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A Rhythm-Based Serious Game for Fine Motor Rehabilitation Using Leap Motion

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Abstract: This paper presents a system to deliver automated and noninvasive fine motor rehabilitation through a rhythm-based game using a Leap Motion Controller. The platform is a rhythm game wherein hand gestures are used as input and must match the rhythm and gestures shown on screen, thus allowing a physical therapist to represent an exercise session as a series of patterns involving the user's hand and finger joints. Fine motor rehabilitation plays an important role in the recovery and improvement of the effects of diseases and conditions such as stroke, Parkinson's disease, multiple sclerosis, among many others. Individuals with these conditions possess a wide range of impairments such as fine motor movement. The proposed serious game is adaptive to the player to enable access to patients across a wide range of ability. In two pilot studies in collaboration with the South West Advanced Neurological Rehabilitation (SWAN Rehab) in Phoenix, Arizona, we compared the performance of individuals with fine motor impairment to individuals without impairment to determine the accessibility of the proposed serious game, i.e., to assess whether the platform is adaptive to a user's range of motion to allow an individual with fine motor impairment to perform at a similar level as a non-impaired user. We also separately evaluated the adaptive calibration algorithm to understand its impact on an individual's performance.

Keywords: Rehabilitation, Serious Games, Leap Motion

1. INTRODUCTION

Fine motor rehabilitation plays an important role in achieving functional gains following a physical impairment caused by a disease, condition or trauma such as stroke, cerebral palsy, spinal cord injury, among many others. During rehabilitation, a physical or occupational therapist administers exercises to improve a patient's range of motion, strength, comfort, and conditioning, and reduce unwanted symptoms such as spasticity. Repeated practice of movements, as well as the intensity of these movements, is crucial for regaining motor functions [1]. The idea of repeated practice over a long period of time leverages the neural underpinning of neuroplasticity, which is the ability of the brain to rewire itself by changing and forming new neural connections over time.

To achieve the degree of exercise needed for recovery, therapists often prescribed exercises that can be done in the home setting, e.g., flipping playing cards, placing pegs in holes, etc.—simple exercises to develop fine motor skills. But compliance is an issue given the simplicity and tediousness of the aforementioned activities. The exploration of serious games, or games with a purpose, to enhance patient engagement during at-home rehabilitation, has been actively investigated for decades. However, comparatively less work has been done to explore serious games for fine motor rehabilitation. Moreover, with the advent of accurate and low-cost finger and hand motion capture, such as the Leap Motion Controller, it is timely to evaluate the use of these technologies in rehabilitation, and innovate new and more engaging game designs based on technological capabilities.

2. RELATED WORK

2.1 Music in Therapy

Music has been used in varying therapy avenues and has been shown to be beneficial. Firstly, a connection between rhythm and brain function has been shown, and this can ultimately be leveraged in therapeutic applications [2]. Some work has investigated music-based therapeutic serious games for rehabilitation. MusicGlove [3] is a glove with embedded sensors to track finger movements for rehabilitative exercises involving music games. A study ran using MusicGlove showed subjects improved some fine hand function more so after using MusicGlove than traditional therapy. In another study assessing MusicGlove, Friedman et al. [4] showed that using music with rehabilitative exercises improved hand motor performance as well as motivation.

2.2 Leap Motion Controller in Therapy

The Leap Motion Controller is a low-cost device to noninvasively tracking finger and hand movements. Previous work has shown that this sensor can provide clinically useful data for wrist movements [5]. A pilot study demonstrated that the Leap Motion Controller has the potential as a rehabilitative device for elderly stroke survivors [6]. There has also been some work using serious games, where researchers used Leap Motion in the video game Fruit Ninja to help rehabilitate stroke patients and measure performance, where the findings suggested that the Fruit Ninja game was informative for progress monitoring [7]. A primary limitation of existing work in this space is a lack of a calibration mechanisms for adjusting the gameplay to the functional ability of the subject, which leads to one of two cases in most approaches: either the approach targets a very specific population of subjects and is inaccessible to subjects with lower motor ability and less useful for subjects with higher motor ability, or the system requires the subject to wear additional equipment to enable regular gameplay. To avoid these issues, we decided to focus on developing and evaluating a calibration method which would not only allow for a greater variety of subjects to benefit from gameplay, but also allow the game to adapt to a subject's functional ability as he or she improves over the course of rehabilitation.

2.3 Other technologies

There are other technologies that have been used or developed for hand rehabilitation. One such example is the Microsoft Kinect, which has limitations on the granularity of which data points are collected [8]. The Nintendo Wii remote can and has been used for upper limb rehabilitation by leveraging its easily accessible motion data [9].

3. PROPOSED APPROACH

3.1 Hardware: Leap Motion Controller

The Leap Motion Controller is a hardware sensor that uses two monochromatic IR cameras and three infrared LEDs that allow a user to use his or her hands for interaction within a virtual environment. The Leap Motion takes 2D frames generated by its cameras and converts these into 3D positional data [10]. The sensor has a fairly large interaction area (8 cubic feet). Since the sensor is focused on a smaller area, the Leap Motion Controller provides more granular tracking of the fingers and hands compared to similar vision-based, markerless technologies on the market.

To utilize and access this information, the V2 Leap Motion Software Development Kit is used for positional tracking, motions and gestures, and frame tracking. The positional tracking allows access and viewing of arm, finger, and bone positions within range of the Leap Motion. Data such as palm velocity, orthonormal basis, and length and width can be viewed and accessed. In addition, there are three recognized gestures already implemented through the Leap Motion API: swiping, circle, and tap.

The Leap Motion Controller is priced at USD $79, making it affordable to patients and practitioners. One of the biggest benefits with the Leap Motion Controller is that the setup is simple and cross compatible. As shown in Figure 1, the Leap Motion Controller is easy to set up: Once plugged into a computer via USB, the user can begin playing the game without any configurations.

3.2 Software: The Game

To help patients maintain engagement during fine motor rehabilitation, we developed a rhythm-based serious game for use with the Leap Motion. The system consists of the Leap Motion Controller connected to a computer via USB, and the game. The game was developed utilizing Unity Game Engine, C#, and the Leap Motion APIs. This game, inspired by the game Guitar Hero, starts out with a calibration phase, followed by actual gameplay. During gameplay, there is music playing in the background and notes, which are synchronized with the music, fall down from the top of the screen.

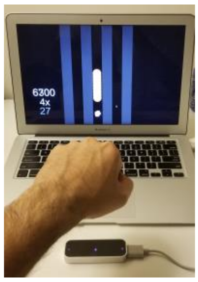

Fig.1 Leap Motion Controller Setup

The two types of notes in this game, shown in Figure 2, are single notes, which require only briefly gestures, and long notes, which require the user to hold the gesture for a few seconds.

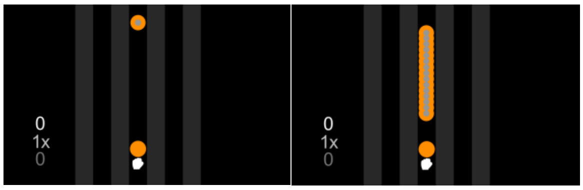

Fig. 2 Single Note (Left), Long Note (Right)

The user uses only one hand (his or her impaired hand) when playing the game. To gain points, a user does a specified gesture to eliminate each single or long note. The session implemented for the song used in the user studies consists of a total of 83 notes. There is no penalty for not hitting the note exactly on time. The point system gives a base number of 100 points per note hit when on the default 1x streak (less than 20 notes hit consecutively), 200 points per note when on a 2x streak (which occurs when 20 notes are hit consecutively), 300 points per note when on a 3x streak (which occurs when 30 notes are hit consecutively), and 400 points per note when on a 4x streak (which occurs when 40 notes are hit consecutively). There is no penalty when a note is missed, however, the streak count and multiplier are reset.

To ensure the game functioned as a rehabilitative platform, compared to typical rhythm games of this type, the pacing of the appearance of notes (or the time gap between notes) was slowed down by setting the gap to at least one full vertical screen width. In this design, the user need only focus on the timing of one note at a time and would have enough time to be able to form the correct gesture even in the case of a weak grip. This design could later be adapted such that once the functional ability of the hand is improved, faster note sequences could be implemented to maintain proper challenge levels.

Table 1 Impaired Group - Study One Data

Subject #	Motion Used	Notes Hit (/83)	Percent Hit	Max Notes Streak	Overall Score	Calibration
1	Wrist	44	0.53	21	4600	20mm
2	Fist	80	0.96	33	10600	0
3	Fist	82	0.98	45	15600	0
4	Fist	69	0.83	39	10100	0
5	Fist	76	0.91	57	16000	0
6	Fist	83	1.00	83	24500	0
7	Fist	76	0.91	27	8400	0
8	Fist	79	0.95	61	17500	0
9	Fist	77	0.92	33	10700	0
10	Fist	69	0.83	21	7100	0.85
11	Fist	77	0.92	35	11500	0
12	Fist	83	1.00	83	24500	0
13	Fist	81	0.97	64	18600	0
14	Fist	83	1.00	83	24500	0
Mean		75.6	0.91	48.92	14585.71	

Table 2 Non-impaired Group - Study One Data

Subject #	Motion Used	Notes Hit (/83)	Percent Hit	Max Notes Streak	Overall Score	Calibration
1	Fist	75	0.90	39	10500	0
2	Fist	82	0.98	74	21700	0
3	Fist	80	0.96	48	14200	0
4	Fist	78	0.93	21	8000	0
5	Fist	79	0.95	22	8200	0
6	Fist	78	0.93	38	10900	0
7	Fist	77	0.92	26	8400	0
8	Fist	79	0.95	21	8300	0
9	Fist	83	1.00	83	23500	0
10	Fist	75	0.90	69	19500	0
11	Fist	83	1.00	83	24500	0
12	Fist	73	0.87	24	7800	0
13	Fist	81	0.97	42	13800	0
14	Fist	80	0.96	32	10500	0
Mean		78.7	0.94	44.42	13557.14	

3.3 Software: Calibration and Gestures

We applied a human-centered approach in developing the system. The game utilizes a calibration phase before starting gameplay. The purpose of calibration is to adapt the interaction to an individual's range of motion before beginning gameplay. The Leap Motion APIs and positional data allowed for easy adaptability of the game.

Two exercises were considered for the game. The first and default exercise is opening the hand from a fist. This exercise utilized the 'Hand.grabStrength' value from the Leap Motion API, which allowed determining whether a hand is open or closed. The function returns a 0 to 1 decimal value where 1 represents a closed hand (fist) and 0 represents an open hand. Calibration captures the user repeating this movement, calculates an average, and stores this as the "goal" value. During gameplay, a note is hit when a user achieves a value less than or equal to his or her goal value.

The second exercise is a wrist extension exercise. This exercise utilized the 'Hands.WristPosition' value from the Leap Motion API, which provided the positional value of the wrist. It is a vector value with the coordinates of the wrist position in millimeters. The *y* value of this measure is used to assess how high the wrist is raised. Calibration captures the user repeating this movement, calculates an average, and stores this as the "goal" value. During gameplay, a note is hit when a user achieves a value greater than or equal to the "goal" value. Based on a patient's abilities, a therapist could prescribe either or both of the aforementioned exercises.

4. STUDY ONE

Error! Reference source not found..1 Aim

The purpose of this pilot study was to evaluate a rhythm game designed to adapt to users' wrist and fingers range of motor, and assess whether participants with physical impairments could play the game just as

Table 3 Study Two Data

Subject #	Gender	Impaired Arm	Disability	Calibration Result	Score with Calibration	Non-Calibration Score	Notes
1	Female	Left	Stroke	0	3900	4000	First trial calibrated. Second trial un-calibrated
2	Male	Right	Stroke	0.72	3700	400	First trial not calibrated. Second trial calibrated
3	Female	Right	Stroke	0.39	3600	1100	First trial calibrated. Second trial un-calibrated
4	Female	Left	Stroke	0	3700	3800	First trial not calibrated. Second trial calibrated
5	Female	Right	Stroke	0	1600	100	First trial calibrated. Second trial un-calibrated
6	Male	Left	Stroke	0.72	3000	500	First trial not calibrated. Second trial calibrated
7	Male	Right	PD	0.21	3600	2400	First trial calibrated. Second trial un-calibrated
8	Male	Right	Stroke	0.54	2500	2000	First trial not calibrated. Second trial calibrated

well as those without physical impairments based on the accessibility afforded by the proposed calibration algorithm. This study was approved by ASU's Institutional Review Board (IRB).

Error! Reference source not found..**2 Subjects**

Fourteen participants with physical impairment in the upper extremities were recruited through SWAN Rehab in Phoenix, Arizona. Fourteen participants without any physical impairment were recruited through ASU via class announcements and word-of-mouth. All twenty-eight participants were 18 years of age or older. Of the fourteen participants recruited through SWAN, each demonstrated mild to moderate upper extremity impairment, and were evaluated for their ability to at least be able to move their wrist up and down to any degree to be able to play the game. We worked with the therapists at SWAN to communicate study information directly to their patients throughout the day.

Error! Reference source not found..**3 Apparatus**

For this study, the research team set up the technology in SWAN Rehab in a room so that patients present the day-of could participate. The simple setup consisted of having a laptop and Leap Motion Controller on a table, and the subject sitting on a chair or wheelchair. An armrest was used to help participants reach the proper height above the Leap Motion needed for accurate detection. The armrest also helped reduce fatigue.

Error! Reference source not found..**4 Procedure**

The total duration of this study per participant was five to fifteen minutes. To begin, after having received the consent form and consenting to participate, the subject was asked to sit down and rest his or her arm on an armrest. Once the subject's arm was rested, a short calibration phase took place. During the calibration, the Leap Motion Controller was used to determine the subject's range of motion. Subjects were asked to open their hand if they have mobility in their fingers or raise their hand through a fist motion if they do not have mobility in their fingers. After calibration was completed, the game session began for around two minutes and thirty seconds to the song "Eye of the Tiger". The subject was told to complete or hold the same motion done during the calibration phase when the on-screen note reaches a certain point on the screen for the full duration of the music. The Leap Motion Controller recorded data about the subject's motions in real-time and acted as an interface between the subject and the game.

We stored each participant's objective performance measures, described next. The data recorded by the controller included: exercise used (opening/closing fist or flexing/extending wrist), user's range of motion, number of single notes hit, number of long notes hit, and overall score.

5. STUDY ONE: RESULTS

Of the fourteen participants with physical impairment, thirteen did the fist opening exercise, while one did the wrist extension exercise. All of the non-impaired participants did the fist opening exercise. Table 1 and 2 depicts the data collected, showing how successful an individual performed when playing the game.

The impaired group hit an average of 75.64 notes (91.13% accuracy), obtaining an average score of 14,585.71. The non-impaired group hit an average of 78.78 notes (94.92% accuracy), obtaining an average score of 13,557.14. To determine if there is significance between the notes hit of the two groups as well as if there is significance between the overall score of the two groups, two different unpaired two sample t-tests (two-tailed) were done. For notes hit, the null hypothesis that the notes hit for the non-impaired group is (statistically) equal to that of the impaired group, fails to reject with $p = 0.280$. Similarly, for the total score, the null hypothesis that the total score for the non-impaired group is (statistically) equal to that of the impaired group, fails to reject with $p = 0.675$.

6. STUDY ONE: DISCUSSION

We found that the non-impaired group hit notes at an average higher accuracy, showing that the group hit more notes than the impaired group. On the other hand, we found that the impaired group obtained a better overall score and had a higher maximum notes streak. This indicates that although the impaired group hits less notes overall, they hit more notes consecutively, allowing them to earn a better score due to the streak multiplier. In addition, there were more perfect scores (3) from impaired participants than non-impaired participants (2).

One possible reason for this is that it was observed that participants with impairment anticipated notes more than non-impaired participants. Two *t*-tests were conducted on the two groups' notes hit as well as overall score. With *p*-values over .05, we fail to reject that the two groups are statistically the same. This suggests that the two groups are similar, showing that impaired participants play at the same competency as the non-impaired participants, even though some differences were seen with notes hit and overall score.

As seen in Table 1 and 2, there was more variance in scores of the non-impaired group. One reason might be from fatigue of doing the exercise repeatedly in a short amount of time. This was observed with the lowest score in the impaired group. In addition, for some participants in the non-impaired group, there was some discomfort in having to rest the hand on the armrest while extending out their arm to ensure that their hand was detectable by the Leap Motion. Given that most of the impaired group could fully open their hand, achieving a calibration score of 0, we conducted a follow-up study to assess the calibration method itself with participants who had greater variability in their calibration scores.

7. STUDY TWO

7.1 Aim

In Study 1, it was determined that when calibration was present, subjects with impairment could perform on an even playing field with those who did not have impairment; however, it is also necessary to determine whether the presence of the calibration step is required to achieve this level of performance in subjects with impairment. Hence, the purpose of this secondary pilot study was to evaluate if calibration has an impact on a user's score. This study was approved by ASU's IRB.

7.2 Subjects

Eight participants with motor upper extremity impairment were recruited from SWAN Rehab in Phoenix, Arizona. All participants were 18 years of age or older, and demonstrated mild to moderate upper extremity impairment. Participants with physical impairment were recruited through SWAN Rehab, where therapists were informed of the study, and communicated study information directly to their patients throughout their day. There were four male subjects and four female subjects, and five of them played with their right arm, while the other three played with their left. Seven of the patients had a stroke, and the other had Parkinson's disease.

7.3 Apparatus

The research team set up the technology in SWAN Rehab in a room so that patients there the day-of could participate. The simple setup consisted of having a laptop and Leap Motion Controller on a table, and the participant sitting on a chair or wheelchair. An armrest was used for users to help individuals reach the proper height for motion capture and reduce fatigue.

7.4 Procedure

The total duration of this study was twenty-five minutes. It consisted of two phases for each subject, with a 10-minute break between phases. Each subject participated in two gameplay phases for a single session: calibration phase and no-calibration phase. The ordering of these two phases was randomized for each subject to avoid learning effects. To begin, after having received the consent form and consenting to participate, the subject was asked to sit down and rest his or her arm on an armrest. For the calibration phase, a short (5-minute) calibration took place. This is the same calibration that was used in Study 1. After calibration, the game session began for around one minute to the song "Eye of the Tiger". The subject was told to complete or hold the same motion done during the calibration phase when the on-screen note reaches a certain point on the screen for the full duration of the music. The non-calibration phase was exactly the same as the calibration phase, except that no 5-minute calibration preceded the gameplay, and a default template for range of motion was used instead of measuring the subject's range in calibration. The data collected related to how the subjects performed.

8. STUDY TWO: RESULTS

Table 3 shows the data collected from the second study. The data shows how successful an individual performed when the gamed used calibration vs. when calibration was not used. There were eight individuals who partook in the study, where three of the individuals had a calibration of 0 and the others had a calibration value between 0.21 and 0.73.

When the game was calibrated, the group had an average score of 3200.00. When the game was not calibrated, the group had an average score of 1787.50. To determine if there was any significance between a user's performance when the game is calibrated versus not calibrated, a paired *t*-test was performed. For the total score, the null hypothesis that the difference between the score with calibration and the score without calibration is zero is rejected with $p < 0.05$.

9. STUDY TWO: DISCUSSION

We wanted to validate that calibration allowed an individual to play the rhythm-based game more successfully. To evaluate calibration, we had eight impaired participants play the game both with and without calibration. The average score with calibration is significantly higher than without calibration. We found that in all cases where calibration was not at 0, the user had a higher score with calibration than without calibration, showing that they performed better. Two of the participants (#1 and #4) with a calibration of 0, achieved a score that is nearly the same, which would be expected since there would not be a difference in gameplay. Participant #5 is the outlier who scored significantly higher in the first study when calibration wasn't a factor. We suspect that this participant experienced fatigue by the second condition. With a p-value that is less than 0.05, there is strong evidence that the alternative hypothesis is supported. This suggests that there was a significant difference between the calibrated and non-calibrated scores.

10. CONCLUSION AND FUTURE WORK

This paper presented a low-cost system that can deliver automated and noninvasive fine motor rehabilitation through a rhythm-based game. Utilizing a Leap Motion Controller allowed for the adaptability of the game so that it could be played by varying ranges of motion. In taking a human-centered approach to create a game that could be played at a competent level for any individual who could perform one of two basic exercises, these preliminary results are promising. The results indicate that the impaired group could play at the same level and just as well as the non-impaired group. Additionally, it was shown that calibration (as opposed to playing without calibration) does lead to a more successful score.

These are preliminary studies with small participant populations, and so future work is needed to continue investigating the proposed rhythm-based serious game with much larger patient populations. It should be noted that at this stage of evaluation, no claims have been made about the potential for the implementation of this serious game in rehabilitation programs to result in greater health outcomes or more rapid functional recovery for users; rather, its goal is to provide accessible gameplay that serves as a meaningful abstraction of basic rehabilitative hand motion therapy, and this accessibility and usability was the primary focus of the first two studies. Besides a larger participant pool and longitudinal studies with participants to determine functional gains over time, difficulty adaptation can be explored. Currently, gameplay difficulty is static, yet could be adapted dynamically to enable users to maintain a state of "flow"; i.e., the right amount of difficulty so that they remain engagement without becoming frustrated. The game will adjust its difficulty, frequency of notes, and types of notes based on how well a user is performing.

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