Virtual Therapeutic Environments with Haptics: An Interdisciplinary Approach for Developing Post-Stroke Rehabilitation Systems

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Abstract – Stroke is the leading cause of serious, long-term disability among American adults. Each year, nearly 400,000 people survive but suffer from neurological disability. Patients' motivation and engagement during rehabilitation therapy is important because the amount, type and intensity of practice available to the patients during the recovery process is critical for the functional recovery after stroke. In the current paper we will introduce a National Institutes of Health-supported interdisciplinary project, involving researchers from the fields of Communication, Cell Neurobiology, Computer Science, Psychology, and Physical Therapy, to develop virtual therapeutic environments for post-stroke recovery. The purpose of the project is to develop virtual environments (VEs) that include different levels of haptic sensory feedback and to evaluate the effectiveness of these applications for neurorehabilitation training. The current system development, including applications using the PHANToM and CyberGrasp (haptic devices) as well as future research plans are discussed.

Keywords: haptics, virtual reality, stroke rehabilitation, telerehabilitation, video games, interdisciplinary.

1. Introduction

Stroke is the leading cause of serious, long-term disability among American adults and the third leading cause of death in the United States [1]. Each year over 700,000 people suffer a stroke [1], and nearly 400,000 survive with some form of neurological disability [2]. As a consequence, the estimated direct and indirect cost of stroke in 2005 reached $56.8 billion placing a tremendous burden on both the private and public health resources of the nation [1].

Stroke often results in limited movements with the impaired limb even though the limb is not completely paralyzed. This loss of function, termed "learned disuse," is most obvious during the early post-injury period but, can improve with rehabilitation therapy. Studies have shown that the potential for the degree of functional recovery after stroke involves not only the level of initial impairment but the amount, type and intensity of practice available to the patient during the recovery process [3], [4].

In rehabilitation therapy it is important to maintain patients' motivation and engagement when confronting them with a repetitive series of retraining challenges. In this regard, an understanding of gaming features and their integration into virtual reality (VR)-based rehabilitation systems to enhance patients' motivation is a useful direction to explore for stroke rehabilitation. Novel VR environments may allow patients to be motivated by gaining success in virtual skills that build towards actual skills even when the actual skills are still limited. Incorporating haptics (rendering of the sensation of shape and texture) into the virtual test

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environments may enable patients to practice everyday skills in which real objects are simulated.

The current paper will introduce an interdisciplinary project, involving researchers from the fields of Communication, Cell Neurobiology, Computer Science, Psychology, and Physical Therapy, to develop virtual therapeutic environments for post-stroke recovery.

2. Related Work

2.1. Virtual reality

VR has now emerged as a promising tool in many domains of therapy and rehabilitation [5], [6], [7], [8], [9]. Continuing advances in VR technology along with concomitant system cost reductions have supported the development of more usable, useful, and accessible VR systems that can uniquely target a wide range of physical, psychological, and cognitive rehabilitation concerns and research questions [10].

What makes VR application development in the rehabilitation sciences so distinctively important is that it represents more than a simple linear extension of existing computer technology for human use. VR offers the potential to create systematic human testing, training and treatment environments that allow for the precise control of complex dynamic 3D stimulus presentations, within which sophisticated interaction, behavioral tracking and performance recording and analysis is possible. Much like an aircraft simulator serves to test and train piloting ability, virtual environments (VE) can be developed to present simulations that assess and rehabilitate human functional performance under a range of immersive stimulus conditions that are not easily deliverable and controllable in the real world. When combining these assets within the context of functionally relevant, ecologically valid virtual environments, VR provides numerous assets for rehabilitation beyond what is currently available with traditional methods [8], [10]

The Haptics and Virtual Environments Lab at University of Southern California developed a series of immersive motor rehabilitation scenarios that can be delivered in both a stereoscopic Head Mounted Display (HMD) and via PC-based projection displays. These applications are currently being tuned to foster motor interaction in a series of game-like scenarios to assess and rehabilitate eye-hand coordination, range of motion and other relevant motor activities.

Significant effort has been put into the interface design that will allow a physical therapist the capacity to configure the stimulus presentation parameters according to the needs of the client to promote optimal motor action based on both therapeutic need and/or the specific research question. The capacity for a person to become engaged in a gaming task and become less focused on the fact that they are being tested may provide a more “pure” gauge of naturalistic ability. As well, a compelling clinical direction may involve leveraging gaming features and incentives for the challenging task of enhancing motivation levels in clients participating in rehabilitation. We report below on new work incorporating haptics into these virtual rehabilitative environments.

2.2. Haptics

Haptics involves the modality of touch and the sensation of shape and texture an observer feels when virtually 'touching' an object with a force-feedback stylus, instrumented data glove with exoskeleton, or other robotic device [11].

There are several recent reports of research in which haptics has been studied for its potential in post-stroke rehabilitation. Broeren, Georgsson, Rydmark, and Sunnerhagen [12] used a 3D computer game to promote motor relearning in a patient suffering from a left arm paresis. The treatment was delivered through the ReachIn VR platform, which features stereoscopic visualization and force feedback with a PHANToM haptic device. The subject's performance was evaluated on a specific hand function task, striking a virtual ball to knock over bricks in a pile. Grip force, endurance and the pattern of arm movement showed improvement after treatment.

Connor, Wing, Humphreys, Bracewell and Harvey [13] tested the efficacy of hapticallyguided errorless learning (EL) with a group of patients with post-stroke visuo-perceptual deficits. In the errorless learning condition unproductive or incorrect approaches to objects within a virtual environment are prevented by applying a counter-resistive force when the patient moves in the wrong direction. Connor et al. [13] found that errorless learning training with haptic guidance benefited some patients, but not all.

Boian, Deutsch, Lee, Burdea and Lewis [14] developed a prototype virtual reality-based rehabilitation environment using a haptic device called the 'Rutgers Ankle.' The patient navigates a virtual environment with a PC host which puts him or her through a series of exercises, using the Ankle as a foot joystick. Boian et al. reported some gains in gait speed and muscle strength for study participants.

Although the use of VR environments and haptics for stroke rehabilitation has been studied in many disciplines (e.g. [15], [16], [17]), our project is unique in many ways: (1) we have created robust techniques for recording and playing back the activities of the user during a haptics-enhanced VR session regardless of the type of device employed. This playback capacity is useful in training applications where a trainee is attempting to carry out a series of skilled movements in the manner of an expert trainer, and it also facilitates assessment of improvement in motor relearning over time, where the hand/finger coordinates and joint angles between the fingers can be treated as time series data and compared before and after various interventions; (2) we have implemented algorithms which allow us to anticipate incorrect movement trajectories by the user and head off errors before they occur, a technique which may be useful for "errorless learning;" (3) we have developed a spoken dialog system fully integrated with our haptic systems which permit voice control of the interface, input devices including force feedback devices, and access to the help system. This feature allows the user to navigate the interface without fine or gross motor control and leaves the hands free to concentrate on the training exercise; (4) We have created modifications which make it easier for the user to locate objects in the virtual environment and to remain "in contact" with them, such as "sticky" object surfaces and "snap-to" features which move the haptic cursor to digital objects with voice commands; (5) From experience gained in our research on Internet-based mutual touch and collaborative environments [18], we have developed strategies that will allow the patient's activities to be guided by a rehabilitation therapist at a remote location, so that the therapeutic regimen can be free of some of the normal constraints of time and place. We have created methods for collaboration between users of haptic devices who are physically separated by many miles, such that it is possible, for example, for a therapist to guide the hand motions of a rehabilitation client over the network, even from a remote location. This "hand-over-hand" guidance capability creates a sense of immediacy and presence in virtual training environments.

3. Virtual Therapeutic Environments with Haptics

3.1. Description of the project

The purpose of the project is to develop virtual environments (VEs) that include different levels of haptic sensory feedback and to evaluate the effectiveness of these applications for neurorehabilitation training. The tasks to be performed within these VEs span a range of activities from everyday functional tasks to game-like activities designed to motivate specific motor action that is believed to underlie more functional behavior. The outcome of this work is to create VE applications that will be evaluated for both the usability of the VE interface and display devices by patient populations following stroke and for the impact that training in these environments has on both motor performance and cortical reorganization.

The virtual rehabilitation environments which we have designed will serve stroke patients in the subacute phase who are currently receiving therapy at a neuro-rehabilitation service in the greater Los Angeles area. Patients will range in age from their mid-twenties to their late seventies. Our role is to develop task-specific virtual exercise environments which will trigger and reinforce the compensatory brain mechanisms that facilitate recovery from stroke. Behavioral experience (motor skills training tied to specific tasks such as making coffee) is believed to accelerate these neuroplastic processes. We are also creating environments which will allow testing the effects of mere visualization (watching the motor skills tied to a specific task being enacted, as opposed to actually performing them).

Recovering stroke patients will engage in interaction within a simple virtual environment consisting of a background and one or more three-dimensional objects, some of which may be "rigid-body" objects like a 3D model of a coffee pot, and others of which are "deformable" or change shape upon haptic input from the user, like a virtual rubber ball.

3.2. System developments

We are currently in development of three VE systems using three different types of haptic feedback devices. The haptic devices that we have available can be applied to a progressive set of training tasks such as precise fine motor movements, fine and gross motor hand activities, and gross reaching movements that involve full arm, shoulder and torso activity.

3.2.1. The PHANToM

The PHANToM is a small, desk-grounded robot that permits simulation of single or two-fingertip contact with virtual objects through a thimble or stylus (see Figure 1). This 6DOF device tracks the x, y, and z Cartesian coordinates and pitch, roll, and yaw of the virtual probe as it moves about a three-dimensional workspace, and its actuators communicate forces back to the user's fingertips as it detects collisions with virtual objects, simulating the sense of touch.

Fine motor movement can be trained using the PHANToM Device. This device will be used as the interface for a series of tasks that allow patients to move a small coin into a slot on a vending machine, to rotate small objects to obtain a better view of the objects, to move a ball through a maze-like tube, and to pick up and deform a cube to put it through a smaller hole using two PHANToMs (activities for a pinch training). These applications can display the objects and motor action on a standard PC monitor that can be set for both mono and stereo viewing.

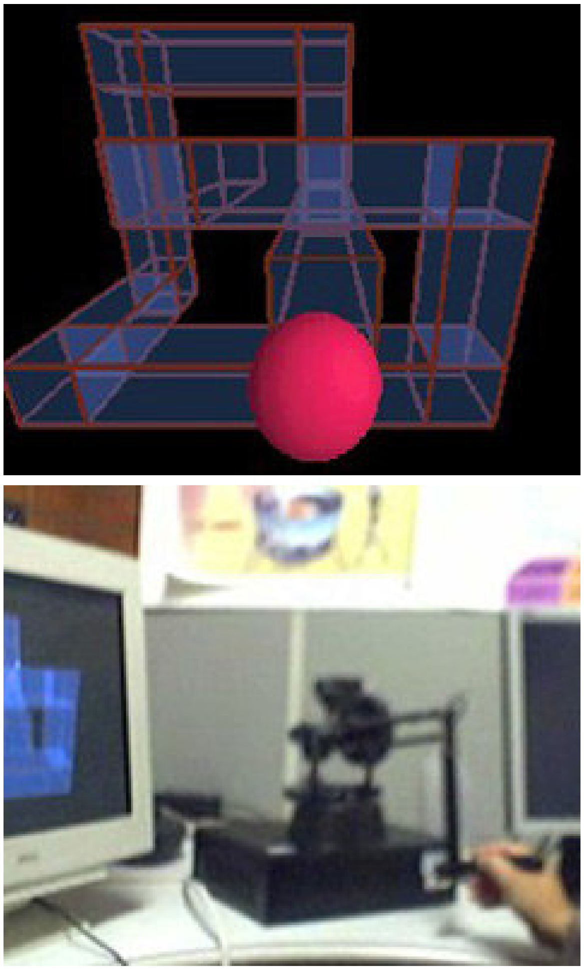

Figure 1. The Space Tube Demo: Picture above is a screen shot of the demo. Picture below shows a person using PHANToM for the demo.

3.2.2. The CyberGrasp

The CyberGrasp is an exoskeletal device that fits over a 22 DOF CyberGlove, providing force feedback (see Figure 2). The CyberGrasp is used in conjunction with a tracker to measure the position and orientation of the hand in three-dimensional space. Fine and gross motor hand activities can be trained using the CyberGrasp using both a standard PC monitor (both for mono or stereo viewing) and within an immersive head mounted display (HMD).

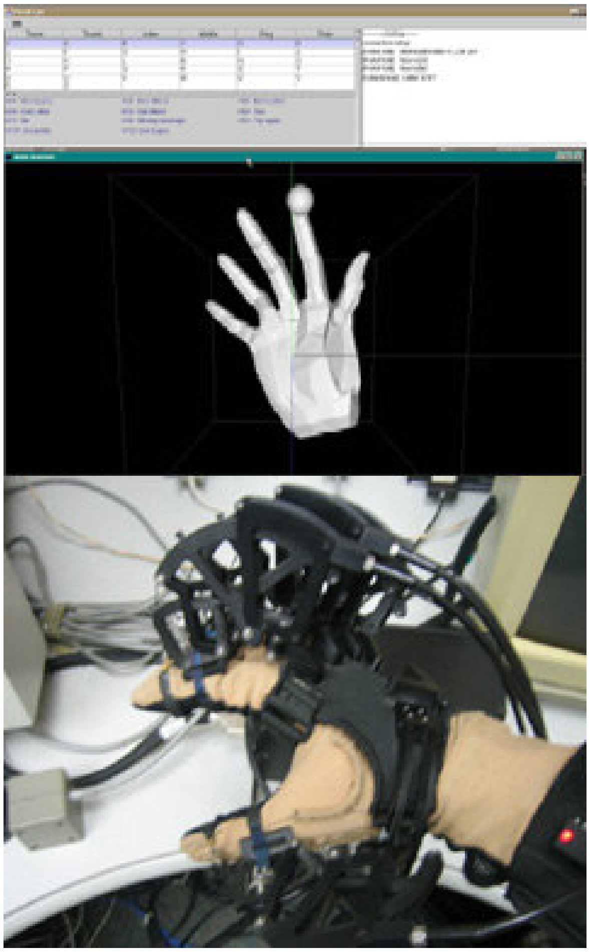

Figure 2. The Mutual Touch Demo: Picture above shows the user's view of the demo. Picture below shows a person's hand wearing CyberGrasp for the demo.

We intend to use this device as the interface for a series of hand reaching and grasping tasks with functional objects of various shapes and sizes. The tasks include reaching for a vessel of water and pouring it into a glass, placing books on appropriate shelves, and stacking up four different objects in orders. If performed correctly patients will feel the sensation of a solid cylindrical object inside their palms. They will then, for example, be instructed to "pour" from the can by completely inverting it and holding this position for ten seconds. Then the patients will be instructed to place the can back in its original resting place. In the visualization condition, the patients will either (a) watch a video of this exercise or (b) wear the CyberGlove/CyberGrasp and be passively taken through the motions as a previously recorded "pouring" session is replayed. The user interfaces will require minimal input from the user, and will be completely navigable with voice commands (e.g., "result," "next task," "repeat,").

3.2.3. The vibrating mechanisms

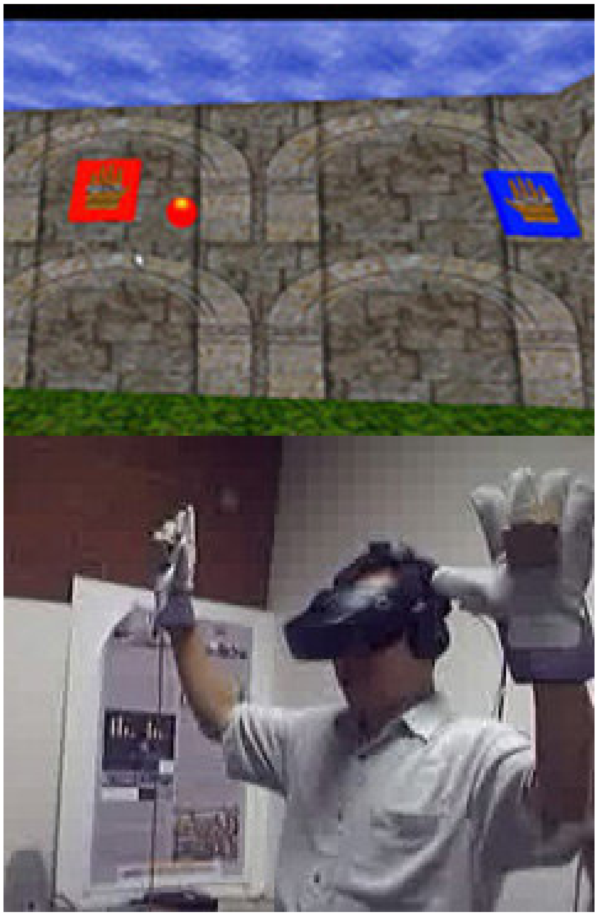

Figure 3. The Virtual Handball Demo: Picture above is the user's view of the demo in the HMD. Picture below shows a person trying the equipments for the demo.

This application will use vibrating mechanisms on the palm of the hand to simulate contact/collision with moving objects in a series of game based environments designed to exercise gross arm, shoulder and torso movement (see

Figure 3). Patients can view their hand actions within the scenarios via an HMD for full immersion and from both projection displays and PC monitors. The scenarios will allow the patient to participate in virtual handball, play goalie in a virtual soccer game, and reach through a maze of objects that requires patients to only make contact with targets and to avoid very fragile glass objects.

4. Discussion and Future Work

We will soon begin initial patient testing of the environments to enhance usability and to iteratively evolve the interaction parameters. We are closely collaborating with the other members of the project to design the application interactions from a biokinesiology perspective to maximize therapeutic movement with cortical reorganization goals in mind. During this time, the systems are being programmed to deliver standardized packages of training trials across difficulty levels that can be chosen based on the particular patient's level of impairment. As well, operational interfaces will be designed that allow the rehabilitation professional to easily adjust stimulus parameters and interactional challenges "on the fly" based on individual patient need and progress. All systems will provide intuitive feedback as to the success of the individual actions of the patient and deliver performance data at the end of the trials for assessment of rehabilitative gains by the patient and rehabilitation professionals and for research purposes.

Using haptics and VEs in stroke rehabilitation will yield many advantages over traditional rehabilitation therapy. Two important features among many others would be patients' motivation and instant feedback from the system. Integrated game-features in VEs are likely to motivate patients for their active and enjoyable participation in therapy sessions. Instant feedback from the haptics data enables therapists to design tailored therapy sessions for each stroke patient. Customized therapy is essential in stroke rehabilitation because each patient suffers from different degrees of impairment.

Finally, we believe that the interdisciplinary project that we have introduced is a desirable approach in developing advanced stroke rehabilitation programs using haptics and VR technologies due to the complexities involved in stroke patients and their rehabilitation therapy.

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