Using these different cases, we attempted to create different conditions that users play the game in. Before each set, we used the tripod to briefly show the height that the user should move to, and moved it away for sets that did not have the (b) tripod as the visual.

Since our sets were discrete, we automatically recalibrated the system before each set of ten repetitions and recaptured participants' default poses. This nullified the need to continuously update the default pose vector (see Section 6.3.7.1).

The first participant completed only one session in which we recorded her motions measured using both the Wii remotes and the motion capture system. The second participant completed four sessions on different days to capture day-to-day motion variability. We counterbalanced learning effects using a Latin Squares designs.

6.4.3 Data and Analysis

During the user sessions, we collected the accelerometer readings of the Wii remotes and took videos of the participants. For the first participant, we also recorded her motions using the motion capture system.

We note that while the Wii Remotes and motion capture system are capturing related information, they are not capturing identical information. This is in part due to the physical placement of the Wii remotes and the reflective markers. We were able to track the participant's torso motions with reflective markers placed on the upper back because the harness covered the middle back (see Figure 6.4 and Figure 6.7). Because the upper back moves more than the middle back when a person arches, the motion capture recorded larger angular changes compared to the torso Wii remote. To enable comparisons, we normalized each signal using the largest recorded angle of the session for each device.

As motion signals were recorded using different devices (laptop with Wii remotes and motion capture system), they were not perfectly aligned in time. Given two signals $a(t)$ and $b(t)$, we aligned them as follows:

$$\arg min_t \; e(a(t), b(t), t)$$

Where e is the error function that finds the error between the two signals that we define below. Thus, we align the two signals in a way that minimizes the error between them.

Given the two time-aligned, normalized motion signals $a(t)$ and $b(t + t_a)$, we calculated the error between them by integrating the absolute value of the difference between the two signals and dividing it by the time. This represented the error per unit time between the two signals:

$$e(a(t), b(t + t_a), t) = \frac{\int_t |a(t) - b(t + t_a)|}{t}$$

We calculated the Wii Remote error with respect to the motion capture data for both the arm and the body angle signals of the first participant. We normalized and aligned both the Wii remote angle signals and motion capture angle signals for each set, calculated the error between them and averaged them to find the Wii error with respect to motion capture data.

To calculate the second participant's consistency error, we wanted to find the average error between different sessions of the second participant. We did not directly compare the corresponding exercise sets because unlike the first participant's data, they did not belong to the same session but different sessions in different days. Timing differences would create unnecessarily large error values if we compared them directly. Instead, we hand-segmented each of the ten exercise repetitions in a set, aligned the corresponding exercise repetitions in the two sets that we wanted to compare, calculated errors for each and averaged them. This accounted for the timing differences between motions on different days.

6.4.4 Results

Table 6.1 lists the results of the error measurements of Wii remote data compared to the motion capture data of the first participant's motions (first row) and the error measurements between the Wii remote data of the second participant's motions from four different sessions. We calculated the error values both for the arm and the torso.

Table 6.1. Error measurements for the Wii remotes and the user.

Error type	Arm	Torso
Wii remote error	3% (SD: 0.5%)	6% (SD: 1%)
User error over sessions	5% (SD: 0.9%)	16% (SD: 4%)

We assume that the user error that we measured, which is the average error between the second participant's daily motions, is representative of the error that a user may introduce in motion measurements. We observe that the error of our system is lower than the user error, both for the arm and the torso. This suggests that the error that our system introduces may be bounded by the difference between how a healthy person intends to move and how he or she actually performs.

6.4.5 Discussion

Overall, we found that the measurement error using the Wii Remotes is lower than the daily motion variation of a healthy person. Our work in Chapter 4 indicates that people who have experienced a stroke are likely to have high daily variation in motion, which we expect to be more than that of a healthy person. Since the error of our system is lower than the error that a healthy person may introduce, it should also be lower than the error that people with stroke may introduce. Therefore, we believe this is an acceptable error level to enable compensation measurements through our game.

While there is room for further improving the accuracy, we note that our compensation measurement method represents a significant advance over current comparable practices for measuring compensation. For example, chair-mounted pressure sensors are only useful for measuring the pressure while the back touches the chair [112]. Once the user starts to compensate and the back leaves the chair, it is not possible to detect the amount of compensation anymore. Another alternative is visual judgment of a therapist, which is likely to be less precise than accelerometer measurements and would vary between therapists [79].

With a way of detecting both shoulder exercise and torso compensation, and a certain level of confidence over our compensation and exercise measurements, our goal is to develop games that use them together as inputs. Another goal is to use compensation measurements as indicators on the level of compensation that participants perform while playing the games and try to reduce it using game content. However, we do not know how we should create such a game because we are not aware of a game for stroke survivors using both exercise and compensation as inputs. Furthermore, we do not know how we can use games to encourage users to compensate less. We would like to find out how to address these issues in the rest of the document.

Chapter 7

Formative Study: Designing a Compensation-Aware Game

To move closer to our goal of reducing compensatory motions in therapeutic exercise through video games, we created a video game that meaningfully uses exercise and compensation inputs.

Although compensation is a major problem in unsupervised therapeutic exercise at home, very few researchers use devices suitable for unsupervised home use to detect compensation [3, 4]. Our work in Chapter 3 and Chapter 4 was the first to use compensation in a game. We only subtracted compensation to ensure that the game is played only using exercise motions and the game otherwise ignored compensation. Thielman et al.'s work in which they provided an audio signal in response to compensation showed that reacting to the sensed compensation can be useful to improve intervention outcomes [112]. While they did not measure a significant reduction in compensation during exercise, we hypothesize that using compensation in a game-based interaction can be helpful in changing users' exercise behaviors and help them to perform less compensation.

7.1 Goals

Our goals in this study were to create a game that uses exercise as the main input, gives simple feedback about compensation, be difficult enough to cause users to compensate and ease data collection during game play.

Our main goal was to create a game that uses the sensed compensation in addition to the exercise as user input. We wanted to create a game that is played mainly through the exercise motions like our previous work in Chapter 3 and Chapter 4, while at the same time informing the user about the compensation level inspired by Thielman et al.'s work [112]. We refrained from preemptively giving compensation a more important role in the game (i.e., game success did not depend on compensation input) so that our game could be comparable to Thielman et al.'s approach in the sense that it simply informs the user about compensation.

We wanted to create our game in a way that participants will naturally compensate while playing it, so that we can measure the reductions in compensation through modifications that we would make on the game later.

Another goal was ease of data collection. After observing in Chapter 4 that arbitrarily designed games can make it difficult to extract meaningful information about participants' motion abilities, we wanted to design our game in a way that makes collecting data easier.

To fulfill these goals, we conducted an iterative, formative study to develop and improve a game that uses exercise and compensation as inputs.

7.2 Participants

We recruited eleven participants with stroke from ages 43 to 72. Six of them were female and five of them had their left side affected by stroke. Participants ranged from three to eleven years post stroke, and had various levels of disability.

7.3 Session Description

We had one session with each participant that took approximately one hour. Sessions took place in participants' homes. Following a questionnaire to record participants' background and stroke history, we assisted participants with putting on Wii remote attachments. Participants sat in front of an external monitor connected to a laptop that ran the game.

We first demonstrated the shoulder abduction/adduction motion to the participants and told them that exercises are more useful with less compensation. We asked them to complete a calibration session (see Section 7.5.1). Later we introduced them to the game and asked them to play using the exercise motion.

During the sessions we made live modifications to the game using the laptop and quickly tested our ideas on what may work with the participants. Sessions took between one to three hours and ended with semi-structured interviews to understand participants' experiences.

Figure 7.1. The balloon game: the player moves the balloon vertically to catch parachute jumpers.

7.4 Initial Base Game Design

In our game, the player controls the vertical position of a hot air balloon as it flies in front of a horizontally scrolling background (see Figure 7.1). The player's goal is to snag parachute jumpers at varying heights on the screen. The participant performs shoulder abduction/adduction exercises as he or she moves the balloon up and down to collect the parachutes (see Figure 7.2). We spaced parachutes 6.5 seconds apart and had no simultaneous displayed parachutes to make the game approachable for players with a high level of motor disability.

We attached Wii remotes on the arm and the back using an arm strap and the harness that we developed, calibrated them, and extracted the normalized exercise value and the compensation angle as we explained in Chapter 6. We used the normalized exercise value to determine the vertical position of the hot air balloon so that the participant cannot use compensatory motions to succeed in the game. We mapped the compensation angle to the balloon's left and right tilt to provide participants with an awareness of the torso motion.

Figure 7.2. A participant with stroke testing our base game with Wii remotes attached to the arm with an armband and to the back with the harness that we designed.

7.5 Lessons Learned

We made several changes to our base game during our formative study to capture appropriate calibration data, encourage therapeutically beneficial motions, ensure adequate challenge, and provide suitable feedback during the game.

7.5.1 Include Calibration as a Part of the Game

Games that attempt to influence compensation behavior must capture two distinct types of calibration information: range of motion and a compensation profile. Initially, we determined these values all at once during a short calibration session separate from and before the game, in which we instructed participants on how they should move. However, users were conscious of their motions during this calibration and as a result these motions were not representative of their motions during the game. We tried a number of different methods and found that seamlessly including calibration in the beginning of the game session and have it be very similar to the game was most successful in capturing the necessary calibration information. We used a two stage calibration process at the beginning of the game: we first captured the motion range and then the expected compensation.

7.5.1.1 Step 1: Capturing the Motion Range

We captured an initial crude approximation of motion calibration by asking the participant to perform the exercise motion 3 or 4 times. Using this approximation, the player then began a calibration level that behaved like the full game except that the balloon did not tilt. We placed six pairs of parachutes at the high and low ends of the screen while resizing the range with users' successes and failures with the high parachutes. Every time the user caught a high parachute we increased the range to make it more difficult and every time he or she missed a high parachute we shrunk the range to make it easier. We did not increase the range if he caught the very last one to ensure that we do not end up with a range that is beyond the participant's range. At the end of this process, we obtained a motion range that the participant is able to reach, but would not be able to reach if it was larger.

This approach was more effective in capturing range of motion compared to other approaches in which we either asked participants to move as much as possible, or they tried to reach fewer targets.

7.5.1.2 Step 2: Capturing Sample Compensation Behavior.

After capturing the range of motion, we captured compensation behavior by sending 20 parachute targets one by one, with the same pseudorandom position sequence as the actual game. This way we captured how the user would be moving had the game actually started. We observed that this resulted in compensation behavior that is quite similar to compensation behavior during game play. We later used the mean compensation captured during this calibration process as the threshold to activate compensation feedback in the game.

This approach was more effective in capturing compensation behavior compared to other approaches in which we either asked participants to use their bodies or tried to force them to compensate by asking them to reach targets that are too high.

7.5.2 Encouraging Therapeutically Beneficial Motions

Encouraging therapeutically beneficial motions required us to place both low and high targets, provide obstacles and align success indicators with desired behaviors.

7.5.2.1 Place Targets at Both Motion Range Extremes

Using repetitive motions that cover the entire motion range are a preferred way to maximize the therapeutic use of exercise motions. To achieve this, we initially placed most parachutes near the top of the screen in a pseudorandom way and left time between targets. We assumed players would choose to lower their arms to rest between targets. However, some participants preferred to keep their arm raised to minimize the motion between targets. We countered this by placing some targets at the bottom of the screen, which encouraged players to assume a low resting position in between high targets.

7.5.2.2 Obstacles Promote Controlled Motions

We observed that some participants used a timed jerking motion to reach target positions at the high end of their range. They did not have much control over such motions, which can decrease their therapeutic value. Accordingly, we introduced buildings as obstacles which required users to move the balloon above the building and hold their arms up stationary for a short duration. This was difficult for some players, even though they could reach targets placed higher than the building tops. As they observed that jerky motions caused them to hit the buildings, they opted to use more controlled motions for the targets that followed.

7.5.2.3 Use Player's Success Indicators to Shape Motion Behavior

We found it important to ensure that desired and undesired behaviors correspond to meaningful in-game success indicators. In our initial game, if a player crashed into a building the game played a sound but did not change the player's score. This did not cause some users to spend sufficient effort to avoid the buildings. After we added a score deduction, users became reluctant to hit buildings. This is an example behavior change that games can cause when we provide appropriate consequences. After a series of user tests we decided to give five points for each parachute and deduct five points for hitting buildings. This helped simple accounting when users wanted to keep track of their scores, and allowed us later to use single scores as a reduced score feedback for compensation (see Section 8.2).

7.5.3 Ensuring Adequate Challenge with Short, Difficult Tasks

The varying range of players' motor disabilities made it difficult for us to provide adequate challenge for all players. For instance, making the game slow enough for participants with the least motion reduced the challenge for others. To address this we introduced a new target that is intentionally too challenging for most users, but only rarely appears to avoid frustration. We introduced a moving cloud that appeared in front of the balloon and quickly moved up and down a few times while sending out little clouds that the user can pick up for extra points. We also played an upbeat music while the cloud was active. Whether they succeeded in collecting the little clouds or not, most users found the cloud to be exciting and looked forward to its next arrival. In addition, some users counted how many of the little clouds they were able to catch each time and used it as a self-assessment measure.

7.5.4 Providing Suitable Feedback during Gameplay

We found that some of our assumptions while developing the game did not meet the expectations of participants. We modified our game's feedback to reduce unwanted surprises by ensuring only arm motion affected balloon height, avoiding punishment for compensation during rest, and always providing compensation feedback.

7.5.4.1 Only Arm Motion Should Appear to Affect Balloon Height

We initially used the input mapping that we designed in Chapter 6: the difference between the arm angle and the body angle determined the vertical location of the balloon. Body motions had a negative contribution to the balloon height to prevent participants from using compensation to move the balloon higher. As a side effect, when a player was at rest while playing our initial game, the balloon appeared to move on its own because of his or her body motions, which often surprised the player. Users expected to see the balloon move vertically only as a consequence of moving their arms and did not expect the balloon to move as a result of body motions when their arms were at rest. We addressed this issue by continuously switching between two different height functions for the balloon. When the balloon was higher than a threshold, the first function set the balloon height by computing the difference between the arm and body angles. When the balloon was low, the second function used only the arm angle to set the balloon's height. Using only one threshold to switch between the two functions created a visible jump. We set the two height value thresholds and interpolated the value between these thresholds to ensure continuous motion of the balloon.

$$t = \frac{h - h_l}{h_h - h_l}$$

$$h = \begin{cases} (1-t)\dfrac{\theta}{\theta_{max}} + t\dfrac{\theta - \alpha}{\theta_{max}} & h_l \leq h \leq h_h \\ \dfrac{\theta - \alpha}{\theta_{max}} & h > h_h \\ \dfrac{\theta}{\theta_{max}} & h < h_l \end{cases}$$

where h is the normalized balloon height, h_l and h_h are the low and high thresholds for the height. This prevented the body angle from affecting the balloon height while the user is not exercising, while preventing compensation to help move the balloon higher while the user is performing the exercise motion.

7.5.4.2 Avoid Punishing Compensation during Rest

We added simple compensation feedback to the game towards the end of our iterative design to test simple punishment feedback. If a player tilted the balloon past a threshold, then the game played a sad "aww" sound. This made sense to participants when they tilted the body for compensating during exercise. However, they also triggered the "aww" sound when they were not exercising but shifting in their seat and moving their bodies. They found this to be surprising because they associated the sound with performing the exercise incorrectly. We subsequently suppressed the "aww" feedback when the balloon was below a certain height threshold h_e and resolved the issue.

7.5.4.3 Always Provide Body Motion Feedback

Although it is important to not penalize users while they are at rest, it is still important to provide feedback about torso motions by tilting the balloon to make users aware of it. Since the issues in both Section 7.5.4.1 and 7.5.4.2 required ignoring body motions when the balloon was low, we experimented with removing the balloon's tilt feedback when a player's arm was low. This had the adverse effect of preventing participants from understanding the relationship between their torso motion and the balloon tilt—they had to see the balloon tilt at all times to make the mental mapping between tilting of the balloon and body motions. We enabled body tilt while the balloon was low to preserve this understanding.

7.5.4.4 Do Not Reduce Challenge with Extra Cues

Some users had problems in their vision that reduced their field of view. To notice all the parachute targets they had to move their head up and down and scan the monitor. However, sometimes they missed the highest parachutes. To prevent this from happening, we thought it would be useful to have an early warning about the upcoming target and where it is going to be. However, when we asked these users with visual limitations, they consistently rejected the idea. The users with the worst eyesight (one eye blind, other with 5% vision) said that he would not like it. He said that he "liked the challenge, wanted to figure it out on [his] own". Another user said: "I think that would be a giveaway. I think you shouldn't warn somebody. I think they should see it and function. That's just it, you don't want it too easy, you want it a little difficult. You want to have to work at it. If you are not working at it you are not doing anything." All the users with vision problems liked to challenge themselves and opposed the idea that the game should help them in this regard. As a result, we did not include early warning signs in our game.

7.6 Discussion

As a result of our iterative design, we created the balloon game that appropriately calibrates to the users' motions. The game enables them to perform repeated shoulder abduction/adduction exercises by moving the balloon vertically to pick up parachute jumpers. The buildings provided challenge in terms of requiring them to keep their arms up, and the cloud provided extra challenge and excitement.

In addition to moving the balloon with exercise motions, users tilted the balloon with their body motions. This made them conscious of their compensatory motions which they may have not noticed otherwise. We observed that this caused some users to reduce the compensation that they perform, while others focused more on the gameplay and did not worry about compensation.

Having compensation be a part of user input introduced the possibility for the game to react to it and to convince the user to compensate less. However, since user motivation is one of the key issues in home-based stroke therapy, this should be done carefully to maintain enjoyment and not to discourage users from playing. We are not aware of studies that address this issue and want to find out possible solutions in the rest of this document.

Chapter 8

Designing Effective Feedback for Reducing Compensation

The balloon game that we developed in the previous chapter was effective in making users aware of compensatory motions that they performed. We also observed in our user tests that some users were performing less compensation when we turned on the tilt feedback compared to no tilt. While this was promising, we wanted to improve our game in a way that actively changed the users' behaviors so that they performed less compensation during exercise motions.

We continued our iterative design process from the previous chapter. We continued to make live modifications in our user tests while users were playing the game. We quickly improved our game modifications by testing and adjusting different aspects of the game in a tight iterative loop and created new versions of the balloon game. These games included in-game compensation feedback mechanisms inspired by operant conditioning.

8.1 Operant Conditioning

Operant conditioning is a psychological technique to modify voluntary behavior [114]. It can be used to increase certain behaviors and reduce others. When users perform a specific voluntary behavior that needs to be increased, they consistently receive a desirable reward such as adding desirable stimulus (i.e., positive reinforcement) or removing undesirable stimulus (i.e., negative reinforcement). Similarly, when they perform a specific voluntary behavior that needs to be decreased, they consistently receive an undesirable punishment such as adding undesirable stimulus (i.e., positive punishment) or removing desirable stimulus (i.e., negative punishment). This causes participants to associate punishments or rewards with their voluntary behaviors. Participants then choose to perform rewarding behavior and avoid punished behaviors. In effect, the occurrence of desired behavior is increased and the occurrence of undesired behavior is decreased. While initially developed using animals, operant conditioning is known to be effective to shape human motor behavior as well [114].

Effective behavior modification with operant conditioning requires that participants perceive punishments and rewards (p/r) as undesirable and desirable respectively [114]. It also requires correctly associating the targeted behavior with the p/r [114]. Thus we attempted to create game feedback that was correctly perceived as a p/r and was associated with compensation.

The use of punishment to shape behavior carries the risk of reducing participants' motivation. Therefore, an additional goal in our study was to ensure that the punishments did not decrease participants' willingness to play our game.

8.2 In-Game Punishment and Reward Events

As we improved our game, we designed and user tested a number of in-game punishment and reward (p/r) events. Below we list the events that users perceived as desirable (rewards) and undesirable (punishment).

8.2.1 Rewards

The purpose of the events below is to reward the user for performing the exercise motion with low compensation. We tested them individually and in combinations during our user tests and observed that users enjoyed it when they caused the following reward feedback elements to appear.

Green balloon. The balloon changes color with a green tint. The intensity of the tint is determined by the intensity of the reward.

Applause sound. The computer plays an applause sound in a loop. The volume of the applause is determined by the intensity of the reward.

Happy face. A happy cartoon face texture appears on the balloon. The opacity of the texture is determined by the intensity of the reward.

+1 score. The user gets one extra point.

Shooting stars. Small stars shoot from the balloon upwards.

Happy sound. The computer plays a happy "yippe" sound.

8.2.2 Punishments

The purpose of the events below is to punish the user for performing the exercise motion with high compensation. We tested them individually and in combinations during our user tests and observed that users preferred not to cause them to appear.

Red balloon. The balloon changes color with a red tint. The intensity of the tint is determined by the intensity of the punishment.

Sad sound. The computer plays a sad "aww" sound. The volume of the sound is determined by the intensity of the reward.

Sad face. A sad cartoon face texture appears on the balloon. The opacity of the texture is determined by the intensity of the punishment.

-1 score. The user loses one point.

Vibrate. The Wii remote on the participant's back vibrates to draw attention to it. We used this with success in our initial tests. However, it became obsolete in the iterative design process because of API limitations and that it was difficult to feel through the thick paperboard of the harness.

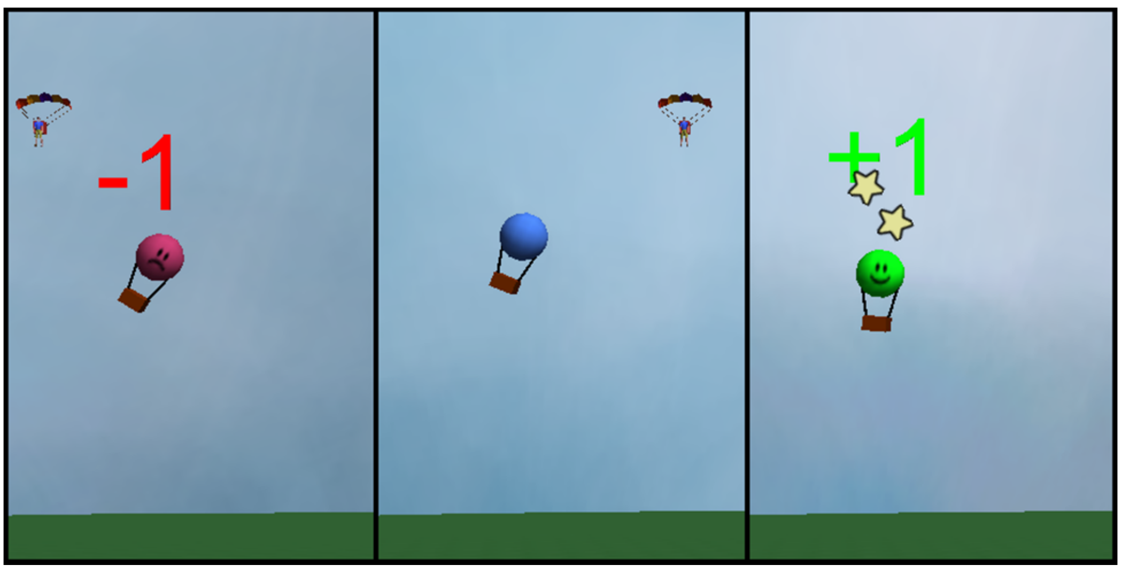

Figure 8.1. Three kinds of compensation feedback. Left: punishment for excessive compensation. Center: No p/r feedback between the two thresholds. Right: Reward for low compensation.

Research suggests that using multiple channels for the same feedback does not necessarily require extra cognitive processing [105]. Therefore, we used multiple p/r events together (see Figure 8.1) for effective feedback that provided both visual and auditory channels in case stroke has reduced sensation in one.

We evaluated participants' perception and association of p/r feedback by watching game replays with participants, pausing near p/r events, and then leading a semi-structured interview about their experience. The interview focused on capturing the participants' thoughts on the p/r feedback, the way it made them feel, whether they correctly associated the feedback with the underlying reasons and whether the feedback had any effect on their desire to play the game. Participants' responses suggested that they perceived p/r events appropriately as desirable and undesirable. Most participants correctly associated the events with compensation, while a small number of participants falsely associated them with catching or missing parachutes. We attempted to mitigate this false association with a pre-game tutorial and in-game signs that reminded them that the cause of the feedback events was compensatory motion. We observed that they helped participants understand the reasons for the p/r events.

We were initially concerned that in-game punishments may discourage participants from playing. Surprisingly, several participants indicated that the punishments encouraged them to play more and get it right the next time.

8.3 Lessons Learned

We used the p/r events to design rich feedback strategies that target reducing compensation in a number of different ways. We learned valuable lessons about how to effectively design p/r strategies in games developed for people with stroke.

8.3.1 Avoid Feedback Confusion with Multiple Thresholds and Continuous Feedback Intensity Mapping

Even though the balloon always tilted with the body motions, we only provided compensation feedback when the balloon was higher than a threshold h_e as we discussed in Section 7.5.4.2. Initially we used a single threshold θ_{pr} on compensation to decide between punishment and reward (see Figure 8.2.a). When the arm height was above h_e and compensation angle was above θ_{pr}, we provided punishment by converting the balloon's color to red, displaying on it the sad face and playing the "aww" sound. When the arm height was above h_e and compensation angle was below θ_{pr}, we provided reward by converting the balloon's color to green, displaying on it the happy face and playing the applause sound. However, when we measured slight variations in compensation angle around θ_{pr}, compensation feedback quickly oscillated between reward and punishment. This created confusion as it gave mixed feedback to the user.

In response, we first changed to two compensation angle thresholds: a lower reward threshold θ_r and an upper punishment threshold θ_p. Participants then received reward feedback when their compensation was below the reward threshold and punishment feedback when above the punishment threshold, with no feedback given in between the thresholds (see Figure 8.2.b). This prevented the mixed feedback that confused users.

Even though using two thresholds prevented the feedback from switching between punishment and reward, abrupt feedback changes still occurred around the threshold values by repeatedly turning feedback on and off. Starting and stopping audio abruptly especially created discomfort. To overcome this, we used the difference between the compensation angle and the respective threshold to calculate feedback intensity, so that the feedback could ease in rather than starting abruptly (see Figure 8.2.c). For instance, as a participant reduced their compensation to near zero, our game would increase the volume of the reward sounds. At the opposite end, if a participant's body tilted too much during exercise, then we colored the balloon with a more opaque red shade proportional to the tilt. Likewise, both kinds of feedback started with low intensities near the thresholds. While this eliminated the abrupt changes, directly controlling the feedback with the user input still caused excessive fluctuations. We overcame this by exponentially smoothing the compensation signal before using it as p/r input. This prevented the abrupt changes and ensured smooth transitions of feedback.

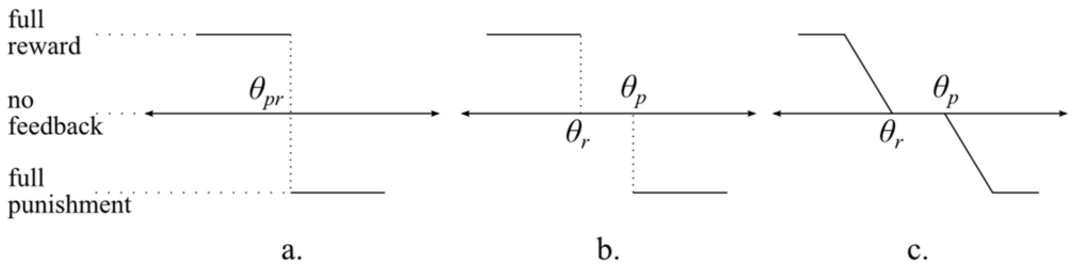

Figure 8.2. The three phases of the feedback function. a. Using a single threshold to decide between punishment and reward. b. Using two thresholds. c. Two thresholds with easing to avoid abrupt changes in feedback.

In our iterative design we tried different approaches for setting appropriate values for the compensation thresholds θ_p and θ_r for each user in a way that reflects the expected compensation behavior, using the compensation behavior that we collected during calibration (see Section 7.5.1.2). Initially, we wanted to set thresholds that bound the occurrences of compensation values. For example, we chose the reward threshold such that compensation went above it only 15% of the time. We found through our user tests that this approach did not create reliable compensation thresholds—it often resulted in very different thresholds in consecutive trials of the calibration process. However, we found that the average compensation was quite stable for users in repeated calibration sessions. Therefore, we used the average compensation as a reference value for the compensation thresholds. We set θ_p to be the average compensation, which meant that during the game users were expected to compensate less than the calibration session. We set θ_r to be half of the average compensation, which was an attainable level of compensation for most users.

8.3.2 Incentivize Behavior Duration with Repeated Feedback

We observed that the effectiveness of an instance of p/r feedback was greatest at the start of its duration and decreased over time as it continued. Once users saw the reward feedback they did not have a strong incentive to keep it on. Similarly if the user decided to ignore punishment feedback to pick up a parachute, there was no extra incentive to encourage them to leave the punishment state. However, we wanted to encourage participants' compensations to stay low for a long time and wanted to encourage them to quit high compensations quickly. While punishment and reward events encouraged change of behavior, we also wanted to encourage shorter durations for undesired and longer durations for desired behavior.

We addressed this by introducing strong, discrete p/r events that are periodically repeated while the main feedback is on. While compensation is above the threshold θ_p, we repeatedly punished users by deducting a point. This amplified the strength of punishments and caused users to prefer to keep punishment short not to lose extra points. Similarly, while compensation is below the threshold θ_r, we repeatedly rewarded them by adding points, displaying shooting stars, and playing a "yippee" sound at the same time. Likewise, this amplified the strength of rewards and caused users to prefer to keep reward long enough to collect extra points and experience the extra rewarding stimuli. We intentionally made reward stronger than punishment to avoid negative effects on motivation. These repeated events started half a second after the threshold was crossed and repeated every two seconds. We observed that these repeated p/r events caused participants to stay shorter in high compensation and longer in low compensation. The extra reward even caused some participants to sneak in extra repetitions in between parachutes.

8.3.3 Withhold Feedback Clearly in a Variable Ratio Schedule

Operant conditioning research suggests that before providing feedback in response to the behavior, withholding it a variable number of times will build anticipation, reduce effects of satiation and result in faster, more lasting learning in the long run. Therefore we wanted to implement variable ratio feedback in our feedback schedule.

However, we anticipated possible issues with a variable-ratio feedback schedule. During our user tests, we observed that the success of our game depended heavily on timing and the presence of feedback. We anticipated that withholding the punishment feedback may allow users to compensate more than they would otherwise. Therefore, in our short-term tests we wanted to see whether a variable ratio schedule would have any adverse effects.

We implemented a variable ratio feedback schedule by randomly suppressing the compensation feedback. Initially we implemented suppression by giving no p/r feedback at all. When we tested this with users, we observed that it did not have the effect of increasing anticipation but made users think that the game was broken during the times that feedback was suppressed. To overcome this issue and to assure users that the game was choosing not to provide p/r, we added back only the color feedback for when the feedback was suppressed. We observed in our user tests that this made them anticipate rewards more. When we asked about why it only changed color, they thought they did not do it quite right that time, although they could not explain how. They had similar thoughts about punishments, but they were concerned less about their suppression compared to rewards.

8.3.4 Adapt to Changing Abilities

Similar to our previous studies (see Section 4.6.2.1), we observed that warm-up and fatigue altered participants' motion abilities over time. After playing the game for a while, some users warmed up and gained more flexibility in their shoulders. Likewise, when they got tired, their motion range decreased again. As motion abilities changed, calibration parameters became slightly inaccurate. We addressed this issue by creating an adaptive version of our game that periodically readjusted itself to changing motion abilities.

Our adaptive game algorithm stored past windows of gameplay and adjusted the calibration parameters such that if the new parameters were used in the past window, the player would have had the desired performance characteristics with the same inputs. We adjusted desired motion range to target a 10% miss rate with high parachutes, and desired compensation thresholds to target a 15% punishment and 30% reward rates during exercise. We identified these target rates during user tests and found that they result in an enjoyable and challenging game experience that appeared to track participants' abilities.

We anticipated that readjusting difficulty according to success would itself affect future success and this feedback loop could arbitrarily increase or decrease difficulty if the user's ambition to succeed was too high or too low. In general, our users showed effort that helped the feedback loop converge quickly to an appropriate difficulty level. One exception came from a participant who had little arm disability and was overly ambitious to avoid punishments. The game became too difficult in the sense that even very little compensation was causing punishments. On the other hand, none of the users caused the game to become too easy by showing too little effort. This indicated that an adaptive algorithm can generally rely on users to cooperate, and should be prepared for exceptional cases at the same time.

8.4 Result

At the end of our iterative design, we added a number of optional elements to our game that we designed through user tests to reduce compensation and adapt to changing abilities in time. We kept all the elements that we introduced in Section 8.2 except vibration. We iteratively refined these game elements so that they were successfully meeting their goals in our user tests. In our user tests we observed that the p/r feedback strategy that we designed using these game elements was changing users' behaviors. When we enabled p/r, users were performing less compensation to avoid punishments and to receive rewards. In addition, the adaptive algorithm was helping prevent the game from becoming too easy or too difficult for users in time. We also observed that variable ratio feedback was causing users to wonder what they did wrong and some users tried harder to succeed.

Because reducing the amount of compensation and maintaining the user motivation were our main priorities, we wanted to verify our observations related to them by quantifying compensation and motivation levels caused by different game elements. This would help identify the effects of different game elements on our goals, and help us make informed decisions on creating games that address compensation appropriately. Our last study in the next chapter is a summative study that experimentally compares different game elements to address this issue.

Chapter 9

Summative Evaluation of Compensation Reduction Techniques

In the previous chapter we created a number of modifications to the base game and improved them through user tests so that they were fulfilling the goals that we designed them for. The base game was an improvement on the state of the art in stroke games, which was simply canceling out compensation [3]. Our base game provided awareness about the degree of compensation, which is comparable to Thielman et al.'s study about chairs with pressure sensors and audio feedback [112]. We further improved the base game in the previous chapter by making it adapt to users' changed abilities, making it more effective against compensation with punishment and reward feedback, and addressing issues of satiation through variable ratio feedback.

Our main goal in this series of studies is to reduce compensatory motions in exercises enabled with video games, while maintaining users' willingness to play. While the base game, the game elements and game modifications seemed to serve their purpose in our user tests, we wanted to see how they affected our main goal. Specifically, we wanted to see the effects of the different game elements on the amount of compensation and willingness to play. For this purpose, we conducted a summative study in which we created different versions of the game that represented different combinations of game elements, and evaluated their effects on compensation and willingness to play.

9.1 Conditions

We created five versions of our game that represent different game elements that we developed:

G1. No Tilt: no compensation feedback, the balloon does not tilt. This represents the state of the art in games [3].

G2. Tilt Only: compensation only tilts the balloon. This is comparable to Thielman et al.'s audio feedback approach [112].

G3. P/R: uses p/r events in response to compensation.

G4. Adaptive: uses p/r events with the adaptive algorithm.

G5. Variable Ratio: uses p/r events with variable ratio feedback.

Comparisons between these game versions would enable us to contrast different game elements. The points that comparing the first three conditions can identify include (1) if simple feedback to make users aware of their compensation has any benefits and whether it is sufficient to reduce compensation, (2) if providing p/r is more effective in reducing compensation, and (3) if p/r feedback reduces willingness to play or not.

In addition to the game elements that we designed to reduce compensation, we developed other game elements with different goals and we wanted to see if they negatively affect compensation and willingness to play. We implemented adaptive calibration with the goal of addressing the changing motion abilities of users.

Contrasting conditions G3 and G4 can show if the adaptive algorithm provides any benefit or harm in terms of compensation and willingness to play. In addition, we implemented a variable ratio feedback schedule for the delivery of p/r feedback that is expected to improve motor learning in the long run. We left evaluating its long-term effects as future work because we did not plan to conduct a long-term test as a part of this study. However, we had concerns about possible negative short-term effects of withholding feedback and wanted to evaluate how it affects compensation and willingness to play by comparing conditions G3 and G5.

9.2 Study Design

We conducted a within-subjects study in which each participant played all five game conditions on different days. We counterbalanced learning effects using a Latin Squares design. We ensured consistency across different users by having all users play exactly the same game with no modifications except for the motion calibration parameters, which are necessary to appropriately challenge users by using their whole motion range. We also ensured consistency across different versions of the game by ensuring that game versions differ only on the points that we listed in Section 9.1 and that everything else was the same between game versions.

9.3 Participants

Eleven stroke survivors (seven female) participated in five user test sessions for a total of 55 user tests. Participants' ages ranged from 43 to 72 years old with their strokes occurring from three to eleven years previous. Participants exhibited a variety of disability levels.

9.4 Sessions

All sessions took place in participants' homes and took approximately 45 minutes. Participants sat in front of a 22" external monitor that was connected to a laptop. As one of our data points was their estimates of session duration (see Section 9.5), we hid clocks in the environment to prevent their direct observation of elapsed session time that could bias their time estimates. Before the first session, we conducted a questionnaire to record participants' background and stroke history. To begin the session, we assisted participants with putting on the Wii remote attachments. We demonstrated the expected shoulder abduction/adduction exercise and asked the users to perform the exercise to play the game.

In a therapeutic use of such a game system, therapists would instruct participants about how to play the game and that they should exercise without compensation. Therefore, we read a script that served a similar purpose and participants completed a simple tutorial that demonstrated each of the three game targets (parachute, building, cloud) to the user. Participants then completed the in-game calibration session. We provided further information about the specific game version as a post-calibration tutorial in which the participant experienced the way the balloon moved and tilted during the game and the kind of feedback provided for compensation.

Based on our earlier user tests, we addressed fatigue by adjusting the session so that users play the game in three five-minute parts with two one-minute breaks in between. After the game was over, the participant answered a questionnaire with questions about the participant's time perception and motivation related to the game session. We followed this by a semi-structured interview to understand the participant's experience with the game.

9.5 Data

We recorded the entire game sessions including the Wii remote accelerometer inputs. We also recorded video or audio of the session with the user's consent to watch them later. Our main data point was average compensation levels near parachutes during calibration and during the game. Since the calibration session was identical for each game version, the compensation level during calibration right before the game represented their natural tendency to compensate that day. Likewise, the compensation level during the game represented the user's tendency to compensate while playing the specific game version that day. Their ratio reflected the compensation change that the game version caused. We call this ratio *relative compensation* and used it as the indicator of change in compensation caused by the game version.

We collected two types of data to measure motivation and desire to play: participants' estimates of session duration and responses to the Task Evaluation Questionnaire (TEQ) [27]. Change in duration estimations may mean change in motivation because engagement can skew time perception. Participants that are immersed in an engaging task perceive time to pass slower [24], therefore we wanted to use participants' duration estimates as an indication of motivation and willingness to play. Another type of data that we collected to measure motivation and willingness to play is the results of the TEQ. TEQ is a standard questionnaire that provides scores related to motivation (interest/enjoyment, perceived competence, perceived choice and pressure/tension) in relation to the task that is the game. We conducted TEQ at the end of every user session to collect information that reflects users' motivation related to the game.

9.6 Results

We analyzed the data that we collected to identify significant effects of game versions on compensation and willingness to play. Our analysis showed that game versions caused significantly different compensation levels. We also saw that no game version affected motivation indicators significantly differently than others.

9.6.1 Relative Compensation

We measured effects of game version on the relative compensation that users performed. Figure 9.1 presents the estimated distributions of relative compensation per game version.

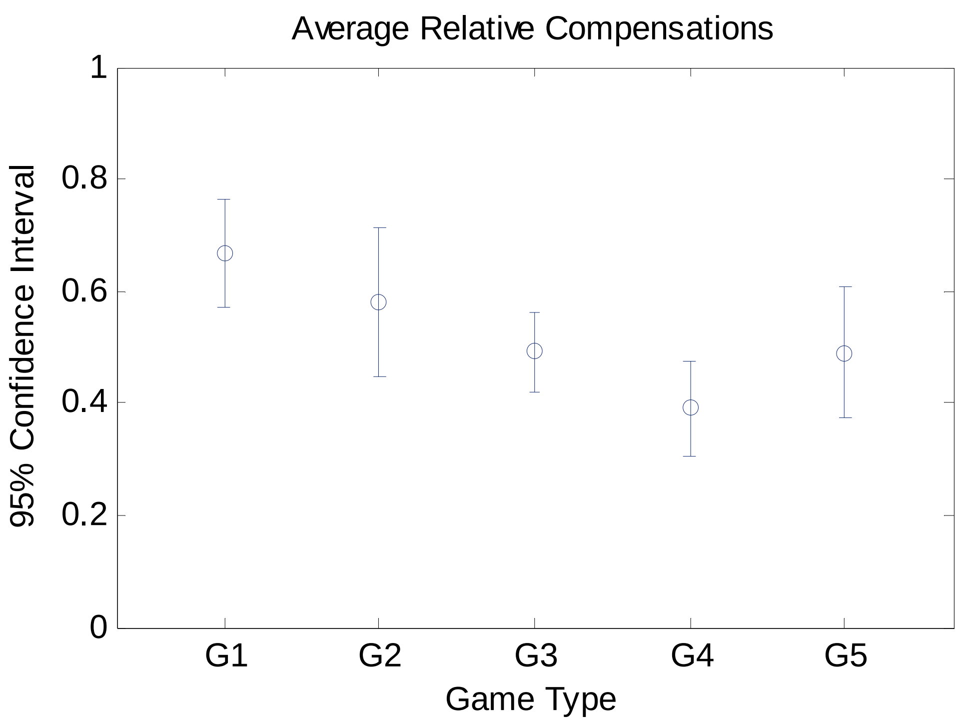

Figure 9.1. Estimated distributions of average relative compensation for each game version. The corresponding names for game versions are G1: No Tilt, G2: Tilt Only, G3: P/R, G4: Adaptive, G5: Variable Ratio (see Section 9.1).

It is interesting to note that even in G1 (No Tilt) users performed less compensation during the game than during calibration ($t(10)=7.807$, $p<0.001$). The calibration stage for collecting compensations did not contain tilting. Unlike other game versions, in G1 (No Tilt) the game was identical to this calibration stage. However, users still reduced the amount of compensation even though we did not introduce any feedback related to compensation. We believe that this was because users warmed up after calibration and were able to raise their arms with less need for compensation.

In addition, Figure 9.1 indicates that means for relative compensation reduced with the introduction of each of tilt (G2), p/r feedback (G3) and adaptive calibration (G4). We also observe that the mean of G5 (Variable Ratio) is close to that of G3 (P/R). To support these observations and determine whether the differences were significant, we performed statistical analysis on the data.

We analyzed the relative compensation in an analysis of variance with game type (G1 vs. G2 vs. G3 vs. G4 vs. G5) as a within-subjects factor. We verified the sphericity assumption with Mauchly's test of sphericity, $p > 0.05$. Using repeated measures ANOVA, we found that the main effect of game type was significant, $F(4, 40) = 8.309$, $p < 0.0001$, $\eta^2 = 0.454$.

To further uncover the effects of game type, we performed post-hoc comparisons using the Bonferroni adjustment for multiple comparisons. There was no statistically significant difference between relative compensations resulting from G1 (No Tilt) and G2 (Tilt Only), and between G2 (Tilt Only) and G3 (P/R). This indicated that introducing balloon tilt over no feedback or introducing p/r events over balloon tilt did not create a significant change.

However, G3 (P/R) reduced relative compensation significantly from the G1 (No Tilt) mean of 0.666 (SD=0.142) to a mean of 0.492 (SD=0.106, $p < 0.05$). Introducing both tilt and p/r events together resulted in a significant reduction in compensation, which shows that using operant conditioning was necessary to statistically reduce the amount of compensation.

Compared to G3 (P/R), G4 (Adaptive) lowered relative compensation even more to a mean of 0.39 (SD=0.128, $p<0.05$). This indicated that changing exercise range and compensation thresholds according to users' abilities during the game helped them reduce the amount of compensation that they performed. This was a curious result that could be because of the exercise motions becoming too easy or the participants working harder. Further investigation revealed that the adaptive algorithm reduced range of motion significantly to 92.5% ($t(10)=2.823$, $p<0.05$), which suggests that exercise became somewhat easier. At the same time, it made the compensation thresholds stricter, reducing the punishment threshold to 82% ($t(10)=3.244$, $p<0.01$) and reward threshold to 79.7% ($t(10)=2.696$, $p<0.05$). The gap between the thresholds also shrunk by 84.2% ($t(10)=3.332$, $p<0.01$). The change in thresholds (18% and 20.3%) was larger than the change in motion range (7.5%), which may suggest that participants tried harder to reduce compensation.

G5 (Variable Ratio) did not result in a significant difference in relative compensation compared to G3 (P/R). This indicated that providing punishment and reward as compensation feedback only part of the time was not detrimental in the sense that it did not increase compensation.

9.6.1.1 Summary

The analysis on relative compensation suggests that providing compensation feedback in the form of balloon tilt and p/r events reduce relative compensation in a statistically significant way. In addition, the analysis suggests that using balloon tilt solely without the punishment/reward events results in only an insignificant reduction in relative compensation. This supports the idea that operant conditioning is effective in encouraging users to perform therapeutic exercises correctly.

Another result that came from this analysis is that it is important to readjust motion expectations of the system that are initially set at the beginning of the session. These adjustments are very effective at reducing relative compensation not only by adjusting the difficulty towards users' needs, but also by encouraging users to compensate at a targeted rate.

9.6.2 Motivation and Willingness to Play

As one of the major challenges for home-based rehabilitation is user motivation, our goal is to create games that users would like to continue to play. Motivation and willingness to play were requirements in our design process; however, our primary focus in designing game elements was promoting correctness of exercises by reducing compensation. Therefore we wanted to assess whether the gains that we obtained through the game elements came with any side-effects that reduced users' motivation and willingness to play. While the game elements successfully reduced compensation, their utility would be in question if they had negative effects on motivation.

The data that we collected consisted of answers to questions related to time perception and results of the Task Evaluation Questionnaire (TEQ) [27]. TEQ has 22 questions and four factors that are computed from user's answers: interest/enjoyment, perceived competence, perceived choice and pressure/tension (see Appendix B). These factors are psychological qualities that are related to intrinsic motivation. While TEQ is a standard survey with proven reliability and validity, we wanted to verify its reliability once more using the answers that our participants provided. Therefore, we calculated Cronbach's alpha [25] for each of the four factors (see Table 9.1).

Table 9.1. Reliability metrics for different factors of the Task Evaluation Questionnaire.

Factor	Cronbach's alpha	Internal consistency
Interest/enjoyment	0.950	Excellent
Perceived competence	0.880	Good
Perceived choice	0.709	Acceptable
Pressure/tension	0.625	Questionable

We observed that internal consistencies were excellent for interest/enjoyment, good for perceived competence, acceptable for perceived choice and questionable for pressure/tension [43]. This suggested that we should take results for the first three factors more seriously than the results for the last one.

We analyzed the data using MANOVA to determine whether game version may have caused a significant change in indicators of motivation (users' answers to time perception questions and factors of TEQ). The analysis showed that there was no statistical significant difference across the results for different game versions (p=0.853).

The fact that there was no statistically significant difference between game versions suggested that users were similarly motivated to play the different versions of the game. To reason about overall motivation levels, we took means across game versions (see Table 9.2).

Table 9.2. Means of motivation indicators.

Variable	Units	Mean	Std. Dev.
Low duration estimate	Minutes	24.655	12.461
High duration estimate	Minutes	33.818	14.86
The game ended too early	Likert scale (1-7)	4.182	1.973
The game ended too late	Likert scale (1-7)	1.927	1.103
Time went by too quickly	Likert scale (1-7)	5.255	1.481
Interest/enjoyment	Likert scale (1-7)	5.881	1.159
Perceived competence	Likert scale (1-7)	5.215	1.073
Perceived choice	Likert scale (1-7)	5.436	1.215
Pressure/tension	Likert scale (1-7)	2.498	1.004

Even though standard deviations for the duration estimates are large, means of users' estimations of duration are close to the actual duration of approximately 30 minutes (including tutorials, calibration and breaks). Users thought the game session ended rather too early (4.182), the session ended quickly (5.255), and did not think that the game session ended too late (1.927). Users seemed to enjoy the game (5.881), they thought they were competent in the game (5.215) and they thought that it was their own choice to play the game (5.436). In addition, they did not seem to be tense about the game (2.498). These results suggest that the users enjoyed the game and that they may be willing to play more.

The fact that there were no statistically significant differences in any of these variables across users may suggest that users similarly enjoyed all the games and punishment and reward events did not negatively affect motivation. This is compatible with our observations and our interviews suggesting that users enjoyed those events more than they disliked them.

9.7 Discussion

Our results indicate that our game significantly reduced compensation compared to the state of the art in games for stroke rehabilitation. While our study was about shoulder exercises and trunk compensation and targeted reduction of compensation, our findings have broad consequences on game-based stroke therapy in general. Our technique and results can be generalized to other exercises used for stroke rehabilitation. In addition, our findings uncover the possibility of adjusting games for brain vs. muscle rehabilitation.

9.7.1 Generalizing to Other Exercises

Our system can easily be used for other shoulder exercises such as shoulder flexion (raising the arm to the front) or shoulder extension (to the back). However, two assumptions in our approach may limit our general applicability to other joints: we assume that (1) compensation is through tilting of the torso and (2) both the exercise and the compensation range have an extremum in which the user tends to be when resting.

We can overcome the first assumption by attaching a Wii remote or another motion sensor to the compensating body part next to the joint (e.g., upper arm for elbow exercise), which is usually relatively easier than attaching to the trunk. One other related assumption was the following: to address free compensation independent of an axis, we made assumptions about the directions that the body would lean to make the exercise easier (see Section 6.3.6.3).

The second assumption may already be satisfied for some exercises. For those other exercises, we can identify users' behaviors when not exercising, classify the exercise and compensation motions, and then ensure that the compensation motion does not improve the exercise. From this we can develop a base game and the rest of our system (p/r events, etc.) should be useful with little modification.

9.7.2 Designing for Brain vs. Muscle Rehabilitation

People who have strokes experience hemiparesis because of the damage in their brain tissue. Although their muscles are intact, they experience weakness in their muscles because of the loss of function in the motor areas of their brains. Initially, the main goal of stroke rehabilitation is to provide examples of motions for the brain to retrain itself. However, as a result of stroke, people use their muscles much less than they did before, which weakens the muscles in time [119]. Therefore, most stroke rehabilitation is a mixture of brain and muscle training. Correctly performed exercise and high numbers of repetitions are crucial for the brain, whereas increasing strength and range of motion are crucial for the muscles. In our study, we saw that games can be designed to prioritize one over the other using calibration adjustments or prioritizing in-game goals.

9.7.2.1 Adaptive Calibration for Different Types of Rehabilitation

Our adaptive algorithm resulted in exercises that are much more correct by reducing compensation at the expense of some range of motion. Although the high reduction in compensation is a great outcome for brain rehabilitation, the loss of range of motion may be less desirable for muscle rehabilitation. The parameters of our adaptive algorithm were influential in having this result as we adjusted it to tolerate some failure in both motion range and compensation. To target the muscles, we can adjust the adaptive algorithm to be more tolerant of growing compensation and less tolerant of shrinking range. This would entice users to use larger motion ranges and to worry less about compensation. Conversely, we can target brain rehabilitation by adjusting the adaptive algorithm to be more tolerant of shrinking range and less tolerant of growing compensation. This would entice users to be more careful about compensation and worry less about performing exercises with a large range of motion. Providing these controls to therapists would give them a useful tool to further customize game systems for participants' needs.

9.7.2.2 In-Game Goals with Different Priorities

Another way games can be adjusted to provide exercise more beneficial for the brain versus the muscles is through adjusting priorities of competing in-game goals. In our game, exercising and reducing compensation were two competing goals, represented by picking up parachutes and avoiding punishment related to compensation. Because picking up parachutes was the main goal in our game, exercise was the main goal and reducing compensation was secondary to it. This was especially apparent in our user tests when users had to choose between reaching for a high parachute while knowingly receiving a punishment and letting the parachute go to avoid compensation punishment. Brain rehabilitation exercises may be better if the user lets go of the parachute to avoid presenting the brain with incorrect exercises, while muscle rehabilitation may prefer otherwise. Games can be designed to set priorities in a way that would best serve the rehabilitation goals.

9.8 Conclusion

Our study addresses an important weakness inherent in conventional stroke rehabilitation and its technology-based alternatives. Rather than imitating current practices, we took a step back and designed a system rooted in addressing compensation, one of the crucial needs of rehabilitation that is insufficiently addressed in current practice. We developed a game based on operant conditioning principles and demonstrated that it reduces compensation significantly better than current alternatives. Using our approach, long-term studies can move towards making home-based stroke rehabilitation with video games a practical and competitive option to supervised therapy.

Chapter 10

Future Work

Our research uncovers a number of research tracks that may help further our knowledge in human-computer interaction related to rehabilitation and games. Our observations suggest that games developed for therapeutic purposes can also address side issues to improve lives of participants. In addition, our results suggest that significant modification of behaviors through games is possible and various behaviors may be addressed by studying them and developing appropriate games for them.

We identified a number of ways games and game systems can be more effective in the rehabilitation process. Games can be used for assessment of various qualities about players in a non-intrusive and abundant way. In addition, through improvements they provide in rehabilitation, using games and game systems may result in reconsidering assumptions inherent in rehabilitation practices.

We also identify research directions that would strengthen the possibility that games can be used for various purposes other than entertainment. Studying ways of increasing the user-friendliness of game systems for people with disabilities can allow games to be used by them more effectively. In addition, finding ways of addressing specific situations of non-gamer users with games can increase their utility. Finding ways of integrating games into lives of such non-gamer users is also required for long-term use of purposeful games.

Lastly, we identify improvements in software and hardware to be used for stroke rehabilitation. To make the process of therapy with games more efficient, improving therapy management software and integrating it with larger IT systems and home-based technology solutions is necessary. As exercise-sensing hardware is one of the key parts of games for stroke rehabilitation, studying advantages and disadvantages of various end-user devices that can be used for detecting motions can result in more effective game systems.

10.1 Therapeutic Games that Improve Lives

The lessons we learned about how to design games for people with stroke can also be useful for other audiences with limitations that are not game players, such as the elderly and people with disabilities because of reasons other than stroke. Furthermore, enabling users to play therapeutic games may create opportunities to improve users' lives in addition to helping them with their conditions. Additional studies for different user populations may result in better games and game experiences.

Although we specifically studied developing therapeutic motion-based video games for stroke survivors, our findings may be useful for developing motion-based games for non-gamer audiences for purposes including strength exercises and motor rehabilitation. Using our findings as starting points and consulting appropriate therapists or medical personnel, games can be developed in ways that do not harm users or exacerbate disabilities. Our studies have already inspired Notelaers et al.'s work on rehabilitation of Multiple Sclerosis using games [86] by providing ideas on how to make games more motivating for users. In addition, Dhillion et al. have used a similar accelerometer-based approach for an iPhone game to be used by the elderly [35]. We believe that working with doctors, therapists and caregivers about their patients and clients would uncover more opportunities for games to be used to help people cope with their conditions or help them get better.

Once people start playing purposeful games for a certain goal (therapy, strength training, psychotherapy, etc.), the game media creates opportunities to provide additional benefits to people's lives. As in the case of stroke, disabilities can alienate people from family members and loved ones. Multiplayer games in which they play together may recreate emotional connections and improve the social lives of the participants in addition to rehabilitating them. The specific target audience of games may also experience common emotional themes that are detrimental for their well-being, similar to the emotional themes that we identified in people with stroke (see Section 4.6.4). Games can be designed to address such emotions and improve people's morale. In addition, games give people something that they can be busy with and pass time in a pleasant way. This was apparent in our tests because most participants looked forward to the next game session. Elderly or disabled people that otherwise do not participate in other activities may find games to be an enjoyable pastime activity.

Some of the side benefits of games that we mentioned may occur even when games are not deliberately designed for these benefits, e.g., users are likely to find well-designed games to be an enjoyable pastime activity. Similarly, studying the design of games from a human-computer interaction perspective to maximize their benefits may result in better experiences that improve participants' lives. Future studies of specific populations to identify human factors related to games are necessary for improved success of games that would be developed for those populations.

10.2 Behavior Modification using Games

We demonstrated that the use of a game developed using operant conditioning techniques can result in a significant behavior change. We believe that a similar approach can work for modifying other types of behavior in other populations as well. Our experience suggests that games designed for other audiences should create feedback strategies inspired by properties of the target audience. We believe that an approach that is similar to ours can improve the results of many game- or feedback-based interventions.

10.2.1 Feedback Strategies Specific for the Target Audience

Our study showed that in addition to their therapeutic use, games can be used to modify users' behavior. By making users aware of their compensation behaviors and providing continuous punishments and rewards, we showed that games can cause users to reduce their compensatory behavior. Although it was already known that operant conditioning can change behavior, designing a game based on it provided an appropriate context to make behavior modification practical. However, designing such a game required discovering the type of feedback that would work with people with stroke. For example, discrete punishment or reward feedback after the completion of a motor activity may be appropriate for general audiences. However, in our iterative design we found that feedback that is continuous and without delay worked better than discrete and delayed feedback. This parallels previous research that identified knowledge of performance (i.e., instant, continuous feedback about motions) to be better for motor learning of people with stroke compared to knowledge of results (i.e., feedback about the motion after it is complete), while it is the opposite for people with no motor disabilities. Another unexpected observation was that some participants did not mind failure. After getting tired in one session, repeatedly failing to pick up parachutes did not stop one participant from trying. Although we expected him to get frustrated, he was determined and he continued to try for a long time with no apparent distress. In our subsequent interview, he explained that failure is something he expects with motor tasks after getting used to his disability. This is a different mindset than a regular game player and may require games to be designed differently than regular games. There may be other subtle differences between people with and without stroke related to the development of games. Other populations may also have similar subtle differences in behavior. Identifying such unexpected properties of target audiences and developing games accordingly may result in better modification of behavior through games.

10.2.2 Addressing Other Behaviors

Our results may be useful for changing various behaviors of various target populations. We anticipate our findings to improve biofeedback applications. In addition, we believe that our findings can address habits of the general population.

Biofeedback is the technique of providing stimulus driven by unconscious body functions to make users aware of them and learn to control them. Its applications range from controlling brainwaves to controlling muscles that the user normally does not have control over. While operant conditioning techniques have been used with biofeedback [111], they may be more effective when used as a part of a game similar to our approach. Although simple games have been developed to be used with biofeedback applications [88], games that are designed with operant conditioning techniques and that address human factors appropriately can further the success of biofeedback applications.

We believe that our results can also be useful for addressing habits of regular users. Through games developed using operant conditioning techniques, it may be possible to address users' unwanted habits and reduce them. Operant conditioning techniques have been used in the past for helping people quit smoking in the past outside the context of games [47]. We believe that making such behavior be a part of games may create better results. Future studies should explore designing games around undesired habits in a way that uses operant conditioning techniques to reduce undesired behavior. For example, tracking users' postures with a necklace-shaped sensor and providing punishment and reward feedback may help them correct their postures in time. Making this be a part of a game in which the user is motivated to collect more rewards and avoid punishments to work towards an in-game goal may be even more effective.

10.3 Games as Assessment Tools

Using games as assessment tools is one of the uses that we identified for games. In our home-based study we found that it was possible to use game data to assess users' motion abilities much more frequently than some of the existing motion assessment tools that therapists use. We believe that it is possible to extend this idea in future work and design therapeutic games that assess various properties of users in a discreet way. In addition to motion abilities, games can be designed to test the problem solving skills and cognitive abilities of users by introducing various challenges of similar difficulty. This may help assess changes in cognitive abilities in time. Detection and assessment of psychological issues is another possible design factor in future games. For example, researchers have used a tabletop system to simulate sandtray therapy, in which a child freely plays with virtual objects and a psychologist interprets the psychological state of the child [49]. Games can be developed with similar purposes and psychologists may interpret in-game behaviors of users to gather information about their mental states.

We believe that one of the advantages of in-game assessment techniques is that the data collection process can be implemented in a way that is not apparent to the user. For example, when a user goes to the clinic for a regular motion assessment session, he or she may be nervous and too conscious about his or her own motions and as a result the assessment may not be accurate. However, collecting data while the user is engaged in playing the game can result in assessments that represent the motion abilities of the user more accurately. Therefore, finding in-game assessment techniques for various types of assessments may provide readings that may be more accurate than alternative methods.

10.4 Developing New Rehabilitation Practices around Technology and Games

In most of our research we tried to keep the current therapy practice and find ways of including video games into it. We took this approach rather than attempting to recreate a new method of therapy practice in order to increase the possibility of therapists gradually adopting such a system. Besides, creating a new way of practice is risky compared to the existing tried-and-true methods. Therefore, we used games as a part of outpatient therapy and found this approach to be effective.

We expect that as games and technology replaces parts of the therapy practice, the current rehabilitation practice will be challenged and the need for redefining the rehabilitation process around technology will emerge. Starting to design the rehabilitation process with games and technology as core components may nullify some of the previous assumptions and may result in a more effective rehabilitation process. However, this would also come with major human-computer interaction issues to be addressed. We believe that studies redefining the rehabilitation process in the future should have a human-computer interaction component to ensure that the technology and the process are designed in ways usable by therapists and clients. Such studies would identify and resolve human factors issues related to the use of games and technology as a core component of the rehabilitation process.

In our work we already started to identify ways in which our games may challenge the current rehabilitation practices. Providing information about the current motion abilities of users, enabling family members to be participants in home therapy and empowering clients to steer the rehabilitation process may cause rehabilitation practices to be different than today's approaches.

For example, the possibility of supplying an immediate report of the users' motion assessments can enable therapists to always have up-to-date information about their clients' motion abilities. This may enable therapists to plan the rehabilitation process differently compared to before. The therapists can quickly identify motion improvements and reshape the exercise process in ways that would support their development.

Our work can also change the rehabilitation process through enabling family members to be active participants through playing multiplayer games together with the client. This is a major difference compared to the way families currently interact with the person with stroke. The person with stroke usually receives care and help from the family members in an inherently unequal relationship. Giving family members an opportunity to actively participate in home exercises in an enjoyable way may change the way home-based rehabilitation works. Therapists may plan rehabilitation differently after observing this dynamic.

Another way that our work may change rehabilitation is through providing opportunities to empower clients to have a more active role in the process and possibly steer its direction. In Section 4.6.4.1, we observe that our participant wanted to have a more active role in the planning of her exercises and imagined ways in which she could repurpose games to help her with motions that we did not address. Having a more active role in therapy may give clients a better sense of involvement and may increase engagement. Although therapists approached this unconventional way of planning rehabilitation with skepticism because of the possibility of unwanted results, we believe that limiting the options that a client has may overcome this issue. For example, the client may choose exercises from a list that the therapist approved and shape the rehabilitation plan by choosing options available through the software. In addition, this idea uncovers the possibility that people with stroke who cannot afford to see a therapist can use an easy-to-customize system to create rehabilitation plans for themselves. An expert system that attempts to mimic how a therapist would manage the rehabilitation process can later oversee the rehabilitation process and ensure that the participant stays within safe limits of exercise. While we do not expect such a system to replace therapists, we expect it to be better than receiving no therapy at all.

Future studies should identify such changes that games can make in rehabilitation, and study them from a human-computer interaction point of view to resolve issues and to create better game systems. Rehabilitation studies can make use of this knowledge to design new methods which should also be supported with studies addressing human factors.

10.5 Making Game Systems User-Friendly for Disabled, Non-Computer-Savvy Audiences

Our home-based study showed that it was not easy to create an interface for people with stroke that they can use at home by themselves to play therapeutic games. Most of these issues were there not only because our participant had a stroke, but also because she had motor disabilities and she was not a computer user. Therefore, the issues that we identified and our solutions to them are likely to be applicable for non-computer users and people with motor disabilities. Although our interface was sufficient for our participant to carry out home exercises with occasional issues, more research is necessary to create a system that she could set up and use at home with no external help.

The issues that our participant ran into created unnecessary friction in her use of our system. In our study we supported our participant and tried to improve her experience. However, it is apparent that the usability of the interface would play a major part whether participants will continue using home-based systems or not. Future studies must strive to understand disabled and non-computer-savvy users better and find ways of creating interfaces that can anticipate issues and can actively resolve them. This may require revisiting a great deal of knowledge about user interfaces that originated from research conducted on able-bodied individuals.

10.6 Better Addressing Situations of Individual Users

In addition to ensuring that systems with therapeutic games are usable by the target audience, it is also important to address users' specific situations better. In our studies we found that our users were different than each other in many respects including the type and severity of motor disability, types and intensities of exercises they needed to perform, likes and dislikes, cognitive abilities, expectations from games, etc. We found that identifying these traits of users and customizing games to better fit their situations were necessary. Although we enabled therapists to customize games through setting multiple difficulty adjustments and simple game options, this was not always sufficient and we occasionally needed to change the game programs. Future studies should further empower therapists so that they do not need the help of a programmer when adapting games to users. One solution that we identify is the development of games that are highly customizable. Another solution is leveraging authoring environments for non-programmers to enable therapists to program games.

Addressing specific situations of individual users require custom games specific for each user's situation. In our studies we enabled customization of games through difficulty and options adjustments in the therapist interface that enabled the therapist to customize games by changing a set of options that we identified together with the therapists. We programmed new options as therapists requested them. Although this was sufficient for our studies, in widespread use of a game system therapists may require additional options and would have to hire programmers to implement them. We believe that studies to develop highly-customizable games can help alleviate the need for programmers and may enable therapists to address most users' needs. This requires a larger wealth of knowledge about the interaction of target audiences with games so that researchers can identify most possible requirements that may surface later. Such a knowledge base can be built incrementally with game systems that collect requirements and capture the ones that could not be met with the existing system. In addition, participatory design can help identify ways of addressing the needs of the target audience and providing them as options in the games.

While highly-customizable games can help therapists address most users' situations, there can be situations where the limited set of possibilities may prevent therapists from fully addressing a certain user's needs. Future studies can leverage authoring environments for non-programmers (e.g., LookingGlass [75], Alice [62], Scratch [97], etc.) to create game-authoring tools for therapists. The success of such authoring environments in non-programmer audiences suggests that therapists may be able to modify and develop games using an appropriately-designed authoring tool. This gives them more power compared to the customizable games because the therapist can freely modify most aspects of a given game. Furthermore, therapists that are more determined can also create new games from scratch to better address a user's needs. Our work has already inspired a study that identifies the language constructs to be used in such an authoring environment and presents guidelines for supporting therapists in programming games [63]. Further studies are needed for successful game authoring tools that can be effectively used by therapists.

10.7 Long-Term Integration of Serious Games into Lives of Non-Gamer Audiences

A major challenge facing home-based therapeutic games is integrating games into the life of a person that does not regularly play them. Therefore, the larger question of how to integrate useful games into lives of audiences that do not otherwise play games should be studied in order to enable the long-term success of not only stroke rehabilitation games but also other serious games targeting other audiences. We identify a number of directions that future research can explore to make games engaging and motivating for users. Letting users be a part of a context larger than the game itself and enabling networked games within this context can provide the necessary social dynamics that may keep users interested in participating. In addition, multiplayer games in which users play together with friends and family members are likely to provide an engaging context and help games be a part of users' lives at home. Another way we anticipate games being engaging is through customized story lines that games are a part of. We believe further research should uncover other ways of integrating serious games into everyday lives of users for continued long-term participation.

Online communities that enable participants to meet and interact with people in similar conditions, and enable them to play online games together can be a powerful way to provide the necessary social structure that can help games be a part of a user's life. The wealth of knowledge about online communities for the general public can be leveraged to create safe and effective environments where people with stroke can find game partners and play therapeutic games while socializing. Studies to identify and resolve human factors issues for such applications can help them be successful. Another option that can be explored is to repurpose online games for the general audience such that they can be played by stroke survivors. While such games can be less useful therapeutically, the access to a broader user base can be more motivating. Requirements of games can be simplified for our audience in ways that enables playing with people from the general audience (e.g., including AI that helps the user by handling parts of the user's responsibilities in games). Studies that enable people with disabilities to participate in popular online games can help integrate games in their everyday lives.

In addition to online multiplayer games, in-person multiplayer games played with friends and family members can also help with the integration of games into everyday lives. In our user tests the children that were present in the house were interested in the game and said that they would play together with the participant if we enabled them to. However, we also observed that they may not be around every day when the participant needed to play games to exercise. Games that can be played with or without a game partner can be useful to enable family members to join the game at will and spend time with the participant. This can help games be part of a social activity shared with the family members and friends, and help participants to create social habits around them.

Another way that we can enable long-term participation is through making games be a part of story lines that unfold in time as users play the games. Similar to a TV series, the story of the game can unfold slowly as the user keeps playing parts of it in the game. This may create a number of opportunities to further address participants' situations. For example, coupled with the authoring tools, games and plotlines can be modified remotely by the therapist and downloaded to the participant's computer. This way the therapist can keep the experience dynamic and adjust it to the user's needs. In addition, stories designed by psychologists can help address the mental state of participants. This way games can have additional therapeutic benefits. Future studies should explore how to make this process effective and study human factors related to it for increased success of games.

In addition to the ideas that came out of our study, researchers should explore other ways of integrating serious games into lives of non-gamer audiences. Such studies may cause the potential benefits that games have to be realized more effectively through continued participation.

10.8 Software Systems to Support and Manage Various Types of Therapy

One of the challenges we faced in our study was the lack of software systems that can manage the therapy progress. We started with a research project developed in our group and improved it to be used for managing the therapy process. In the larger context of rehabilitation, there is a need for software that can be used by therapists and clients to manage the therapy process efficiently. Planning the therapy sessions, prescribing exercises, keeping track of the exercise progress and monitoring improvements are some examples that such a system needs to handle. Since both therapists and clients are not expected to be computer-savvy, human factors should be addressed appropriately to ensure efficiency and effectiveness. Such systems can also be integrated with larger healthcare IT systems that hospitals or clinics use for better tracking and managing the process.

Furthermore, researchers are looking into creating various technological solutions that can help stroke survivors and people with disabilities in their everyday lives [36]. Although such solutions can be developed in isolation, a unified vision that connects such solutions together in one infrastructure can increase the benefits of individual components. For example, a fall-detection system may identify that the user fell on his or her arm and the therapist may use this information to decide to temporarily suspend arm exercises. In addition, other sensing systems can detect improvement in motion abilities in daily tasks and help therapists observe their correlations with in-game motion abilities to have a more complete picture of the client's progress.

10.9 Using Existing Input Devices for Therapy Games

We used Wii remotes and webcams as input devices for our games. While they worked well in within our study, improvements are necessary for wide-spread use of a game system. The requirement to press Wii remotes' buttons and attach them appropriately on the arms and the torso needs to be more user-friendly for a home-based system to be successful in addressing users with limitations. In a larger context, finding ways of using general-purpose motion-based input devices by people with limitations is a research area that should be explored in the future so that such devices can be viable and practical alternatives to be used in motion-detecting technology solutions for this audience. We believe that if appropriately repurposed and made accessible, end-user devices are more likely to enjoy wide-spread adoption compared to special-purpose devices.

Our experience in attaching Wii remotes to body parts to detect therapeutic exercise showed that it is indeed possible for Wii remotes to be used by people with limitations. However, their usability needs to be improved further before they can be used by larger audiences. Especially, making a practical version of our harness prototype is necessary to enable users to put it on by themselves. Similarly, the way we use the webcam needs to become more user-friendly for use by a larger audience. Studies that focus on the specific issues that occur in the use of such devices by people with limitations may help them become a part of an actual home-based game system.

Although Wii remotes and webcams have the potential to be used by people with limitations in practice, they have inherent limitations. Wii remotes have to be attached to the body parts to detect motions, which may not be practical in every situation. In addition, using the accelerometer prevents detecting rotational motions around a vertical axis. While we can use the gyroscope-based Wii motion plus accessory to overcome this issue, the inherent issue of drift should be properly addressed. Similarly, using webcams comes with precision and calibration issues that may occur in home use.

To address limitations of these simple devices, more advanced motion detection devices such as the Kinect [64] can be used for tracking users' skeletal postures and using them in games. This would enable tracking motions more conveniently than the Wii remote and more accurately than the webcam. However, the usability of Kinect for therapeutic exercise is yet to be studied and compared to Wii remotes. Since it is originally developed for use by able-bodied participants in an unobstructed environment, their use with people with limitations should handle different sitting positions and the use of necessary accessories such as arm braces. In addition, the exercise motions may require precision in the depth direction. Studies should test such novel input devices and assess their strengths and weaknesses when used for the purpose of detecting therapeutic exercises. One study reports that Kinect may provide "irregular performance on non-structured environments" [90] and combines it with the use of inertial sensors similar to

Wii motion plus for increased tracking accuracy. More studies should be conducted for better information about limitations of each device.

One additional benefit of attaching sensors such as Wii remotes on users' bodies is that they can also be used to provide tactile feedback (vibration) at the location that the device is attached to. Although we could not use this in our harness design, we believe that this can be a powerful way of providing feedback to the user that needs to be studied further. Questions such as whether different vibration patterns can be detected by users as different kinds of information, or whether the intensity of vibration can determine the feedback strength should be addressed in future studies.

It could be possible that one device may not be sufficient to address all types of therapeutic exercise and a combination of them may need to be used. Therefore, identifying strengths and weaknesses of each device when used for various types of therapeutic exercise may enable therapists to choose the appropriate device based on the therapeutic exercise and available of devices. Identifying human factors related to the use of each device can further improve their use.

Appendix A

Calculating the Axis that a List of Inverse Gravity Vectors Rotate Around

To capture the user's motion behavior in exercise motions that rotate the Wii remote around a horizontal axis, some of our calibration sessions require collecting inverse gravity vectors from the user's sample motions and identifying the axis that the user's motions were causing the vector to rotate around. We later use this axis to map future vectors to one dimensional values that represent the user's progress through the motion. Here we present our method of identifying the rotation axis of a stream of vectors that represent the user's motions.

Given a stream of unit vectors, our goal is to find a pair of vectors among them that have the largest angle between them. The problem is similar to finding a pair of points with the maximum distance out of a given set of points. The main difference is that we are dealing with unit vectors rather than free points. Therefore our domain is the surface of the unit sphere rather than the whole space. The circular nature of the problem makes it more difficult than finding the pair of points with the greatest distance. In addition, the potentially high numbers of vectors that we need to process disqualifies a brute-force solution.

The problem of finding the pair of points with the greatest distance can be solved simply by computing the convex hull of the points and finding the pair of convex hull vertices with the greatest distance. This is an efficient approach that reduces the number of candidate pairs considerably. If we know that our unit vectors are contained in a hemisphere (i.e., no two pairs have an angle larger than π), we can solve the problem similarly by computing the convex hull of the vectors on the surface of the sphere [48] and finding the convex hull vectors with the maximum angle.

While the solution is straightforward on the hemisphere and the rotational motions of most stroke survivors are likely to remain below π, we occasionally came across users with motion ranges that did not fit in the hemisphere. Therefore, we found a way to compute a set of interesting vectors that are likely to be in the extremes, similar to a convex hull. We created a kinetic algorithm to incrementally compute the interesting vectors from a stream of vectors, and used the set of interesting vectors to find the pair of vectors with the larges angle, and an axis perpendicular to them that enables the angle to be greater than π.

A.1 Algorithm

While a solution to the problem of finding an approximate convex hull on the sphere for points that may not be within a hemisphere would solve our problem, we did not come across such an algorithm in the literature. We believe this is because the definition of a convex hull on the sphere becomes open to interpretation once the set of points are spread beyond a hemisphere—one could argue for any hole among the points to be the convex hull.

While such ambiguity is possible in a general set of points on a sphere, our vectors originate from a stream and have an implicit ordering. This additional information enables us to track an approximate "inside" region for the set of vectors on the sphere. Our goal in this algorithm is to find a small number of interesting vectors that we call "border vectors" that are at the edges of this region so that we can reduce the candidate number of vectors for the largest angle. We do this by tracking an approximate centroid vector v_c that is likely to represent the "inside" region. We also track the direction of the "inside" region for each vector v_i using an axis a_i such that if the vector is rotated around that axis, it would rotate towards the "inside" region and the centroid vector.

Definition: Given two vectors v_i and v_j and another vector a, we will define the angle from v_i to v_j around a. We first project the two vectors to the plane that is perpendicular to a and obtain y_i and y_j. Then, we calculate the angle θ between y_i and y_j and around a as follows:

$$\theta = arctan2\left((y_i \times y_j) \cdot a, y_i \cdot y_j\right)$$

We call θ the angle from v_i to v_j around a.

Definition: We say v_j "encompasses" v_k with respect to v_i if the angle from v_i to v_j around a_i is larger than the angle from v_i to v_k around a_i, where a_i is the axis that corresponds to v_i.

A.1.1 Incrementally calculating the Set of Border Vectors

Using these definitions, our algorithm works as follows. Given a new vector v_n and its axis a_n that would turn it towards the centroid v_c, we would like to find out whether v_n should be in the set of border vectors $\mathcal{B}$. We do this by considering all vectors $\forall v_i \in \mathcal{B}, a_i \cdot a_n < 0$, i.e., the axes that turn the vectors towards the centroid are opposite to each other. If there is no vector $v_j \in \mathcal{B}$ such that v_n does not encompass v_j with respect to v_i, we qualify v_n to be added to $\mathcal{B}$. Before adding v_n, we remove $\forall v_j \in \mathcal{B}$ such that $\nexists v_i \in \mathcal{B}$ where v_j encompasses v_n with respect to v_i.

After adding v_n to $\mathcal{B}$, we recalculate the centroid by incrementally interpolating between the vectors in $\mathcal{B}$. For $\mathcal{B} = \{v_1, v_2, \dots, v_n\}$, we find v_c^n where $v_c^i = slerp\left(v_c^{i-1}, v_i; \frac{1}{i}\right)$. Note that while this approach would give the exact centroid for points in space, this is merely an approximation for vectors on the surface of the sphere. However, we found the centroid calculated this way to yield to correct results. After calculating v_c^n, we update v_c as follows

$$v_c \leftarrow sign(v_c \cdot v_c^n)v_c^n$$

This way we make sure that the centroid vector does not flip to the opposite direction. This is the step that enables us to maintain vectors that exceed a hemisphere. After updating v_c, we update $a_i, \forall v_i \in \mathcal{B}$ similarly:

$$a_i' = v_i \times v_c$$

$$a_i \leftarrow sign(a_i \cdot a_i')a_i'$$

This algorithm enables us to keep a set of border vectors that are likely to contain the pair of vectors in the stream with the largest angle in between. Note that this is not necessarily the convex hull and there are cases in which it may not find the correct results. However, in our tests with typical inputs, it proved to be dependable.

A.1.2 Finding the Axis of Rotation using the Set of Border Vectors

After the example motion that the user performs is complete, we would like to calculate the axis that the vectors are likely to have rotated around. We calculate this by first finding candidate pairs of vectors $\mathcal{C} = \{(v_i, v_j) | a_i \cdot a_j < 0\}$. For each $(v_i, v_j) \in \mathcal{C}$, we calculate the corresponding axis $a_{ij} = slerp(a_i, -a_j, \frac{1}{2})$ and the angle θ_{ij} as the angle from v_i to v_j and around a_{ij}. We choose (v_i, v_j) with the largest θ_{ij} and use the corresponding axis a_{ij} as the axis that the input vectors are likely to have rotated around. We use v_i and v_j as the maximum and minimum vectors of the motion range.

Appendix B

Video Game Exit Questionnaire

As a part of our summative study in Chapter 9, we administered the below questionnaire to users. The first four questions relate to their time perception and the rest of the questions are from the standard Task Evaluation Questionnaire (TEQ) [27].

1. Please estimate how long you played the game by giving a maximum and a minimum duration.

For each of the following statements, please indicate how true it is for you, using the following scale:

1	2	3	4	5	6	7
not at all true			somewhat true			very true

2. The game session ended too early.

3. The game session took too long.

4. Time went by quickly while playing the game.

5. While I was playing the game I was thinking about how much I enjoyed it.

6. I did not feel at all nervous about playing the game.

7. I felt that it was my choice to play the game.

8. I think I am pretty good at playing the game.

9. I found the game very interesting.

10. I felt tense while playing the game.

11. I think I did pretty well at this game.

12. Playing the game was fun.

13. I felt relaxed while playing the game.

14. I enjoyed playing the game very much.

15. I didn't really have a choice about playing the game.

16. I am satisfied with my performance at the game.

17. I was anxious while playing the game.

18. I thought the game was very boring.

19. I felt like I was doing what I wanted to do while I was playing the game.

20. I felt pretty skilled at the game.

21. I thought the game was very interesting.

22. I felt pressured while playing the game.

23. I felt like I had to play the game.

24. I would describe the game as very enjoyable.

25. I played the game because I had no choice.

26. After playing the game for a while, I felt pretty competent.

B.1 Subscale Scores

Below are the four different subscale scores calculated from the questionnaire. The numbers next to each score indicate the answers to questions that need to be averaged to find the score. The entries with (R) indicate that the score for that question needs to be inverted (subtracted from 8) before used for averaging.

Interest/enjoyment:	5, 9, 12, 14, 18(R), 21, 24
Perceived competence:	8, 11, 16, 20, 26
Perceived choice:	7, 15(R), 19, 23(R), 25(R)
Pressure/tension:	6(R), 10, 13(R), 17, 22

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Vita

Gazihan Alankus

Date of Birth April 8, 1980

Place of Birth Kayseri, Turkey

Degrees

Ph.D. Computer Science, Washington University in St. Louis, December 2011

M.S. Computer Science, Middle East Technical University, June 2005

B.S. Computer Science, Middle East Technical University, June 2002

Publications

Gazihan Alankus, Rachel Proffitt, Caitlin Kelleher and Jack Engsberg, "Stroke Therapy through Motion-Based Games: A Case Study," *ACM Transactions on Accessible Computing (TACCESS),* in press

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