Super Pop VR™: An Adaptable Virtual Reality Game for Upper-Body Rehabilitation

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Abstract. Therapists and researchers have studied the importance of virtual reality (VR) environments in physical therapy interventions for people with different conditions such as stroke, Parkinson's disease, and cerebral palsy. Most of these VR systems do not integrate clinical assessment of outcome measures as an automated objective of the system. Moreover, these systems do not allow real-time adjustment of the system characteristics that is necessary to individualize the intervention. We discuss a new VR game designed to improve upper-arm motor function through repetitive arm exercises. An automated method is used to extract outcome measures of upper extremity movements using the Fugl-Meyer assessment methodology. The accuracy of the system was validated based on trials with eighteen adult subjects. With a corresponding average assessment error of less than 5%, the developed system shows to be a promising tool for therapists to use in individualizing the intervention for individuals with upper-body motor impairments.

Keywords: Cerebral Palsy, virtual reality gaming environment, Fugl-Meyer assessment, physical therapy and rehabilitation.

1 Introduction

Therapists and researchers have studied the use of virtual reality environments as part of corresponding physical therapy interventions for various patient demographics. Virtual reality (VR) refers to a computer technology that creates a three-dimensional (3D) virtual context and virtual objects that allow for interactions by the user [1]. Previous research has shown that VR environments present many benefits in the rehabilitation of individuals with motor skill disorders. Not only do they improve compliance for individuals working with their exercises [2], but they also enhance exercise effectiveness [3]. Based on this evidence, this research presents a new in-home VR game designed to improve patients' upper-body mobility through the repetition of movements associated with an individualized intervention protocol. The novelty of the system resides in the use of a 3D depth camera to capture and store

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depth images while analyzing the subject's arm movements in real-time using the Fugl-Meyer assessment methodology [4],[11]. In addition, VR game parameters can be modified by the clinician in order to match the intervention protocol to the capabilities of the user.

This research focuses on rehabilitation activities for children with cerebral palsy. The term *cerebral palsy* (CP) describes a group of disorders of the development of movement and posture causing activity limitations that are attributed to non-progressive disturbances in the developing fetal or infant brain [5]. The Center for Disease Control and Prevention reports that CP is the most common motor disability in childhood. Often, people with CP have the inability to control some of their muscles resulting in poor movement coordination. Approximately half of the children with CP may sustain dysfunctions in upper extremity activities such as reaching, grasping, and/or manipulating objects [1]. For patients with CP, especially if detected at an early age, therapists recommend participation in physical therapy interventions in order to reduce further development of the effects of the disorder.

2 Background

Virtual reality systems have been developed to aid rehabilitation specialists in physical therapy treatments for children with cerebral palsy. Reid et. al [6] made a pilot study to show the benefits of a VR system for children with CP. Her studies suggest that a virtual environment allows for increased play engagement and the opportunity for children to practice control over their movements.

Golomb et. al [7] investigated whether an in-home remotely monitored VR videogame can help improve hand function and forearm bone health in an adolescent with hemiplegic CP. This pilot study showed that the system is prone to poor efficiency because of possible faulty Internet connections thus discarding the possibility of assessing patients remotely.

Commercially available gaming consoles have also been used in the rehabilitation process of individuals with CP in order to provide low-cost options. Deutsch et. al [8] used a Wii console to augment the rehabilitation of an adolescent with CP. The subject used a Wii controller to manipulate objects in the virtual environment. Although the participant in this study showed improvement both in performance and in learning, the research showed that the system is limited only to patients who are able to grasp the controller. Jannink et. al [9] used a motion capturing product for the PlayStation 2 platform called the *EyeToy*. Although this system presents a relatively low-cost in-home virtual environment, it lacked the ability to adjust the level of difficulty of the game to the child's capacity. To make this system more suitable for rehabilitation purposes, the option to select the desired game settings needs to be added and feedback about performance should be incorporated to increase motor learning.

Other motion capture systems require the use of additional equipment, like cyber gloves [10]. These types of systems implement the use of the IREX (Interactive Rehabilitation EX-ercise) platform. It tracks the motion of the gloves worn by the user and it maps the movements into the virtual environment. Although a novel system, it doesn't allow for a low-cost in-home rehabilitation tool.

3 Methodology

3.1 Objective

While there have been many VR systems developed for use as part of physical therapy interventions for children with CP, none incorporate a formal method of evaluating the user's upper-body motor skills in real-time and in the comfort of their own home. The goal of this research is to present a low-cost VR gaming system designed to overcome these limitations. An adaptable user interface allows the therapist or caregiver to select the desired game settings based on the user's capabilities. Users are engaged in repetitive movements during game play and are assessed in real-time by the system. Outcome measures are evaluated by quantizing one of the physical therapeutic metrics from the Fugl-Meyer assessment: range of motion (ROM).

In this paper, we focus on providing proof-of-concept evidence that: the VR system can accurately output the results of one of the metrics from the Fugl-Meyer assessment in real-time as part of the design of an in-home rehabilitation tool.

3.2 Description of Overall System

The VR game was developed to work on any general-purpose computer system running a Windows 64-bit operating system. A 3D depth camera is used to capture and store depth images from the user's arm movements. This research used the Microsoft Kinect 3D camera because of its widespread adoption and the availability of an open source software development kit. No additional equipment is needed.

The developed virtual reality application is called SuperPop VR™. When playing, the user is immersed in a virtual world where virtual bubbles appear on the screen surrounding the user. The goal is to pop as many bubbles as possible in a certain amount of time by moving a hand over the center of the bubble. The 3D depth camera is used to track the position of the user's hands (Fig. 1).

There is a set of green bubbles called Super Bubbles (SBs). Based on the user's intervention protocol established by the therapist, there is a point in time where all yellow and red bubbles on screen get erased and a set of two or three SBs appear one at a time. Each set of SBs highlights the trajectory that the therapist will use to evaluate the user's rehabilitation outcome metrics. For example, if the experimental protocol is designed to improve the user's maximum ROM, the therapist would position three SBs such that they are spaced with a slightly greater angle than the user's effective ROM (90^{o} trajectory example shown in Fig. 2). This way, through practicing the specified repetitive motion that will appear throughout the game, the user will progressively increase his/her ROM given that he/she will be forced/motivated to reach the next super bubble. When popping these bubbles, the 3D camera captures and saves depth images of the assessment arm to be run through the metrics code for evaluation in real-time (see Section IV: **Kinematic Assessment**).

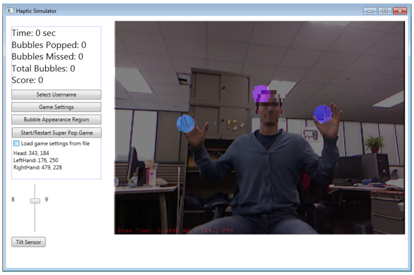

Fig. 1. Main Graphical User interface of the *Super Pop* Game

Fig. 1 also shows the main graphical user interface (GUI), which shows the virtual environment and depicts the user's progress during game play. In addition, four main buttons are located at the left side of the GUI. The first three buttons access secondary GUIs that provide the therapist options for customizing the intervention protocol of the game. The 'Bubble Appearance Region' GUI allows the therapist to select the workable region in which regular bubbles will appear and the position of the SBs. This interface allows for personalized sessions accommodating the different body structures of the users. The combination of options and features provided by the different interfaces give the therapist the freedom to match the level of difficulty of the game to the user's capacity.

3.3 Game Parameters

The difficulty of each game can be set by selecting different combinations of the following parameters: game duration in seconds, total number of levels, game speed in bubbles per second, bad bubble ratio, bubble size, good bubble score, and bad bubble score. These parameters serve different purposes in the rehabilitation protocols. The size of the bubbles and the bad bubble ratio are linked to the user's accuracy and fine motor skills. Intervention protocols designed for users with poor accuracy and/or poor fine motor skills will include larger bubbles and a lower bad bubble ratio such that the user doesn't have to worry about avoiding bubbles. The speed of the bubbles is linked to the speed of the user's movements. Intervention protocols for users with slower movements will include games with bubbles that appear at a lower rate. A scoring system is added to the game in order to motivate the users to pop some bubbles while avoiding others. Given that the SBs mark the point where the camera will capture depth images; these are worth twice as much as the good bubbles in order to increase the motivation to pop them.

All the game levels have equally distributed durations determined by dividing the total game duration by the total amount of levels. At each passing level, the game

Fig. 2. Example of a 90° trajectory created by the position of the three Super Bubbles

increases its difficulty by: increasing the game speed, increasing the bad bubble ratio, and/or decreasing the bubble radius.

4 Kinematic Assessment

The goal of the VR system is to autonomously evaluate the user's performance during game-play using the Fugl-Meyer assessment methodology. This method is a cumulative numerical scoring system for measurement of motor recovery, balance, sensation, and joint ROM [4]. Given that this research focuses only on non-touch upper-arm rehabilitation, we limit these preliminary experiments to measuring the ROM of the user's movements. This process is accomplished with the following algorithms.

4.1 Assessment of Arm Movements

A computational method for assessing upper body movements was developed in [12]. This method uses computer vision techniques to determine the user's outcome metrics through a non-touch scenario during game play.

First, a methodology called Motion History Imaging (MHI) is used to represent the user's movements using temporal templates [13]. The result is a scalar-valued image where more recently moving pixels are brighter in intensity. Once the user's movements are recognized, a contour representing the shape of the movements is extracted. A canny edge detection algorithm is used to extract the edges of the contour representing the upper-arm movement. Given that there are always unwanted contours in the image, a convex hull of the edge detected image is calculated. Afterwards, the RANdom SAmple Consensus (RANSAC) determines the best possible line fit by iteratively selecting a random subset of the original input data and returns points from the original input data that are inliers [14]. Once the points that create the upper and lower lines are recognized, the slopes of each line are used to calculate the angle between the two lines. That is,

$$ROM = \left|\arctan\left[(m_2 - m_1)/(1 + m_2 * m_1)\right] * (180/pi)\right| \tag{1}$$

where m_1 and m_2 are the slopes of each line respectively. The maximum angle found over the total amount of saved images gives the ROM of the user's movements.

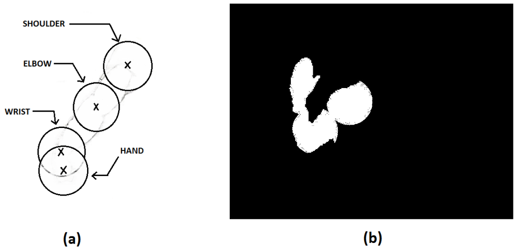

Fig. 3. (a) Imaginary circles drawn around the coordinates of the four arm joints with centers in the corresponding joints, and (b) Silhouette of a left arm isolated from the rest of an image (arm pixels in white for better visualization).

Although the aforementioned algorithm was successfully shown to output Fugl-Meyer assessment values that correlate with ground-truth data [12], it relies on the assumptions that: 1) the user's sagittal plane is perpendicular to the optical axis of the camera, 2) the user's elbow must be straight, and 3) only the arm under evaluation can move during an experiment such that the MHI doesn't take into consideration the movement of other body limbs. If these assumptions aren't met, the accuracy of the results is reduced. Given that the standard VR game play violates these assumptions - since it requires users to face the camera and bend the elbows in order to pop the bubbles - we modified the aforementioned algorithm to not only increase the accuracy of the assessment results but also enable the assessment methodology to run in real-time.

4.2 Extracting Upper Body Limbs

One of the assumptions of the previous approach was that only the assessment arm can be moved in order for the MHI to work. To improve the accuracy of the results, our algorithm isolates the arm from the rest of the image. We first identify the user's body contour in the image using the depth data obtained from the camera. As such, let

$$\begin{aligned} &\Phi = \{\phi_0, \phi_1, \ldots, \phi_{\Sigma-1}\} \\ &\Omega \subset \Phi \end{aligned} \tag{2}$$

where Φ is the depth data array, Σ is the total number of elements in Φ, and Ω is a subset of the depth data array that contains the elements belonging to the user's body contour. Each element of Φ, ϕ_i for i = 0, 1, …, Σ-1, corresponds to each of the pixels of the captured image. Each element is a 16 bit integer where the highest 13 bits represent the measured depth of the corresponding pixel in millimeters, and the lowest 3 bits represent the player index. We can define the lowest 3 bits of ϕ_i as:

$$L = \phi_i \quad AND \quad 0x0007 \tag{3}$$

An element of Φ is also an element of Ω if the equivalent decimal value of the lowest three bits of the integer is different than zero. Otherwise, the pixel is not included in the subset meaning that it's a part of the background of the captured image. That is, based on the definition of Equation (3):

$$\phi_i \in \Omega \quad if \quad L \neq 0x0000 \quad \forall i = 0,1,...,\Sigma - 1 \tag{4}$$

After separating the user's body contour from the rest of the image background (identifying the members of subset Ω), the next step is to separate the user's assessment arm from the body contour. Using the depth data, we can extract the coordinates of the user's arm joints (hand, wrist, elbow, and shoulder) during game play. Four imaginary circles are drawn around the four arm joints of the assessment arm (Fig. 3a). The radii of the circles are empirically determined such that the circles cover most of the assessment arm. These circles are used to determine if a given pixel in the image belongs to the arm or not using the following procedure.

Based on Equations (2), (3), and (4), Equation (5) calculates the (x,y) coordinates of the elements of Ω. That is

$$\begin{array}{l} y = floor(i / width) \\ x = i - y * width \end{array} \quad \forall \phi_i \in \Omega \tag{5}$$

where i is the index of element ϕ_i, width is equal to the number of pixel columns the images have (640), and *floor(m)* is a function that rounds the value of m to the lowest integer. Images obtained from the Kinect are 640 by 480 pixels, which means the depth data array contains a total of 307,200 elements. The resulting (x,y) coordinates are used to calculate the Euclidean distance between the pixels corresponding to the ϕ_i members of Ω and all four arm joints. If at least one of the calculated distances is less than the selected radii of the imaginary circles surrounding the arm joints, then the pixel corresponding to element ϕ_i is part of the user's assessment arm and it is assigned an RGB value that is slightly darker than the rest of the image. Otherwise, the pixel is ignored. This is an iterative process that is repeated for all elements in the depth data array every time the algorithm is called.

Fig. 3b shows the silhouette of the isolated arm resulting from this process. A set of images like this one is used as input for the assessment algorithm. Since all irrelevant information is removed from the images, the previous assumption where users can only move the assessment arm doesn't have to be met. Thus, the assessment algorithm in [12] can make more accurate calculations which allows for real-time assessment of the user's arm during game play.

5 Testing Environment

Ten male and eight female abled bodied adults within the ages of 19–27 years old were recruited for this study. Each participant was asked to play the game twice in order to provide assessment metrics for both arms. The SBs were placed such that they created a 90^0 trajectory in an adduction motion from start to end. A set of SBs would appear every 20 seconds and each SB would stay on screen for a maximum of 5 seconds. Some individuals with cerebral palsy may have difficulty standing up for

Table 1. Average and standard Deviation of the Measurements and Measurement Error

	Range of Motion (Degrees)		**Error from 90⁰ (Degrees)**	
	Left Arm	Right Arm	Left Arm	Right Arm
Average	93.1765	92.8772	4.0954	4.0123
Standard Deviation	3.6894	4.1319	2.6323	3.0418

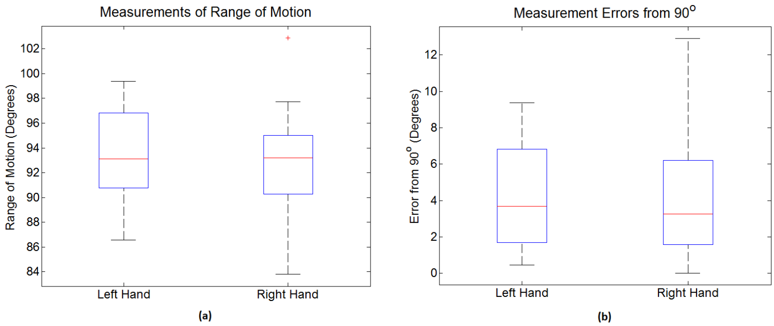

Fig. 4. (a) Boxplot showing the distribution of the range of motion measurements, and (b) Boxplot showing the error of the measurements from the 90⁰ motion

extensive periods of time due to limitations in their functional motor abilities [5],[15]. As such, to better simulate realistic use, subjects were asked to play the game sitting down in front of the depth camera. Before each game, the following instructions were given to the users: *Pop the yellow and green bubbles (these are worth 5 and 10 points respectively), and avoid the red bubbles (these are worth -5 points each).* Afterwards, the users were asked to play for the duration of two minutes for each game.

6 Results and Analysis

Fig. 4a and 4b show boxplots for the range of motion (ROM) measurements and the error of the measurements from the 90⁰ motion respectively. All the ROM measurements were calculated in real-time. Table 1 shows the average error and standard deviation of error. Results show that the system is able to calculate the ROM with an average error of **4.0954⁰ ± 2.6323⁰** and **4.0123⁰ ± 3.0418⁰** for the left and right arm respectively. Given that the overall error is less than 5%, we believe that the presented VR system provides a viable approach to performing real-time assessment of rehabilitation metrics. This fact, coupled with the ability to customize the game play settings, enables the ability to individualize the intervention protocol. We believe this is a necessary step for creating a system that can serve the therapy needs of individuals with upper-body motor impairments, such as children with cerebral palsy.

Another observation throughout the experimental sessions is that all the users were focused during game-play. Based on a study made by [16], 69% of people with motor impairments don't perform the recommended exercises which can further develop their symptoms. In order to encourage patients to work on their therapy exercises, we developed the VR system such that users can see their therapy sessions as a game and not just a repetitive set of movements which can be tedious.

7 Conclusion and Future Work

The ***Super Pop VR Game™*** is a virtual reality system designed to assist individuals with limited upper-body movement in achieving their rehabilitation goals. The VR system presented in this work allows for individuals to use it in the comfort of their homes without the need for additional equipment. This enables therapy interventions to be accessible to a larger demographic of patients with disorders that affect their motor skills. Most importantly, the system allows the therapist to select the parameters of any game such that they match with the user's needs. The experiments showed that the presented VR system is able to accurately calculate the range of motion as part of the implementation of the Fugl-Meyer assessment methodology in real-time. This is a necessary first step in designing an in-home rehabilitation tool for individuals with neurological movement disorders such as cerebral palsy.

Future work for this research is to incorporate additional tests from the Fugl-Meyer methodology as well as other assessment methodologies [17]. This will provide more comprehensive assessment of the outcome metrics of a user. Moreover, the results from the outcome metrics will later be used as feedback for the VR gaming system in order for it to automatically adapt to the user's limitations and needs. This control and adaptation approach will play an important role in rehabilitation given that the games will be able to adjust to the users in real-time providing more individualized therapy sessions targeted to the specific needs of each individual.

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