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Integrated Versus Isolated Training of the Hemiparetic Upper Extremity in Haptically Rendered Virtual Environments

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Abstract

This paper describes the preliminary results of an ongoing study of the effects of two training approaches on motor function and learning in persons with hemi paresis due to cerebrovascular accidents. Eighteen subjects with chronic stroke performed eight, three-hour sessions of sensorimotor training in haptically rendered environments. Eleven subjects performed training activities that integrated hand and arm movement while another seven subjects performed activities that trained the hand and arm with separately. As a whole, the eighteen subjects made statistically significant improvements in motor function as evidenced by robust improvements in Wolf Motor Function Test times and corresponding improvements in Jebsen Test of Hand Function times. There were no significant between group effects for these tests. However, the two training approaches elicited different patterns and magnitudes of performance improvement that suggest that they may elicit different types of change in motor learning and or control.

I. Introduction

In persons with stroke, hand function generally recovers more slowly and to a lesser extent than proximal upper extremity function, even when both sets of effectors are similarly impaired immediately after the stroke [1,2]. One explanation of this phenomenon may be an ineffective management of the inhibitory relationship that exists between cortical areas controlling proximal and distal effectors of the upper extremity. A mutually inhibitory relationship between proximal and distal UE effectors in persons with stroke has been demonstrated experimentally [3]. Several studies demonstrate that this phenomenon can be

modulated through physical behavior [4,5]. A similar inhibitory relationship has been proposed to exist between right and left effectors of persons recovering from stroke [6]. Studies have shown that this inhibitory relationship between right and left effectors may be modified though coordinated training of both arms at the same time [6]

No studies comparing changes in motor control, motor learning or hand function simultaneously elicited by integrated or isolated training of the UE in persons with strokes have been published to date. We have designed a system using adaptive robots, integrated with virtual targets or complex virtual reality gaming simulations in order to provide coordinated or isolated training of the hands and fingers

Several small studies using robots, to provide coordinated movements of the hand and arm have produced mixed results. Krebs et al describe a study in which an intense program of proximal robotic training produced larger proximal motor function gains than a program of integrated training. Neither program elicited improvements in distal motor function [7]. Housman et al describe a study comparing an integrated training program facilitated by a robot with a control group performing a set of traditional, mostly isolated, impairment based activities. Subjects in both groups made improvements in motor function that did not differ significantly [8]. A small pilot by Adamovich et al compared the two training paradigms described in this paper. The two groups demonstrated different patterns of kinematic change and improvement in hand function but the two groups were too small to adequately test the hypothesis [9].

This paper will describe initial results from an on-going clinical trial using a haptic, six degrees of freedom robot and virtual environments to compare integrated training of the hand and arm together (HAT) and isolated training of the hand and arm separately (HAS). The question this study will attempt to answer is whether a coordinated UE training program will produce different motor learning dynamics and/or different functional outcomes than a similar volume and intensity of isolated arm and finger training.

II. Methods

The hardware and software utilized in this protocol are described in detail elsewhere [10,11]. Brief descriptions follow.

A. Hardware

1) Hand—The system supports the use of CyberGlove (Immersion, USA) instrumented gloves for measuring finger angles and a CyberGrasp (Immersion, USA) for haptic effects. The CyberGrasp device is a lightweight, force-reflecting exoskeleton that fits over a CyberGlove data glove and adds resistive force feedback to each finger. The CyberGrasp is used to facilitate individual finger movement by resisting flexion of the adjacent fingers in patients with mass grasp deficits thus allowing for isolated movement of each finger. The Ascension Flock of Birds (Ascension) is used for tracking hand position. Orientation is recorded in real time and translated into three dimensional movements of the virtual hands shown on the screen in a first-person perspective.

2) Arm—The arm simulations utilize the Haptic MASTER (Moog NCS, The Netherlands), a 3 degrees of freedom, admittance controlled (force controlled) robot. Three more degrees of freedom (yaw, pitch and roll) can be added to the arm by using a gimbal, with force feedback available only for pronation/supination (roll). TrackStar (Ascension) a magnetic tracking system is used to measure the rotation of the forearm to record pronation and supination movements. A three-dimensional force sensor measures the external force exerted by the user on the robot. In addition, the velocity and position of the robot's

endpoint are measured. These variables are used in real time to generate reactive motion based on the properties of the virtual haptic environment in the vicinity of the current location of the robot's endpoint. This allows the robotic arm to act as an interface between the participants and the virtual environments enabling multiplanar movements against gravity in a 3D workspace. The haptic interface provides the user with a realistic haptic sensation that closely simulates the weight and force found in upper extremity tasks.

B. Simulations

We have developed simulations for the hand alone, the arm alone, and the hand and arm together using Virtools software package (Dassault Systemes, France) with the VRPack plug-in which communicates with the open source VRPN (Virtual Reality Peripheral Network, Taylor) and C++/OpenGL. The Haptic Master Application Programming Interface (API) allows us to program the robot to produce haptic objects, including walls, blocks, cylinders, toruses and spheres as well as haptic effects, such as springs, dampers and global forces. The Haptic Master measures position, velocity and force in three dimensions at a rate of up to 1000 Hz to produce the haptic environment.

1) Hand Simulations

a) Piano Trainer: The piano trainer is designed to help improve the ability of subjects to move each finger in isolation (fractionation) either during, or isolated from arm movement. It consists of a complete virtual piano arranged in a two dimensional space. The simulation can be utilized for training the hand alone (Piano 1), to improve individuated finger movement, or the hand and the arm together (Piano2) to improve individual finger motion in coordination with arm movement. An adaptive algorithm shapes fractionation requiring more isolated finger flexion to elicit a key press as participants succeed and less stringent requirements if their performance diminishes.

b) Space Pong: Space pong trains the subjects' ability to coordinate finger flexion and extension or wrist deviation (yaw) in order to react to and engage a moving target. The participant controls the paddle with their finger or wrist position. Feedback is provided through the number of successful hits.

2) Arm Simulations

a) Reach/Touch: The goal of the Reach/Touch game is to improve forward, sideways and overhead reaching ability. A three dimensional stereoscopic visual environment is presented using a shutter glass system (CrystalEyes, USA). This environment increases the sense of depth which normalizes reaching trajectories. The participant moves a virtual cursor through this space in order to touch ten targets presented randomly. The size of the work space is calibrated for each subject, and gradually increases by 10% every other day during the training period. Haptic assistance is provided if the subject is not able to reach a target within a predetermined time interval.

b) Blood Cell: The Blood Cell simulation focuses on improving the speed & accuracy of frontal plane shoulder & elbow movements. The user moves a virtual space-ship through an environment representing the interior of a human blood vessel. Objects within the blood vessel represent obstacles and 2 different targets. A dual cognitive/motor task is required to negotiate the game successfully. Game speed, global forces, work space, and target/obstacle density can be adjusted to accommodate sensory and cognitive processing. Targets can be concentrated in quadrants to emphasize movement in a specific area of their reachable space. Feedback regarding their success is presented using scores.

3) Hand and Arm Simulations

a) Plasma Pong: The Pong paddle is moved with shoulder flexion and the target is engaged with finger extension, requiring the integration of shoulder flexion and finger extension. The trajectories and speed of the target are non-predictable, necessitating constant conscious attention and feed-forward processing.

b) Hummingbird Hunt: This game provides practice in the integration of reach, hand-shaping and grasp as participants grasp and release a bird while it is perched on different objects located in a 3D workspace. The flight path of the bird is programmed into three different levels, low, medium and high allowing requiring a progression of the arm and shoulder excursion required to transport the hand to catch the bird.

c) Hammer: This simulation trains a combination of three dimensional reaching and repetitive finger flexion and extension. It exercises movement of the hand and arm together by having the subjects reach towards a wooden cylinder and then use their hand (via repeated finger extension) to hammer the cylinders into the virtual floor.

The workspace size can be scaled to requiring a progression of the arm and shoulder excursion required to transport the hand. Adaptive algorithms can adjust the amount of finger movement necessary to hammer targets or the area of the top of the target. These algorithms shape both proximal stabilization and distal mobility. This simulation was also be utilized for arm training alone. In arm alone mode, the user rotates their forearm (pronation/supination) to hammer the cylinder into the floor.

A. Subjects and Training Paradigms

See Table 1 for subject characteristics. Seven subjects practiced approximately three hours/day for 8 days on simulations that trained the arm and hand separately (HAS). These simulations included Piano, 1, Space Pong, Reach Touch, Hammer (pronation/supination) and Blood Cell. Eleven other subjects practiced for the same amount of time on simulations that trained the arm and hand together (HAT), which included Piano2, Hammer (finger extension), Hummingbird

B. Measurements

The primary outcome measures were the Wolf Motor Function Test and the Jebsen Test of Hand Function, standardized clinical batteries designed to measure motor functions which were performed the day before and the day after the eight training sessions. The secondary measures are the kinematic and force measurements derived from the VR system during training. Reaching kinematics were measured during performance of Hammer1 for HAS subjects and Hammer2 for HAT subjects. Finger kinematics was measured during Piano training for both groups. The movement smoothness is the normalized integrated jerk [11]. Accuracy denotes the percent of correct key presses. Fractionation is calculated as the difference in metacarpal-phalangeal (MCP) joint angle between the cued finger and the most flexed non-cued finger. To facilitate visual comparison between the groups, kinematic measurements are displayed as changes in the scores relative to the first day of training.

III. RESULTS

The eighteen subjects made improvements in WMFT (mean = 16.7 SD=3.8) which was statistically significant ($F(1,16)=45.638$, $p=0.0001$) and JTHF (mean= 37.4, SD= 33.1) which was also statistically significant ($F(1,16)=15.438$, $p=0.001$). HAT subjects made larger mean percent improvements (SD) improvements in WMFT (25%(11) and JTHF (25%(15)

than HAS subjects (15% (13) for WMFT and 21%(17) for JTHF. These differences in improvement do not reach statistical significance.

Figure 1 describes changes made during Virtual Piano Trainer performance. Left panel shows changes in the average time to complete ten key strokes. HAS subjects demonstrate gradual improvements after the second day and a trend toward decreasing variability across the group. HAT subjects make a larger change that remains more varied. Right panel shows changes in average finger fractionation over the eight training days. Both groups demonstrate similar changes over the first six days but these changes are not maintained by the HAS group while the HAT group continues to improve. Figure 2 describes changes made by the two groups in measurements of performance during the two types of Hammer training. Top left panel shows changes in task completion time that are similar to those demonstrated during piano training with the more complex HAT task taking longer to learn but these subjects also demonstrate larger improvement. Top right panel shows changes in the average path length required to complete a ten target sequence of Hammer task. HAT subjects improve faster and continue to improve over the entire trial than HAS subjects. It is important to note that target placement for these two training modes were identical. Bottom left panel describes changes in reaching trajectory smoothness. HAT subjects demonstrated much larger variability without consistent improvement over the first three days but then make large improvements over the balance of training. HAS subjects make steady progress but demonstrate less than half of the improvements demonstrated by the HAT subjects.

IV. Discussion

HAT subjects demonstrate larger changes in all six kinematic measures including proximal and distal measures. These changes are accompanied by larger changes in upper extremity function demonstrated by HAT subjects, as measured by the WMFT and JTHF. These results differ from those of Krebs, whose subjects demonstrated larger proximal effector improvement in the isolated training group and Housman who showed no difference in improvement. We feel that the large overall changes in clinical test scores and differing patterns of motor learning indicate that further study of these two training approaches are indicated. Larger samples are indicated to definitively evaluate the differences between the two groups.

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Fig. 1. Left Changes in average duration (sec) for ten key presses demonstrated by HAS subjects (squares) and HAT subjects (triangles). Right Changes in average difference between cued finger MCP angle (radians) and average of all other MCP joints for entire day. Error bars = SEM.

Fig. 2.

a. Changes in average duration (sec) for ten key presses demonstrated by HAS subjects (squares) and HAT subjects (triangles). b. Changes in average length of path (meters) required to engage ten targets during Hammer task. c. Changes in trajectory smoothness (values divided by 1000). d. Changes in average excursion (meters) after target acquisition for each ten targets. All analyses performed on 11 HAT subjects and 5 HAT subjects. Error Bars = SEM.

Table 1

Subject Characteristics

	HAS (n=7)	HAT (n=11)
Age (years)	55.6	58.7
Years Since Stroke	3.6	4.4
CMA	5.3	5.5
CMH	4.3	4.5

CMA=Chedoke McMaster Arm Impairment Inventory, CMA=Chedoke McMaster Hand Impairment Inventory.