

Haptics-Enhanced Virtual Environments for Stroke Rehabilitation

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Abstract— This paper introduces a National Institutes of Health-supported interdisciplinary project, involving researchers from the fields of Communication, Cell Neurobiology, Computer Science, and Physical Therapy. The purpose of the project is to develop virtual therapeutic environments that include different levels of haptic sensory feedback for post-stroke rehabilitation. Various applications have been created within virtual environments using the PHANToM and CyberGrasp (haptic devices), ranging from everyday functional tasks to game-like activities designed to motivate patients and to maximize therapeutic movement with cortical reorganization goals in mind. Current system development as well as future plans for clinical tests in Phase 2 are discussed.

Keywords—haptics, stroke rehabilitation, therapy, virtual reality.

I. INTRODUCTION

Virtual reality (VR) has now emerged as a promising tool in many domains of therapy and rehabilitation [1], [2], [3], [4], [5]. Continuing advances in VR and haptics 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 [6], surgery-related applications [7], and related research questions. Among many of these potential applications, we are particularly interested in developing haptics-enhanced VR environments for post-stroke rehabilitation.

According to American Heart Association, stroke is the leading cause of serious, long-term disability among American adults. Each year nearly 400,000 survive with some form of neurological disability from a stroke [8]. 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 [9]. Stroke often

results in limited movements with the impaired limb even though the limb is not completely paralyzed. This loss of function, however, can improve with rehabilitation therapy depending on the amount, type and intensity of practice available to the patient during the recovery process [10], [11].

Because of the importance of rehabilitation therapy for post-stroke recovery, it is critical 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. Besides, incorporating haptics (rendering of the sensation of shape and texture) into the virtual test environments may enable patients to practice everyday skills in which real objects are simulated. The instant feedback from the haptics data may contribute to developing a set of tailored therapy sessions for each stroke patient.

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.

II. RELATED WORK

A. Virtual Reality

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 (VEs) 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

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within the context of functionally relevant, ecologically valid VEs, VR provides numerous assets for rehabilitation beyond what is currently available with traditional methods [4], [6].

The Haptics and Virtual Environments Lab at University of Southern California developed a series of immersive motor rehabilitation scenarios that can be delivered in a stereoscopic Head Mounted Display (HMD), via PC-based projection displays, and two types of autostereoscopic display: lenticular and parallax barrier. 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. 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.

B. 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 [12].

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 [13] 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 [14] tested the efficacy of haptically-guided 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. [14] found that errorless learning training with haptic guidance benefited some patients, but not all.

Boian, Deutsch, Lee, Burdea and Lewis [15] 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. [15] 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. [16], [17], [18]), 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 [19], 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.

III. PROJECT

The purpose of our project in the Interdisciplinary Study of Neuroplasticity and Stroke Rehabilitation (ISNS) is to develop virtual therapeutic environments that include different levels of haptic sensory feedback and to evaluate the effectiveness of these applications for neurorehabilitation training. Specifically, 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 is believed to accelerate these neuroplastic processes. Thus, 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 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. Recovering stroke patients will engage in interaction within a simple virtual

environment consisting of a background and one or more three-dimensional (3D) objects, some of which may be "rigid-body" objects like a 3D model of blocks and tubes, and others of which are "deformable" or change shape upon haptic input from the user, like a virtually deformable cube.

A. System Developments

We are currently in an iterative design cycle of usability testing and refinement of tasks, using different types and combinations of haptic feedback devices, which can be host to a progressive set of training tasks from precise fine motor movements to reaching movements that involve full arm, shoulder and torso activity. In the current paper, we will introduce a variety of rehabilitation tasks using three different haptic devices.

1) *Spatial Rotation*: A manual virtual reality spatial-rotation task (VRSR) was developed based on the Mental Rotations Test (MRT) [20] investigating the mental rotation ability of individuals. The task targets hands-on assessment and training of visuospatial skills including the supination and pronation function. In the task, patients are asked to manipulate one set of blocks into superimposition with the target configuration using a ball-like specified interaction device [21] (see Figure 1 and Figure 4). Although the interaction device in the Spatial Rotation task does not provide users with force-feedback or the sensation of touch, it can capture and log the haptics data such as movement paths along with time spent on successful superimposition. This precise measurement of user responses enables therapists to develop a tailored therapy for each stroke patient.

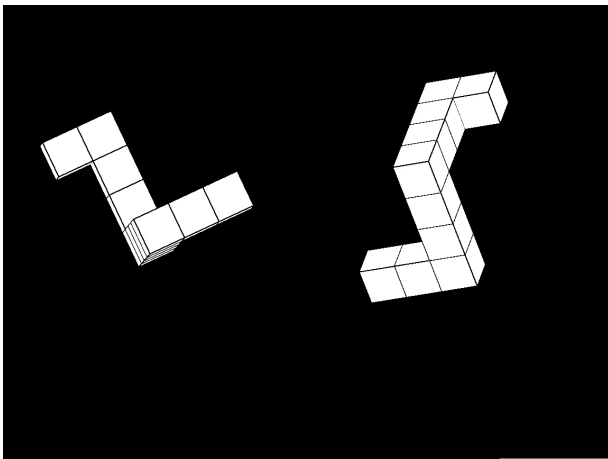


Figure 1. Screen shot of Spatial Rotation task

2) *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. 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 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.

Currently, two tasks using one PHANToM device have been designed for use in motor retraining applications. In one task (Ball and Cube), patients are asked to move all cubes hidden among spheres into an aperture by using a 6DOF device, without touching the spheres. The number of cubes and spheres changes according to the difficulty level. The fewer cubes and spheres, the easier the task is. Scores are calculated based on the number of collisions between the PHANToM and spheres. The fewer collisions there are, the higher the score is. In another task (Space Tube), patients are asked to navigate the PHANToM device inside a tube from the entry port to the exit port without touching the sides of the tube (see Figure 2 and Figure 5). Collisions are signaled with sound and force feedback. The tube may have a few corners to negotiate. Also, there may be barriers inside the tube, so that users have to break through these barriers to reach the exit port by applying sufficient force. Difficulty levels can be set by altering the number of barriers and the shape (orientation, number of segments) of the tube. Attraction force is also applied to help users reach the entry port of the tube when the position of the PHANToM device is outside the tube. The color of the PHANToM cursor changes according to four states: outside, not touching (the PHANToM is outside of the tube and not touching it), outside and touching, inside and not touching, and inside and touching. Scores are calculated by the duration of collisions and the duration of navigation.

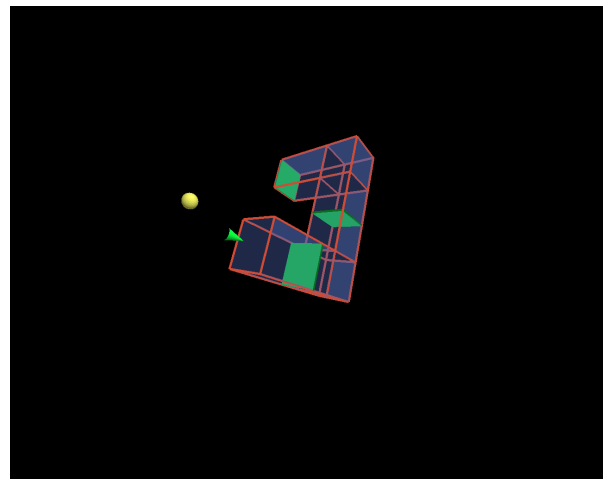


Figure 2. Screen shot of Space Tube task

3) *CyberGrasp*: The CyberGrasp is an exoskeletal device that fits over a 22 DOF CyberGlove, providing force feedback (see Figure 3). 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).

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 that are currently under developments 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.

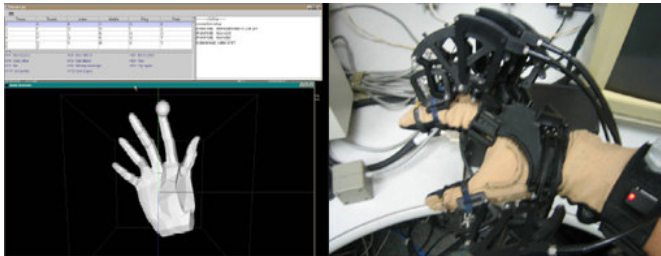


Figure 3. A networked communication experiment with the CyberGrasp: the Mutual Touch Demo. Picture on the left shows the user's view of the demo. Picture on the right shows the CyberGrasp.

B. Clinical Pilot Trials

In our first clinical pilot trials, we conducted a test of two tasks (the Spatial Rotation task and a modified version of the Space Tube task) promoting recovery of supination and pronation function with voluntary stroke patients who are currently receiving therapy at a USC neurorehabilitation center. The first pilot subject was an 80-year old male who suffered a right cerebrovascular accident resulting in a left hemiparesis 6 months earlier. This subject was right hand dominant. The second pilot subject was a 50 year old female who suffered a left cerebrovascular accident that resulted in a right hemiparesis 3.5 years earlier. The second subject was right-handed before her stroke and now uses her left hand.

The Spatial Rotation task consists of 20 trials per each difficulty level with a total of 5 difficulty levels. The Space Tube task also consists of 20 trials per each level with a total of 3 difficulty levels. The first subject tried four levels of the Spatial Rotation task (see Figure 4) and two levels of the Space Tube task. The second subject tried five levels of the Spatial Rotation task and two levels of the Space Tube task (see Figure 5).

Overall, both the patients and the therapist were satisfied with their experience with our new rehabilitation tasks. Specifically, the second subject was extremely enthusiastic about the task and indicated that she would like to use the system for rehabilitation at home with her grandchildren watching. Our first subject liked the system but was not as enthusiastic as the second subject. However, one interesting

feedback from the first subject was that he could not "cheat" on the supination and pronation exercise with the Spatial Rotation task the way he could with the usual card-flipping exercise used for the same purpose. In the Spatial Rotation task, the subject is required to manipulate one set of blocks into exact superimposition with the target configuration, which prevents the client from doing the exercise in an inappropriate way.



Figure 4. The first subject doing the Spatial Rotation task.



Figure 5. The second subject using the PHANTOM for the Space Tube task.

C. Interface Design (Tele-rehabilitation)

In addition to task-specific virtual exercise environments, we are developing user interfaces specifically designed to enhance the therapist-patient relationship and the usability of the virtual rehabilitation systems. Among many important features, we introduce two essential characteristics of our system interface: goal setting and speech recognition.

1) *Goal Setting*: Goal setting has been advocated for rehabilitation because it is believed to ensure patient-centered rehabilitation so that the rehabilitation satisfies patients' requirements rather than just the professional's agenda [22], [23], [24]. However, in practice, therapists do not usually

engage in goal setting with patients. This could be accounted for by several factors. First, patients sometimes are unable to set realistic goals, confusing hopes and desires with goals. Second, even when goals can be achieved, patients tend to compare their current progress against their pre-stroke capabilities, which makes their achievements seem less impressive than might otherwise be expected. Third, patients who have just experienced a stroke might not yet be aware what achievable goals could be in their particular case. Fourth, due to the innate power differential between therapist and patient, patients often simply accept the goals assigned to them by their therapists.

Some evidence has showed that rehabilitation is more effective if goals are set, especially when the patients are involved in the goal setting process [25], [26]. Standards established by professionals in rehabilitation and physiotherapy also encourage therapists to have patients actively involved in the goal setting process. Therefore, we will incorporate a goal setting function in our virtual therapeutic environments.

Our goal setting function is guided by previous research on goal setting for rehabilitation. First, goals should be set an appropriate level of challenge for the patients [22], [27]. The patients usually will have a higher expectation than what realistically can be achieved. The therapist thus needs to negotiate the goals with the patient [25]. Second, patients' views need to be elicited and encouraged. Third, there are short-term and long-term goals. Short-term goals need to be reviewed and modified frequently. The new short-term goals will determine the new long-term goals. Fourth, the patients should be offered a menu of pre-set goals from which to choose based on their different levels of disability [2], although the list is merely suggestive and the patient is not obliged to use any of them. To fulfill the functions, our interface will include peer-to-peer audio conferencing developed by researchers at the University of Southern California [28], [29] for the therapists and patients to discuss and revise goals during telerehabilitation sessions as well as face-to-face meetings. Here we describe what the telerehabilitation interface will be like.

Telerehabilitation will be implemented through a web-based interface which requires log-in by a therapist and a patient. The goal setting interface will include the following modules: goal generator, goal reviewer, goal editor, and info and progress of the patient. When the therapist logs in, all the patients' profiles will be displayed. The therapist can choose one patient for more specific information. When the patient logs in, the patient can only see her own information. On the first day of goal setting, after both the patient and the therapist log-in, they will be directed to the page with pre-set goals, which will be prepared based on focus group discussion of therapists and patients as well as previous examples of goal setting. These pre-set goals will be organized on a hierarchical structure, from short-term goals to long-term goals, from general goals to more specific goals that are related to the patient's personal life, such as their occupation and hobby. The patient then can choose her intended goals and click "send" to send to the therapist through the Internet. The

therapist will receive the goals instantly and review them. The therapist then can discuss the goals with the patient using the peer-to-peer audio conferencing embedded in the webpage. The therapist will let the patient know what achievable goals are and then negotiate with the patient and settle on the goals. The therapist then will send the goals back to the patient and also keep a record in the database. Later on, the therapist and the patient can log in to review the goals, or edit the goals during the rehabilitation process. The new goals will be saved to the online database and can be reviewed for reference in the future if necessary.

This interface encourages the patient to take the initiative to set the goals and provides the platform for discussion and negotiation of these goals between the patient and the therapist. Specifically, by having pre-set goals or examples available to the patient prior to the initial discussion with the therapist, the patient can have a general idea about what her goals can be. Besides, having the patient select her intended goals by herself without the physical presence of the therapist may result in patient-centered rehabilitation. Of course, these pre-selected goals by the patient can be revised to more specific and realistic goals during the telerehabilitation session with the professional therapist.

2) *Speech Recognition*: Because of stroke patients' limited movements with the impaired limb, a hands-free interface that can be controlled by speech commands is necessary on the patient's side. A user-independent speech recognizer such as IBM ViaVoice will be used for many anonymous users. Currently, we are working with researchers in speech science not only to develop a dialog capability to support a hands-free interaction with the environment but also to recognize and respond to signs of frustration based on vocal signals from the user. In addition, the speech recognition system will be integrated into the peer-to-peer audio conferencing system to provide a real-time voice-to-text conversion for database logging. These archives of communication between a therapist and a patient will be easily searched for by simple keywords or dates. The speech recognition system will be used to collect survey data from patients for the purpose of evaluation. To complete the survey, patients will read questionnaires on a computer screen and give answers by speech.

IV. DISCUSSION AND FUTURE WORK

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. 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. As our haptics-enhanced virtual therapeutic system is iteratively tested, refined, and evolved, we are entering into the second phase of clinical trials with the additional participation of more stroke patients.

Using haptics and VR 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.

In the future, developing low-cost systems such as using game-console type of devices (e.g. full body interaction video games such as the Bodypad for PS2 and Xbox) is necessary for a better implementation of rehabilitation systems.

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, not to mention technical difficulties in new technologies.

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