Virtual Reality Game for Upper Limb Exercises Based on Constraint Induced Therapy

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ABSTRACT
This paper discusses the design and preliminary evaluation of a virtual reality game, titled Project Star Catcher, for those with weakness on one side of their upper bodies. The game mechanic is adapted from constraint induced therapy, an established therapy method where users are asked to use the weaker arm by physically binding the stronger arm. Our adaptation innovates from physical to psychological binding by providing rewards for using the weak arm. Players are rewarded by scoring points when performing a rehabilitative motion to catch falling stars in an immersive, cosmic virtual reality. Project Star Catcher was developed for HTC Vive and a preliminary evaluation was tested by users with developmental disabilities. The results suggest that users are generally compliant with the game rules of using the weaker arms, but qualitative observations revealed that there are noticeable variations in user strategies for playing Project Star Catcher. We concluded the paper with a set of design considerations for rehabilitation games for those with developmental disabilities.

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INTRODUCTION
Physical therapy is often needed for patients with a variety of medical conditions, including orthopedic, neuromuscular, cardiovascular, pediatric, and oncological conditions. For these patients, in 2014, Medicare spent $7 billions in inpatient rehabilitation therapy (which includes physical therapy) for 339,000 patients. Currently, Medicare caps outpatient physical therapy spending at only $1900/person/year, to be shared between physical therapy and speech and language pathology payments. Nineteen percent of beneficiaries with these complex impairments exceed this cap, spending on average $3,013 out-of-pocket [1]. The need for cost-effective and efficacious treatments to address these impairments is therefore very apparent [5]. One of the solutions to reduce cost is to move inpatient treatment programs into outpatient complemented with home exercise programs.

The main issue with home exercise programs, however, is that a patient’s progress is often influenced by their ability to understand and comply with a home exercise program. The compliance rate for such programs can be quite low, due to perceived barriers to exercise, lack of positive feedback, and degree of helplessness [4, 8]. Patients who set goals collaboratively with their physical therapist (PT) have higher compliance rates [6]. While home regimens traditionally involve PTs choosing verbal instructions and printed pictures, higher-tech studies with home exercise programs associated with telemedicine, virtual reality, and robotic programs have been shown to be effective in promoting compliance [11, 3, 7].

These higher-tech home exercise programs often use sensors, either to passively monitor a patient’s status, provide feedback so an action can be modified, or use actuators to assist the patient in completing a motion [2, 9]. The sensors can include accelerometers, gyroscopes, microphones, bio-chemical sensors, motion detectors, GPS, and EMG. Several Kinect-based systems were proposed for rehabilitation, using avatars to portray the correct motion, or using therapy-based games, etc. [13]. The feedback provided by these systems ranged from auditory, such as music or beeps; tactile, such as vibrational cues; to visual, with a screen showing correct position or pressure color indicators. While these systems are quite sophisticated, in reviewing these systems we came up with a conclusion that in many of these systems the user interface and exercise programs were designed without much involvement from the target users from the beginning and without grounding their design choices in established health intervention theories/programs.
The system reported in this paper is a home exercise program for upper limb rehabilitation with the following characteristics:

1. It employs Virtual Reality games as a motivation-inducing medium (using HTC Vive head-mounted display).
2. It provides immediate feedback to users about their exercise performance through motion tracking sensors.
3. Its exercise program is adapted from an established physical therapy program called “modified Constraint Induced Therapy” (mCIT) [10].

CONSTRAINT INDUCED MOVEMENT THERAPY
Constraint induced movement therapy (CIMT) involves massed and intensive practice with the more affected upper extremity and includes 2 components: the use of the unaffected upper extremity is restrained during 90% of waking hours, and at the same time, the more affected upper extremity receives repeated and intensive training for more than six hours per day [10]. CIMT has been widely used and studied compared to traditional rehabilitation techniques and “could improve functional performance and increase the usage of the more affected upper extremity” [10]. Although research shows benefits from CIMT, in a survey of stroke survivors, 68% of respondents said they were unlikely to comply with the therapy protocol due to either logistical aspects (length and duration of therapy) or aspects of the therapy itself (wearing a physical constraint for a long period) [12].

Modified constraint-induced therapy (mCIT) is a form of CIMT that requires less engagement and compliance from the patient. Researchers have designed a modified CIMT that has a shorter intensive training period as well as shortening of the period that the unaffected upper extremity is constrained [14]. For example, a patient may visit a therapist several times per week and in each thirty minute session the patient practices focused exercises using their weak arm. This therapy has been demonstrated to increase the mobility and use of the patient’s arm only if they have some mobility remaining in their wrist and fingers [14]. The program our system was designed for follows mCIT instead of CIMT, with a slight modification. Instead of physical constraint, we utilize the game mechanics to provide reward constraint. Specifically, we provide more reward if the participant uses their weak arm, and considerably less reward if the participant uses their strong arm.

Our research question is: “Is it possible to translate physical constraint into psychological constraint through game mechanics that is understandable by our target population: people with developmental disabilities?”

SYSTEM DESIGN
Project Star Catcher (PSC) incentivizes rehabilitative arm motion by catching falling stars in a cosmic virtual reality while collecting motion data. It was developed for the HTC Vive virtual reality system that consists of a headset, wireless controllers, and lighthouses. The headset has a resolution of 2160 x 1200 pixels with a 90Hz refresh rate and 110° field view, which is known to minimize motion sickness. Both the controller and headset have over fifty sensors including a MEMS gyrooscope, accelerometer, and laser photosensors. Linear actuators are used in the controllers to provide haptic feedback. The lighthouse base station emit pulsed infrared lasers that sweep horizontally and vertically at a rate of 60Hz to track the user’s movements up in a 4.6m x 4.6m space by hitting the headset’s photosensors. Overall, the system has an accuracy of +/- 2mm and tracking jitter of 0.3mm in the XY plane and 2.1mm in the Z plane. We used stereo speakers to provide sound effects. This results in an immersive experience of sight, sounds, and haptic.

In PSC gameplay, the HTC Vive controllers are visualized in the player’s hands as a “Star Catchers” that are colored either red or green. In front of or above the player is an ethereal, cosmic galaxy that starts fall from, shown in figure 1. Stars are caught when the player touches them with a Star Catcher, resulting in haptic feedback as the controller vibrates, figuratively feeling the stars being caught, and an attached speaker plays an exciting sound. Players can be sitting or standing during gameplay. A green colored Star Catcher is given to the hand of the arm that needs rehabilitative motion, while the healthy arm is given a red colored Star Catcher. More score points are earned catching stars with the green Star Catcher than the red one; this is done so that the player is rewarded for achieving motion with their weakest arm. The stars are colored bronze, silver and gold to indicate different speeds of falling. The bronze star falls at 75 percent of the base speed, silver at 100, and gold at 125 percent. The base speed is adapted to each individual player’s reaction time.

PSC was developed in Unity v5.5.0f3 with the SteamVR plugin v1.2.0, which connects HTC Vive hardware to Unity. Both are open source and have documentation for C# and Java. Using the Unity physics engine, the RigidBody class was used to model starts and the HTC Vive controllers were modeled as Capsule Colliders that detected contact with stars. Stars randomly spawn at different locations along a half circle in front of the player in three game modes - stars fall from 0° (directly above the user) in Mode 1, 45° in Mode 2, 90° (di-
Figure 2. Project Star Catcher Evaluator Interface

rectly in front of the user) in Mode 3 - to vary motions and body posture when catching stars.

The evaluator user interface, as seen in figure 2 start menu has the following inputs: Reward Multiplier, Punishment Multiplier, Speed Multiplier, Game Mode, Player Name, and Data File Name. Reward and Punishment Multipliers allow a therapist to customize the amount of score points earned for the green and red Star Catchers, respectively. Game Mode allows selecting modes 1, 2, or 3. Player Name allows PSC to provide identifying information to data collected during gameplay. Data File Name is used to name the Text file that stores output from PSC. Data is collected at a rate of 60Hz during gameplay and saved in a Text file in the following format for each datum: Time [s], Score, Last Caught, Positive Catches, Positive Arm Position(x,y,z) [m], Positive Arm Rotation(x,y,z) [°], Negative Catches, Negative Arm Position(x,y,z) [m], Negative Arm Rotation(x,y,z) [°], Headset Position(x,y,z) [m], Headset Rotation(x,y,z) [°]. The file can be analyzed with MATLAB or an equivalent tool by a medical professional to analyze the progress of the player’s arm rehabilitation, e.g., Excel.

USER EVALUATION

PSC was tested with six participants with developmental disabilities recruited through Hope Services. Hope is a local non-profit organization that promotes independence for people with a variety of developmental disabilities, including Autistic Spectrum Disorder, Down Syndrome and cerebral palsy, by providing jobs and by changing attitudes about the abilities of these people in the workforce and in the community. Table 1 summarizes the sociodemographics and the disability of the participants. The session started with the participants filling in the consent form and the video and audio release form. A professional caretaker was around to explain in a way that is understandable to the participants.

After getting an explanation of game, the players were introduced to Modes 1, 2, and 3 for about 1 minute each. The players then selected their preferred mode and played for 5 minutes each. During the 1 minute introductory modes that the participants’ reaction times were calculated and a base speed for the falling stars were customized to each user during their 5 minute trial so that the stars were too slow or too fast for each individual participant. During game-play, it was noted that the HTC Vive did not cause motion sickness or noticeable tracking jitter.

The play session was videotaped. After the session, the participants were interviewed using a retrospective testing method, in which the experimenter and the participant reviewed the video together, and the reviewer stopped the video at multiple points and asked the participant directly to explain certain behaviors when deemed necessary.

RESULTS AND DISCUSSION

Quantitative Data

Our system was developed to adapt the modified Constraint Induced Therapy program by changing a physical constraint into a psychological constraint, specifically by using game mechanics to provide more reward if the participants use their weak arms to catch the falling stars of varying speeds. To enable us to do a proper comparison of the compliance rate, we normalized the number of the stars caught by each participant into percentages for a specific star color. So for example, if Participant Co caught 20 bronze stars with the weak arm and 20 with the strong arm in the five-minute session, then it’s calculated as 50-50. Figure 3 shows the percentages of the stars caught by the six participants with the weak (green) and (strong) arms. In general, we can see that the participants are mostly compliant to the game rule. Specifically, they try to use the weak arms as much as they can. The exception is Participant Ty, who slipped into using mostly the strong arm for the gold stars (that are the fastest of the three colors). Participant Fa almost had the perfect compliant, having only one gold star caught with the strong arm, and Participant Pp were also highly compliant, also again, just like Participant Ty, slipped into using the strong arm in gold star condition.

Figure 4 shows the median of the percentages of these six participants by star color. This figure shows that in general, the participant are quite compliant in using the weak arms, averaging 60-70 percent of the time even when the stars are falling at 125 percent of the speed they are comfortable with.

Qualitative Data

The qualitative data reported in this study consists of a combination of (i) themes extracted from the interviews and (ii)
observations obtained from the experimenters during the play sessions. The interviews were transcribed and analyzed by two experimenters using content analysis, more specifically open coding to extract themes. The observations were extracted by two people watching the videos together but coded the behaviors independently. The two video coders then compared the behaviors and resolved differences in coding.

Participants thought the games were fun and did not request significant changes or improvements to the games, beyond “more games” and “happier music.” When asked what they thought of the rewarding music (when they caught the stars with the weak arm) and haptic feedback on the controller (when they caught the stars with the strong arm), most participants stated they did not even notice the music or vibration. Similarly, when asked whether they felt that the star colors were visible, most did not notice that there were three colors, although they noticed that some stars fell faster than other stars. Finally, when asked whether they preferred the game or the physical therapy exercises that they currently do, everybody unanimously preferred the game, which they concluded was more fun and entertaining than their usual exercises.

Observations from gameplay yielded a rich set of results, mostly in the strategies that different participants employed in catching the stars. The observations can be summarized as follows:

1. Some participants were consistent in their strategy in catching the stars while others changed strategies multiple times in the span of 5 minutes. Figure 5 shows a participant that changed strategies multiple times, and these three samples represent a wide angle catch (top), resting between falling stars (middle) and two-hands together so that the strong arm supports the weak arm but hoping that it still count as weak arm catch (bottom). We noticed that this particular participant had more than 10 strategies.

2. Some participants learned that if they continuously swiped the arm side by side, they will catch more stars so some participants constantly made frantic swiping motions for the whole 5 minutes.

3. The most common strategies are: poking the stars, swiping side by side, and swiping up and down.

4. Some participants only looked down and some only looked up to catch the stars either at the beginning or the end of falling, while some constantly moved their heads up and down in nodding motions.

5. No participant ever showed any sign of frustration when they were unable to catch the stars. Some were disappointed when 5 minutes were over and asked if they could play longer.

6. One participant in wheelchair had quite a difficulty in the trial modes as he tended to rest his head on his wheelchair at an angle so that he did not look straight. The HTC VIVE could not compensate for such a large angle and the stars were falling at an angle that was inconsistent with what other users saw. We corrected this for the actual game play, but this could be a good takehome message for developers of
Discussion
This paper reports on the design and evaluation of a VR game that adapts an established physical therapy program through its game mechanic. The game was evaluated by its intended users, people whose one side of their upper limbs weaker than the other side. Our user evaluators are also those with some form of developmental disabilities, which is not directly what the game addresses, but our user evaluation session was very helpful in guiding us in simplifying the instruction, the game mechanic, and the reward structure, while still maintaining the idea of constraint induced therapy.

The scoring system and virtual reality experience of Project Star Catcher encouraged players to actively participate in rehabilitative motions while having fun. The preliminary evaluation of Project Star Catcher provided us with some design considerations for rehabilitation games that we could share with people working with similar population or developing similar system. It is also plausible to state that the compliance rate of the user goes down when the stars are harder to catch. This can be seen in Figure 3, there is a noticeable trend that the users end up using their strong arm to catch the gold stars whereas the strong arm catching rate is less for silver and bronze stars. Improvement to PSC can be to spawn more high reward stars closer to the green Star Catcher to encourage players to use their weak arm. The immersive experience made the game exciting to play, but adding different types of games will make it more interesting according to participants. Because participants developed strategies to randomly catch stars by randomly waving their arms in a swiping motion, other game types can focus on emphasizing precision and patterns in their motion.

Gathering quantitative and qualitative data enabled us to relate the performance data with the qualitative explanation of why the performance data is what it is. One big lesson we learned is that, at least with people with developmental disabilities that worked with us, observation data was more meaningful than interview data. This could be because the developmental disability render their verbal responses to be less elaborate, or that they were too polite to critique our design. However, our observation data did revealed that everybody enjoyed the game, as they verbally stated, and the fact that some of them would like to play more also indicated that the game was not boring, as they also stated.

There were several lessons that we also gathered, that we will summarize in the Conclusion section for developers of similar systems. Essentially, one thing that we learned is to keep the game simple and without too many competing stimuli. For example, we colored the stars differently to indicate different speed. These were not even noticed and in hindsight, the colors were not necessary, the participants would have noticed that there were faster and slower stars.

CONCLUSION AND FUTURE WORK
Rehabilitation exercises can be boring, uncomfortable, and sometimes painful. This experience may result in less con-

Figure 5. The examples of strategies some participants adopted: top is a wide catch, middle is resting between falling stars, bottom is supporting weak arm with strong arm.
sistent participation from patients, especially those with developmental disabilities. We aim to contribute to a more fun way of performing physical exercise through a Virtual Reality game that rewards efforts in exercising weaker arms for those whose one side of upper limbs are weaker than the other side. Our game was designed using a user-centered design method involving all the stakeholders since its early prototyping and is based on an established therapy method called Constraint Induced Therapy.

Our study indicated that it is possible to convert physical constraint proposed by Constraint Induced Therapy method into psychological constraint through game mechanic that is understandable by people with developmental disabilities. Our data suggests that these users were compliant until the difficulty level exceeds their comfort level.

Our study provided us with some design guidelines for other researchers and practitioners in similar areas:

1. Reduce the variety of stimuli to the minimum without sacrificing the goal of the therapy. Some of our users did not even notice some feedback or color variations as they were not directly related to their goals
2. Stay within the comfort level of the users in terms of game speed, range of motion, etc to maintain compliance rate
3. Always triangulate quantitative and qualitative data, especially when working with people with disabilities that tend to be polite and might not be as elaborate as we expect
4. Not all qualitative or quantitative data are equal - in our study we found that observation was more insightful than interview data

There are several plans for future work, including asking stroke survivors with hemiparesis to evaluate our system, making the system to have a larger variety of games, and reducing the variety of stimuli to the necessary ones. However, we believe that we are in the right direction on developing a VR game based on an established therapy program that is portable, fun, and understandable while being able to provide compliance data in a simple way.

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