Published in final edited form as:

IEEE Int Conf Rehabil Robot. 2011 ; 2011: 5975431. doi:10.1109/ICORR.2011.5975431.

A Comparison of Motor Adaptations to Robotically Facilitated Upper Extremity Task Practice Demonstrated by Children with Cerebral Palsy and Adults with Stroke

Qinyin Qiu,

Department of Biomedical Engineering, New Jersey Institute of Technology, Newark, N.J., USA, 07102

Sergei Adamovich,

Department of Biomedical Engineering, New Jersey Institute of Technology, Newark, N.J., USA, 07102

Soha Saleh,

Department of Biomedical Engineering, New Jersey Institute of Technology, Newark, N.J., USA, 07102

Ian Lafond,

Department of Biomedical Engineering, New Jersey Institute of Technology, Newark, N.J., USA, 07102

Alma S. Merians, and

Department of Rehabilitation and Movement Sciences., University of Medicine and Dentistry of New Jersey, Newark, N.J., USA, 07103

Gerard G. Fluet

Department of Rehabilitation and Movement Sciences., University of Medicine and Dentistry of New Jersey, Newark, N.J., USA, 07103

Qinyin Qiu: qq4@njit.edu

Abstract

Nine children with cerebral palsy and nine adults with stroke were trained using 5 different upper extremity simulations using the NJIT-RAVR system for approximately nine to twelve hours over a three week period. Both groups made improvements in clinical measurements of upper extremity function and reaching kinematics. Patterns and magnitudes of improvement differ between the two groups. Responses to training required adjustment of the robotic system to accommodate the rehabilitation needs of children with cerebral palsy.

Keywords

cerebral palsy; stroke; robot; virtual reality; virtual reality

I. Introduction

Cerebral palsy is a central nervous system syndrome characterized by abnormal muscle tone attributed to non-progressive insults in the fetal or infant brain. The development of rehabilitation approaches for this population is challenging and expanding slowly. Leaders in the rehabilitation field are calling for translational studies applying rehabilitation techniques developed for persons with stroke to children with CP [1].

Robotically facilitated practice of activities designed to improve proximal upper extremity motor performance in persons with stroke is a well studied treatment modality [2, 3]. Only two systems of rehabilitation robots, the InMotion2 and NJIT-RAVR have published studies related to upper extremity rehabilitation of both children with CP [4, 5], and adults with stroke [6, 7]. To date, no comparative studies of the responses to this type of training in these two populations are published. This paper will begin the process of assessing training systems and programs utilizing robots designed to train the hemiparetic UE of adults with stroke in similarly impaired children with CP by describing differences in motor function adaptations made by these two groups to two similarly presented programs of proximal upper extremity training utilizing a six degrees of freedom admittance controlled robot interfaced with complex, haptic virtual environments. In addition, the process of adjusting virtual environment presentations and training programs to meet the specific rehabilitation needs of children with CP will be introduced.

II. METHODS

Hardware

The NJIT-RAVR system utilizes the Haptic Master® (Moog, The Netherlands) a 6 degree of freedom force-controlled robot combined with a ring gimbal. The Haptic Master Application Programming Interface (API) is used to program the robot to produce haptic effects, such as springs, dampers and global forces such as gravity. A three-dimensional (3D) force sensor measures the external force exerted by the user on the robot are measured in 3D real time to generate reactive motion. End-point position and velocity is measured at a frequency of 1000Hz which allows the movement arm to act as an interface between the participants and the virtual environments. A ring gimbal is utilized as the end effector of the robot and records orientation angles of the forearm, forearm rotation (i.e. roll) wrist flexion / extension (pitch) as well as ulnar and radial deviation (yaw) are measured by the gimbal and translated into avatar movement in the VE. An active force that assists or resists forearm rotation is generated and recorded by the robot; the other two degrees of freedom are recorded passively. The height of the positioning system was oriented in relation to the Haptic Master in order to obtain an initial position of 90 degree of elbow flexion with the humerus resting against the participant's trunk for all games.

A. Simulations

1) Bubble Explosion: The Bubble Explosion simulation the speed and accuracy of shoulder and elbow movements during a series of reaching movements in a 3D work-space. The subject moves a virtual cursor in order to touch a series of ten haptically rendered bubbles

with an adjustable radius floating in a 3D environment. Location of the targets is predefined in an external configuration file that can be modified to achieve specific movement goals. Stereoscopic glasses are used to enhance depth perception, which produces more normal upper extremity trajectories [19] and increases the sense of immersion.

2) Cup Reach: The screen displays a three-dimensional room with a haptically rendered table and set of shelves. The shelves are at three different levels in height. The simulation utilizes a calibration protocol that allows the height, width and distance to the shelves to be adjusted to accommodate the movement abilities of the subject. Individual virtual cups with a handle will appear on the table, and a red square indicating where the cup is to be placed is displayed. Haptic obstacles are employed in this simulation to provide tactile feedback, which shapes trajectories performed by the subject. Collisions with the tables, shelves and other cups provide intrinsic feedback related to the accuracy of reaching trajectory. The weight of the haptic cups can be adjusted, which can provide normal kinesthetic feedback resulting in normal muscle activation patterns. Anti-gravity assistance can allow subjects that do not have the requisite strength to perform a 3D reaching activity. A damping effect can be applied by the Haptic Master, which stabilizes the subjects' 3D trajectories.

3) FallingObjects: The purpose of the FallingObjects simulation is to improve upper extremity reaching towards a moving object. Subjects are presented with targets falling from six points across the top of the screen, three on each side of their midline. The subjects move their hand as quickly as possible from midline to the target, trying to catch it as quickly and high on the screen as possible. Feedback related to the speed of each catch, the total number of successful catches and the height of each successful catch is presented.

4) HammerHM: HammerHM simulation focuses on improving forearm rotation. During training, a target (vertically oriented wooden rod) appears in the middle of the screen. The subject reaches the target peg and uses repetitive forearm rotation movements to swing a virtual hammer, driving the target into the ground. The rotation angle required to successfully hammer down the wood is adjustable for different subjects according to their impairment level. A new target appears after each trial is completed.

5) Spaceship: The Space-ship simulation focuses on improving the speed & accuracy of frontal plane shoulder & elbow movements. The subject moves a virtual space-ship through a representation of a human blood vessel. Objects within the blood vessel represent obstacles or targets. 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.

B. Subjects—Each of the two groups of subjects described in this paper is participating in an ongoing study related to their particular pathology. They were recruited through support groups and clinician referral. Stroke subjects completed an informed consent procedure. The guardians of CP subjects all completed an informed consent procedure and the CP subjects completed an assent procedure. Protocols for each population were approved by the Internal Review Board of the New Jersey Institute of Technology.

1) Cerebral Palsy Group: We trained nine children with CP, eight boys and 1 girl ages 7 to 15 years (mean 10.1). Seven of the children were ambulatory with mild to moderate hemiplegia (MACS level II–IV). Two were non-ambulatory, using power wheelchairs for mobility with spastic quadriplegia. Each of these two children demonstrated moderate impairments of the upper extremity used for training and testing (MACS Level III).

2) Stroke Group: We trained nine adults, six men and three women, ages 42 to 77 (mean 54.2) with sub acute or chronic stroke (mean 23.3 months since CVA). All nine subjects were ambulatory (five with an assistive device) with mild to moderate UE hemiparesis (Chedoke McMaster Arm Impairment Inventory Stage 4 to 6).

C. Training Paradigms—Both groups are part of larger training studies specific to their diagnosis. All of the proximal UE training activities performed by the two groups is described below.

1) CP Group: CP subjects used the NJIT-RAVR System for one hour, 3 days a week for three weeks which is consistent with the longest training times described in published studies of robotically facilitated UE training of children with CP (REF). Subjects performed the Bubble Explosion simulation to initiate each session for performance testing purposes. The HammerHM simulation followed and forearm rotation performance was collected during this simulation. Simulations three through five are completed for approximately ten minutes each, completing the training sequence.

2) CVA Group: Stroke subjects used the NJIT-RAVR System for ninety minutes, 4 days a week for two weeks. which is consistent with the longest training times described in published studies of robotically facilitated proximal UE training of adults with CVA(REF) The training protocol was performed in a similar order to that described in the CP training section, with each simulation being performed for fifteen to twenty minutes. As part of their participation in a larger study of persons with stroke, the adult subjects performed an additional ninety minutes of finger training. During finger training the subjects was fully supported minimizing the involvement of the proximal UE musculature trained in the simulations described above. Based on these conditions we are assuming that the finger training will not have significant impact on the measurements discussed in this paper.

D. Testing Procedure—Both groups performed batteries of clinical testing on the day prior to and the day immediately following training that were designed as outcome measures for the diagnosis specific studies mentioned above, which are described elsewhere [4, 8]. This paper will consider timed tests of forward, sideways and hand to mouth reaching that are common to both testing batteries for comparison purposes. Kinematic measures collected during daily performance of the Bubble Explosion and Hammer HM simulations will be reported for both groups. Forearm rotation measurements collected during HAMMER HM simulation training describe supination movements for the CP subjects and pronation movements for the stroke subjects.

E. Data Analysis—Timed reaches for the two groups are analyzed using repeated measures ANOVA. Changes in Path Length and Movement Time are analyzed using mean

and standard deviation of the groups for each training day. Pre to post-test changes in the stroke group's peak pronation velocity and the CP group's peak supination velocity during Hammer training will be reported as percent changes.

III. RESULTS

A. Timed reaching performance

Both groups made statistically significant improvements in hand to mouth and forward reaching tests as well as the composite of the three timed reaches. Only the CP group made a statistically significant increase in sideways reach. The CP group made larger improvements in each of these measurements with all comparisons reaching statistical significance (See Table 1).

B. Kinematic Measures

Both groups made statistically significant improvements in Path Length, Duration and Trajectory Smoothness which suggests improvements in motor skill and possibly motor control. The children with CP demonstrated lower initial levels of performance for each of these measurements. Differences were statistically significant on day one for duration and path length. The children with CP made larger improvements in path length and adults made a larger improvement in movement time. Both demonstrated similar levels of trajectory smoothness on the first training day with the adults with CVA subjects making larger improvements. The children's performances varied more within the CP group and the improvement trend across the study period was more regular for the subjects with CVA (See Figure 3). Roll plane movement changes for the children with CP were large (43% increase in supination velocity) but negligible for the adults with stroke (4% increase in pronation velocity).

C. Responses to simulations

The Hammer Training simulation was initially designed to train pronation ability for adults with CVA. Children with CP frequently present with pronator teres spasticity, limiting their active supination range of motion and speed. The system was modified to utilize supination motion to swing the virtual hammer.

The children with CP demonstrated significant problems performing the Hammer Simulation despite having the ability to perform the reaching aspect of the task and sufficient active supination range of motion to cause the Hammer to turn. We modified the activity by stabilizing the endpoint during hammering allowing the children to train supination with varying levels of shoulder elevation and elbow extension without the need to stabilize the arm endpoint during interaction with the object. Subsequent iterations of the CP training program will emphasize stabilization of the UE during performance of the Bubble Explosion simulation.

Stroke subjects performed all eight, ninety minute training sessions with no more than three breaks of less than two minutes. None of the training logs revealed consistent issues with attention. In contrast, early in the trial several of the children demonstrated decreasing

enthusiasm for training as evidenced by frequent requests for rest breaks, complaints of fatigue or breaks in attention during training. We changed the visual presentations and sounds for several simulations to make them more appealing to children resulting in more consistent participation.

IV. Discussion

Both groups of subjects demonstrated improvements in all of the kinematic measurements collected during training. This is consistent with the responses of adults [8] and children [4, 10] to our system as well as adults with CVA[11] and children with CP [5, 12] using the InMotion 2 Robot. The children with CP demonstrated larger changes in path length and roll plane velocity while the adults made larger changes in smoothness and duration. In addition the children's' improvements in robotic training performance translated to larger improvements in the timed reaching activities from the clinical examination.

Interestingly the adults made larger improvements in smoothness than the children with CP as a result of this training program. Improvements in smoothness have been associated with neurologic recovery in persons with stroke [16]. Large improvements in trajectory smoothness as a result of training with InMotion 2 system have been demonstrated by both diagnostic groups [12, 17].

The children with CP demonstrated an inability to keep the endpoint of the robot stable during the supination part of the activity. This could be due to poor selective motor control [18] or an inability to stabilize proximal segments during distal movement [19]. Proximal stabilization is a construct associated with higher levels of UE motor function in persons with stroke [19]. The NJIT RAVR system has demonstrated the ability to improve this construct in persons with stroke [20]. A less strenuous task using different combinations of movements may be necessary to train this ability in children with CP. Future iterations of our CP training program will attempt to address this question.

The adults with stroke rarely solicited feedback related to their performance. The children with CP consistently solicited feedback related to their scores, previous scores and the scores of other children. This is consistent with the motor learning literature describing higher reliance on extrinsic feedback by children learning motor skills than adults learning similar skills[21]. In addition, several of the children with motivation issues demonstrated improved attention and compliance when the therapists set goals related to their scores for each game within a session or emphasized their previous best performances during training. Early studies of the effect of virtual game action on technology based rehab activities have identified a beneficial additive effect of game action for training performance and motor adaptation in persons with stroke [22] and children with CP [23]. Our anecdotal experiences support the findings of these studies.

The training programs discussed in this paper differ slightly in terms of execution and overall training volume, limiting our ability to make definitive conclusions. This said, the data we present suggests that children with CP and adults will interact with and adapt to simulated therapeutic activities differently. Fortunately, the flexibility of robotic systems

and VE should allow teams of therapists and engineers to adapt systems designed for stroke rehabilitation to accommodate the unique rehabilitation needs of children with CP.

REFERENCES

1. Kerkovich DM. Transformational technologies in single-event neurological conditions: Applying lessons learned in stroke to cerebral palsy. *Neurorehabil Neural Repair*. 2009; 23(7):747–765. [PubMed: 19710288]
2. Kwakkel G, Kollen BJ, Krebs HI. Effects of Robot-Assisted Therapy on Upper Limb Recovery After Stroke: A Systematic Review. *Neurorehabil Neural Repair*. 2007
3. Mehrholz J, Platz T, Kugler J, Pohl M. Electromechanical and Robot-Assisted Arm Training for Improving Arm Function and Activities of Daily Living After Stroke. *Stroke*. 2009 Mar 12.
4. Fluet GG, Qiu Q, Saleh S, Ramirez D, Parikh H, Kelly D, Adamovich SV. Interfacing a haptic robotic system with complex virtual environments to treat impaired upper extremity motor function in children with cerebral palsy. *Dev Neurorehabil*. 13(5):335–345. [PubMed: 20828330]
5. Fasoli SE, Fragala-Pinkham M, Hughes R, Hogan N, Krebs HI, Stein J. Upper Limb Robotic Therapy for Children with Hemiplegia. *Am J Phys Med Rehabil*. 2008; 87(11):929–936. [PubMed: 18936558]
6. Merians AS, Tunik E, Fluet GG, Qiu Q, Adamovich SV. Innovative approaches to the rehabilitation of upper extremity hemiparesis using virtual environments. *Eur J Phys Rehabil Med*. 2009; 45(1): 123–133. [PubMed: 19158659]
7. Volpe BT, Lynch D, Rykman-Berland A, Ferraro M, Galgano M, Hogan N, Krebs HI. Intensive sensorimotor arm training mediated by therapist or robot improves hemiparesis in patients with chronic stroke. *Neurorehabil Neural Repair*. 2008; 22(3):305–310. [PubMed: 18184932]
8. Merians AS, Tunik E, Fluet GG, Qiu Q, Adamovich SV. Innovative approaches to the rehabilitation of upper extremity hemiparesis using virtual environments. *Eur J Phys Rehabil Med*. 2008
9. Yogev-Seligmann G, Rotem-Galili Y, Mirelman A, Dickstein R, Giladi N, Hausdorff JM. How Does Explicit Prioritization Alter Walking During Dual-Task Performance? Effects of Age and Sex on Gait Speed and Variability. *Phys Ther*. 2010; 90(2):177–186. [PubMed: 20023000]
10. Qiu Q, Ramirez DA, Saleh S, Fluet GG, Parikh HD, Kelly D, Adamovich SV. The New Jersey Institute of Technology Robot-Assisted Virtual Rehabilitation (NJIT-RAVR) system for children with cerebral palsy: a feasibility study. *J Neuroeng Rehabil*. 2009; 6:40. [PubMed: 19917124]
11. Rohrer B, Hogan N. Avoiding spurious submovement decompositions: a globally optimal algorithm. *Biol Cybern*. 2003; 89(3):190–199. [PubMed: 14504938]
12. Frascarelli F, Masia L, Di Rosa G, Cappa P, Petrarca M, Castelli E, Krebs HI. The impact of robotic rehabilitation in children with acquired or congenital movement disorders. *Eur J Phys Rehabil Med*. 2009; 45(1):135–141. [PubMed: 19293759]
13. Krakauer JW. Motor learning: its relevance to stroke recovery and neurorehabilitation. *Curr Opin Neurol*. 2006; 19(1):84–90. [PubMed: 16415682]
14. Reinkensmeyer DJ, Iobbi MG, Kahn LE, Kamper DG, Takahashi CD. Modeling reaching impairment after stroke using a population vector model of movement control that incorporates neural firing-rate variability. *Neural Comput*. 2003; 15(11):2619–2642. [PubMed: 14577856]
15. Magill, R. *Motor Learning: Concepts and Applications*. New York: McGraw-Hill; 2001.
16. Rohrer B, Fasoli S, Krebs HI, Volpe B, Frontera WR, Stein J, Hogan N. Submovements grow larger, fewer, and more blended during stroke recovery. *Motor Control*. 2004; 8(4):472–483. [PubMed: 15585902]
17. Rohrer B, Fasoli S, Krebs HI, Hughes R, Volpe B, Frontera WR, Stein J, Hogan N. Movement smoothness changes during stroke recovery. *J Neurosci*. 2002; 22(18):8297–8304. [PubMed: 12223584]
18. Sanger TD, Chen D, Delgado MR, Gaebler-Spira D, Hallett M, Mink JW. Definition and classification of negative motor signs in childhood. *Pediatrics*. 2006; 118(5):2159–2167. [PubMed: 17079590]

19. Lang CE, Beebe JA. Relating movement control at 9 upper extremity segments to loss of hand function in people with chronic hemiparesis. *Neurorehabil Neural Repair*. 2007; 21(3):279–291. [PubMed: 17353458]
20. Merians, A.; Fluet, GG.; Qiu, Q.; Saleh, S.; Lafond, I.; Adamovich, SV. Integrated arm and hand training using robotics and virtual reality simulations. *Proceedings 8th Conference International Society Disability and Related Technologies*; Aug 31–Sep 3, 2010; Vina del Mar,-Valparaiso Chile. p. 1-8.
21. Sullivan KJ, Katak SS, Burtner PA. Motor learning in children: feedback effects on skill acquisition. *Phys Ther*. 2008; 88(6):720–732. [PubMed: 18339797]
22. Mirelman A, Bonato P, Deutsch JE. Effects of Training With a Robot-Virtual Reality System Compared With a Robot Alone on the Gait of Individuals After Stroke. *Stroke*. 2008 Nov 6.
23. Deutsch JE, Borbely M, Filler J, Huhn K, Guarrera-Bowlby P. Use of a low-cost, commercially available gaming console (Wii) for rehabilitation of an adolescent with cerebral palsy. *Phys Ther*. 2008; 88(10):1196–1207. [PubMed: 18689607]

Fig. 1. Screenshots of training simulations performed by adults with CVA and children with CP. a) Bubble Explosion, b) Cup reach, c) Falling Objects, d) HammerHM, e) Space Ship.

Fig. 2.
Pediatric subject using NJIT RAVR system to perform HAMMER simulation.

Fig. 3.
Children with CP, red lines, adults with stroke, blue lines. Left: Daily changes in path length. Center: Daily changes in Movement Time. Right : Daily changes in smoothness.

TABLE I

Reaching kinematic changes

Clinical Measurement	CP difference (SD)	CVA difference (SD)	F	p
sideways reach	.52 (.84)*	.05 (.20)	19.088	0.0005
forward reach	.83 (.89)*	.20 (.31)*	4.626	0.0426
hand to mouth reach	1.33 (2.04)*	1.11(1.99)*	6.455	0.0218
composite	2.55(2.64)*	1.62 (2.16) *	15.081	0.0013