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## Robots integrated with virtual reality simulations for customized motor training in a person with upper extremity hemiparesis: a case report

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### Abstract

**Background and Purpose**—A majority of studies examining repetitive task practice facilitated by robots for the treatment of upper extremity paresis utilize standardized protocols applied to large groups. Others utilize interventions tailored to patients but don't describe the clinical decision making process utilized to develop and modify interventions. This case report will describe a robot-based intervention customized to match the goals and clinical presentation of a gentleman with upper extremity hemiparesis secondary to stroke.

**Methods**—PM is an 85 year-old man with left hemiparesis secondary to an intracerebral hemorrhage five years prior to examination. Outcomes were measured before and after a one month period of home therapy and after a one month robotic intervention. The intervention was designed to address specific impairments identified during his PT examination. When necessary, activities were modified based on the patient's response to his first week of treatment.

**Outcomes**—PM trained twelve sessions using six virtually simulated activities. Modifications to original configurations of these activities resulted in performance improvements in five of these activities. PM demonstrated a 35 second improvement in Jebsen Test of Hand Function time and a 44 second improvement in Wolf Motor Function Test time subsequent to the robotic training intervention. Reaching kinematics, 24 hour activity measurement and the Hand and Activities of Daily Living scales of the Stroke Impact Scale all improved as well.

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**Discussion**—A customized program of robotically facilitated rehabilitation resulted in large short-term improvements in several measurements of upper extremity function in a patient with chronic hemiparesis.

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## INTRODUCTION

Repetitive task practice (RTP) is an activity-based therapeutic approach designed to rehabilitate the upper extremities of persons with hemiplegia secondary to strokes.<sup>1, 2</sup> Important factors related to the effectiveness of this intervention include maintenance of high levels of intensity throughout practice sessions and performance of higher repetitions of activity than performed in more traditional approaches to upper extremity rehabilitation.<sup>3</sup> Multiple authors describing the training of upper extremity reaching and functional activities in virtual environments have demonstrated that motor skills can be learned through repetitive practice within both immersive and non-immersive and visually simple and complex virtual environments.<sup>4</sup> For example, it has been shown that changing the visual gain of a movement can harness small degrees of active finger movement and use them to perform meaningful activities in virtual environments.<sup>5</sup> Robotics and virtual environments have been utilized to facilitate the intensity and volume requirements of RTP.<sup>6, 7</sup> To date, the majority of the interventions using these robotic systems have been studied using standardized experimental protocols in groups of patients, using a uniform set of impairment based upper arm movements. Two studies describe attempts at customizing interventions, one utilized custom force fields to shape reaching trajectories of individual patients to conform to a goal trajectory,<sup>8, 9</sup> a second combined standardized, impairment based robotic activities with a customized, traditional inpatient rehabilitation program.<sup>8</sup> Several systems strive to individualize interventions via more adaptable physical interfaces<sup>10</sup> adapted tasks,<sup>11</sup> adapted feedback or physical components of the system.<sup>12</sup> However, none of the studies utilize a multifaceted intervention that selects activities to match the specific impairments demonstrated by a patient or addresses their individual goals.

Two robotically facilitated virtual rehabilitation systems, the NJIT-RAVR system and the NJIT Track-Glove system were used in this case report. The NJIT-RAVR system uses a CyberGlove and a Haptic Master, a 3-degrees of freedom, force controlled robot. Three more degrees of freedom (yaw, pitch and roll) are added to the arm by using a gimbal, with force feedback available for pronation/supination (roll). A three-dimensional force sensor measures the external force exerted by the user on the robot. In addition, velocity and position of the robot's endpoint are measured at 1000 per second allowing the robotic arm to act as an interface between the participants and the virtual environments. This enables movement against gravity in a 3D workspace. The Track/Glove uses a CyberGlove and the Flock of Birds motion sensors for finger and arm tracking. Simulations were programmed using either C++/OpenGL, the Virtools software package or the Haptic Master's Application Programming Interface. These allow one to program the robot to produce haptic effects such as gravity and haptic objects like blocks, cylinders, walls, tables and shelves. When compared to other robotic training devices, the novel aspects of the NJIT-RAVR and Track-Glove training systems are; 1) it is the only robotic system that trains three dimensional reaching and hand opening movements in an integrated fashion, 2) it is fully integrated with a variety of activity-based virtual reality gaming simulations, and 3) it incrementally

modifies task constraints based on a participant's performance of each repetition of an intervention. In previously published studies using the NJIT-RAVR and Track-Glove systems, the experimental protocols used a standardized approach to test the capabilities of this system to train patients on activities that integrate arm and finger movement and compare this approach to training the arm and hand in isolation.<sup>6</sup> The virtual reality simulations used, feedback provided to the patient, the progression of difficulty, and positioning of the patients in relation to the robot were applied uniformly to all patients that met inclusion criteria, without regard to individual therapeutic goals, specific impairments or responses to the intervention.<sup>6, 13</sup> This case report describes a clinically relevant use of the system that was designed specifically for an individual patient. Therefore, this case report adds a new dimension to the body of work previously published on robotically-assisted interventions. Simulations were chosen that addressed the motor impairments identified during his examination that limited his ability to perform goal activities. The simulations were configured in terms of required movement patterns, speed, range of motion and task parameters to maximize his ability to benefit from them. The simulations were further modified based on his responses to the first few training sessions.

It is timely to provide clinically relevant individualized case reports, to inform clinicians about the potential use, methods of application and challenges encountered in providing interventions that utilize robotic/virtual reality systems. This report will demonstrate the process and challenges of developing a therapeutic intervention utilizing robots and virtual environments as well as the process of examining the generalization of motor skills attained using these technologies into real world activities.

## **CASE DESCRIPTION: HISTORY AND SYSTEMS REVIEW**

PM is an 85 year-old gentleman with left hemiparesis secondary to an intracerebral hemorrhage (ICH) and subsequent craniotomy five years prior to this examination. Past medical history includes paroxysmal atrial fibrillation, atrophic right kidney, recurrent urinary tract infections and several bouts of pneumonia. Surgical history includes a permanent pacemaker placement 35 years prior to examination (PTE).

Rehabilitation history following the ICH five years PTE included sixteen weeks inpatient rehabilitation, followed by nine months of outpatient physical therapy (PT) and occupational therapy (OT). After a hiatus PM received two to three hour biweekly sessions of OT in his home for approximately one year followed by a combined PT and OT program focusing on ambulation, balance, transfers, sensory integration and upper extremity function for the next three years. This was his therapy routine prior to the robotic intervention. A summary of these interventions, specifying the tasks performed is included in Appendix 1 (<http://links.lww.com/JNPT/A19>).

PM lives with his wife and a live-in home health aide. PM performs bed mobility and transfers with contact guard / close supervision, requires maximum assistance for lower body dressing and moderate assistance for toileting and upper body dressing. He performs grooming and feeding with supervision. The patient uses a power wheelchair for mobility but is able to walk up to 150 feet with contact guard using a cane.

## EXAMINATION

PM reported no pain during the exam. Light touch and proprioception were within normal limits. PM demonstrated decreased visual attention to his left hemi-space. Cognition was within functional limits but assessment was confounded by PM's visual perception and use of bilateral hearing aids. Passive range of motion was comparable in both UE but PM demonstrated 1+4 spasticity of the shoulder extensors and elbow flexors measured by the Modified Ashworth Scale.<sup>14</sup> PM was able to flex his hemiparetic shoulder 108° against gravity and extend his hemiparetic elbow, wrist and fingers to neutral against gravity. PM demonstrated partially isolated, movement against gravity at all joints of the upper extremity and fine motor coordination impairments of the hand.

## CLINICAL IMPRESSION

PM was identified as a suitable candidate for this intervention for several reasons. He demonstrated sufficient motor abilities to interact with the system and the endurance to perform ninety minutes of treatment. Gross mobility, postural control and perceptual impairments had been addressed effectively with his home therapy program but he had not performed a focused intervention to address his upper extremity function in eighteen months. His goals, improved use of the impaired upper extremity during transfers and dressing and improved use of the upper extremity during eating, grooming and computer activities are typical for a person in the chronic stage of stroke recovery.<sup>15</sup> Several motor skills that are critical components of his goal activities can be addressed by the NJIT-RAVR system<sup>5, 16</sup> and his sensory and motor impairments were comparable to those of persons that had interacted with this system productively in the past.

## INTERVENTION

We hypothesized that interventions targeting motor control and function limitations would translate into improvements in the timed batteries of real-world activities, measures of twenty-four hour activity and participation. This protocol was approved by the Institutional Review Boards of the New Jersey Institute of Technology and the University of Medicine and Dentistry of New Jersey.

### Parameters

PM performed twelve, sixty to ninety minute sessions of training over four weeks with two robotically facilitated virtual rehabilitation systems, the NJIT-RAVR system (See Figure 1a) and the NJIT Track-Glove system (See Figure 1b), which are described in detail elsewhere.<sup>5, 16</sup> This training duration was chosen with the goal of achieving the 16 hours of practice associated with improvements in UE function<sup>3</sup> and to exceed the 300 repetitions/session that is the smallest number of repetitions associated with neuroplasticity.<sup>2</sup> PM performed no upper extremity interventions other than the robotic intervention described in this paper, during this time period, but he performed ambulation and lower extremity strengthening two to three times per week with his home PT. PM performed the same six simulations at all of the sessions. These simulations were chosen by the physical therapist managing the intervention (the primary author) from a suite of ten simulations to address the

component skills of the activities PM identified as goals. Calibration of the workspaces and positioning of the patient in relation to the system was performed by the primary author with the assistance of PM's home therapists who attended each robotic training session. This team monitored training performance and made adjustments to the robotic training intervention. A biomedical engineer was available during training to facilitate major adjustments as necessary. Based on time signatures from the records of each simulation, each activity was performed for nine to twelve minutes during the first week and between twelve and fifteen minutes per session in the three subsequent weeks. The variation in these times was predominantly related to set-up. Activity times were distributed evenly to allow for balanced practice of all of the targeted skills.

## Procedures

A brief description of each simulation, the therapeutic goals it was designed to address, the performance measure designed to track progress, the feedback provided, the range of repetitions performed, and the approach to increasing the intensity of the activity are described in Table 1. A discussion of the configuration and application of each simulation as they relate to the patient's goals are described below.

PM had difficulty buttoning buttons, donning glasses and keyboarding due to an inability to flex fingers individually. We utilized the Virtual piano trainer simulation (Figure 1b & Table 1) to address this impairment. PM played scales and drills with his hand stationary and attempted simple songs with his hand moving across the entire keyboard. The simulation measures fractionation, the difference between the flexion angles of the finger designated to press a key and the average of the other fingers. When the appropriate finger is used and the target fractionation is achieved, the note sounds. PM made little progress during training with the Virtual Piano Trainer simulation as measured by his first three daily fractionation scores (Table 2). We added an exoskeleton robot, the CyberGrasp to assist PM in maintaining extension of the non-designated fingers (Figure 1c). For example, when the index finger is cued, the middle, ring and pinky fingers are held in extension by the Cybergrasp, there is no extension force on the index finger, allowing it to flex independently of the others. This switching of resistance based on which finger is cued provides a different stimulus than would be afforded by an un-programmed, dynamic finger extension splint that holds all fingers in extension.

PM used the CyberGrasp during the entire second week of training. During week three, PM used the CyberGrasp during the first five minutes of each session with the Virtual piano trainer, finishing the fifteen minute block without the robot. PM did not use the CyberGrasp at all during week four. PM demonstrated steady improvements in daily fractionation score after week one (Table 2). The mean number of repetitions per session for this simulation was 172 (range: 118 – 225).

PM demonstrated difficulty controlling the aperture of his hand during grasping activities that impacted dressing, eating and grooming. We utilized the Space Pong simulation (Table 1) to address this impairment. PM played the pong game against the computer controlling the paddle with flexion and extension of his fingers. Game score served as feedback. During week one, PM had difficulty performing the Space Pong simulation as evidenced by very

low accuracy scores, due to an all or nothing quality of his hand opening (Table 2). After week one, we decreased the gain from patient movement to virtual movement by 30%. This increased the amount of finger movement required to produce paddle movement allowing PM to control his paddle accurately. Gain was increased by 15% on day 6 and back to 100% on day 10. The mean number of repetitions per session for this simulation was 52 (range: 36 – 72).

PM had difficulty opening his hand, with his shoulder elevated, making it difficult to return cups to a table without spilling. We utilized the Hammer simulation in dynamic mode to address this impairment (Table 1). PM reached to targets in a virtual space and hammered them using a repetitive finger extension movement. Vibration from the NJIT-RAVR simulated physical contact with the peg when PM hit them successfully. A hammering sound signaled when successful movements were performed. We utilized an algorithm that increased the target area, decreasing shoulder stability demands when PM completed targets slowly. We decreased the target area, which increases the need to stabilize the arm when he completed targets quickly. During the first two weeks of the trial, PM made steady improvements in endpoint deviation, a measurement of extraneous movement, while performing the Hammer finger extension simulation in dynamic mode (Table 2). He maintained these gains during the final two weeks of training. The mean number of repetitions per session for this simulation was 21 (range: 10 – 35).

We utilized the hammer simulation in static mode (with the arm fixed in space) to train a repetitive pronation movement in varying degrees of elbow extension and shoulder flexion (Table 1). Pronation is a critical component of eating and grooming skills that PM had identified as targets for improvement. PM did not make significant improvements in his ability to pronate his upper extremity with his shoulder flexed and elbow extended during the use of the Hammer simulation in fixed mode (Table 2). We increased the gain between pronation and hammer movement which decreased the amount of motion the patient had to perform in order to hammer the peg but this manipulation did not result in a consistent increase in pronation excursion. The mean number of repetitions per session for this simulation was 28 (range: 20 – 40).

PM had difficulty making large excursion forward reaches, secondary to synergistic extension of his trunk during shoulder flexion that limited his ability to utilize grab bars during transfers. We utilized two simulations to improve this action. The Reach-Touch simulation trained shoulder active range of motion without trunk movement (Table 1). During this simulation, PM moved a cursor to touch ten targets in a 3-d workspace presented in stereo. An exploding sound was heard when the appropriate target was touched. Time to touch each set of ten targets was shown at the end of each set along with PM's best time for the day. We increased the workspace in which PM performed this simulation daily. PM maintained his movement times despite the increases in workspace (Table 2). The mean number of repetitions per session for this simulation was 44 (range: 20 – 51).

We utilized the Cup Reaching simulation to address shoulder elevation combined with trunk movement (Table 1). During training with this simulation, PM attached his hand to a virtual cup, and placed it on one of nine spaces on a virtual shelf. We set the height, width and

distance of the shelves based on PM's maximum reaching excursions, measured weekly, with PM's trunk moving freely and encouraged him to flex at the trunk to increase his forward reaching distance. Force feedback was provided to prevent PM from moving the virtual cup through the shelves or virtual table during performance of this simulation to encourage more natural behavior. The weight of the virtual cups was lowered if fatigue caused a visually-obvious flexion synergy at the shoulder and elbow. In addition, the time to place each cup was provided immediately after each repetition. The excursion of his forward reach improved during performance of the Cup Reaching simulation while movement time decreased (Table 2). Prior to calibrating the workspace on Day 10, the Physical Therapist managing the trial encouraged PM to challenge himself. This resulted in a much larger increase in reach excursion that PM maintained well during the last week of training. The mean number of repetitions per session for this simulation was 39 (range: 17 – 63).

### Responses to Intervention

PM tolerated this intensive intervention very well, was focused and required no encouragement to maintain attention during the training. PM described himself as “tired” after training sessions but did not need to modify his daily activities to accommodate the exertion. On training day three, during the hammer simulation, he complained of shoulder pain while pronating his forearm with his shoulder flexed to approximately 80 degrees. These complaints subsided immediately after we lowered his arm position during this simulation and did not reoccur.

## OUTCOMES

### Testing Procedure

The first author, who was not blinded to the intervention, performed all outcome measures. Data was collected one day before and one day after 12 sessions of robotically facilitated training. To examine at the body structure / function level we used the Upper Extremity Fugl-Meyer Assessment (UEFMA) and the Reach to Grasp Test (RTG).<sup>17</sup> For the UEFMA intra-rater reliability (ICC = 0.87) and interrater reliability (ICC= 0.99) are both high and the correlation between UEFMA score and FIM score is statistically significant ( $r= 0.76$ ) in persons with stroke.<sup>18</sup>

The Reach to Grasp test (RTG) is a kinematic analysis of a reach, grasp, transport, release sequence that was not specifically trained during our intervention.<sup>19</sup> Time to peak velocity (TTPV) of the first reaching movement was used to analyze PM's ability to coordinate his shoulder and elbow, and time after peak velocity (TAPV) to initiation of the object transport movement to evaluate PM's ability to fine-tune grasp and initiate object transport. Hand trajectories of PM performing the entire three-movement sequence are presented to demonstrate changes in his ability to coordinate the shoulder and elbow joints (see Fig. 2c).

To test for changes at the activity level we utilized a combination of the Wolf Motor Function Test<sup>20</sup> (WMFT), the Jebsen Test of Hand Function (JTHF)<sup>21</sup> and the Nine Hole Peg Test<sup>22</sup> (NHPT). The WMFT has high levels of interrater reliability (ICC = 0.97) and test-retest reliability (ICC= 0.90).<sup>23</sup> Two studies by Wolf et al showed that the test can differentiate the more affected extremity and the less affected extremity in persons with

chronic stroke.<sup>19</sup> The modified JTHF has been demonstrated to have good levels of intra-rater reliability ( $r = 0.72$ ) and good concurrent validity with the Action Research Arm Test (ARAT) ( $r = 0.87$ ) and Nine Hole Peg Test ( $r = 0.84$ ) in persons with stroke.<sup>24</sup> The NHPT has demonstrated high levels of intra-rater reliability (ICC = .86)<sup>25</sup> and strong correlations with the JTHF ( $r = 0.87$ ) and ARAT ( $r = 0.79$ )<sup>24</sup> in persons with stroke. During performance of the UEFMA, the therapist noticed PM had difficulty dissociating shoulder flexion and trunk extension and added the Modified Functional Reach Test<sup>26</sup> (MFR) to measure this construct objectively. The MFR has been demonstrated to have high intra-rater reliability (ICC = 0.95) and a statistically significant correlation with postural sway during forward reaching ( $r = 0.48$ )<sup>26</sup> in persons with CVA.

We tested for changes at the activity level in his home environment by using an Actigraph tri-axial accelerometer. We collected UE acceleration data for 24 hours immediately after each testing session. Metrics included total vertical plane activity,<sup>27</sup> and total roll plane activity. Roll plane motion was added because pronation and supination movements tend to be a smaller component of non-purposeful movement than the vertical flexion activity measured in other studies.<sup>28</sup> Total activity measurements in each plane were measured in one-second epochs. Any epoch in which the peak acceleration exceeded 0.16 meters per second squared was identified as an active epoch in that plane. The number of active epochs was totaled for the day and divided by sixty to produce a total activity time in minutes for each 24 hour period.<sup>27</sup> In addition, the ratio of the total vertical plane activity of the impaired arm compared to the total vertical plane activity of the unimpaired arm was calculated.<sup>29</sup> To test for changes at the participation level, PM completed the hand, mobility, activities of daily living and social participation subscales of the Stroke Impact Scale (SIS). This is the only self-report measure in the outcome battery. Each scale has been established as reliable and valid measurements in persons with strokes of moderate severity.<sup>30</sup>

PM demonstrated a four-point improvement in the UEFMA after the month of robotically facilitated training (Table 3). Moreover, during the RTG post-test, PM demonstrated large improvements (146 milliseconds) in TTPV, a measure of shoulder and elbow coordination (Figure 2b). Finally, TAPV, a measure of the ability to fine tune grasp, improved by 101 milliseconds (Figure 2b). Visual inspection of the movement trajectories of the entire three-phase activity demonstrates considerable improvements in smoothness of the movement and consistency of the trajectory (Figure 2 c & d).

PM's improvements in UE activity measures were impressive as well (Table 3). He showed a 35 second improvement in the JTHF after the robotic intervention, and a robust 44 second improvement in the WMFT which exceeds the published MCID of 2.7 seconds<sup>31</sup> (Table 3). PM showed a seventeen second improvement in function level items of the WMFT and a 27 second improvement in activity level tasks (can to mouth, card turning, towel folding, key turning and checker stacking). NHPT improved fourteen seconds which was smaller than the MCID of 30 seconds published for this test<sup>32</sup> and MFR distance increased 10 inches following robotic training (Table 3).

Twenty-four hour activity measurements demonstrated across the board improvement subsequent to robotic training as well (Table 3). Active vertical plane movement increased



by 26 minutes. Roll plane movement increased by 13 minutes. The ratio of impaired arm to unimpaired arm movement increased from 41% to 51%. PM demonstrated an improvement of six points in the social participation scale, eight points in the ADL scale and seven points on the hand scale of the SIS.

## DISCUSSION

This case report addressed the developing need to explore how to effectively use robotic/virtual reality technology for individualized treatment programs. It describes a novel contribution to the growing robotic rehabilitation for stroke by presenting the outcomes of a personalized robotic intervention based on the findings of a patient's physical therapy examination. We demonstrated the decision-making process and application of a haptic robot system that is integrated with activity-based virtual reality simulations for the management of a gentleman with hemiparesis post-stroke. As in customary physical therapy care, the intervention was tailored for the patient and modified over time based upon the subject's responses. The control systems governing the patient's robotic interactions and the feedback presented by the virtual reality simulations were adapted to address his impairments, functional limitations and goals.

PM had a consistent volume of physical and occupational therapy, far above the usual amount received by patients post stroke, yet he made substantial changes after this intervention. A critical dosage or intensity of training necessary for the improvement of hand function may not have been achieved during his home therapy sessions despite the long treatment times. The challenge of providing sufficient repetition in traditionally implemented rehabilitation has been documented.<sup>2, 3</sup> Higher levels of efficiency in terms of the number of repetitions of task-based activity performed in a given period of time are a significant advantage afforded by technology based rehabilitation. The novelty of the activities, the intensity of the cognitive experience, the progressive adaptation of the activities and the focus on hand movements may have also influenced the improvement seen in this patient following this intervention. This report demonstrates the flexibility of the NJIT-RAVR and Track-Glove systems and the ability to individualize a robotic intervention. Following a search of over 200 articles, it appears that this approach has not been adequately examined in the existing literature.<sup>7, 10, 11</sup>

This patient's changes in movement kinematics were accompanied by robust changes in the real-world WMFT and JTHF outcome measures. It has been hypothesized that transfer of learning is more successful when there is similarity between practice characteristics and desired outcome;<sup>33</sup> therefore specificity of practice is important. Although the majority of tasks used during this training paradigm were activity based, one cannot argue that the practice characteristics of a virtual environment and the real-world are similar. It is therefore interesting to conjecture what aspects of the robotic/virtual reality training influenced the robust changes in the outcome measures. Variation in practice is also considered an important component necessary for retention and generalizability of skills.<sup>34, 33</sup> This patient was trained using not only a variety of tasks, but importantly the kinematic and task requirements of each task were modified and adapted at a level that would be difficult and in some cases impossible without the use of an integrated robotic / VR system. Thus the patient

had to consistently select an appropriate movement pattern within the changing context of the task. This may have facilitated the transfer of learning seen in the execution of the real-world outcome measures.<sup>34</sup> Variation in the activities performed during Constraint Induced Movement Therapy (CIMT) has been proposed as the reason those subjects improve on the WMFT.<sup>1</sup> Although there are substantial benefits to therapy that includes a robotic/virtual reality intervention, there are also substantial challenges. The system is costly and at this point in time, patient-centered systems require engineering skills to individualize the robotic and simulation parameters.

Two limitations to this study were the non-blinded assessment of outcomes and the lack of follow-up data due to PM's repeated urinary tract infections post-intervention. The fact that the timing the final outcome measures were performed immediately following the intervention limit our ability to make claims related to the durability of the changes PM made during the robotic intervention. Finally, there was extensive interdisciplinary collaboration between three therapists during the implementation of this intervention not usually typical in current health care setting in the U.S.

This extensive description of an individualized robotic/virtual reality intervention has shown how it can be successfully used as an intervention incorporating an individualized patient-client management model and that a person participating in such an intervention can generalize the motor adaptations they make during practice into real world function, at least in the short-term. Future directions should include rigorous investigations of the effects of adaptive modifications of task parameters and the manipulation of the scaling of the relationship between visual feedback and participant movement. Further study of the implementation of robotic and virtually simulated rehabilitation activities within the framework of the patient client management model will also be necessary to establish the usability and effectiveness of these technologies in clinical settings. In addition, investigation into neurological mechanisms underlying the generalization of motor adaptations made during technology based interventions into real world motor skills may be necessary to fully justify their continued development and use.

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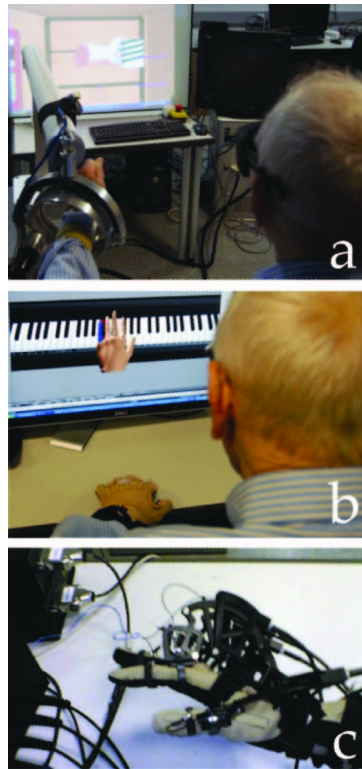
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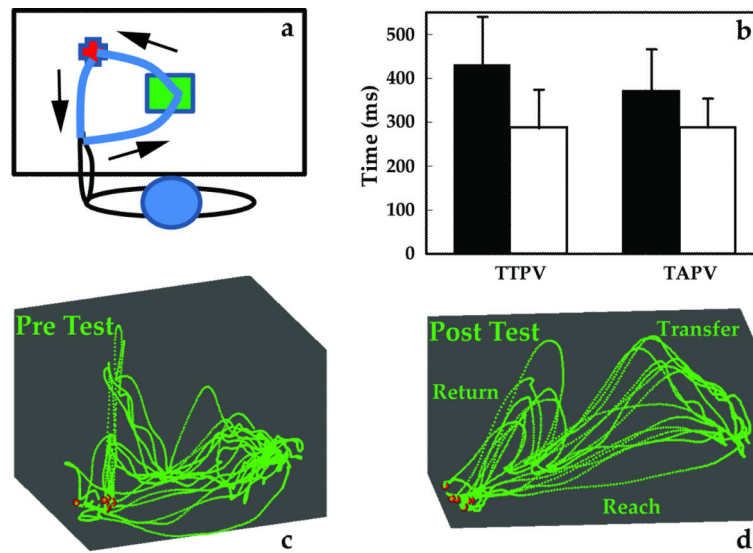
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**Figure 1.**

1a. Patient performing Cup Reach simulation using NJIT-RAVR system. 1b. Patient performing Piano Trainer simulation utilizing NJIT-TrackGlove system. 1c. The CyberGrasp, a cable actuated exoskeleton robot, worn over the TrackGlove system to assist in the extension of non-targeted fingers during Virtual Piano Trainer performance.


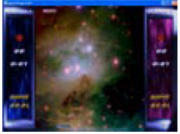






**Figure 2.**

2a. Schematic of RTG test. 2b. Pre Test and Post-Test values for Time to Peak Velocity of Movement 1 and Time from Peak Velocity of Movement 1 to Initiation of Movement 2. 2c. Trajectories during ten repetitions of reach to grasp, transport, release and return of a 30mm diameter disc prior to training. 2d. Trajectories of same activity immediately after training.

Table 1

## Training Simulations and Treatment Strategy

| Virtual Reality Simulation  | Game   | Impairment                                   | Metric   | Strategies  |
|---|--|--|--|---|
| <p>Piano</p>                     | <p>Patient plays scales and simple songs. Each key is cued and the finger to press it designated.</p>  | <p>Decreased Finger Individuation</p>        | <p>Fractionation<br/>Time to press keys</p>                            | <p>Algorithm sets fractionation target based on performance. Utilize CyberGrasp™ to teach movement pattern if subject does not respond to algorithm.</p>                      |
| <p>Space Pong</p>                | <p>Patient plays a pong type game against the computer. Subject moves the paddle to the right by opening their fingers and to the left by closing them.</p>        | <p>Decreased Finger Extension modulation</p> | <p>Accuracy</p>  | <p>Decrease proportion of subject movement (finger extension) to paddle movement if accuracy does not improve with practice. Increase proportion when accuracy increases.</p> |
| <p>Hammer Extension Dynamic</p>  | <p>Patient reaches for a target peg and hammers it into the floor by flexing and extending his fingers. Hammer only hits the target when it is in target area.</p> | <p>Decreased Shoulder Stabilization</p>      | <p>End point<br/>Deviation Time to hammer pegs</p>                     | <p>Decrease the size of the target as time to hammer pegs decreases.</p>  |
| <p>Hammer Pronation Fixed</p>  | <p>Patient hammers peg into the floor by pronating his forearm. Robot holds hammer stable over the target peg.</p>   | <p>Decreased Shoulder-Elbow Isolation</p>    | <p>Peak pronation range<br/>Time to hammer pegs</p>                    | <p>Decrease proportion of subject movement (pronation) to hammer movement as time to hammer pegs decreases</p>  |
| <p>Cups</p>                    | <p>Patient attaches virtual hand to virtual mugs and places them on virtual shelves in a 3-d workspace.</p>  | <p>Decreased Shoulder-Trunk Isolation</p>    | <p>Time to place nine cups on shelf<br/>Reaching trajectory length</p> | <p>Increase volume of workspace as time to place cups on shelf decreases Recalibrate workspace weekly</p>   |
| <p>Reach-Touch</p>             | <p>Patient moves cursor to touch ten targets in a in a 3-d workspace.</p>  | <p>Decreased Shoulder AROM</p>               | <p>Time to touch ten<br/>Trajectory length</p>                         | <p>Increase size of workspace as duration decreases Recalibrate workspace weekly.</p>   |

**Table 2**

Daily Training Kinematics and Percentage Changes

| Simulation-metric-unit                  | Day 1  | Day 2  | Day 3   | Day 4   | Day 5    | Day 6   | Day 7    | Day 8    | Day 9   | Day 10 | Day 11  | Day 12  |
|---|--------|--------|---------|---------|----------|---------|----------|----------|---------|--------|---------|---------|
| Piano -Fractionation -deg               | 10 (8) | 1 (2)  | -2* (4) | 4* (10) | 14* (13) | 9* (14) | 10+ (14) | 15+ (12) | 7+ (13) | 7 (14) | 20 (13) | 22 (16) |
| Space Pong-Accuracy- sec                | 10 (4) | 11 (2) | 11 (2)  | 8 (3)   | 9 (4)    | 9 (3)   | 10 (3)   | 9 (4)    | 8 (2)   | 10 (3) | 9 (3)   | 9 (4)   |
| Reach Touch -workspace- cm <sup>3</sup> | .23    | .20    | .23     | .34     | .40      | .41     | .37      | .40      | .41     | .72    | .72     | .82     |
| Cup Reach - Time- sec                   | 12 (3) | 12 (6) | 8 (5)   | 6 (4)   | 4 (2)    | 5 (3)   | 4 (3)    | 6 (4)    | 4 (2)   | 5 (3)  | 6 (5)   | 6 (4)   |
| Cup Reach -reaching distance- cm        | 15     | 19     | 21      | 22      | 24       | 21      | 26       | 29       | 29      | 38     | 40      | 38      |

deg=degree, cm=centimeters, sec=second, cm<sup>3</sup>=cubic centimeters

\* trained with CyberGrasp™ 100%

+ trained with CyberGrasp™ 50%



| Measure (% Change)                                      | Pre-Test | Post-Test | Percent Change * |
|---|----------|-----------|------------------|
| Wolf Motor Function Test time <i>seconds</i>            | 164      | 124       | 26               |
| Wolf Motor Function Test- Proximal time <i>seconds</i>  | 34       | 18        | 31               |
| Wolf Motor Function Test - Distal time <i>seconds</i>   | 130      | 106       | 25               |
| Wolf Motor Function Test -Activity time <i>seconds</i>  | 113      | 90        | 22               |
| Wolf Motor Function Test -Function time <i>seconds</i>  | 51       | 34        | 36               |
| Upper Extremity Fugl-Meyer Assessment (Max=56)          | 50       | 52        | 8                |
| Upper Extremity Fugl-Meyer Assessment Proximal (Max=32) | 28       | 32        | 10               |
| Upper Extremity Fugl-Meyer Assessment- Distal (Max=24)  | 22       | 22        | 16               |
| Jebsen Test of Hand Function time <i>seconds</i>        | 247      | 197       | 18               |
| Nine Hole Peg Test time <i>seconds</i>                  | 114      | 104       | 19               |
| Modified Functional Reach Test distance <i>inches</i>   | 12       | 24        | 71               |
| Impaired Vertical Activity time <i>minutes</i>          | 130      | 155       | 33               |
| Impaired Roll Activity time <i>minutes</i>              | 148      | 161       | 18               |
| Upper Extremity Ratio (impaired/unimpaired)             | 41       | 51        | 24               |