Evaluating the Post-Stroke Patients Progress Using an Augmented Reality Rehabilitation System

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Abstract

A stroke has been considered one of the leading causes of death in the world. Survivors suffer from major or minor disabilities in their motor functions so that they are unable to carry on their daily activities, therefore, they go through a rehabilitation process to recover their motor abilities up to a certain point. Recently, the fields of virtual reality and haptic have been investigated for use in rehabilitation. In this paper, we propose a novel approach based on Augmented Reality (AR) technology with two main goals as driving forces: First, the system enhances the patient involvement in the rehabilitation exercise, and second, the system measures the patient performance without the direct supervision of a therapist. We called this system AR-REHAB, for Augmented Reality REHABilitation. In addition, the system is empowered with an intelligent decision support engine to assess the patients’ progress to help therapists fine-tune the exercises designed to measure the degree of recovery in the patient’s disability. The therapist, who subjectively evaluates the patient’s performance and fine-tunes the exercise accordingly, must run these tests.

However, patients living in rural areas cannot take advantage of such therapy because it requires special facilities available only in rehabilitation centers within urban areas. In addition, since these types of treatments concentrate on patient’s motor functionality, training procedures comprise trivial and boring tasks repeated until the patient performs them properly.

In this paper, we present an AR-REHAB system that utilizes AR technology to provide patients with an entertaining environment for treatment. Furthermore, the system incorporates a Decision Support Engine (DSE) to provide therapists with assistive recommendations regarding patients’ exercise progresses in treatment. The rest of the paper is organized as follows: section 2 explains the rationale for the development of this system and depicts some related work. In section 3, we present the design philosophy and propose architecture for the system. Section 4 describes the implementation details and section 5 explains a preliminary evaluation study we have conducted involving fifteen healthy subjects. Finally, in section 6, we summarize the paper contents and provide perspective for future work.

1. INTRODUCTION

Brain damage due to a stroke can cause death or bring a permanent disability to a survivor. A stroke is one of the main reasons for chronic disabilities in the world. Most of the people who survive from a stroke suffer from minor to major disabilities in their functional motor capabilities. Therefore, they are unable to maintain their daily activities. The Canadian health-care system spends more than 2.7 billion dollars in post-stroke therapy. Additionally, post-stroke patients spend up to three million hours a year in hospitals to recover from a stroke [1].

In order to improve sensory-motor abilities and cognitive functions damaged by a stroke, therapists usually perform Occupational Therapy (OT) to patients. The aim of this type of therapy is to recover patient’s motor functions in their upper or lower limbs as much as possible in order to let them carry out their daily activities more normally. In the traditional method of such therapy, therapists execute special types of exercises to iteratively teach and train the patients basic motor movements, e.g. how to handle a box and move it to a shelf. In addition, assessment of a patient’s progress in treatment is performed by employing special tests to measure the degree of recovery in the patient’s disability. The therapist, who subjectively evaluates the patient’s performance and fine-tunes the exercise accordingly, must run these tests.

2. RELATED WORK

Virtual Reality rehabilitation systems could change tedious rehabilitation exercises into more entertaining ones that contain a variety of visual and auditory motivating items. Moreover, they provide capabilities to systematically design the exercise environment by easily changing the virtual environment. In addition, since various exercises could be constructed using one system setup, we can save more space, cost, and effort needed to setup the same exercises in a rehabilitation center. Additionally, since the VR rehabilitation system automates some procedures, one therapist can supervise several patients at the same time. Thus, such configuration provides health services to a
larger group of patients, and as a result, promotes the proper coordination of stroke rehabilitation.

Several studies highlighted the use of the VR technology in brain damage therapy and several systems have been developed to serve that [2], [3]. The authors in [4] have reviewed current systems that have been developed, specifically for motor function rehabilitation, and have successfully demonstrated the effectiveness of the VR technologies in improving specific motor functions.

The only, but critical, disadvantage of the VR approach is that patients are unable to feel or touch virtual objects although this rehabilitation is the process of improving physical motor skills by touching and moving. To overcome this, haptic technology was introduced into VR rehabilitation systems to provide subjects with artificial computer generated force feedback while they perform their exercises. However, for hand motor function rehabilitation, most of the existing systems deploy hand wearable haptic devices that provide multipoint haptic interaction, such as CyberForce. Generally, these devices are bulky and require significant effort to wear even by healthy subjects. This is a serious problem for stroke patients because inertia of the bulky device degrades their hand and arm movements. In addition, such haptic devices are costly and usually attached to special supportive machines that prohibit its associated system from being portable. Moreover, most of these haptic devices are tiresome and their usage results in some fatigue in the arm and shoulder of patients. Thus, some patients may easily lose their interests in such systems especially those who are more senior in age. All this has been pointed out by a team of therapists who came to evaluate our haptic based rehabilitation system with the bulky CyberForce. The results were published in [5]. Nonetheless, haptics based systems for stroke patients are reaching a higher level of maturity. Some research has been done on rehabilitation of upper and lower extremities, such as the hand motor function in [6] [7] [8] [9], the arm [10] and the ankle [11].

Those Issues mentioned above encouraged us to search for a new method to overcome the limitations of the three methods: traditional rehabilitation, immersive VR-based, and haptic-based. As a result, we have developed a new Augmented Reality (AR) based rehabilitation tool, called AR-REHAB, which leads to the advantages of VR and haptics based rehabilitation systems with much reduced complexity and cost. In AR-REHAB, subjects see real world scenes and manipulate real objects in their exercises. Therefore, subjects experience real interaction forces instead of computer-generated ones. Excluding bulky haptic devices from the system decreases the hardware and software complexity of the system and the overall expenses of the system. This is because subjects are still able to touch the real objects and items they are manipulating. In the mean time, the system presents virtual augmentations to create an entertaining game-like environment for the patient.

To the best of our knowledge, just a few attempts were made to develop AR based rehabilitation systems. Researchers in [12] developed an augmented reality system to train stroke patients for Grasp-and-Release tasks. The system renders the subject’s real hand inside the virtual environment using a Head Mounted Display (HMD) for the subject to grasp and move virtual objects. In addition, this system is equipped with an assistive glove to help patient’s extend their fingers during the Grasp-and-Release task. Using a Joystick, the therapist modifies positions, orientations, and sizes of virtual objects in the virtual environment to best fit the patient’s needs.

GenVirtual is a musical game that employs augmented reality for motor and cognitive rehabilitation by stimulating the memorization of colors and sounds [13]. The aim of the game is to follow a sequence of sounds and colors produced by the virtual objects that constitute a musical instrument. The game renders virtual cubes with different colors over a real world scene captured by a webcam. When the subject’s hand overlaps with one of these virtual cubes, the system plays a corresponding melody. In addition, the system allows the therapist to control, assign, and generate music melodies through its user interfaces.

These systems did not consider the use of real objects to enable patients to touch and interact with the environment. Using AR-REHAB, the subjects are able to experience real force while they perform their exercises. In addition, displaying fully immersive virtual objects in real world scene promotes engagement of subjects in their treatment sessions. Also, the employment of a decision support component in our system allows the ongoing evaluation of patients’ progress during their therapy and alerts the therapist to recommended actions.

Currently, the AR-REHAB system captures different user data to draw a recommendation regarding the progress of the patient by using a decision support engine. The analysis process is accumulative and autonomous; it is done without the intervention of the OT during the test session. It tracks the patient’s performance and, at any given moment of time, may decide whether the patient's exercise should proceed to another level or if the patient should repeat the same exercise. Usually, the recommendation is based on a continuous long-term analysis of patient data, and thus involves recording the patient’s related data over multiple sessions.
3. AR-REHAB SYSTEM

The AR-REHAB system comprises the following components: a webcam, a head mounted display, a data glove, and the decision support engine. The webcam captures the real world scene whereas the Head Mounted Display (Proview XL50 from Rockwell Collins Inc. [14]) renders the augmented scene back to the subject. The data glove (CyberGlove from Immersion Inc. [15]) reads the subject’s hand spatial characteristics while the patient performs the task.

3.1 Exercises

The system in its current implementation includes two exercises: the shelf exercise and the cup exercise. In the shelf exercise (Figure 1), the subject is asked to move a real kitchen object (a mug) back and forth numerous times to a shelf along a guided path presented in front of him/her. In another configuration, the subject moves the object to an empty space on the shelf while the rest of the space is filled with virtual objects, as shown in Figure 1.

The cup exercise involves handling a real cylindrical cup across the real space, lifting it in a straight motion along a prescribed path, and repeating the exercise for a specified number of times (Figure 2). The subjects are asked to move their hands as steadily as possible.

3.2 Architecture and Design

Figure 3 presents the high-level architecture of the AR-REHAB system. The ARRendering component receives the real world scene captured by a camera and computes the pose (position and orientation) of a special marker in the scene. This pose is used to superimpose virtual objects onto the real scene. The Session_Recorder records the behavior of the patient during his/her exercise session into the Patient_Movement database by using the Glove_Interface. This behavior includes positions and orientations of the hand and the fingers, grasping forces on the finger-tips, and time stamps for the logged data. Right after the patient finishes one session, the Session_Evaluator updates the Patient_Treatment data by computing the patient’s performance based on the criteria assigned to this particular exercise. The Decision_Support Engine (DSE) periodically reads the Patient_Treatment data and draws a conclusion or recommendation regarding the progress of the patient. The analysis process is accumulative and autonomous; meaning that it is done without the therapist’s intervention for a long period.

The OT_User_Interface represents the main graphical user interface (GUI) for the system. Through this component, the OT can instruct the system to modify the patient’s exercises using the Exercise_Adapter that feeds the AR_Rendering and the Session_Recorder components with the proper parameters to adapt the current configuration of the system.

3.3 Patient Quality of Performance

Evaluation of patient performance in the DSE is done by calculating the Quality of Performance (QoP), which includes eight factors that can be extracted from the data recorded by the system while the patient is performing his/her exercise session. We define these factors below; however, their detailed computation complexity and usage will be the subject of our future work:

- **Task Completion Time (TCT):** the time that it takes the patient to finish a specific task.
- **Hand Coordination (or synchronization):** the ability of the subject to move his/her hand precisely following a prescribed visual cue.
- **Compactness of Task:** the spatial workspace used by the subject to perform the test.
• **Hand Steadiness**: the level to which the hand movement of the subject is tremor free.

• **Speed of Hand Movement**: the arithmetic mean of the patient’s hand speed that is recorded during his/her treatment session.

• **Kinetic Energy**: the function of the subject’s total mechanical work while performing an exercise.

• **Grasping Angles**: the sum of the grasping angles of all fingers in the patient’s hand.

• **Finger Grip Acceleration**: finger speed over time (or finger acceleration) during a gripping activity.

4. IMPLEMENTATION

The AR-REHAB system is implemented using C++ language. The ARToolkit [16] is used to analyze the captured scene to search for suspected marker patterns. Once a marker is recognized, the ARToolkit computes the orientation and position of the camera in relation to the marker, and identifies the 3D position where a virtual object must be augmented. Then, the HMD renders back the augmented scene to the user. The VirtualHand API [17], from Immersion Inc., provides the pose of the hand through the CyberGlove and detects collisions between the hand model and virtual objects in the environment.

Since several QoP parameters are subjective and highly dependent on aspects such as the patient’s progress level and the considered task, the DSE is implemented with a Neuro-fuzzy logic inference system. At this time, we have developed a simple version of the DSE using the well-established Mamdani inference model [18]. Figure 4 shows the fuzzy system for evaluating patient performance in the cup exercise. The QoP output function is divided into four membership functions; in increasing order, they are VeryWeak, Weak, Average, Excellent, and Perfect.

The AR-REHAB user interface supports two types of users: therapists and patients. For a patient, the system directly loads the current exercise that the patient is undertaking in the treatment course when he/she logs in. The exercise starts when the patient clicks the “Start Exercise” button; the session recording is started and a timer is shown on the screen. When the prescribed session finishes, the exercise session is closed and a summary of the patient’s performance is presented including the task completion time, number of collisions between the patient’s hand and virtual objects, and the system’s observations of the patient’s performance during the session based on the above fuzzy inference model.

Figure 3. Architectural Overview

Figure 4. The therapist console screen
The therapist manages the patient's information through the therapist console screen (Figure 5). First, the therapist adds new patient data to the system and assigns him/her with a startup treatment course. The treatment course includes one or more exercises that a patient should perform several times a week. In addition, the therapist can change the treatment plan for an existing patient, and let him/her carry out new exercises depending on the patient’s performance. Moreover, the therapist can view the performance charts for any patient as well as his/her performance history. Finally, pop-up recommendation messages may appear to therapists to alert him/her about possible changes in the patient’s progress, and he/she can also access the history of previous DSE messages already sent.

Figure 5. Mamdani fuzzy inference model for cup exercise

5. EVALUATION STUDY

In this section, we describe our preliminary analyses and findings that illustrate the capability of the AR-REHAB system to provide therapists with powerful rehabilitation tools that are entertaining and intelligent. To prove the effectiveness of our system, we have designed two hand exercise experiments. Fifteen healthy male subjects participated in the experiment. The task was designed based on available exercises to illustrate two important factors of the Quality of Performance (QoP): hand steadiness and eye-hand coordination. A more elaborated study that covers all QoP factors is the subject of our future paper. In the first task using the cup exercise, each subject was asked to lift the cup and move it in a steady movement along the X-axis and then along the Y-axis 10 times alternatively. The second experiment involved performing the guided shelf exercise back and forth 10 times.

Figure 6 shows the result of plotting the position trace of the first subject hand movement in the XY-plane. It helps extract a conclusion regarding the steadiness of the hand movement. From closer observation to the figure, the subject’s hand movement is steadier in the vertical axis (Y-axis) than the horizontal axis (X-axis). In addition, the subject’s hand movement is unstable in the right side of the horizontal axis.

To examine eye-hand coordination, we used the result of the second task that involves the shelf exercise. Figure 7 shows the position tracking for the second subject’s hand movement in the YZ-plane. It clarifies the capability of the subject to follow a prescribed path by his/her hand. We could see that the subject’s hand movement is taking a curved path back and forth to the shelf even though the prescribed path presented to the subject is in a straight line. This is mainly due to the occlusion problem. Since the virtual line is always superimposed onto the captured real scene, users cannot perceive the depth difference between the hand and the prescribed virtual line. In order to solve this problem, we should extract the hand part of the captured scene and render it on the virtual line when it is closer to the user.

Figure 6. XY-plane hand position trace for subject 1
6. CONCLUSION

In this paper, we have presented a new rehabilitation system for post-stroke patients. The system utilizes augmented reality technology to constitute more realistic and entertaining exercises. The system provides the therapist with the means to quantitatively measure the patient’s performance and treatment progress. Moreover, the system contains a decision support engine that helps the therapist monitor patient progress and be aware of significant changes. The preliminary results have given us more confidence regarding the potential of the system as a practical rehabilitation tool.

Currently, we are completing the development of the DSE unit based on the evaluation factors we mentioned earlier in this paper. In the near future, we would let post-stroke patients test the system under the supervision of a team of therapists from the Ottawa General Hospital. In addition, we are planning to extend our systems further to include more rehabilitation exercises.

7. REFERENCES


