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Recovery of Hand Function in Virtual Reality: Training Hemiparetic Hand and Arm Together or Separately

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Abstract—**This study describes a novel robotic system using haptic effects and objects, in rich, three- dimensional virtual environments (VEs) for the sensorimotor training of the hemiparetic hand. This system is used to compare effectiveness of two training paradigms, one using activities that train the hand and arm together (HAT) as a functional unit to training the hand and arm in similar conditions, separately (HAS). Four subjects practiced three hours/day for 8 days using (HAS) robotic simulations. Four subjects practiced same amount of time using HAT simulations. HAT group improved 23% in the Wolf Motor Function Test and 29% in the Jebsen Test of Hand Function, whereas HAS group only improved 14% and 8%. HAT group also demonstrated larger decreases in hand trajectory length in the VE-based training that involved reaching and object placing, indicating improved limb segment coordination, (40% HAT; 19% HAS). Both groups improved the smoothness of robotically measured hand trajectories 56%, suggesting improved motor control. During virtual piano training, subjects showed similar improvements in key press accuracy (17% HAT; 20% HAS) however, the HAT group demonstrated larger improvements in average time needed to press a key (151% HAT; 60% HAS). Our initial findings suggest that training the arm and hand as a unit following stroke may be more effective for improving upper extremity function than training the hand and arm in isolation.**

I. INTRODUCTION

Virtual reality technology may be an appropriate means to provide plasticity-mediated therapies in patient populations including stroke and cerebral palsy. Computerized systems are well suited to this and afford great precision in automatically adapting target difficulty based on individual subject's ongoing performance [1]. Virtual environments can monitor feedback specificity and frequency, and can provide adaptive learning algorithms and graded rehabilitation activities that can be objectively manipulated to create individualized motor learning paradigms. Thus, they provide a rehabilitation tool that can be used to exploit the nervous systems' capacity for sensorimotor adaptation.

Currently there are several computerized systems under development to train upper arm movement; however, none of these systems focus on hand rehabilitation [2]. The impact of even mild to moderate deficits in hand control effect many activities of daily living with detrimental consequences to social and work-related participation. Because of fiscal constraints, current service delivery models favor gait-training and proximal arm function [3]. Recovery of hand function is thus is an important but difficult and challenging aspect of rehabilitation.

The prevailing paradigm for upper extremity rehabilitation describes the kinesiological need to develop proximal control and mobility of the shoulder prior to initiating training on the hand [4]. This has been the accepted rehabilitation method for many years. An increasing number of human and animal studies [5] [6] have reported that movement practice increases the area and density of motor cortex correlated with that movement, and that new patterns of representation emerge after intensive motor practice. It is not clear whether this expansion of cortical representations occurs through sharing of cortical tissue among representations [7] or through competition for cortical territory [5] [8]. In general there is better return of upper arm function post-stroke than of the hand [9]. One theory suggests that early motor activity of the upper arm and shoulder may hinder recovery of hand function because of cortical competition facilitated through intensive motor activity. Two small studies exploring the concept of providing additional hand training during conventional therapy [6] or training the hand while the upper arm is deafferented and deefferented through regional anesthesia [8] have shown positive changes in hand function.

We have previously developed a virtual reality based training system for hand rehabilitation for patients post-stroke [10] [11]. We were able to track ongoing performance levels, use the data to precisely adapt the difficulty levels of the tasks to be learned and record precise kinematic and kinetic outcome measures on the patients' temporal and spatial components of hand motion. Using this system, patients improved in and retained gains made in range of motion, speed, and isolated use of the fingers. Importantly, these changes translated to improvements in functional outcome measures. As a group, subjects improved their Jebsen Test of Hand Function (JTHF) scores by 12% [12]. However, the system was focusing on training hand alone,

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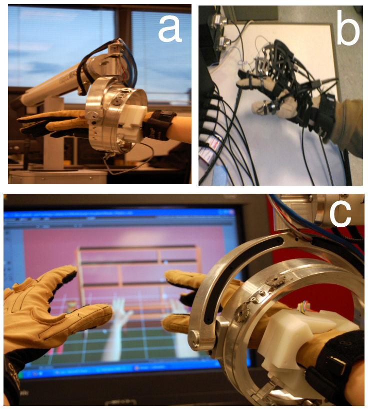

Fig. 1. **a.** Hand & Arm Training System using a CyberGlove and Haptic Master interface that provides the user with a realistic haptic sensation that closely simulates the weight and force found in upper extremity tasks. **b.** Hand & Arm Training System using a CyberGlove, a CyberGrasp and Flock of Birds electromagnetic trackers. **c.** Close view of the haptic interface in a bimanual task.

and could only accommodate patients with impairments in the top quartile. We have now refined and broadened the system in order to more closely model physical therapy practice and in order to accommodate patients with greater impairments. We present here the results of a pilot study where this system was used to retrain both the hand and arm in isolation for one group of subjects as well as a second group of subjects that trained the hand and arm together as a functional unit in order to explore the possibilities of avoiding competition for neural territory between proximal and distal structures by training them as a unit.

II. METHODS

We have developed a unique exercise system that provides for haptic guidance of arm movement in three-dimensional (3D) space which is adaptive in real time as well as on a trial-by-trial basis. The system consists of interactive virtual reality simulations and external hardware integrated to interact with the virtual environments (Fig. 1a, 1b).

A. *Hardware*

1) *Hand:* The system supports the use of CyberGlove [13] instrumented gloves for hand tracking and a CyberGrasp [13] for haptic effects. The CyberGrasp device is a lightweight, force-reflecting exoskeleton that fits over a CyberGlove data glove (Fig. 1b) 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 more pronounced deficits allowing for individual movement of each finger. The Ascension Flock of Birds is used for arm tracking [14]. Hand position and orientation as well as finger flexion and abduction is recorded in real time and translated into three dimensional movements of the virtual hands shown on the screen in a first-person perspective.

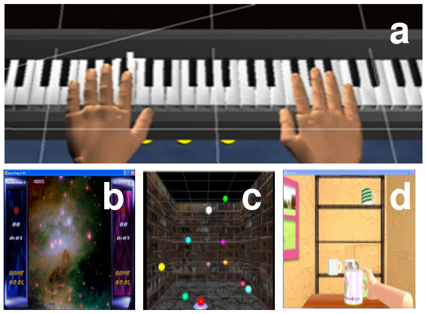

Fig. 2. a. Piano Trainer consists of a complete virtual piano that plays the appropriate notes as they are pressed by the virtual fingers. b. Pong trains the subjects' ability to coordinate finger flexion and extension in order to react to and engage a moving target. c. Reach/Touch is accomplished in the context of aiming /reaching type movements in a functional, three-dimensional workspace. d. Placing Cups displays a three-dimensional room with a haptically rendered table and shelves.

2) *Arm:* The arm simulations utilize the Haptic MASTER [15], 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). 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 [16] (Fig. 1a, 1b).

B. *Simulations*

We have developed simulations for the hand alone, the arm alone, and the hand and arm together using Virtools software package [17] with the VRPack plug-in which communicates with the open source VRPN (Virtual Reality Peripheral Network) [18] 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 and records these data for off-line analysis.

1) Hand Simulations

a) *Piano Trainer:* The piano trainer is designed to help improve the ability of subjects to individually move each finger in isolation (fractionation). It consists of a complete virtual piano that plays the appropriate notes as they are pressed by the virtual fingers (Fig. 2a). The simulation can be utilized for training the hand alone (Piano 1) to improve individuated finger movement (fractionation), or the hand and the arm together (Piano 2) to improve arm trajectory as well as finger motion.

b) *Space Pong:* Space pong trains the subjects' ability to coordinate finger flexion and extension in order to react to and engage a moving target (Fig. 2b). The participant controls the paddle with their finger position. The trajectories of the target are non-predictable, thus necessitating a high level of conscious attention and feed-forward processing. Feedback is provided through the number of successful hits.

2) *Arm Simulations*

a) *Placing Cups*. The goal of the "Placing Cups" task is to improve upper extremity range and smoothness of motion in the context of a functional reaching movement. The screen displays a three-dimensional room with a haptically rendered table and shelves (Fig. 2c). The participants use their virtual hand (hemiparetic side) to lift the virtual cups and place them onto one of nine spots on one of three shelves. To accommodate patients with varying degrees of impairments, haptic effects like gravity and antigravity forces can be applied to the cups, global damping can be provided for dynamic stability and to facilitate smoother movement patterns, and the three dimensions of the workspace can be calibrated to adjust the range of motion required for successful completion of the task.

b) *Reach/Touch*. The goal of the Reach/Touch game is to improve speed, smoothness and range of motion of shoulder and elbow movement patterns (Fig. 2d). Subjects are immersed in a 3-dimensional stereo workspace aided by stereoscopic glasses [19] to enhance depth perception, increase the sense of immersion and to facilitate normal trajectories. The participant moves a virtual cursor through this space in order to touch ten targets presented randomly. Haptic assistance is provided if the subject is not able to reach a target within a predetermined time interval.

3) *Hand and Arm Simulations*

a) *Plasma Pong*. The Plasma Pong and Space Pong (see above) are adaptations of existing games in which we have transferred the game control from the computer mouse to one of our input devices. Plasma Pong trains upper arm and hand movement together (Fig. 3a). 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 of the target are non-predictable, thus necessitating constant conscious attention and feed-forward processing.

b) *Hummingbird Hunt.* This simulation depicts a hummingbird as it moves through an environment filled with trees, flowers and a river (Fig. 3b). The game provides practice in the integration of reach, hand-shaping and grasp using a pincer grip to catch and release the bird while it is perched on different objects located on different levels and sections of a 3D workspace. The flight path of the bird is programmed into three different levels, low, medium and high allowing for progression of the arm and shoulder excursion required to transport the arm to catch the bird.

Fig. 3. **a**. Plasma Pong requires the appropriate integration of shoulder flexion and finger extension. **b**. Hummingbird Hunt provides a pleasant encouraging environment in which to practice repeated arm and hand movements. **c**. Hammer Task trains a combination of three dimensional reaching and repetitive finger flexion and extension

c) *Hammer Task*. The Hammer Task trains a combination of three dimensional reaching and repetitive finger flexion and extension (Fig. 3c). Targets are presented in a scalable 3D workspace. 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 floor. The haptic effects allow the subject to feel the collision between the hammer and target cylinders as they are pushed through the floor or wall. Adjusting the length of the cylinders, the amount of anti-gravity assistance provided by the robot through the gimbal and the time required to successfully complete the series of cylinders adaptively modifies the task requirements and game difficulty.

C. *Measurement*

Four subjects (mean age=51; years post stroke =3.5) practiced approximately three hours/day for 8 days on simulations that trained the arm and hand separately (HAS). Four other subjects (mean age=59; years post stroke =4.75) practiced for the same amount of time on simulations that trained the arm and hand together (HAT).

Two types of outcome measures were used in this study. The primary dependent measures are the clinical tests; all subjects were tested pre and post training on two of our primary outcome measures, the JTHF and the Wolf Motor Function Test (WMFT) [20]. The secondary measures are the kinematic and force measurements derived from the VR system during training. Several simulations were designed to produce kinematic measurements for these purposes including the Virtual Piano Trainer, Hammer Task, Reach – Touch and Cup Placing. The other simulations in this experiment are training activities that do not produce performance data. These include measures such as time to task completion (duration), accuracy, velocity, smoothness of arm motion and force generated by the subject. The movement smoothness is the normalized integrated jerk [21]. Accuracy denotes the proportion of correct key presses.

III. RESULTS

The HAS group that practiced arm and hand tasks separately showed a 14% and a 9% improvement (calculated as pretest aggregate time minus post-test aggregate time

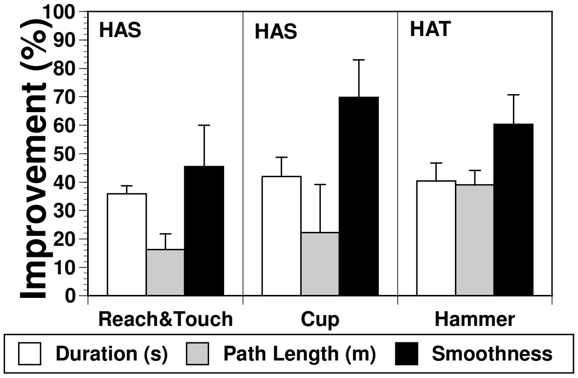

Fig. 4. Percentage of improvements in kinematic measures for 4 subjects after 8 sessions of training the hand & arm separately (HAS) and 4 subjects after 8 sessions of training the hand and arm together (HAT).

divided by pretest aggregate time) in the WMFT and in the JTHF whereas the HAT group showed a 23% and a 29% improvement, respectively. Small sample size did not allow for more rigorous statistical analyses.

There were also notable changes in the secondary outcome measures; the kinematic data (Fig. 4) derived from the virtual reality simulations performed under testing conditions which did not include haptic assistance. Subjects in both groups showed similar improvements in the time to complete each game, and in the smoothness of their hand trajectories, indicating better control [22]. However, the subjects in the HAT group showed a more pronounced decrease in the path length. This suggests a reduction in ineffective arm movements with more efficient limb segment interactions.

For training on the virtual piano simulations, subjects showed similar improvements in key press accuracy (percent change HAS=20%; HAT=17%). However, the subjects that trained using the arm and the hand together were able to complete the task much more quickly (percent change HAS=60%; HAT=151%).

IV. CONCLUSION

The HAS and HAT groups were both exposed to similar combinations of virtual environment, haptic objects and haptic assistance. Training volumes, schedules and the feedback provided subjects was consistent as well. Despite these similarities, the two groups appear to respond differently to the independent condition of training the effectors of the upper extremity separately versus training the entire extremity as a functional unit when measured by the clinical test scores. Training the hand and arm as a functional unit may present a better balance of proximal and distal activity leading to more effective cortical reorganization in response to training. While our sample size prohibits claims for causation, we believe that our data justifies further investigations of this phenomena as well as the broader question of training induced competition for neural territory in persons recovering from stroke.

REFERENCES

[1] P. S. Lum, C. G. Burgar, P. C. Shor, M. Majmundar, M. Van der Loos, “MIME robotic device for upper limb neurorehabilitation in subacute stroke subjects: A follow up study,” *Journal of Rehabilitation Research and Development*, vol. 42, pp. 631-642, 2006.

[2] J. L. Patton, F.A. Mussa-Ivaldi, “Robot-assisted adaptive training: custom force fields for teaching movement patterns,” *IEEE Transactions in Biomedical Engineering*, vol. 51, no. 4, pp. 636–646, 2004.

[3] G. Buccino, A. Solodkin, S.L.Small, “Functions of the mirror neuron system: implications for neurorehabilitation,” *Cogn Behav Neurol* , vol. 19, no. 1, pp. 55-63, 2006.

[4] S. Lennon, D. Baxter, and A. Ashburn, “Physiotherapy based on the Bobath concept in stroke rehabilitation: a survey within the UK,” *Disabil Rehabil* , vol. 23, no. 6, pp. 254-262, 2002.

[5] R. J. Nudo, B. M. Wise, F. SiFuentes and G. W. Milliken, “Neural substrates for the effects of rehabilitative training on motor recovery after ischemic infarct,” *Science,* vol. 272, pp. 1791-1794, 1996.

[6] P. Hlustik, A. Solodkin, D. C. Noll and S. L. Small, “Cortical Plasticity During Three-Week Motor Skill Learning,” *Journal of Clinical Neurophysiology*, vol. 21, no. 3, pp. 180-191, 2004.

[7] M. Kossut and E. Siucinska, “Learning-induced expansion of cortical maps--what happens to adjacent cortical representations?” *Neuroreport*, vol. 9, no. 18, pp. 4025-4028, 1998.

[8] W. Muellbacher, C. Richards, U. Ziemann, G. Wittenberg, D. Weltz, B. Boroojerdi, L. Cohen and M. Hallett, “Improving hand function in chronic stroke,” *Arch Neurol*, vol. 59, no. 8, pp. 1278-1282, 2002.

[9] C. E. Lang, J. M. Wagner, D. F. Edwards, S. A. Sahrmann and A. W. Dromerick, “Recovery of grasp versus reach in people with hemiparesis poststroke,” *Neurorehabil Neural Repair,* vol. 20, no. 4, pp. 444-454, 2006.

[10] S. V. Adamovich, A. S. Merians, R. Boian, M. Tremaine, G. C. Burdea, M. Recce and H. Poizner, “A virtual reality (VR)-based exercise system for hand rehabilitation after stroke,” *Presence*. vol. 14, pp. 161-174, 2005.

[11] A. S. Merians, H. Poizner, R. Boian, G. Burdea and S. V. Adamovich, “Sensorimotor training in a virtual reality environment: does it improve functional recovery poststroke?” *Neurorehab Neural Repair,* vol. 20, pp. 252-267, 2006.

[12] R. Jebsen, N. Taylor, R. Trieschman, M. Trotter, and B. Howard, “An objective and standardized test of hand function,” *Archives of Physical Medicine and Rehabilitation*, pp. 311-319, 1969.

[13] Immersion, "Cyberglove," Available: http://www.immersion.com, 2006.

[14] C. T. Ascension, "Flock of Birds," Available: http://www.ascension-tech.com.

[15] Moog FCS Corporation, Haptic Master, Available: http://www.fcs-cs.com, 2006.

[16] R.Q. Van der Linde, P. Lammertse, E. Frederiksen, B. Ruiter, “The HapticMaster, a new high-performance haptic interface,” *Proceedings Eurohaptics*, pp 1-5, July 8-10, 2002, Edinburgh, UK.

[17] Dassault Systemes, Virtools Dev 4.0, Available: www.virtools.com, 2005.

[18] R. M. Taylor, “The Virtual Reality Peripheral Network (VRPN),” Available: http://www.cs.unc.edu/Research/vrpn, 2006.

[19] RealD/StereoGraphics, CrystalEyes shutter eyewear, Available: http://www.reald.com, 2006.

[20] S. Wolf, P. Thompson, D. Morris, D. Rose, S. Winstein, E. Taub, C. Giuliani, S. Pearson, “ The EXCITE Trial: Attributes of the Wolf Motor Function Test in Patients with Subacute Stroke,” *Neurorehabilitation & Neural Repair*, vol. 19, pp. 194-205, 2005.

[21] H. Poizner, A. G. Feldman, M. F. Levin, M. B. Berkinblit, W. A. Hening, A. Patel, S. V. Adamovich, “The timing of arm-trunk coordination is deficient and vision-dependent in Parkinson's patients during reaching movements,” *Exp Brain Res*. vol. 133, no. 3, pp. 279-292, 2000.

[22] B. Rohrer, S. Fasoli, H. I. Krebs, R. Hughes, B. Volpe, W. R. Frontera, J. Stein, N. Hogan, “Movement smoothness changes during stroke recovery,” *J Neurosci*, vol. 22, no. 18, pp. 8297-8304, 2002.