A Spatial Augmented Reality System for Post-Stroke Hand Rehabilitation

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Abstract. This paper features a Spatial Augmented Reality system for rehabilitation of hand and arm movement. The table-top home-based system tracks a subject’s hand and creates a virtual audio-visual interface for performing rehabilitation-related tasks that involve wrist, elbow, and shoulder movements. It measures range, speed, and smoothness of movements locally and can send the real-time photos and data to the clinic for further assessment. To evaluate the system, it was tested on two normal subjects and proved functional.

Keywords. Spatial Augmented Reality, Post-stroke Hand Rehabilitation

Introduction

Stroke represents a major health concern for the American public, ranking as a leading cause of disability. Approximately 7,000,000 Americans have suffered a stroke, and approximately 795,000 new strokes occur each year in the U.S. [1]. Similar figures reported from other countries. About 80% of acute stroke survivors lose arm and hand movement skills [2]. Stroke rehabilitation is a challenging process. Movement impairments after stroke typically require intensive treatments, hands-on physical, and occupational therapy for several weeks after the initial injury. Unfortunately, due to economic pressures on health care providers, stroke patients are receiving less therapy and going home earlier [2]. Therefore, an important goal for Rehabilitation Engineering (RE) is to develop technology that allows individuals with stroke to practice intensive movement training without the expense of an always-present therapist [3]. We have developed a low-cost, Spatial Augmented Reality system that allows individuals with stroke to practice hand and arm movement exercises at home or at clinic with minimal interventions of a therapist.

Different from Virtual Reality (VR) in which the real world is fully replaced with a virtual environment, Augmented Reality (AR) does not replace the real world but augments a user’s view of the real world with virtual objects. Applying AR technology in RE is a new paradigm for the research in Assistive Technology (AT) [4]. AR-based RE devices provide the patient with better control over augmented environment in such a way that he feels more realism and interact in a more intuitive way.

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We designed intuitive and natural interactions that can help a patient practice the foundation of manual activities that are central to activities of daily living, such as reaching, wrist-tilting, pointing, and grasping. Involving the patient in such simulations of daily activities is expected to have the additional advantage of fostering a more positive psychological approach to the rehabilitation experience. Moreover, the proposed system can be adapted to a portable low-cost home-based device that includes communications for remote interaction with a therapist and medical team. Thus the patient can work independently, without a constant need for therapist interaction.

1. Related Work

Rehabilitation engineering applications are specially designed to recover certain impaired functions of individuals with disabilities. Since our focus in this paper is motor function, in the following, we discuss the state-of-the-art research that has been carried out in AR-RE domain.

Luo et al. [3, 4] measured the force and assist finger extension using mechanical devices. They presented a training environment for rehabilitation of hand opening in stroke survivors. This environment integrated Augmented Reality with assistive devices for the process of repetitive training of grasp-and-release tasks. One potential criticism of the system is that therapist intervention was necessary, as the patient needs to wear equipment that would be hard to don without assistance. Correa et al. [5, 6] developed GenVirtual, an AR game musical, that provided a natural, fingertip/toe tip-based interaction. The intention of this work was to help patients with motor coordination. On the other hand, GenVirtual had little effect for individual with low mobility. Alamri et al. [8] proposed a framework that takes advantages of the AR-based rehabilitation processes with a 2-D web camera and fiducial markers. The system supported the training of daily activity, though, due to use of fiducial markers, the setup can be complex in the absence of a therapist.

Compared to the above platforms, our system requires the patient to wear minimal equipment: two small color markers on their fingers. The second difference is that our platform is a Spatial Augmented Reality system, using an inexpensive projector to augment virtual objects. This projector lets user have a large range of motion on therapy table to do variety of movements. Third contribution of the system is that our designed exercise program includes fundamental hand movements which cover a wider range of stroke patients with different impairments.

2. Methods and Materials

AR rehabilitation is an interesting and useful adjunct to traditional therapy by leveraging benefits of both real and virtual world training such as providing immersive experience for users, objective quantification of the training process, and motivating way of using massed practice. By developing an AR rehab system, the coordination system of user’s real world unifies with the virtual world. This let patients feel as if the assistive virtual objects, that are displayed to help them carry out their exercises, are actually present and belonged to real world rather than being apart in a separate screen.

Experiment Setup: our setup includes a conventional computer, a low cost webcam, and a projector. The subject sits in front of a table that serves as a platform for virtual objects to be projected on it. The subject’s hand movements are followed by a camera,
while he is looking on the table and interacting with the virtual objects superimposed on it (Figure 1). Our system has the potential to be used locally, in a clinical environment, as well as remotely, in the patient’s home where it would remain accessible by a therapist through a telerehabilitation system. The system’s setup is easy to learn for the patients, making the system comfortable to use even without therapist’s presence.

Vision-based system: we developed several vision algorithms to locate and track the hand of the subject using color marker and motion information. The system can quantify the motion captured by camera using computer vision methods.

Along with the implementation of the system, we designed several tasks based on daily life activities. These involve primitive postures of the hand including reaching, tilting, pointing, and grasping, which require control on various hand parameters such as: range, speed, smoothness of movement, and size of grip (Table 1). This way, we measure some important performance factors that can be used to assess a patient's progress across weeks of therapy. We also calculate the completion time of each task for the subjects.

Giving dynamic feedbacks on performance of the user throughout the tasks such as playing sounds and augmenting virtual objects in response to the user, the system increases the quality of subject’s interaction with it.

<table>
<thead>
<tr>
<th>Part</th>
<th>Posture</th>
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<tr>
<td>Adduction/Abduction</td>
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<td>Arm</td>
<td>Reaching</td>
<td>Task 1</td>
<td>Velocity, Hand position, Smoothness, Time of completion</td>
</tr>
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3. Rehab Exercises

In the following, we will discuss the AR rehab exercises that we designed as part of our system. Note that our suggested primary tasks have the potential to be used in variety of interactive and engaging games that can keep patients engaged and motivated despite the fact that they are performing continuous repetitive movements.

Task 1, Reaching: in this task (Figure 2(a)), three melody boxes are projected on the subject’s desk, in different orders. The subject is expected to reach out for the
projected box. As soon as the hand enters the area of active box, a drum note is played. This is the basis of an engaging game to help subject reach out for different targets in a certain period of time, using active-box hints that correspond to different notes of a melody. At the end of the game, the subject can see his score on the screen which has been calculated based on how fast and correct he could reach out the active box and eventually make a pleasant music. In this game, we are using occlusion-based interaction (subject’s hand entering the area) as well as dynamic feedback (sound).

Task 2, Pronation/supination (tilting) of wrist: in this task (Figure 2(b)), the subject is asked to hold a cup and tilt it as if he is pouring its content on the table. As the task starts, the subject should empty the cup’s content in 5 or more tilt-and-hold-still postures. To give him more natural feel of pouring water on the table, as the subject tilts the glass, virtual water (blue circle) is displayed beneath the cup, which simulates the amount of water that has been already poured out. The more the subject repeats tilting the cup the larger the blue circle becomes. We monitor the changes in area of blue circle to get a sense of how well the subject is able to do the task smoothly and in control. By employing the daily life tasks as mentioned above, we believe patients get more confidence in their real life activities as they already practiced doing them in therapies’ sessions. In this task, we leverage dynamic feedback (growing blue circle) to let subject know whether he is controlling the task at a normal, healthy pace.

![Figure 2. Task 1: Reaching melody boxes to play drum sounds; (b) Task 2: Holding and tilting a mug to gradually pour virtual water; (c) Task 3: Pointing to melody boxes to play drum sounds; and (d) Task 4: Grasping random size-position circles](image)
Task 3, Pointing: for this task (Figure 2(c)), we ask the subject to wear two small color markers: one on his wrist and the other on his index finger. Then we ask him to point to different melody boxes that are projected on the table and make various sounds out of them. The pointing action is repeated in two postures: one involves adduction/abduction (Figure 2(c) top) and the other one involves flexion/extension of wrist (Figure 2(c) bottom). Here, again, playing sound as dynamic feedback help the subject know that he has successfully targeted each box throughout the task.

Task 4, Grasping: in this task (Figure 2(d)), we target those patients who have a problem opening their hand for grasping. We ask the subject to wear the same color markers as previous task but this time one on the thumb and the other on their index finger of the impaired hand. The subject then has to grasp a random size circle that appears on a random position on the desk. Due to the circle’s different sizes and positions, the subject had to adjust finger position to generate the correct size grasp in order to get the circle. A sound (dynamic feedback) is played to let the subject know when he has succeeded and shall proceed to the next grasp.

4. Results, Discussion and Conclusion

The purpose of this pilot study was to prove the system is functional, anticipating potential problems and gaining experience using the technology in a laboratory setting.

Figure 3(a) illustrates the position of the subject's hand while each was reaching out the melody box. As can be seen, the subject’s hand traverses back and forth between a common point (start of movement) and the three melody boxes that were projected on the table. Figure 3(b) shows tilting angle of the mug while the subjects were gradually pouring water on the table. Figure 3(c) illustrates wrist and index finger positions of the subjects to examine whether they were able to perform the pointing task. Figure 3(d) demonstrates thumb and index finger positions while the subjects were trying to match their grip’s size to the size of the projected circle.

Augmented Reality technology has the potential to impact traditional rehabilitation techniques. This approach has the potential to address a number of needs in stroke rehabilitation. Chief among these is the use of a high ecology environment that is maximally relevant to functional goals. Performing tasks in an Augmented Reality environment might generalize to real life settings to a greater extent than with other computer-based approaches. As an extension of this, object affordance can be directly adjusted by the therapist, with real objects incorporated into tasks as desired. This system can control for extraneous distractions that sometimes exist in real life therapy environments, and furthermore the therapist can choose how many extraneous objects to include in each trial. The system insures safety and comfort, for example, no water is spilled on the subject or wires when the tilting task is performed by a patient with post-stroke hemiparesis.

A key advantage of the current approach is the tasks practiced in therapy can be modified by a therapist based on a patient's specific needs. For example, the size, texture, or friction characteristics of an object can be varied in relation to motor or sensory deficits. The language requirement for task performance can be adjusted from zero to high; in this way, patients with aphasia are eligible to use the system, in contrast with some rehabilitation approaches. An object's location, orientation, or attentional valence can be easily adjusted, a feature of particular value to patient's with neglect after non-dominant hemisphere stroke. The cognitive demands of a task can be adjusted
in numerous ways using this approach, a feature useful for the treatment of patients with cognitive impairments, a common finding after stroke. Attentional valence can also be adjusted, for example, the same grip might be to hold an ice cube in a cafe or a gold nugget in a mine. This is particularly relevant to maximizing patient motivation, a perennial concern across the weeks of stroke rehabilitation, and also has implications for vocational rehabilitation.

![User study results with the first subject (upper plots) and the second subject (lower plots) performing tasks 1-4: (a) Reaching; (b) Tilting; (c) Pointing; and (d) Grasping](image)

**Figure 3.** User study results with the first subject (upper plots) and the second subject (lower plots) performing tasks 1-4: (a) Reaching; (b) Tilting; (c) Pointing; and (d) Grasping

The current report describes development of a Spatial Augmented Reality system for rehabilitating upper extremity function after stroke. A novel performance-driven exercise program was outlined, in which a patient practices primary hand gestures mostly used in daily activates. These gestures include reach, tilt, point, and grasp, examining parameters such as range, speed, and smoothness of hand, arm, and wrist movements. The AR rehabilitation system was evaluated with two healthy subjects as a proof of concept.

Further studies are planned to elucidate the clinical efficacy of our AR therapy for stroke patients. As future work, we also plan to add haptic feedback [9] to our system. This is especially important for those patients who need to recover their muscle strength. With haptic feedback [11], [12], we can even improve the effectiveness of the rehabilitation systems and make interaction process more realistic. To reach this target, instead of using bulky equipment, we generally use personal and daily-life objects such as cup, book, pen, etc [10], [13]. These have the added advantage of high task ecology with respect to activities of daily living. In addition, future work will include more engaging games to increase the variety of therapy solutions and adaptability to patient abilities, so that a therapist or patient can match the amount of challenge necessary to
keep the rehabilitation advancing. In these games, we take advantage of skin detection methods and Microsoft Kinect [14] for more accurate and natural 3-dimensional positioning.

References


