VR Post-Stroke Hand Opening Rehabilitation: An Approach Utilizing Virtual Reality, Body Othosis and Pneumatic Device

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***Abstract*—Impairment of hand function is prevalent among stroke survivors, motivating the search for effective rehabilitation therapy. Recent studies have suggested that for upper extremity functional recovery, repetitive training with virtual reality is helpful. Repetitive training can be facilitated with assistance from mechanical devices. Thus, we have developed a training environment that integrates augmented reality (AR) with assistive devices for post-stroke hand rehabilitation. The AR element of our environment utilizes head mounted display and virtual objects for reach-and-grasp task training. The assistive device consists of either a body-powered orthosis (BPO) or a pneumatic-powered device (PPD), both of which are incorporated into gloves. This environment can be easily set up and calibrated, is customizable for individual users, and requires active user participation. Additionally, it can be used with both real and virtual objects, as desired. We are currently conducting pilot case studies to assess ease of use and efficacy. At present, one stroke survivor from each of the three training conditions, AR-with-BPO, AR-with-PPD and AR-only (acting as the control), has completed the 6-week training paradigm. Preliminary findings suggest user acceptance of the technology and some potential for beneficial effects.**

***Keywords*—Stroke, Hand Rehabilitation, Augmented Reality, Assistive Device, Feedback Control.**

I. Introduction

Stroke is among the leading causes of adult disability in the United States [1,2,5]. Chronic impairment of the upper extremity occurs in roughly one-third of all stroke survivors [5]. While finger flexion often appears spontaneously within weeks after a cerebrovascular accident, finger extension is less likely to exhibit recovery [9] and creates difficulty for voluntary hand opening. The resulting distal limb impairment is especially problematic, since proper hand function is crucial to carrying out activities of daily living. A study from the UK reported that over half of the subjects studied depended on others for assistance in ADLs six months post-stroke [7].

Thus, a great need for hand rehabilitation therapies exists. None of the current therapies, however, has been wholly successful. For example, the effectiveness of electrical stimulation may be reduced by hypertonia. Usage of Botulinum toxin [6] further weakens already paretic muscles. Participation in constraint-induced training [12] requires some initial voluntary extension, thereby limiting eligible stroke survivors.

A combination of two different technologies, however, may be beneficial. The first is virtual reality (VR), which is able to present pre-set or online computed rehabilitation tasks with minimized setup and breakdown time. VR also provides many important possibilities that are not possible in real-world applications. For example, with precise hand position tracking and kinetic calculations, a stroke survivor user ("user" for short in the text hereafter) can manipulate virtual objects that are free of mass but can still provide force feedback. The second technology entails assistive devices. Research has already shown that devices which permit the active production of repetitive movements are helpful for arm rehabilitation after stroke. Therapeutic straight-line reaching assisted by the ARM Guide [8] resulted in improved active range of motion and peak velocity. In another experiment, assisted unilateral training with a PUMA robot led to increased Fugl-Meyer Motor Assessment scores [10].

Similar results may be achievable with the hand. We know of two systems which can readily provide assistance to finger extension in coordination with VR: the Rutgers-II ND Hand Master haptic device [14] and the CyberGrasp glove (Immersion Inc.) [15]. There are some drawbacks with each. With the Rutgers-II ND, the visual feedback is provided to the user through VR displayed on a non-stereo desktop monitor ("Fish Tank"). Thus, the user is unable to see his/her real hand together with the virtual scene. Additionally, the size of the virtual display is quite limited. Due to the use of pneumatic pistons residing within the palmar space, the maximal PIP flexion angle the glove allows is 45º, thereby limiting grasp simulation. CyberGrasp is designed more for haptic application purposes; its price and weight (over 500g) are relatively prohibitive for clinical use.

Thus, we have developed a training environment that integrates augmented reality (AR) and assistive devices. This environment addresses the limitations of Rutgers-II ND and CyberGrasp. AR allows the user to move objects with no weight while seeing his/her own hand overlaid with the virtual scene simultaneously. Our experience suggests that see-through AR is much less disorienting to stroke survivors than fully immersive VR. Also, by incorporating head-tracking and stereoscopy, the virtual scene is made panoramic rather than flat, as that of Fish Tank VR. Assistance for finger extension is provided through either a body-powered orthosis (BPO), with cables acting on the dorsal side of the hand to pull the fingers, or a pneumatic-powered device (PPD) with an air bladder on the palmar side of the hand to push the fingers into extension. The two assistive devices share some common favorable characteristics: the pieces attached to the hand are lightweight (less than 100g) gloves; they work with AR in a coordinated manner; assistance is provided in accordance with a user's voluntary attempt and under the ultimate monitoring and control of the therapist. This design diminishes the potential for excessive assistance. Lastly, the monitoring/control interface presented to the therapist incorporates visual, audio and force feedback using commercial hardware.

In pilot experiments, two stoke survivors participated in training under AR-with-BPO and AR-with-PPD conditions, respectively. Another stroke survivor, acting as a control subject, was trained with AR but no device assistance was provided. While the control subject showed little post-training improvement, both subjects under the integrated environment showed some signs of quantitative and qualitative improvements in hand function.

II. Methodology

A. Overview of The Training Environment

In our environment, the user is seated, wearing both head mounted display (HMD) goggles and either the BPO or PPD. The HMD shows 3D stereo virtual objects and contextual. The user is then trained to perform grasp-and-release tasks of virtual objects. Dynamic assistance of finger extension is provided through the assistive device. For BPO, the assistance is controlled by the voluntary movement of the user's unaffected arm; for PPD, assistance is controlled by a combination of electromyography (EMG) signal along with the difference between present hand opening angle and desired hand opening angle. A therapist, who can be either on-site with the user or watching off-site through a video camera feed, supervises the user's movement. The therapist can modify the virtual scene dynamically to best meet the needs of the user. An example on-site setup with BPO is shown in Fig. 1.

Our environment is made up of four main components: AR element, the BPO/PPD element, therapist monitor/control element and a networking element interfacing the therapist side and the user side.

B. The AR Element

Individual VR applications utilize one of four display strategies: HMD, augmented display, Fish Tank and projection-based display. Our user environment uses an HMD display, namely, a SONY PLM-S700 Glasstron. The Glasstron provides a horizontal view angle of 28º, simulates a virtual 30" screen at 1.2 meters away from the viewer, and has adjustable see-through using an LCD shutter system. It is lightweight (120g for head device) and can be worn comfortably by the user. By adjusting the see-through level, the amount of the actual environment visible through the goggles is altered. This allows the user to see his/her own hand along with the virtual object.

The scene, as shown in Fig. 2, shows the surroundings as well as the object to grasp. Proper perception of depth and object size is achieved by both rich visual cues (e.g., table, floor, stationary objects) and field stereo. Objects are specially designed to have certain sizes and shapes. These instruct the user as to the proper hand posture and opening width needed for grasping. Also, objects can only be grasped when the user's hand contacts the virtual object's surface at "hotspots". Hotspots are points predefined on the object's surface, at the location of normal grasping. They are invisible, so the constraint they introduce is implicit to the user.

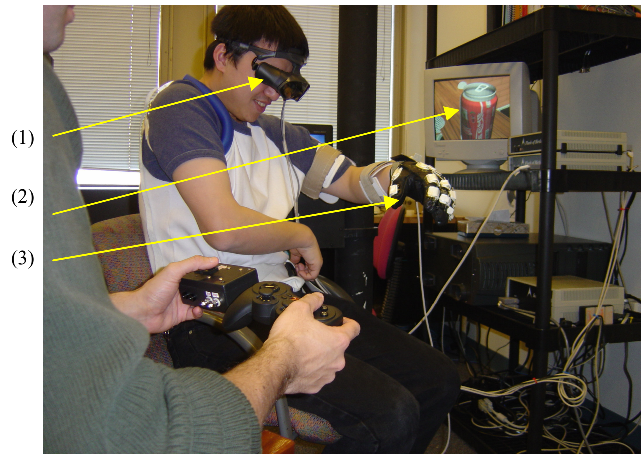

Fig. 1. On-site setup of the training environment using BPO. The therapist is holding both the joystick and control switch (see section D) in his hands. (1): HMD, (2): Fish Tank, (3): BPO.

Several software packages are used for building the AR element. The Coin3D [Systems In Motion] library implements scene graphs, and it provides a comprehensive range of graphics and interactive objects. The CAVE Library [VRCO, Inc.] manages display parameters to establish the sense of depth and scale. The Trackd tool [VRCO, Inc.] reads the magnetic head and hand trackers' [Flock of Birds, Ascension Tech] positions and orientations, and provides these data to the rendering thread transparently.

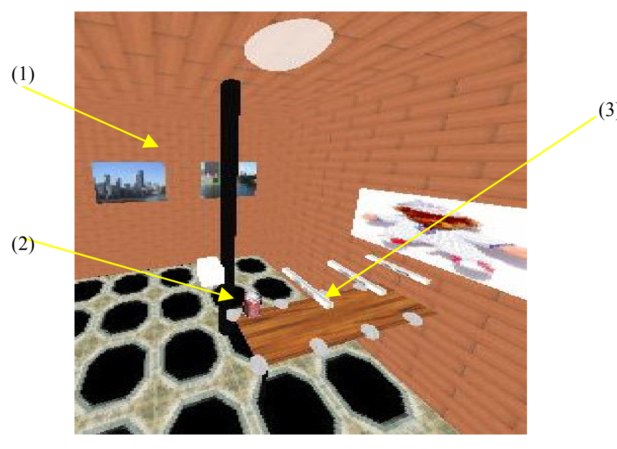

Fig. 2. Overview of virtual object and surroundings displayed in HMD. (1): Room, (2): Object, coke can, (3): Markers to provide 3D cues. Every object is specially designed with a certain shape and size. Objects are chosen for familiarity and interest to the user to improve motivation.

VR objects persist on hard disk in VRML format and map one-to-one to files. We implement two levels of object management to achieve scalability and flexibility. The first level is “object library”. Each folder that contains object files is scanned and an XML-format index file is generated for the folder. The index file contains entries of each object’s size, location, hotspot numbers, and other information like suggested hand opening width. In this step, a “sanity check” for the files is also done to ensure the index contains only valid objects. The second level is “library view”, which integrates all the libraries so that all objects appears to be in one large repository, thus the details of individual libraries are hidden and dynamic remapping is possible. Another functionality the second level provides, as its name suggests, is that the therapist can use his own definition file to create a local “view” of the whole repository. These definition files are plain text format and need only contain object names.

C. The Assistive Device Element

1) The BPO

The BPO, as shown in Fig. 3, is based on prosthetics technology. A glove covers the paretic hand, and cables from the glove travel up to a standard figure-of-8 shoulder harness through metal cable housing. The cables actuate the finger joints. Namely, biscapular abduction and glenohumeral flexion pull on the cables, thereby forcing the fingers to extend. This single control moves all fingers simultaneously in a manner akin to that of control of the prehensor in arm prostheses. Alternatively, the cable can be run to a handle held by the unimpaired hand; extension of the unimpaired arm extends the fingers on the impaired side. In either manner, the user controls the amount of assistance provided to finger extension. The cable housing over the MCP and PIP joints also serves to prevent hyperextension of these joints.

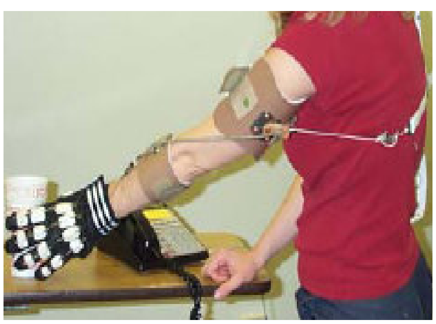

Fig. 3. the BPO. A zipper sewn into the palmar side of the glove facilitates donning.

The orthosis is light (450g) and easy to wear. The part of the device that directly acts on the impaired hand resides entirely on the dorsal surface so there is no interference with palmar grasp. Finger movement space is also maximized (90º PIP flexion angle). The amount of assistance utilized to extend the fingers is quantified by an in-line force sensor [Sensotec Inc.]. The sensor, spliced into the cable between the cuff and harness, detects the amount of force in the cable; this force serves as an estimate of the degree of assistance provided. Force is also encoded into sound pitch to provide audial feedback for the subject, as well as being sampled and stored for subsequent analysis.

One practical issue for body-powered therapy is that when the user becomes familiar with the device, they tend to overly rely on the device rather than using their own hand. Our design addresses this issue by two means: one, as mentioned, is through the cable housings, proper adjustment of their lengths can regulate cables’ maximum free movement distance, thus limit maximum assistances that could be provided; the other is through force feedback to the therapist (see section D), when excessive assistance is noticed by the therapist, he/she will give proper instructions to prevent user from doing so.

2) The PPD

The PPD as shown in Fig. 4 is a polyester glove placed on the subject’s hand. The glove contains an air bladder situated on the inner surface of the glove such that it contacts the palmar surface of the hand. Inflation of the air bladder forces straightening of the palmar surface, and consequently extends the fingers. The bladder is connected through a servo valve [Pressure Control Valve, QB02005, Proportion-Air] to a pressure reservoir [1104360, Jun-Air]. The servo valve allows pressures between 0-5 psi to inflate the glove. Another port on the bladder is connected to a pressure relief valve [check valve w/ 6.1 psi spring, 246301000, Halkey-Roberts] that opens at 6.1 psi to avoid over-inflation.

Angle measurements from the proximal interphalangeal (PIP) joint of the index finger and metacarpophalangeal (MCP) joint of the middle finger are recorded using electro-goniometers [F35, Biometrics]. Muscle activity is recorded using active surface EMG electrodes [Delsys Inc.]. Electrodes are placed on the flexor digitorum superficialis (FDS) and extensor digitorum communis (EDC) muscles of the gloved arm to sample muscle activity. Each EMG signal is passed through the DelSys amplifier, full-wave rectified, and low-pass filtered before sampling.

Feedback control of the PPD uses an EMG signal and PIP/MCP angles as input and air pressure as output. Actual joint angles are compared with the desired trajectories necessary for opening the hand sufficiently to grasp the object. These desired finger trajectories are derived from the stereotypical spiral trajectories (Eq. 1) observed in a study by Kamper et al. [16] examining fingertip trajectories during grasp in neurologically healthy subjects. The spiral trajectory may be expressed in Cartesian coordinates (Eq. 2). With the addition of a constraint relating DIP angle to PIP angle, inverse kinematics may be used to translate fingertip location into MCP, PIP and DIP joint angles.

$$\begin{aligned} r &= A * (\exp(\theta * \cos(b) / \sin(b))) \\ A &= 1.3394 * (ld + lm + lp) - 23.255 \\ b &= 1.633 \end{aligned} \quad (1)$$

(r and θ represent the position in polar coordinates where r represents the distance from the origin and θ represents the angle or rotation. ld, lm, and lp: lengths of the distal, middle and proximal phalange respectively measured on the index finger of each subject.. Units are in mm).

The equations used to represent the finger end-point in terms of joint angles are:

$$\begin{aligned} x &= ld * \sin(\theta_1 + \theta_2 + \theta_3) + lm * \sin(\theta_1 + \theta_2) + lp * \sin(\theta_1) \\ y &= ld * \cos(\theta_1 + \theta_2 + \theta_3) + lm * \cos(\theta_1 + \theta_2) + lp * \cos(\theta_1) \\ \theta_3 &= 0.7\theta_2 \end{aligned} \quad (2)$$

(θ_1, θ_2, and θ_3 are MCP, PIP, and DIP joints respectively. The locations of x and y are shown in Fig. 5. The origin is at the center of the MCP joint).

A computer controlled proportional-derivative controller regulates the pressure necessary to maintain the required angle for both the PIP and MCP joints during reaching. The control regulates pressure to the glove based on the greatest angular flexion error. When the fingers are extended further then the set-point, pressure to the glove is reduced to maintain the necessary joint angles.

Fig. 4: Picture of the glove that contains the bladder on the palm of the hand. The electro-goniometers are attached with Velcro to the volar surface of the glove over the PIP and MCP joints.

EMG feedback is incorporated to ensure active participation of the user. The system senses muscle activity through the electrodes; air pressure is only provided to assist extension when EDC activity exceeds a predetermined threshold.

Two different control strategies are employed for the grasp portion of the grasp-and-release training dependent on whether virtual or actual objects are used. When virtual objects are displayed to the user, the system monitors the point at which the hand is sufficiently extended to hold the object. When this is true, a signal is sent to the AR element to allow grasp of the object. The object is then attached to the user's hand when the hand is properly positioned in space over the displayed object. When the virtual object is held, the glove control system continues to regulate pressure to maintain the desired joint angles in order to simulate holding a real object. When real objects are displayed to the user, the therapist is responsible for determining when the hand is in position to grasp the object. This is detailed in section D.

The release portion of the therapy session is accomplished by monitoring EDC activity. A threshold based on the subject's maximum recorded EDC activity is set. When the object is held, and activity greater then this threshold is recorded from the EDC muscle, a pressure of 5 psi is used to inflate the glove in order to assist the subject in object release.

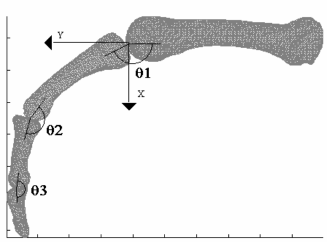

Fig. 5: Image of finger representing location of (x, y) origin.

D. The Therapist Monitor/Control Element

The therapist-side element serves two functions: monitoring and control. During training sessions, the user's hand movement is supervised by the therapist. This can be done by either the therapist staying on-site with the user, or watching through a camera link. Under both circumstances, the therapist is also shown the exact scene that the user views, but in Fish Tank display. This display for the therapist is especially useful when the user has problems with distance and depth perception, as the therapist can guide the user. When the therapist determines that the user's hand is sufficiently opened (dependent on impairment level of the hand and the current task), she/he flips a switch to set the hand state to be "ready", which means that the user's hand is in the correct posture to grasp the object once the hand reaches the proper location in space, as determined by the hand tracker. Once the hand contacts a hot spot on the object, the object now moves with the user's hand. After manipulation of the object, the therapist instructs the user to let go of the object. When the therapist determines that the hand has been sufficiently opened, she triggers "release" of the virtual object with the toggle switch.

A Logitech RumblePad2 force feedback joystick is used by the therapist to dynamically control the virtual scene. Online modifiable parameters of the virtual scene are the position and orientation of the object in 3D space, as well as its size. This makes configuration of the environment convenient as no thorough pre-calculations are needed for these parameters.

The therapist is provided with dynamic feedback of subject performance. For BPO, the assistive force recorded by the in-line sensor is displayed as a running waveform on a computer screen, in addition to the audio feedback. For PPD, the waveforms are for EMG, MCP/PCP angles and air pressure, companied by audio prompt for air pressure as well. Under both BPO and PPD, it is possible to encode for the assistance provided to extend the impaired hand by providing force feedback to the therapist through the joystick. The force magnitude is represented by the intensity of joystick vibration.

E. Therapist Side and User Side Communication

Successful coordination of the user-side element and therapist-side element requires inter-communication between them. Three kinds of data comprise the traffic stream: 1) force sensor data (for BPO) or EMG/angle difference/servo pump control combination data (for PPD) from user side to therapist side, with bandwidth consumption of about 10kbps; 2) head and hand tracker positions and orientations, from user side to therapist side; bandwidth consumption is also about 10kbps; 3) control commands issued by the therapist, from therapist side to user side; this traffic is random (every one or more seconds) and has negligible bandwidth consumption. To meet the need for tele-rehabilitation, the bandwidth and response time requirements must be able to be satisfied by the network. Our environment's overall bandwidth requirement is about 20-30kbps, and response requirement is about 8-10ms each way (to meet the 100Hz sampling/control rate). These are all within the capability of today's broadband network services: LAN, DSL and T1.

F. Preliminary Experiment

Three male stroke survivors, rated between Stage 2-3 of the Stage of Hand portion of the Chedoke-McMaster Stroke Assessment scale [13] respectively, participated in training sessions using the environment for 6 weeks. One of them was using AR with BPO, one was using AR with PPD and one was using only AR with no assistive device provided. The 30-minute training sessions were held three times per week. In each session, the subject tried to grasp 15 virtual objects followed by 15 real objects. The therapy was performed on-site.

III. RESULTS

Subjects underwent standard functional tests, i.e. box & blocks [11] and Rancho [4], before and after the six-week training sessions. Both tests map better performance to higher scores. Table 1 indicates that the subject undergoing AR-with-BPO slightly improved scores on both box & blocks and Rancho; the subject undergoing AR-with-PPD slightly improved the Rancho score, but actually performed worse on the box & blocks; the subject undergoing AR-only showed no change in these scores.

Treatment Used	Chedoke Level	Box&Blocks		Rancho	
		Pre	Post	Pre	Post
AR w/BPO	2	1	4	5	6
AR w/PPD	3	3	1	3	4
AR only	2	0	0	4	4

Table 1: Pre- and post-training functional test results of three stroke survivors under different scheme of therapies.

Besides the functional tests, we used a custom-developed apparatus to further assess the change of voluntary MCP extension. Speed and maximum displacement were measured for voluntary extension against no load. A servomotor system, described in [13], maintained zero-load through servo-control of the motor about zero torque.

The test results are shown in Table 2. The subject undergoing AR-with-PPD showed some improvement in both peak angular speed and angular displacement toward extension. The subject undergoing AR-only exhibited increase in peak velocity, but the amount of extension was so small as to render it of little functional consequence. The subject undergoing AR-with-BPO showed no change in either measure.

Treatment Used	Peak Angular Velocity		MCP Maximum Displacement	
	Pre	Post	Pre	Post
AR w/BPO	11.055	11.21	9.3388	10.5125
AR w/PPD	115.94	124.19	39.066	45.996
AR only	12.924	31.327	2.3323	4.7353

Table 2: Pre- and post-training values for peak MCP angular speed (in degrees/second) and MCP maximum displacement (in degrees) during voluntary extension.

An analysis was also performed on the assistive force data collected from BPO over time. Fig. 6 shows the normalized force during each training session. Assistive force first increased largely from session 4 to session 6. This increase may have arisen from greater patient familiarity with the orthosis which allowed the patient to make greater use of it. Starting from session 6, the needed assistive force started to decrease, revealing a significant descending slope ($p = 0.03$). The overall decrease is 14.5% from pre- to post-training.

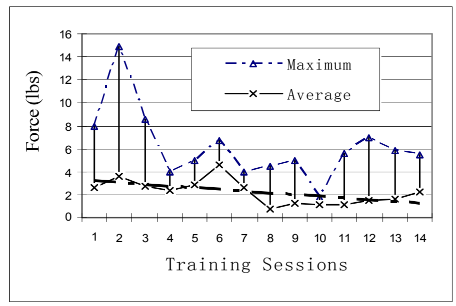

Fig. 6. Assistive forces recorded during each training session for AR-with-BPO. Dashed line shows the fitted trend of average force.

IV. DISCUSSION AND CONCLUSIONS

In this paper, we present a training environment for rehabilitation of hand opening in stroke survivors. This environment integrates augmented reality, assistive devices and the process of repetitive training of grasp-and-release tasks. Compared with current hand rehabilitation robotic devices, it is relatively low-cost and small in size, thus has the potential for use in clinics and even at home. The networked feature also allows application in tele-rehabilitation.

The preliminary experimental results, functional tests scores, peak angular MCP extension speed, MCP maximal displacement, and BPO assistive force, show that after 6 weeks of training, there was an encouraging trend of modest improvement of finger extension capability in the impaired hand. Both the user and therapist reported that the environment was user friendly due to the lightness of the assistive devices and the simple steps needed for set up of the environment. We believe that therapies using this environment are promising. Further studies to examine the efficacy of the environment are ongoing.

V. ACKNOWLEDGMENT

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