An Augmented Reality Training Environment for Post-Stroke Finger Extension Rehabilitation

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Abstract— **Finger extension is an important hand function and is crucial for object exploration and manipulation. Unfortunately, the impairment of this motor function is common among stroke survivors. A training environment incorporating Augmented Reality (AR) in conjunction with assistive devices has been developed for the rehabilitation of finger extension. The environment consists of three components: the stroke survivor user element consisting of AR equipment/software and body-powered orthosis; the therapist element comprised of monitoring/control interface with visual, audio and force feedback; and the networking module which interconnects these two. In this paper we present the structure of this environment along with the results from a pilot case study with a stroke survivor.**

Keywords—**Finger Extension Rehabilitation, Training Environment, Augmented Reality, Body-powered Device.**

I. INTRODUCTION

Arm function is acutely impaired in a majority of stroke survivors, with approximately one-third of these individuals developing chronic hemiparesis [1], [3]. The chronic deficits are especially prevalent in the distal upper extremities. In fact, finger extension is the motor function most likely to be impaired [2], [4].

This distal limb impairment is especially problematic, because proper hand function is crucial to manual exploration and manipulation of the environment. In addition, loss of hand function is a major source of disability in stroke, preventing effective self-care by the stroke survivor and limiting return to work. One study in the UK reported that more than half of the subjects studied were dependent on others for help in the activities of daily living six months post-stroke [5].

Thus, a great need for finger extension rehabilitation 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 (CIT) [12] requires some initial voluntary extension, thereby limiting eligible stroke survivors.

Research has already shown that devices which permit the active production of repetitive movements are helpful for arm rehabilitation after stroke [7] [8] [9]. Similar results may be achievable with the hand. In fact, a group of researchers conducted such training sessions for the hand [14]. They employed the Rutgers-II ND Hand Master glove, a haptics device, for hand rehabilitation. However, there are two drawbacks with this system. First, due to the use of pneumatic pistons residing within the palmar space, the maximal PIP flexion angle the glove allows is 45º [11], thus limiting grasp simulation. Second, the visual feedback is provided to the stroke survivor user ("user" for short in the text hereafter), through virtual reality (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. We developed an environment to train users to perform grasp-and-release tasks. Design of the environment was guided by the concepts of CIT and repetitive training. Virtual objects are presented through Augmented Reality (AR), which allows the user to move objects with no weight while seeing his/her own hand overlaid with the virtual scene simultaneously. Assistance with finger extension is provided through a body-powered orthosis with cables on the dorsal side of the hand. The assistive device and the AR work in a coordinated manner, under the ultimate monitoring and control of the therapist. The monitoring/control interface incorporates visual, audio and force feedback using commercial hardware.

The prototype of this environment was finished in 2004 and we have completed a pilot experiment with a stoke survivor. Preliminary results show a quantitative decrease in the amount of force needed from the assistive orthosis to open the hand. This improvement mirrors the functional improvement measured in a grasp-and-release task.

II. METHODOLOGY

A. Overview of The Training Environment

In our environment, the user is seated, wearing both head mounted display (HMD) goggles and an assistive orthosis. The HMD shows virtual objects and surroundings and provides see-through functionality so that the user can see his own hand overlaid with the virtual scene. The user then is trained to perform grasp-and-release tasks of virtual objects. The cable-driven orthosis provides dynamic assistance of

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finger extension, as controlled by the user. 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. On-site set up is shown in Fig. 1.

Our environment is made up of three main components: the user-side element, the therapist-side element, and the networking component interfacing the two sides.

B. *The User Element*

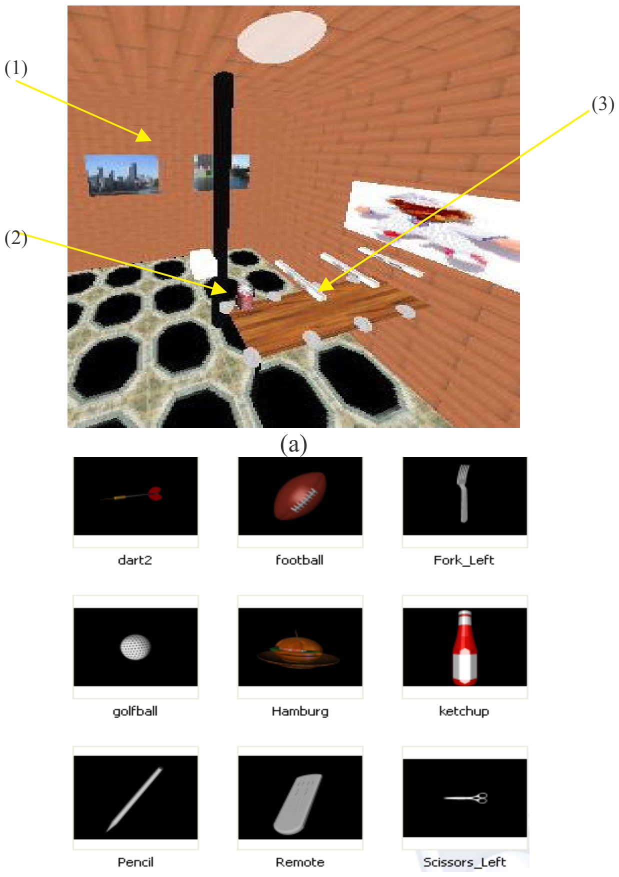
The user element consists of the AR equipment and software and the assistive body-powered orthosis.

Individual VR applications utilize one of four display strategies: head mounted display, augmented display, Fish Tank and projection-based display. Our user environment uses 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. Simultaneously, field stereoscopy is provided through its fast switching between left and right eye projection screen displays. 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 own hand along with the virtual object. Additionally, our experience has suggested that see-through AR is much less disorienting to the user than fully immersive VR.

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 stereoscopy. Presently, there is a guiding dot displayed at the same position of the subject's hand to help locate the hand in the scene. We plan to incorporate finer hand representation to improve the user's sense of depth in our phase II project. 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. The therapist is holding both the joystick and control switch in his hands. (1): HMD, (2): Fish Tank, (3): Orthosis.

Several software packages are used for building the AR environment. 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.



(a)

(b)

Fig. 2. (a): Overview of virtual object and surroundings displayed in HMD. (1): Room, (2): Object, coke can, (3): Markers to provide 3D cues. (b): Part of the objects gallery. Every object is specially designed of certain shape and size, also is of daily use (sports, food, culinary etc.) so that the user's motivation can be raised.

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.

Assistance to finger extension is available through a body-powered orthosis. The device, based on prosthetics technology, is shown in Fig. 3. **Error! Reference source not found.**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. Body-powered assistive orthosis. A zipper sewn into the palmar side of the glove facilitates donning.

The orthosis is light (450g) and easy to wear and has been tested for subject safety for our subject, to avoid discomfort or harm. 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 sampled and stored for subsequent analysis.

C. *The Therapist 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 judgment, as the therapist can guide the user. When the therapist empirically determines that the user's hand is sufficiently opened, 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-session calibration is needed for these parameters.

The therapist is provided with dynamic feedback of subject performance. The assistive force recorded by the in-line sensor is displayed as a running waveform on a computer screen, in addition to the audial feedback. It is also easy to encode assistive force into the force feedback of the joystick. By doing this, the therapist can actually feel the force magnitude.

D. *Communication Between the Elements*

Successful coordination of the user element and therapist element requires inter-communication between them. Three kinds of data comprise the traffic stream: 1) force sensor data, from user side to therapist side, bandwidth consumption is 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 is has neglectable 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.

E. *Preliminary Experiment*

A male stroke survivor, rated Stage 2 of the Stage of Hand portion of the Chedoke-McMaster Stroke Assessment scale [13], participated in training sessions using the environment for 6 weeks. The 30-minute training sessions were held three times per week. In each session, the subject tried to grasp 15 virtual objects. Force data and hand tracker positions were sampled at 100Hz and recorded in files. The force data was used for analysis of training effects. As the therapy was performed on-site, the video stream was not used. Since data were transferred over a 100Mbps LAN, network delays and jitters could be neglected.

III. RESULTS

The force data collected were first normalized by two factors: object size and grasping time; and then averaged. Object size is defined as the diameter of the virtual object's bounding box; grasping time is defined as the period from initiation of attempted grasping to determination of the "ready" grasping hand posture, as determined by the therapist.

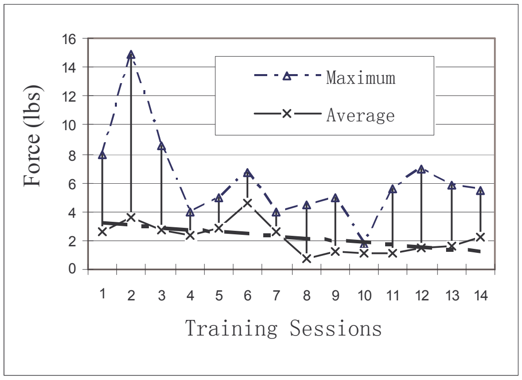


Fig. 4. Assistive forces recorded during each training session. Dashed line shows the fitted trend.

Fig. 4. shows the normalized force data during each training session. From the chart, we can see that the assistive force first increased largely from session 4 to session 6. This increase may have arisen from greater user familiarity with the orthosis which allowed the user to make greater use of it. Starting from training session 6, the assistive force needed started to decrease. Linear regression analysis revealed a significant descending slope ($p = 0.03$). The overall decrease is 14.5% from pre- to post-training. The decrease in force corresponded with an improvement in grasping, as measured with the box-and-blocks test. The subject increased the number of acquired blocks from one to four.

IV. DISCUSSION AND CONCLUSIONS

In this paper, we present a training environment for rehabilitation of finger extension in stroke survivors. This environment integrates augmented reality, a body-powered assistive device and the process of repetitive training of grasp-and-release tasks. It is relatively low-cost and small in size; thus it has the potential for use in clinics and even the home. The networked feature also allows its application for tele-rehabilitation.

The preliminary experimental results show that after 6 weeks of training, there was an encouraging trend of a reduction in assistive force, indicating that the subject may be more capable of finger extension in the impaired hand. Both the user and therapist report the environment to be user friendly due to the lightness of the assistive orthosis 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.

In the future, two areas in particular will be targeted for improvement: 1). environment mobility, currently limited due to the Flock of Birds trackers and transmitter 2) assistance of extension of individual fingers.

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