Multi-User Virtual Reality Therapy for Post-Stroke Hand Rehabilitation at Home

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ABSTRACT

Our paper describes the development of a novel multi-user virtual reality (VR) system for post-stroke rehabilitation that can be used independently in the home to improve upper extremity motor function. This is the pre-clinical phase of an ongoing collaborative, interdisciplinary research project at the Rehabilitation Institute of Chicago involving a team of engineers, researchers, occupational therapists and artists. This system was designed for creative collaboration within a virtual environment to increase patients' motivation, further engagement and to alleviate the impact of social isolation following stroke. This is a low-cost system adapted to everyday environments and designed to run on a personal computer that combines three VR environments with audio integration, wireless Kinect tracking and hand motion tracking sensors. Three different game exercises for this system were developed to encourage repetitive task practice, collaboration and competitive interaction. The system is currently being tested with 15 subjects in three settings: a multi-user VR, a single-user VR and at a tabletop with standard exercises to examine the level of engagement and to compare resulting functional performance across methods. We hypothesize that stroke survivors will become more engaged in therapy when training with a multi-user VR system and this will translate into greater gains.

Keywords: Stroke, Virtual Reality, Rehabilitation, Upper Extremity, Serious Games, Social Interaction, Interactive Environments.

1. INTRODUCTION

Stroke is the leading cause of major, long-term disability in adults in the United States [1]. Every 40 seconds someone in the U.S. has a stroke [2] and more than 700,000 people suffer a new or recurrent stroke each year. The majority of stroke survivors endure chronic impairment [1], which dramatically impacts their lives physically, psychologically and socially. Stroke incidence is even greater in low to middle income countries. Around 50% of all stroke survivors will have residual hemiparesis involving the upper extremity [4, 5], which can have a profound, adverse impact on self-care, employment, and overall quality of life. A number of studies [6, 7, 8, 9] have shown that upper extremity motor control can still be improved, even in stroke survivors with chronic hemiparesis subsequent to stroke. Many patients continue to be highly motivated to achieve further gains after standard rehabilitation has been completed, seeking out new methods, technologies and practices that can improve upper extremity motor control.

Repetitive movement practice proved to be crucial for maximizing therapeutic benefits [15]. The necessary repetition of rehabilitation exercises can be tedious, however [10, 11, 12] and many patients, including stroke survivors, discontinue treatment long before optimal results have been achieved. Lack of motivation, disengagement, and boredom contribute to impeded progress in rehabilitation [13]. Additionally, opportunities for task practice in the clinic are becoming increasingly limited due to shortened hospital stays [14] and a reduced number of allotted outpatient therapy sessions (Figure 1). Furthermore, lack of transportation can prevent outpatient stroke survivors from taking full advantage of the available therapy sessions.

Tele-rehabilitation seems a possible solution, but current tele-rehabilitation systems [7, 16] largely consist of teleconferencing between the therapist and the client. Therapist-client interaction is limited and quantitative measurement of performance is lacking. Instead, we propose a multi-user virtual reality environment (VRE) in which the therapist and client can interact with each other and with objects in the VRE. An inexpensive motion capture system allows control of avatars, as well as collection of movement kinematics. Our system is innovative, because it brings the therapist and client together in the virtual space to work together in real-time. Alternatively, or additionally, the client can participate with a training partner, potentially another patient, providing additional motivation and encouragement. One study showed that impaired subjects prefer competitive/cooperative multi-user rehabilitation games compare to single-user rehabilitation games [17]. This system can mitigate issues related to transportation and limited clinical access by providing home-based training environment developed specifically for upper extremity rehabilitation.

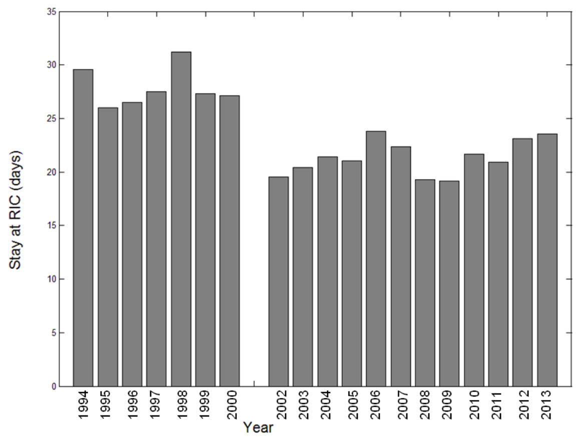

Figure 1: *Length of stay post-stroke at in-patient rehabilitation facility at the Rehabilitation Institute of Chicago in 1994-2014.*

2. SYSTEM DESIGN

The goals of our project are to design and test a multi-user VRE for home-based rehabilitation of upper extremity motor control after stroke. It will allow fellow stroke survivors and/or therapists to interact with each other in the same virtual space, and keep users engaged and motivated through competitive and collaborative multi-user interaction and inspirational advanced 3D computer graphics. Our system is designed to train movements important to rehabilitation and to provide feedback of performance to users and clinicians. It promotes independent therapy in the home environment where access could be greatest. Potential advantages of home rehabilitation do include:

• Ample time and flexible opportunities for practice
• No transportation issues
• Helping to maintain patient's participation through social interaction / Easing the isolation
• Using existing technologies (computer and broadband)
• Improving compliance
• Amplifying progress in therapy

We hypothesize that expanding the opportunity to train in the home will significantly increase the amount of upper extremity training performed. This should lead to improved outcomes.

The design of this system is highly flexible, providing an appropriate level of challenge dependent upon the capabilities of the user and adapting to maintain that level of challenge as the user improves. Testing aims include:

• Evaluation of user engagement in the VRE in a clinical setting
• Determination of the motivational impact of the multi-user environment in the home setting

Our long-term goal is to augment and extend clinical therapy by facilitating home-based training of upper extremity motor control to improve the quality of life for stroke survivors. This paper addresses the pre-clinical phase of a multi-year project that is underway as part of a sponsored center, Machines Assisting Rehabilitation from Stroke (MARS 3), hosted at the Rehabilitation Institute of Chicago. The VRE and underlying architecture are described, along with the methodology for a pilot study.

3. SYSTEM ARCHITECTURE

Our system consists of a multi-user server, two client computers with Kinect (Microsoft Corp., Redmond, WA) wireless tracking running VREs connected to the server, and three different multi-user games. The user directly controls the virtual arm and hand, in order to control the avatar and the view within the room.

Clients can access a central server located in the RIC hospital from their homes remotely via Internet connection. Our system allows up to four individuals to simultaneously inhabit the same scene (more clients can be added in the future). The sensor input from all 4 users (e.g., 2 stroke survivors, a family member and a therapist) can be read on local computers and then transferred through the Internet to a central server, which then updates each VRE accordingly (Figure 2). To maintain privacy and security, entry to VRE is password protected and file encryption is used.

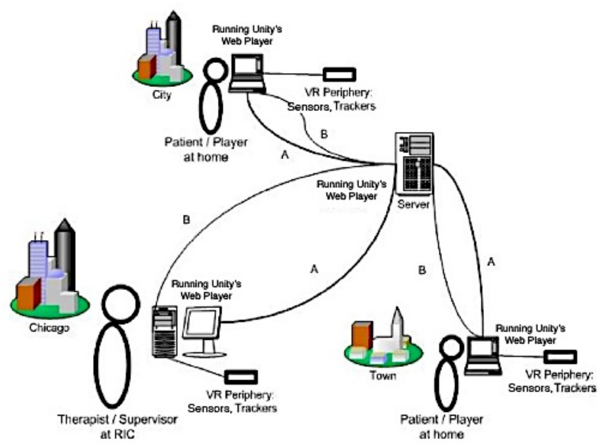

Figure 2: *Block diagram displaying data flow through the system between local, home-based client computers and a central server. Tracking data for the head and hand of each user is transmitted to the central server, which updates the global scene in Unity accordingly. The proper view of that scene is then sent to the local computer for each user.*

Each user controls its own avatar, which is free to move about the VRE. Kinematic data from the Kinect in the game scene is continuously updated according to the orientation and position of the user, and the virtual avatar moves in accordance with the user's actual movements. The signals from Kinect and used to update the scene. The joint angles from hand sensors are transmitted wirelessly to the user's computer running VRE and the avatar posture is updated accordingly. Tracking of head and hand position and orientation is needed for updating the user view of the VRE and determining interactions with virtual objects, respectively.

4. DEVELOPMENT

The project was developed using Unity game engine (Unity Technologies Inc., CA) to produce a multi-user VRE system and implement the direct voice communication between the players. The Unity3D graphics engine is written in C# libraries and free to download. Unity also has comprehensive support for multi-user networking that would allow for rich virtual interactions between users. To synchronize Unity across the communicating VREs and to streamline the integration of real-time multi-user avatars we developed custom plugins scripted using C#. To implement voice communication, we purchased an application from the Unity store and adapted it to our needs. The 3D scene is displayed on computer monitors for each connected user in real time. The VRE consists of two scenes: living room and kitchen. The scenes, 3D objects, and avatars were developed using Autodesk Maya (Autodesk Inc., CA). The avatar skeleton was developed using Maya and rigged to be controlled by Kinect data. Our scene has very rich graphics and aesthetics, which helps to create a strong sense of presence and is important for influencing perception and emotion to encourage therapeutic practice.

We developed a dedicated graphical user interface (GUI) that facilitates control of the entire system for each user. Specifically, the GUI allows control of the audio transmission, guides password protected client-server connection, displays game scores, displays the number of current multi-user connections, allows the therapist to switch game modes, and draw the challenging shapes depending on the level of subject capabilities.

In addition, Kinect interface (C# adaptation from Microsoft SDK) is used to perform the following tasks:
- Control views and avatars' interactions with virtual objects,
- Send skeleton data over Microsoft's UDP client,
- Allow decoupling of the VRE from the Kinect,
- Select functionality models of the posture and range.

The three multi-user games were created, each designed to address facets of upper extremity motor control, such as reach-to-grasp, hand/art coordination, and lateral pinch: Ball, Retracing and Food Fight games (Figure 3).

In the Ball game participants hit a ball back and forth across table using left and right hands (Figure 3, Middle: Ball game). This game was designed to quantify amount of hand movement and joint movement. The collisions and dynamics of the ball and other game objects are determined by Unity's physics engine.

In the Retracing game one participant draws a 3D shape in the air and other participants erase the shape. To help with the perception of depth, the semi-opaque 3D cube outlining the constantly changing boundaries of the drawn 3D shape in real time, was designed and scripted (Figure 3, Top: Retracing game). In this game we measure accuracy and speed of motion using custom developed algorithms. This game fosters interaction and collaboration between individual subjects and encourages exchange of user-generated content by allowing participants to draw three-dimensional shapes and share them with fellow stroke survivors in real-time.

In the Food Fight game participants grab and throw different food items (Figure 3, Bottom: Food Fight game). Mesh deformations and special effects for crashed objects were integrated to enhance the engagement.

Hand motion range sensors by Xsens 3D motion tracking technology (Xsens Technologies B.V., Netherlands) are measuring the active range of motion (ROM). Hand and arm joint angles are tracked from Xsens 3D motion tracking sensors worn on the hand and shoulder.

Our system offers the exciting potential of having a remote therapist participate directly in the rehabilitation session, such as to play a game of virtual catch with the client (e.g., a Ball game). Additionally, pairs of clients will be able to play games specifically designed for two (e.g., a Food Fight game) or to perform the existing exercises together, in parallel, or in competition.

Figure 3: *Multi-User tasks. Top: Retracing game. Middle: Ball game. Bottom: Food Fight game.*

5. STUDY

The goals of this study are to examine whether a multi-user VR environment does improve engagement in upper extremity therapy over other potential home-based options, such as single user VR or conventional exercises, and to compare resulting functional performance across methods. Participation in this intervention study provides the opportunity to perform upper extremity rehabilitative training with multi-user VR, single-user VR as well as standard tabletop exercises. The level of engagement and changes in active range of motion will be measured. We hypothesize that stroke survivors will be more engaged in therapy when training with the multi-user VR system and this will translate into greater gains.

Our pre-clinical testing will evaluate user engagement in the VRE in a clinical setting and determine the motivational impact of the multi-user VRE in the home setting. One of the purported benefits of VR is the stronger engagement in the rehabilitation training. Our study will test whether a VRE does indeed spur greater engagement, as measured on clinical scales, and whether patients prefer this therapy during an intervention study with sub-acute stroke subjects. With the multi-user VRE, social interaction is still possible without the need for physical proximity. We anticipate that this module will improve compliance for home-based therapy. In addition, the compliance with a prescribed training protocol during an intervention will be tested. We hypothesize: training compliance and intensity will be greater when performed with someone (the buddy or therapist) than when performed alone. Our findings will address the efficacy of home-based multi-user environments in promoting therapeutic training. The system developed could be readily distributed.

6. PROTOCOL, SUBJECTS AND MEASURES

A total of fifteen stroke survivors will participate in a three-week intervention study consisting of three one-hour training sessions each week. All training will be performed in the Coleman Hand Rehabilitation Laboratory at the Rehabilitation Institute of Chicago. Subjects will either perform sets of seated arm-hand exercises under supervision of research staff or practice movements within the VRE with the research staff. During each week the subject will participate in a specific type of therapy:

- performing supervised sets of seated arm-hand exercises;
- performing upper extremity tasks in a single-user VRE
- performing upper extremity movements in a multi-user VRE

The order of the therapy will be randomized for each subject.

We are recruiting a total of 15 stroke survivors who:

- are between the ages of 21 to 80;
- experienced a stroke at least 6 months prior to enrollment;
- have upper extremity impairment as rated at Stage of Arm 4-5 on the Chedoke-McMaster Stroke Assessment Scale.

Subjects are excluded if they have:

- neurological, neuromuscular, or orthopaedic disease;
- contracture/pain in the digits
- vision problems which would preclude the ability to follow a cursor on a computer screen.

A questionnaire employing the Likert scale [18, 19] and the Intrinsic Motivation Index (IMI) [20] will be self-administered after each week to measure the level of engagement with the therapy. An additional questionnaire specifically addressing the multi-user VRE will be administered at the end of the corresponding week of treatment. A final questionnaire directly comparing the three therapies will be administered at the end of the study. The active range of motion (ROM) for hand placement in the environment will be measured using the hand motion tracking sensors (Xsens 3D, Technologies B.V., Netherlands). The number of movements made during each training session will also be recorded. The nonparametric Friedman test will be run to compare subject engagement, as measured by the Likert and IMI scores. Repeated measures ANOVA will be used to compare the change in volume in active ROM among the therapies and movement quantity. Subject number is based upon the wish to detect an effect size of 0.35 at $\alpha = 0.05$ with 80% power. Thus, a total of 15 subjects are required to complete the study [21].

7. CONCLUSIONS

Our presentation will demonstrate our system and several multi-user stroke-specific games. We are currently still in the process of recruiting subjects to test the system and VRE prior to the start of IRB-approved clinical efficacy study to investigate the use of our system within a rehabilitation protocol. At this point, three stroke survivors have successfully completed the protocol. While it is early to assess feasibility, the three participants responded largely positive about the environment, social interaction and the exercises performed. They expressed interest in utilizing the system for rehabilitation. We anticipate study completion throughout 2016 and preliminary findings might be added by the time of the conference.

8. ACKNOWLEDGEMENTS

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