Reducing Compensatory Motions in Video Games for Stroke Rehabilitation

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ABSTRACT
Stroke is the leading cause of long-term disability among adults in industrialized nations; approximately 80% of people who survive a stroke experience motor disabilities. Recovery requires hundreds of daily repetitions of therapeutic exercises, often without therapist supervision. When performing therapy alone, people with limited motion often compensate for the lack of motion in one joint by moving another one. This compensation can impede the recovery progress and create new health problems. In this work we contribute (1) a methodology to reliably sense compensatory torso motion in the context of shoulder exercises done by persons with stroke and (2) the design and experimental evaluation of operant-conditioning-based strategies for games that aim to reduce compensatory torso motion. Our results show that these strategies significantly reduce compensatory motions compared to alternatives.

Author Keywords
Stroke rehabilitation; compensation; video games; design.

ACM Classification Keywords
H.5.m [Information Interfaces and Presentation (e.g., HCI)]: Miscellaneous;

General Terms
Human Factors, Design.

INTRODUCTION
Stroke is the most common cause of long-term disability among adults in industrialized nations [23]. About 80% of people who survive a stroke experience motor disabilities, such as hemiparesis [18] (a partial paralysis of one side of the body), that severely constrain their lives [16]. Research using animal models suggests that hundreds of daily repetitions of therapeutic motions can help in recovering motor control following a stroke. Yet, during typical outpatient therapy, clients and therapists meet weekly for an hour or less. During these meetings, clients typically perform only tens of motions [17]. Research suggests that motion-based video games can provide a motivating context in which players will perform the number of repetitions necessary for recovery [1,2,3,5,6,10,11,14].

However, few current therapeutic games ensure that players perform motions correctly. Persons with stroke who have a limited range of motion in a joint often compensate by moving another joint to perform tasks easier. For example, a person with limited shoulder motion may lean back to raise the hand higher when reaching. Compensatory motions like leaning are often subconscious [19], can impede progress towards recovery [7] and can create new health issues [7]. To have the greatest impact, home-based therapeutic games must appropriately address compensatory motion [2,3,12]. To date, little research has addressed compensation in the context of motion-based video games.

The goal of this work is to explore (1) how to reliably sense compensatory torso motion in the context of shoulder exercises and (2) how to design compensation feedback within a therapeutic game to effectively reduce compensatory torso motion. In this paper, we describe (1) the design and validation of a method for detecting torso compensation, (2) the iterative design of a therapeutic game incorporating compensatory motion feedback and (3) the results of a summative study comparing five compensatory motion feedback strategies on players' compensation behavior and willingness to play. We found that introducing in-game compensation feedback with incentives and disincentives significantly reduced compensation by 26%. Further, continuously updating game parameters according to players' changing abilities reduced compensation by an additional 21%. These results suggest that games can encourage performing therapeutic exercises correctly by reducing compensatory motions, which currently requires the supervision of a therapist.

RELATED WORK
Our related work falls into three categories: (1) addressing compensation in conventional therapy, (2) addressing compensation in home therapy supported by technology and games, and (3) using operant conditioning to shape game player behaviors.

Addressing Compensation in Conventional Therapy

People recovering from a stroke often use compensatory motions without realizing that they are compensating [19]. During sessions with a therapist, the therapist can provide feedback on compensation behavior. But this is not sufficient to help clients reduce their compensatory motion behavior during therapeutic exercise at home. Further, compensation in unsupervised exercise remains an open problem in therapy. While there is research demonstrating the detrimental effects of compensation [7,19], research on helping clients reduce compensation is limited. Prior research has explored using trunk restraints to physically prevent compensation [24], and detecting forward torso compensation using a pressure sensor on a chair and providing audible feedback in response [21]. Neither approach has been evaluated in an unsupervised setting. Further, unsupervised use of trunk restraints may not be practical for people with motor disabilities. The pressure sensor approach can only detect forward torso compensation and has no tolerance. We extend the work in [21] by contributing a method for detecting a wider range of compensatory motions.

Addressing Compensation in Technology and Games

Researchers have proposed a number of solutions for home-based therapy using technology and games [1,2,3,4,5,6,10,11,14]. While the need to address compensation has been acknowledged in analyses [12], the majority of efforts only enabled therapeutic exercise without evaluating exercise correctness [1,4,5,6,10,11,14].

Two prior telerehabilitation systems have explored compensation, using motion capture [15] and with therapist supervision through video conference [20]. However, these approaches are not economically feasible for widespread home use. The issue of compensation is also largely unaddressed in video game based therapy. One exception is our previous work that identified the need to address compensation [3]. We used Wii remotes to detect exercise and compensation separately and removed compensation from exercise motions. This prevented players from making the game easier through compensation, but did not actively help them learn not to compensate.

Operant Conditioning and Games

Operant conditioning is a psychological technique that can modify human motor behavior through punishments and rewards [22]. It is one of the psychological techniques that inspired machine learning algorithms such as reinforcement learning. Operant conditioning techniques appear in some commercial video games [13]. While analyses identify its use in games [25], game authors do not typically publish their specific strategies or lessons learned. Our work contributes a successful usage of operant conditioning to shape player behavior and lessons learned in the process.

GOALS AND APPROACH

In this work, our goals are to (1) reliably sense compensatory torso motion in the context of shoulder exercises and (2) design therapeutic games that help players reduce compensatory torso motion.

We conducted five studies to achieve these goals. Figure 1 summarizes the relationship between these studies.

1. An iterative, formative study of a method for detecting torso compensation.
2. A validation study that quantifies our torso compensation method's error as compared to a motion capture system.
3. An iterative, formative study of a game design, requiring therapeutic exercise and eliciting natural compensation.
4. An iterative, formative study of in-game compensation feedback mechanisms that discourage compensation.
5. A summative study comparing compensation behavior in versions of our game with five different operant-conditioning strategies for reducing compensation.

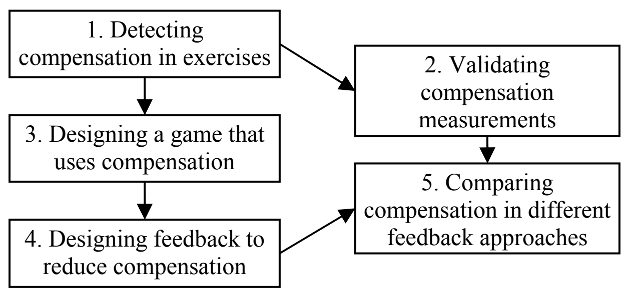

Figure 1. The relationship between the five studies.

FORMATIVE STUDY: DETECTING COMPENSATION

We conducted an iterative, formative user study in order to develop techniques to accurately detect compensatory motions. We used the formative study to evaluate (1) a Wii remote harness that enables tracking of 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.

Detecting Compensation User Sessions

Three female Occupational Therapy (OT) doctoral students and four participants with stroke (three female, ages 55-60) participated in seven, 45 minute, single user sessions. After obtaining consent, we assisted the user in putting on two Wii remotes on the upper arm and the torso. We asked participants to sit on a chair, as they would during a typical therapy session. To prevent the back of the chair from interfering with the Wii remote, we asked participants to sit towards the middle of the seat and refrain from leaning back.

We asked the participant to move an on-screen sprite using shoulder abduction/adduction in order to catch oncoming targets. In addition to moving vertically with shoulder abduction/adduction, the sprite also tilted with torso compensation. During play, we adjusted the difficulty settings (motion range, target frequency and speed) for appropriate challenge such that participants demonstrated some compensatory motion behavior.

Detecting Compensation Data

We computed the orientation of each Wii remote using accelerometer readings and used a lowpass filter against noise. These orientations lacked yaw angles because of the limitations of accelerometers. However, this was not an issue as our exercises did not require the yaw angle [2]. We also recorded video of the participant for later review.

Lessons Learned on Detecting Compensation

Over the course of the study, we learned several lessons about the design of the torso harness (see Figure 2) and the compensation detection algorithm.

Figure 2. The harness we designed to track the torso motion with a Wii remote.

Attach the harness around the neck, not the shoulders.

Initially, we designed a backpack-style harness with two straps going over the shoulders. However, this design resulted in erroneously responding to players' shoulder shrugging motions. To prevent this, we settled on a design in which the straps go diagonally around the neck, with a soft cloth cover to prevent rubbing against the skin.

Stabilize the Wii Remote against the back to prevent rolling

In some user tests, the harness did not prevent the Wii remote from rolling against the player's spine, leading to incorrect readings. To prevent this, we fastened a rectangular cardboard to the back of the Wii remote holder. We observed that this was sufficient to minimize the rolling motion of the Wii remote, even in cases where the harness loosened over the course of a game session.

Participants do not always compensate the same way

We originally assumed that participants' compensatory motions would rotate the torso Wii remote around a single, user-specific axis. Accordingly, we identified these axes in the calibration stage and used them to compute angles during gameplay. However, as some users attempted to reduce the compensation feedback, they began to compensate around an axis perpendicular to the original axis identified during calibration. This minimized the angles that our algorithm captured. For example, a user started out by leaning to the side to compensate and gradually transitioned to leaning back. Although the player was still compensating, the single-axis algorithm could not identify the compensation.

To correct this, we removed the assumption of a fixed axis. We calculated and maintained a resting pose orientation, and calculated the angle of rotation between that and the live orientation of the Wii remote. Unlike the fixed-axis case, this angle is always positive and it does not tell the direction that the user leaned towards. We wanted to map these orientations to a signed angle that represents the direction like in the fixed-axis case, so that we can correctly tilt an on-screen avatar and decide whether the motion makes the exercise easier or more difficult. We classified orientations so that tilting the torso backwards and away from the player's affected arm is positive compensation (i.e. it decreases the motion's difficulty), and tilting the body forwards and towards the affected arm is negative compensation. This enabled addressing any leaning direction and representing it with a single signed angle.

Players' default poses may change over time

As playing time increased, we noticed that participants' resting pose vectors 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.

We avoid this by updating 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 use exponential smoothing to slowly move the previous resting pose vector towards the captured vector. Over time, this reflects the participant's resting pose.

VALIDATION STUDY: DETECTING COMPENSATION

Through our initial, formative study, we designed a harness and an algorithm for compensation detection. During our second study, we compared the performance of our harness and algorithm to compensation angles measured with a motion capture system in order to validate our compensation detection technique.

Compensation Validation 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 than a similarly sized group of people with stroke. Further, the daily motion variation of OT participants will be less than that of participants with stroke.

Compensation Validation Session Description

We began each session by attaching Wii remotes to the arm and torso of a participant. The first participant also wore reflective markers for a motion capture system (six Vicon IR cameras, millimeter accuracy). Participants then performed ten repetitions of sixteen different shoulder abduction/adduction exercise sets (160 repetitions).

The sixteen exercise sets paired four types of reaching tasks with four types of visual feedback. Each task required participants to raise the elbow to a target. The four task types were: reaching low targets, reaching low targets with resistance (i.e., a Theraband), reaching high targets, and reaching high targets without body movement. The four visual feedback types were: no feedback, a physical tripod to display the target height, a graphical balloon moving on a monitor, and the same graphical balloon that rotates with participants' torso compensation. Before each set, we used the tripod to briefly show the height that the user should move to. We automatically recalibrated before each set of ten repetitions to recapture the participants' default poses.

The first participant completed one session that recorded the difference between motions measured using Wii remotes and motion capture. The second participant completed four sessions on different days to capture daily motion variability. We counterbalanced learning effects using a Latin Squares design.

Compensation Validation Data and Analysis

We calculated and recorded arm and torso angles using device orientations from the Wii remotes and using vectors between markers from the motion capture system (participant one, only) for later analysis. We used these signals (angles in time) to calculate both Wii Remote error and user error values for both arm and body angles.

Wii Remote Error

With participant one, we calculated the error of the Wii remote readings by comparing them to motion capture data.

We note that while the Wii Remotes and the motion capture system captured related information, they did not capture identical information. This is in part due to the physical placement of the Wii remotes and the reflective markers. Because the harness covered the middle back, we placed the reflective markers on the participant's upper back. Because the upper back moves more than the middle back when a person arches, the motion capture recorded larger angular changes than the torso Wii remote. To enable comparisons, we normalized them using the largest recorded angles.

Given the two time-aligned, normalized motion signals (angles in time), 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 percentage of error per unit time.

User Error Over Sessions

We calculated participant two's daily variation with Wii remotes by calculating the error between each pair of the exercise sets from different sessions and averaging them. To calculate the user error, we hand-segmented and aligned each exercise repetition, and then computed the error. This accounted for the timing differences between motions on different days.

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%

Table 1. Error measurements for the Wii remotes and the user

Compensation Validation Results

In Table 1, we observe that the error of our system is lower than the average error between participant one's daily motions, 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.

Compensation Validation Discussion

Overall, we found that the measurement error using the Wii Remotes is lower than the daily motion variation for a person without stroke. As people who have experienced a stroke will tend to have even more daily motion variation, we believe this is an acceptable error level to enable compensation measurement through our game. While there is room for further accuracy improvement, we note that our compensation measurement method represents a significant advance over current practices for measuring compensation (e.g., using a chair-mounted pressure sensor [21] or asking a therapist to visually judge compensation [20]).

FORMATIVE STUDY 2: DESIGNING A BASE GAME

Through our first two studies, we have designed and validated a method for detecting compensation using a harness-mounted Wii remote. Next, we conducted a second formative study to refine the design of a basic game that (1) includes meaningful therapeutic exercises and (2) creates conditions in which players will naturally compensate.

Designing a Base Game Participants

We recruited eleven participants with stroke (six female) from ages 43 to 72. Participants ranged from three to eleven years post stroke, and had various levels of disability.

Designing a Base Game Session Description

We had one session with each participant. 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 made live modifications to the game using the laptop and quickly tested our hypotheses with the participants. Sessions took between one to three hours and ended with semi-structured interviews to understand participants' experiences.

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 3). The player's goal is to snag parachute jumpers at varying heights on the screen, resulting in shoulder abduction/adduction exercises. We spaced jumpers 6.5 seconds apart and had no simultaneous displayed jumpers to make the game approachable for players with a wide range of motor disabilities.

The initial game positioned the hot air balloon vertically according to the difference between the torso angle and the arm angle, such that the player cannot use compensatory motions to succeed in the game. We mapped the player's torso angle to the balloon's left and right tilt to provide players with an awareness of the torso motion.

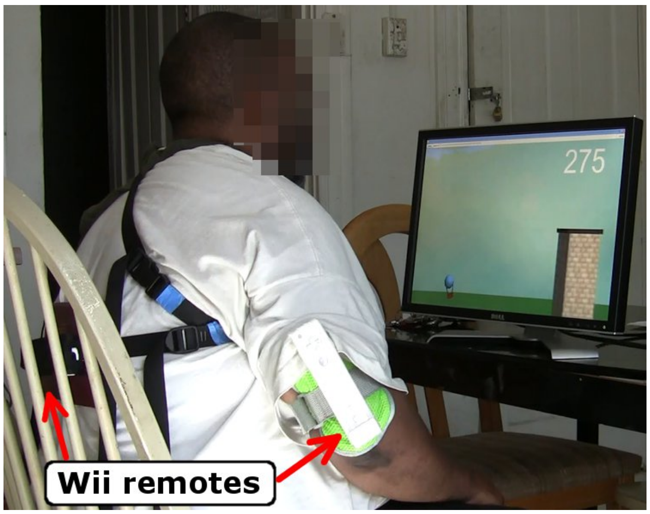

Figure 3. A participant with stroke testing our base game with Wii remotes attached to the arm with an armband and to the back with the harness that we designed.

Lessons Learned: Base Game Design

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

Include Calibration as a Part of the Game

Games that attempt to influence compensation behavior must capture two distinct types of calibration information: motion range and a compensation profile. We initially recorded these values during a short calibration session before a game. However, users were conscious of their motions during this distinct calibration stage and moved differently during the actual game. We found that having a calibration session that looks like the game and seamlessly including it in the beginning of the game session was the most successful approach in capturing accurate information. We used a two stage calibration process: we first captured the motion range and then the expected compensation.

Step 1: Capturing the Motion Range. We captured an initial crude approximation of motion calibration by asking the participant to perform the exercise motion a few 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 ones.

Step 2: Capturing Sample Compensation Behavior. We captured compensation behavior by placing 20 parachute targets with the same pseudorandom position sequence as the actual game. 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 as the threshold to activate compensation feedback in the game.

Encouraging Therapeutically Beneficial Motions

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

Place Targets at Both Motion Range Extremes. 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 the arm raised to minimize motion. Placing some targets at the bottom of the screen encouraged players to assume a low resting position in between high targets.

Obstacles Promote Controlled Motions. We observed some users using a timed jerking motion to reach target positions at the high end of their range. This lack of motion control can decrease motions' therapeutic value. Accordingly, we introduced buildings as obstacles which required users to move the balloon above the building and hold their arms stationary for a short duration. This was difficult for some players, even though they could reach targets placed higher than the building tops.

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. Users became reluctant to hit buildings after we added a score deduction.

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 moving cloud target to provide another type of challenge. The cloud appeared in front of the balloon and quickly moved up and down a few times while sending out little clouds that the user could pick up for points. The cloud appeared infrequently and thus did not cause frustration. Most users looked forward to the next arrival of the cloud, even counting how many little clouds they caught each time as a self-assessment measure.

Providing Suitable Feedback during Gameplay

We modified our game's feedback to reduce unwanted surprises by ensuring that only arm motion affected balloon height, avoiding punishment for compensation during rest, and always providing compensation feedback.

Only Arm Motion Should Appear to Effect Balloon Height. Body motions had a negative contribution to the balloon height to prevent users from moving the balloon higher using compensation. As a side effect, when a player was at rest during our initial game, the balloon appeared to move on its own because of his or her body motions, which often surprised the player. 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. We set two height value thresholds and interpolated the functions between these thresholds to avoid a visible jump.

Avoid Punishing Compensation During Rest. We added simple compensation feedback to the game towards the end of our iterative design. If a player tilted the balloon past a threshold, then the game played a sad "aww" sound. This made sense to participants when their arms were up, but they often triggered the "aww" while at rest by shifting in their seat, which they found surprising. We then enabled the "aww" feedback only above a certain height threshold.

Always Provide Body Motion Feedback. Although it is important not to penalize users while they are at rest, it is still important to provide awareness feedback. We experimented with removing the balloon's tilt feedback for the player's torso motion when a player's arm was low. This resulted in participants no longer understanding the relationship between their torso motion and the balloon tilt.

DESIGNING EFFECTIVE FEEDBACK FOR REDUCING COMPENSATION

With the base game complete, our goal was to add feedback that effectively reduced player compensation. We continued our earlier discussed iterative design process on new game versions. These versions included in-game compensation feedback mechanisms inspired by operant conditioning.

Operant Conditioning

Operant conditioning is a psychological technique to modify voluntary behavior. When participants perform a specific voluntary behavior, they consistently receive desirable rewards (incentives) such as adding desirable stimulus (i.e., positive reinforcement) or removing undesirable stimulus (i.e., negative reinforcement). They also receive undesirable punishments (disincentives) in a similar but opposite way. This causes participants to associate punishments or rewards with their voluntary behaviors. Participants then choose to perform rewarding behavior and avoid punished behaviors.

Effective behavior modification with operant conditioning requires that participants perceive punishments and rewards (p/r) as undesirable and desirable, respectively, while associating their own behavior with the p/r. Thus we attempted to create game feedback that was correctly perceived as a p/r and associated with compensation.

The use of punishment to shape behavior carries the risk of reducing participants' motivation. We tried to ensure that the punishments did not decrease participants' willingness to play our game throughout the design process.

In-Game Punishment and Reward Events

We designed and user tested a number of in-game punishment and reward (p/r) events. Visually we changed the balloon's color from green to red, displayed a sad or happy face on the balloon, and added stars shooting from the balloon. Audibly we played applause and "yippee" sounds as rewards and an "aww" sound as punishment. We also added or deducted single points as p/r events independently from the targets in the game (see Figure 4).

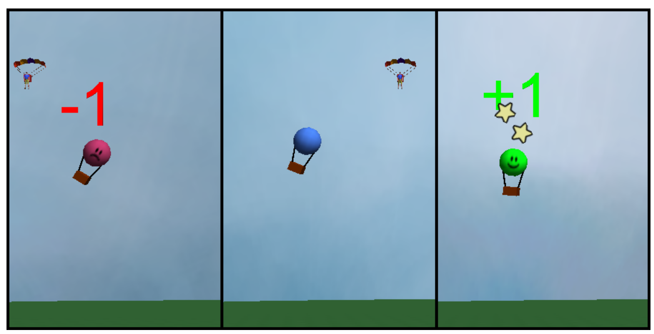

Figure 4. Three kinds of feedback. Left: punishment for excessive compensation. Center: No p/r feedback between the two thresholds. Right: Reward for low compensation.

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. Participants' responses suggested that they perceived p/r events appropriately as desirable and undesirable, although a small number of participants falsely associated them with catching or missing parachutes. We attempted to mitigate this false association with a tutorial and in-game reminders of feedback events' compensatory causes.

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

Lessons Learned in Designing Effective Feedback

We used the p/r events to design a rich feedback strategy that targets reducing compensation.

Avoid Feedback Confusion with Multiple Thresholds and Continuous Feedback Intensity Mapping

The primary p/r feedback elements included the color, the face and the "aww" and applause sounds. We used a single threshold to determine whether to provide positive or negative feedback. This created confusion because compensation feedback could quickly oscillate between reward and punishment when a user's compensation varied around the threshold.

In response, we modified the feedback policy to use two compensation angle thresholds: a lower reward threshold and an upper punishment threshold. Participants then received reward feedback when their compensation was below the lower threshold and punishment when above the upper threshold, with no feedback given in between the thresholds.

Because abrupt feedback changes could still occur at the threshold values, we mapped compensation angle above or below the respective threshold to feedback intensity. As a participant reduced the compensation to near zero, the volume of the reward sounds increased. At the opposite end, if a participant's body tilt exceeded the threshold, the balloon color became a shade of red with the opaqueness proportional to the tilt.

Incentivize Behavior with Repeated Feedback

While participants responded to the onset of p/r feedback, their responses tended to diminish over time. However, in home therapy settings, we want to encourage participants to exhibit reward behaviors continuously and extinguish punished behaviors quickly. We found that strong, discrete p/r events that were periodically repeated accomplished these goals. For example, we rewarded users by adding points, displaying shooting stars, and playing a "yippee" sound. The initial rewards begin half a second after the participant's compensatory motion angle dips below the threshold and repeats every two seconds for as long as the participant remains below the compensation threshold.

Withhold Feedback Clearly in a Variable Ratio Schedule

Operant conditioning research suggests that before providing feedback, 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. On the other hand, we observed in our formative tests that the success of feedback was sensitive to timing. 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 sometimes provided no p/r feedback. Rather than increasing reward anticipation, participants frequently interpreted the lack of p/r feedback as evidence that the game was not working correctly. In order to decouple correctness feedback from incentives and disincentives, we modified the game to provide color feedback at times when the rewards were suppressed. We observed in our user tests that participants anticipated the rewards more strongly. When we asked participants to explain why the game sometimes provides color feedback without a reward, participants stated that perhaps they did not perform the target motion quite right, although they could not identify specific deficiencies. However, this often increased their motivation to get it right in subsequent trials.

Adapt to Changing Abilities

Over the course of a single session, participants' motion abilities can vary considerably. As participants warmed up through game play and tired at the end of sessions, their motion range and compensation behavior varied. Consequently, a single calibration does not maintain an appropriate level of challenge over a game session. We addressed this issue by creating an adaptive version of our game that periodically readjusted itself to participants' changing motion abilities.

Our adaptive game algorithm uses a moving window approach to adjust the calibration parameters such that players successfully reach high targets 90% of the time, are rewarded for low compensation 30% of the time, and are punished for high compensation 15% of the time. To maintain these levels, the game collects game-play data and calculates appropriate calibration values over the past window such that the player would have achieved the aforementioned target rates. We identified our target rates through formative testing. Based on our observations, they result in an enjoyable and challenging game experience that appeared to track participants' abilities.

We anticipated that readjusting difficulty according to success could potentially result in a feedback loop that could increase or decrease the difficulty too dramatically, particularly if the user's ambition to succeed was at either extreme. In general, our users demonstrated an appropriate level of effort and, in our user tests, the feedback loop converged quickly to an appropriate difficulty level. One exception came from a participant who had relatively minor motor disability and was punishment averse. The game became too difficult for this participant; very little compensation triggered punishments. We did not observe any instances in which the game became too easy. While the adaptive algorithm seems promising in most cases, the ability to customize the reward and punishment policies for individual players may be valuable.

SUMMATIVE EVALUATION

We conducted a summative study to evaluate the effect of different compensation feedback policies on users' compensation and willingness to play.

Conditions

We created five versions of our game that employ different compensation feedback policies:

G1. No tilt: no compensation feedback, the balloon does not tilt; this represents the state of the art in games [2]

G2. Tilt only: compensation tilts the balloon; this is comparable to providing compensation awareness as in [21]

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

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

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

By comparing the compensation levels among the first three conditions, we can explore whether or not p/r feedback provides any benefits over simple awareness of compensation behavior. Conditions four and five enable exploration of the benefits of adaptive calibration and variable feedback.

Study Design

We conducted a within-subjects study in which each participant played all five game conditions on different days. We balanced conditions using a Latin Squares design.

Participants

Eleven stroke survivors, four male and seven female, participated in five user test sessions for a total of 55 user tests. Participants' ages ranged from 43 to 61 years old with their strokes occurring from three to eleven years previous. Participants exhibited a variety of disability levels.

Sessions

Sessions took place in participants' homes. We hid clocks in participants' homes to prevent their direct observation of elapsed session time that could bias their time estimates.

We first conducted a questionnaire to record participants' background and stroke history. Following this, we assisted participants with putting on Wii remote attachments.

In a clinical setting, therapists would likely instruct participants on how to play the game and encourage players to perform the game motions without compensating. To simulate this experience, we read a script that addressed these topics. We demonstrated the expected shoulder abduction/adduction exercise, and then participants completed the calibration session. We provided further information about the game and the participant began playing the game in three five-minute segments with one-minute breaks in between. After finishing the game, the participant completed a questionnaire, followed by a semi-structured interview to understand the participant's experience.

Data

We recorded average compensation levels near parachutes during calibration (during which we provided no compensation feedback) and game play. We define relative compensation as their ratio, which represents the change in compensation level that is caused by the game.

We collected two types of data to measure motivation and desire to play: participants' estimates of session duration and their responses to the Task Evaluation Questionnaire (TEQ) [9]. We chose to collect duration estimations because engagement can skew time perception [8]. The TEQ provides scores that indicate motivation in relation to the task that is the game.

Results

We analyzed the relative compensation using an analysis of variance with game version 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 with a large effect size, $F(4, 40) = 8.309$, $p < 0.0001$, partial $\eta^2 = 0.454$. Figure 5 shows the estimated distributions.

We performed post-hoc comparisons using the Bonferroni adjustment for multiple comparisons. There was no statistically significant difference between G1 and G2 or G2 and G3. However, G3 reduced relative compensation by 26% from 0.666 (SD=0.142) of G1 to 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.

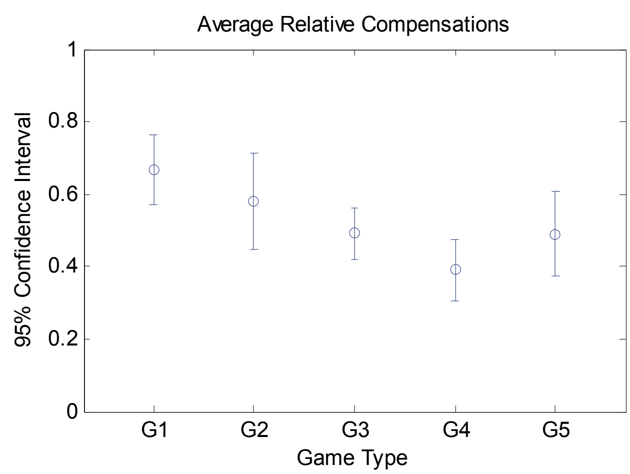

Figure 5. Estimated distributions of average relative compensation for game versions. G4 has the best reduction.

Compared to G3, G4 reduced relative compensation by an additional 21% to 0.39 (SD=0.128, $p<0.05$). Further investigation revealed that the adaptive algorithm also reduced the range of motion significantly to 92.5% ($t(10)=2.823$, $p<0.05$), which suggests that exercise became easier. At the same time, it made the compensation thresholds stricter, reducing the punishment threshold to 82% of the original threshold value ($t(10)=3.244$, $p<0.01$) and reward threshold to 79.7% ($t(10)=2.696$, $p<0.05$). The gap between the thresholds also shrunk to 84.2%

($t(10)=3.332$, $p<0.01$). The change in thresholds was larger than the change in motion range, which may suggest that participants tried harder to reduce compensation.

There was no significant difference between compensation behavior in G3 and G5, suggesting that the variable ratio schedule was not detrimental.

Motivation and Willingness to Play

We found that three factors of TEQ were reliable and one was questionable for our data by computing Cronbach's alpha for each (interest/enjoyment: 0.95, perceived competence: 0.88, perceived choice: 0.71 and pressure/tension: 0.62). We analyzed duration estimates and questionnaire results using MANOVA to determine whether game version may have caused a significant change in indicators of motivation (users' time perception and results of TEQ). The analysis showed that there was no statistical significant difference across the results for different game versions ($p=0.853$), which may mean that users similarly enjoyed all the game versions and punishments did not discourage them.

DISCUSSION

Our results can generalize to other exercises and uncover designing rehabilitation games for the brain vs. the muscles.

Generalizing to Other Exercises

Our system can support 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 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.

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 help 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.

Designing for Brain vs. Muscle Rehabilitation

Stroke damages the brain and not the muscles; however, muscles unused for a long time may weaken [23]. 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. Games can be designed to favor one over the other using calibration adjustments or prioritizing in-game goals.

Calibration Adjustments for Rehabilitation Type

Our adaptive algorithm resulted in much more correct exercises at the expense of some range of motion. Although this is a great outcome for brain rehabilitation, it may be less desirable for muscle rehabilitation. This was a side effect of the parameters of our adaptive algorithm that came from our third formative study. To target the muscles, we can adjust the algorithm to be more tolerant of growing compensation and less tolerant of shrinking range. Reversing this approach could help target the brain.

In-Game Goals with Different Priorities

In our game, exercising and reducing compensation were two competing goals with exercise being the main goal. Users sometimes had to choose between reaching for the parachute while knowingly receiving a punishment, and missing a parachute to keep compensation low. Brain rehabilitation may prefer the user to miss that parachute, while muscle rehabilitation may prefer otherwise. Game feedback and game mechanics can set this priority in a way that would best serve the rehabilitation goals.

FUTURE WORK

Our study provides insights that would be interesting for researchers to explore in future work. We can also extend our work by exploring the use of haptic feedback and addressing other unconscious behavior.

Insights Can Help Other Studies

The results of our studies have implications for other therapeutic contexts. For instance, Thielman et. al.'s study using audio feedback did not observe significantly improved motions in most of the outcome measures [21]. A simple game that incorporates punishments and rewards might increase the observed behavior change. Also, the telerehabilitation studies in [15,20] relied on expensive hardware or a therapist to detect compensation, but detection could be more broadly accessible using our harness and Wii remotes. To be effective alternatives for stroke therapy, video games can address compensation by using our results [1,2,3,5,6,10,11,14].

Explore Haptic Feedback

Vibrating tactile feedback is another capability that Wii remotes provide. We did not use it in our final design because of limitations (i.e., unstoppable vibration, inaccurate timing), and because the cardboard in the harness prevented sensation. However, future studies should explore the use of tactile feedback because it can more effectively draw attention to a specific location on the body. This can be a very effective tool for disambiguation.

Address Other Unconscious Behavior

Most of our participants were surprised to see the balloon tilt when they exercised because they were not aware that they were compensating. While simply making them aware seemed to help some users, p/r events were necessary to reduce compensation significantly. Similarly, other types of unconscious behavior may be addressed using our approach. Specifically, using carefully designed p/r strategies may improve results of biofeedback applications.

CONCLUSION

Our study addresses an important weakness inherent in conventional stroke rehabilitation and its technology-based alternatives. Rather than imitating current practices, we 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 approaches. 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.

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REFERENCES

1. Adamovich, S.V., Merians, A.S., Boian, R., et al. A Virtual Reality—Based Exercise System for Hand Rehabilitation Post-Stroke. Presence: Teleoperators and Virtual Environments 14, 2 (2011), 161-174.
2. Alankus, G., Lazar, A., May, M., and Kelleher, C. Towards customizable games for stroke rehabilitation. In Proc. of CHI 2010, ACM (2010), 2113-2122.
3. Alankus, G., Proffitt, R., Kelleher, C., and Engsberg, J. Stroke therapy through motion-based games: a case study. In Proc. ASSETS 2010, ACM (2010), 219–226.
4. Bach-y-Rita, P., Wood, S., Leder, R., et al. Computer-assisted motivating rehabilitation (CAMR) for institutional, home, and educational late stroke programs. Topics in Stroke Rehab. 8, 4 (2002), 1-10.
5. Broeren, J., Bjorkdahl, A., Claesson, L., et al. Virtual rehabilitation after stroke. Studies in Health Technology and Informatics 136, (2008), 77-82.
6. Burke, J., McNeill, M., Charles, D., Morrow, P., Crosbie, J., and McDonough, S. Optimising engagement for stroke rehabilitation using serious games. Vis Comp 25, 12 (2009), 1085-1099.
7. Cirstea, M.C. and Levin, M.F. Compensatory strategies for reaching in stroke. Brain 123, 5 (2000), 940 -953.
8. Conti, R. Time flies: investigating the connection between intrinsic motivation and the experience of time. Journal of Personality 69, 1 (2001), 1-26.
9. Deci, E.L., Eghrari, H., Patrick, B.C., and Leone, D.R. Facilitating Internalization: The Self□Determination Theory Perspective. Personality 62, 1 (1994), 119-142.
10. Deutsch, J.A., Lewis, J.A., Whitworth, E., Boian, R., Burdea, G., and Tremaine, M. Formative Evaluation and Preliminary Findings of a Virtual Reality Telerehabilitation System for the Lower Extremity. Presence: Teleop and Virt Env 14, 2 (2011), 198-213.
11. Deutsch, J.E., Latonio, J., Burdea, G.C., and Boian, R. Post-stroke rehabilitation with the Rutgers Ankle System: a case study. Presence: Teleoperators and Virtual Environments 10, 4 (2001), 416–430.
12. Egglestone, S.R., Axelrod, L., Nind, T., et al. A design framework for a home-based stroke rehabilitation system: Identifying the key components. In Proc. PervasiveHealth'09, IEEE (2009), 1-8.
13. Fogg, B., Cuellar, G., and Danielson, D.R. Motivating, influencing, and persuading users. In The human-computer interaction handbook. Routledge, 2003, 358–370.
14. Goude, D., Björk, S., and Rydmark, M. Game design in virtual reality systems for stroke rehabilitation. Studies in Health Tech and Info 125, (2007), 146-148.
15. Holden, M.K., Dyar, T.A., Schwamm, L., and Bizzi, E. Virtual-Environment-Based Telerehabilitation in Patients with Stroke. Presence: Teleoperators & Virtual Environments 14, 2 (2005), 214-233.
16. Lai, S.-M., Studenski, S., Duncan, P.W., and Perera, S. Persisting Consequences of Stroke Measured by the Stroke Impact Scale. Stroke 33, 7 (2002), 1840 -1844.
17. Lang, C.E., MacDonald, J.R., and Gnip, C. Counting repetitions: an observational study of outpatient therapy for people with hemiparesis post-stroke. Neur Phys Ther: JNPT 31, 1 (2007), 3-10.
18. Langhorne, P., Coupar, F., and Pollock, A. Motor recovery after stroke: a systematic review. The Lancet Neurology 8, 8 (2009), 741-754.
19. Levin, M.F., Kleim, J.A., and Wolf, S.L. What do motor "recovery" and "compensation" mean in patients following stroke? Neurorehabilitation and Neural Repair 23, 4 (2009), 313-319.
20. Lum, P.S., Uswatte, G., Taub, E., Hardin, P., and Mark, V.W. A telerehabilitation approach to delivery of constraint-induced movement therapy. Rehab Res and Dev 43, 3 (2006), 391-400.
21. Thielman, G. Rehabilitation of reaching poststroke: a randomized pilot investigation of tactile versus auditory feedback for trunk control. J Neuro Phys Ther: JNPT 34, 3 (2010), 138-144.
22. Verplanck, W.S. The operant conditioning of human motor behavior. Psych Bulletin 53, 1 (1956), 70-83.
23. Warlow, C.P., Gijn, J. van, Dennis, M.S., et al. Stroke: Practical Management. Wiley-Blackwell, 2008.
24. Woodbury, M.L., Howland, D.R., McGuirk, T.E., et al. Effects of Trunk Restraint Combined With Intensive Task Practice on Poststroke Upper Extremity Reach and Function: A Pilot Study. Neurorehabilitation and Neural Repair 23, 1 (2009), 78 -91.
25. Yee, N. The Psychology of Massively Multi-User Online Role-Playing Games: Motivations, Emotional Investment, Relationships and Problematic Usage, Avatars at Work and Play. Springer-Verlag, Berlin/Heidelberg, 187-207.