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Coordination Changes Demonstrated by Subjects with Hemiparesis Performing Hand–Arm Training Using the NJIT-RAVR Robotically Assisted Virtual Rehabilitation System

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Abstract—**Various authors have described pre and post testing improvements in upper limb coordination as a result of intensive upper limb interventions. While the ability to alter coordination patterns as a result of repetitive hand-arm movement is established, patterns of change in the relationship between proximal and distal effectors of the UE over the course of multiple sessions of training have not been described in the rehabilitation literature. In this study eight subjects (5 male, 3 female) with a mean age of 56.4 years (SD=14.2) and a mean time since CVA of 54.7 months post-stroke (SD=51.7) were trained for eight, 2-3 hour sessions on four robotically facilitated virtual rehabilitation activities. This paper will present 1) Functional performance and pre and post testing kinematic analysis for the eight subjects 2) More extensive analysis of the change in hand and arm coordination over the course of the eight session intervention demonstrated by one of the subjects from this sample 3) Kinematic analysis of another subject from this sample performing an un-trained reaching and grasping activity, before and after training.**

I. INTRODUCTION

CEREBROVASCULAR accidents can cause impairments in force production and speed of both the proximal and distal effectors of the upper extremity. The functional limitations caused by these impairments are compounded by corresponding impairments in the coordination of effectors as well [1]. These deficits are described as changes in relative timing between proximal and distal movements [2]. Several authors describe improved patterns of shoulder and elbow coordination as a result of reaching interventions in persons following CVA [3]. Others describe analogous improvements in the coordination of reaching and grasping movements as a result of several sessions of training [4]. Short term changes in upper extremity coordination have also been demonstrated in persons with CVA as the result of a single training intervention [5].

While the ability to alter coordination patterns as a result of repetitive hand-arm movement is established, patterns of change in the relationship between proximal and distal effectors of the UE over the course of multiple sessions of training have not been described in the rehabilitation literature to date. Robotically facilitated training offers the unique advantage of the ability to collect detailed kinematic data for every repetition of a multi-session training intervention [6]. This paper will present 1) Functional performance and pre and post testing kinematic analysis for a group of eight hemiparetic subjects that performed an eight day Hand-Arm Training intervention. 2) More extensive analysis of the change in hand and arm function over the course of the eight session intervention .demonstrated by one of the subjects in this sample and 3) Kinematic analysis of another subject performing an un-trained reaching and grasping activity.

II. METHODS

The systems and training paradigm utilized in this study are described in detail in a previously published paper [7]. The system and training paradigm descriptions that follow are brief summaries.

A. Hardware

There are four simulations used in this protocol. Two of the simulations utilize CyberGloves, instrumented gloves for hand tracking and a CyberGrasp for haptic effects (Immersion Inc). The CyberGrasp device is a lightweight, force-reflecting exoskeleton that fits over the CyberGlove. In this study the CyberGrasp is used to facilitate individual finger movement, by resisting flexion of the adjacent fingers. This allows for individual movement of the active finger. Hand position and orientation as well as finger flexion is recorded in real time and translated into three-dimensional movements of the virtual hands. The Ascension Flock of Birds (Ascension Technologies) is used for arm tracking. The other simulations utilize the Haptic MASTER (Moog FCS Corporation) [8], 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.

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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. The haptic interface provides the user with a realistic haptic sensation that closely simulates the weight and force found in upper extremity tasks [9].

B. *Simulations*

The virtual reality gaming simulations have been programmed to translate movement of both the upper arm and the hand using C++/OpenGL or the Virtools software package with the VRPack plug-in (Dassault Systemes) which communicates with the open source VRPN [10]. We used the Haptic Master's Application Programming Interface (API) 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.

1) Plasma Pong

Plasma Pong (Fig. 1a) trains upper arm and hand movement together. The Pong paddle is moved with shoulder flexion and the target is engaged with finger extension, therefore the game requires the appropriate integration of shoulder flexion and finger extension. Feedback is provided through the number of successful hits.

2) Hummingbird Hunt

This simulation depicts a hummingbird as it moves through an environment filled with trees, flowers and a river (Fig. 1b). Water and bird sounds provide a pleasant encouraging environment in which to practice repeated arm and hand movements. The Hummingbird hunt 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 in the range of motion required to successfully transport the arm to catch the bird.

3) Hammer Task

The Hammer Task (Fig. 1c) trains a combination of three dimensional reaching and repetitive finger flexion and extension. Targets are presented in a scalable 3D workspace. The game exercises movement of the hand and arm together by having the subjects reach towards a wooden cylinder and then use their hand (finger extension or flexion) to hammer the cylinders into the floor. For each trial ten cylinders are presented randomly in 9 different locations within the 3D space. Hammering sounds accompany collisions as well. The subjects receive feedback regarding their time to complete the series of hammering tasks. Adjusting the size of the cylinders, the amount of anti-gravity assistance provided by the robot and the time required to successfully complete the series of ten cylinders adaptively modifies the task requirements and game difficulty.

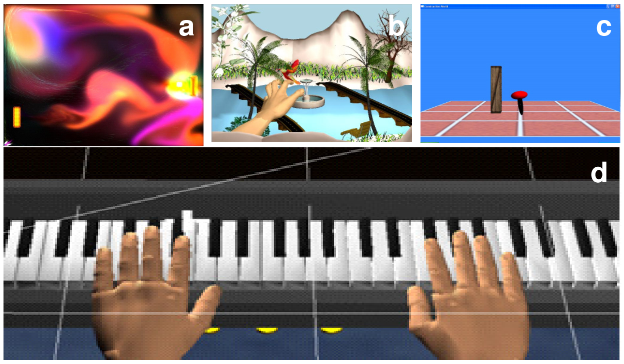

Fig. 1. **a**. Plasma Pong requires the appropriate integration of shoulder flexion and finger extension. **b**. Hummingbird Hunt provides a pleasant encouraging environment in which to practice repeated arm and hand movements. **c**. Hammer Task trains a combination of three dimensional reaching and repetitive finger flexion and extension d. Piano Trainer consists of a complete virtual piano that plays the appropriate notes as they are pressed by the virtual fingers

4) Virtual Piano

This simulation consists of a complete virtual piano (Fig. 1d) that plays the appropriate notes as they are pressed by the virtual fingers. The position and orientation of both hands as well as the flexion of the fingers are recorded in real time and translated into 3D movement of the virtual hands, shown on the screen in a first person perspective. The subjects play short recognizable songs, scales, and random notes. Color-coding between the virtual fingers and piano keys serve as cues as to which notes are to be played. The activity can be made more challenging by changing the fractionation angles required for successful key pressing and manipulating the octaves on which the songs are played.

C. *Subjects and Training Paradigm*

Eight subjects (5 male, 3 female) with a mean age of 56.38 years (SD=14.2) and a mean time since CVA of 54.7 months post-stroke (SD=51.7) were trained for 2-3 hour sessions on all four simulations for eight days. Consent was obtained from all subjects and the protocol has been approved by the Internal Review Boards of both universities.

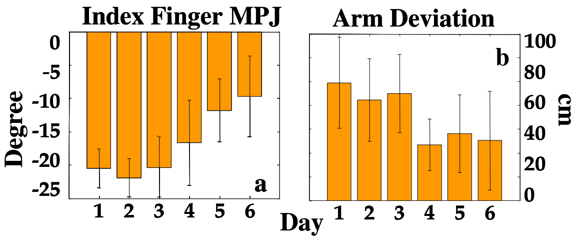

Fig. 2. a. Describes the daily changes in peak index finger extension for a representative subject during Hammer Task. Values approaching zero indicate finger extension b. demonstrates improvements in the same subject's ability to maintain the Hammer over the target, once it was acquired. The smaller values indicate less movement away from the target.

D. Measurements

Kinematic measures were obtained from the hammering task and the piano trainer. For the hammering task simple measures included duration of the movement, measured by the time required to hammer each cylinder and the smoothness of the movement trajectory, which numerically describes the ability to produce smooth, coordinated arm movements versus disjointed collections of sub-movements. We attempted to analyze intra-limb coordination by measuring finger extension amplitude and end point stability during finger movement during the hammering task. For the piano trainer, the simple measures included accuracy, measured by the proportion of correct key presses and duration of the movement, which includes both hand transport and key press time for each song. We also measured fractionation, the ability to isolate the movement of each finger. We also measured the kinematics of a series of untrained reaching and grasping movements for the final subject that participated in this data collection period. The subject reached and grasped each of 5 objects approximately 12 inches from a starting point at their midline, placed them on a target 12 inches away and then returned to the starting point. Joint angles were collected with magnetic sensors and a data glove. Clinical tests of upper extremity function included the Jebsen Test of Hand Function (JTHF), the Wolf Motor Function Test (WMFT), the Nine Hole Peg Test (9HPT) and the Box and Blocks test (BBT) [11-13]. All subjects were tested pre and post training.

III. RESULTS

A. Hammer Task Kinematics

As a group, the Hand-Arm training subjects decreased 53% from pre to post-testing in total movement time which includes arm transport and hammering. The group also made a 56% improvement in smoothness of endpoint movement, suggesting an improvement in motor control [14]. Figure 2a describes the daily changes in peak index finger extension for a representative subject during Hammer Task. Note that a value of zero is analogous to full finger extension. Negative numbers indicate degrees of flexion. Figure 2b describes improvements in the same subject's ability to maintain the hammer over the target, once it was acquired.

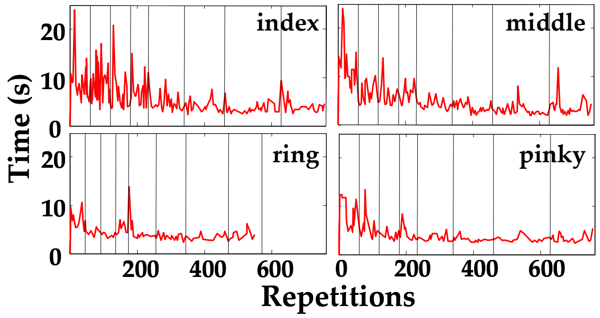

Fig. 3. Demonstrates changes in time to approach and press a virtual piano trainer key over the course of 600 to 800 repetitions for each of the four hemiparetic fingers of a representative subject during an 8 day training intervention.

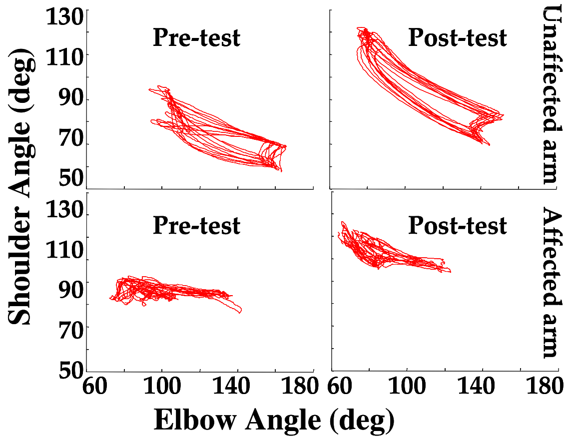

Fig. 4. Relative shoulder and elbow angles of a subject as he performs a horizontal reach, grasp, release and return movement for ten repetitions. Top panels are the non paretic arm, bottom panels are the paretic arm. Pre-test data was collected one day prior to training and post test data was collected two days after.

B. Piano Trainer Kinematics

The 8 subject group achieved a 69% improvement in duration and a 111% improvement in fractionation. Figure 3 demonstrates changes made by a representative subject in key press time for each finger. This measure combines hand transport and finger movement suggesting that performance improved for both effectors. This is confirmed by Figure 3 depicting fractionation changes made by this subject for each finger.

C. Untrained Task Kinematics

Figure 4 demonstrates pre and post training performance in the elbow and shoulder angle relationship during a real – world, horizontal reaching and grasping task. Visual inspection of the post-test loops reveal more consistent performance and a pattern that approximates the loop

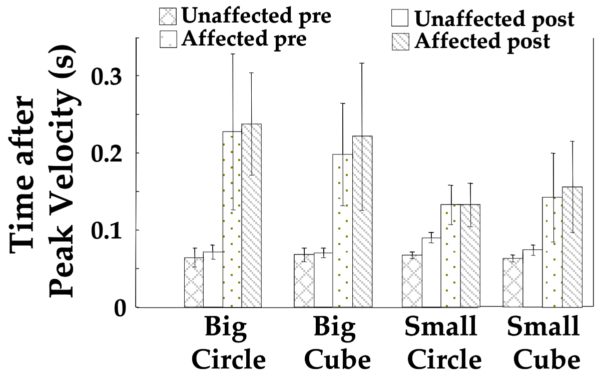

Fig. 5. Pre and post-testing data for average time after peak velocity has been achieved until grasp has been completed for four different object shapes are shown for one subject. Two left columns for each condition are the unimpaired hand. The two right columns are impaired hand performance. Larger values indicate slower movement. Pre-test data was collected one day prior to training and post test data was collected two days after.

TABLE I
CLINICAL TESTS SCORE

	Mean Aggregate Time (SD) Pre-Test	Mean Aggregate Time (SD) Post-Test	Mean Percent Improvement
Wolf Motor Function Test (sec) n=8	57 (12)	41 (9)	27
Jebsen Test of Hand Function (sec) n=8	117 (34)	92 (37)	22
Box and Blocks (# blocks) n=8	35 (9)	39 (10)	9
Nine Hole Peg Test (sec) n= 6	92 (92)	51 (17)	16

produced by the uninvolved arm more closely than pre-test performance.

Figure 5 demonstrates the time after peak finger extension velocity for the same subject for four conditions of reaching. This time period represents the final hand shaping and grasping phases for these movements. This figure presents no clinically significant improvements which may suggest that hand function may require task specific training more than the proximal upper extremity.

D. *Clinical Tests of Upper Extremity Function*

Table 1 summarizes the changes in WMFT, JTHF, BBT and 9HPT performance demonstrated by the 8 subject group in response to training. The group demonstrated statistically significant improvements in all tests except the 9HPT. Two subjects were unable to complete the 9HPT at pre-testing. Both completed the test at post-testing and the remaining subjects demonstrated a 16 % mean decrease in time.

IV. DISCUSSION

Our pilot subject results, which demonstrate improvement in proximal, as well as distal UE kinematics for the two robotic tasks, differ from those of Lin et al [15] who identified improvements in movement time and proximal kinematics but not measures of distal kinematics, following constraint induced movement therapy, a real world correlate of Hand-Arm Training. This paper demonstrates the rich single-subject data that can be produced utilizing robotically collected kinematic data. While this type of information is valuable for post-hoc analysis and dissemination it may also carry the potential for application during a training intervention. Once effective measures have been established, analyzing improvement trends after the first few and subsequent training sessions, may allow for adjustment of task parameters and adaptive algorithms during a multi-session training intervention. The ability to customize an intervention based on performance and control changes may considerably expand a clinician's effectiveness.

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