Published in final edited form as:

Int J Disabil Hum Dev. 2014 September ; 13(3): 401–407. doi:10.1515/ijdh-2014-0334.

Robotic/virtual reality intervention program individualized to meet the specific sensorimotor impairments of an individual patient: a case study

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Abstract

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. This study will describe a virtually simulated, robot-based intervention customized to match the goals and clinical presentation of a gentleman with upper extremity hemiparesis secondary to stroke. MP, the subject of this case, is an 85-year-old man with left hemiparesis secondary to an intracerebral hemorrhage 5 years prior to examination. Outcomes were measured before and after a 1-month period of home therapy and after a 1-month virtually simulated, robotic intervention. The intervention was designed to address specific impairments identified during his PT examination. When necessary, activities were modified based on MP's response to his first week of treatment. MP's home training program produced a 3-s decline in Wolf Motor Function Test (WMFT) time and a 5-s improvement in Jebsen Test of Hand Function (JTHF) time. He demonstrated an additional 35-s improvement in JTHF and an additional 44-s improvement in WMFT subsequent to the robotic

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training intervention. A 24-h activity measurement and the Hand and Activities of Daily Living scales of the Stroke Impact Scale improved following the robotic intervention. Based on his responses to training we feel that we have established that a customized program of virtually simulated, robotically facilitated rehabilitation was feasible and resulted in larger improvements than an intensive home training program in several measurements of upper extremity function in our patient with chronic hemiparesis.

Keywords

hemiplegia; motor rehabilitation; stroke; virtual reality (VR)

Introduction

Robotics and virtual environments are being combined to facilitate the intensity and volume requirements of repetitive task practice [1, 2]. To date, the majority of these interventions have been studied using standardized experimental protocols in groups of patients, using a uniform set of upper arm movements and simulations [3, 4]. Several systems have attempted to individualize the interventions through more adaptable physical interfaces [5], adapted tasks [6], and adapted feedback or physical components of the system [7]. Similarly, in our previously published studies using the NJIT-RAVR and NJIT Track/Glove systems, the experimental protocols used a standardized approach applied uniformly to all included patients, without regard to individual therapeutic goals, specific impairments, or responses to the intervention [1, 8]. This case report attempts to describe a clinically relevant implementation of the system using an intervention protocol designed specifically for an individual patient, thus adding a new dimension to the body of work previously published on robotically assisted virtual reality (VR) interventions. Simulations were chosen that addressed the motor impairments identified during the subject's examination that limited his ability to perform specific goal activities. The simulations were configured in terms of required movement patterns, speed, and range of motion to maximize the subject's ability to benefit from them. The simulations were then further modified based on his responses to the first few training sessions. This case study compares the outcomes of 1 month (12 sessions) of home physical and occupational therapy to 1 month (12 sessions) of individualized robotic/VR training.

Methods

Two robotically facilitated virtual rehabilitation systems, the NJIT-RAVR system and the NJIT TrackGlove system, were used. These two systems when used sequentially in a training session have the capability of training individual fingers of the hand and all motions of the arm. It is fully integrated with a library of 12 activity-based VR gaming and task simulations. For MP we chose six of the simulations: Virtual Piano; Space Pong; two modes of Hammering Task; Cup Placement; and Reach-to-Touch. A CyberGlove[®] (Immersion) was used for hand tracking. Two of the six simulations use the Flock of Birds (Ascension Technologies) motion sensors for arm tracking and the other four use the Haptic Master robot (Moog FCS Corporation). Simulations were programmed using either C++/OpenGL,

the Virtools software package with the VR Pack plug-in (Dassault Systemes) or the Haptic Master's Application Programming Interface. One game was adapted from an existing Pong game in which the game control was transferred from the computer mouse to the CyberGlove.

Subject

MP is an 85-year-old gentleman with left hemiparesis secondary to an intracerebral hemorrhage 5 years prior to his examination. He uses a power wheelchair for mobility but is able to walk short distances and requires moderate assistance for activities of daily living.

Outcome measures

Outcomes measures included kinematic analysis of trained movements utilizing data collected daily by the robotic systems such as finger angles, duration of the combined transport and hammering phase for each cylinder, smoothness of the movement trajectory and deviation of the endpoint obtained during the hammer task and accuracy, duration, and fractionation (ability to isolate the movement of each finger) obtained during the virtual piano task. Clinical measures used to test at the body structure and activity levels consisted of the Upper Extremity Fugl-Meyer (UEFMA) and three-timed tests, the Jebsen Test of Hand Function (JTHF), the Wolf Motor Function Test (WMFT), and the Nine Hole Peg Test (NHPT) [10–12]. In addition, the Modified Functional Reach [13] was used to evaluate our ability to improve MP's ability to bend at the waist while reaching forward, a specific goal he described during his examination. We tested for changes at the activity level outside the laboratory by collecting UE accelerometer data for 24 h immediately after each testing session. Metrics included total vertical plane activity [14], the ratio of impaired to unimpaired UE vertical plane activity [15], and total roll plane activity. Roll plane motion was chosen because pronation and supination movements tend to be a smaller component of non-purposeful movement than the vertical flexion activity measured in other studies [16]. To test for changes at the participation level, MP completed the hand, mobility, activities of daily living and social participation subscales of the Stroke Impact Scale [17].

Procedure and customized intervention

Prior to the VR/robotic intervention MP received combined physical and occupational therapy in his home focusing on ambulation, balance, transfers, and upper extremity function. Data were collected 4 weeks before (pre-test 1) and immediately after the 1-month (12 sessions) period of home therapy (pre-test 2). One month (12 sessions) of VR/robot training began 4 days after the second data collection. The third data collection (post-test) was performed after completion of VR training. During his examination MP described the following goals: i) improved use of his arm and hand during transfers; ii) improved use of his arm during dressing; and iii) improved use of his hand during eating, grooming, and computer activities. MP's goals and the results of his examination were used to choose simulations and strategies for their implementation. Over 4 weeks, of VR training, MP performed 12 sessions of training with the NJIT-RAVR system and the NJIT Track-Glove system, which are described in detail elsewhere [18, 19]. MP performed six different simulations at all of these sessions.

Simulations

MP had difficulty manipulating small objects due to an inability to flex fingers individually. We utilized the Virtual Piano (Figure 1A) trainer to address this impairment. MP combined the performance of scales and drills with his hand stationary and short songs with his hand moving along the length of the keyboard. The simulation measures the difference between the metacarpophalangeal angle of the finger cued to press a key and the average of the other fingers. When a target difference is exceeded, a note plays. This target is controlled by an algorithm using the subject's prior performance. MP made poor progress during training with this simulation over the first 3 days of the intervention (Figure 1, Right Panel). We added the CyberGrasp, an exoskeleton robot, to help MP maintain extension of the noncued fingers during his attempts to bend the cued finger (Figure 1, Middle Panel). The CyberGrasp was used during the entire session during week 2 and during the first 5 min of each session with the Virtual Piano trainer, followed by a 15-min block without the robot during week 3. MP trained without the CyberGrasp during week 4. This strategy was effective for improving finger individuation over the final 3 weeks (Figure 1, Right Panel).

MP also reported difficulty controlling the aperture of his hand as he attempted to grasp objects. We utilized the Space Pong simulation to address this impairment. MP played this pong game using opening and closing of his hand to control the paddle. Initially MP made no improvement in his performance of this game. After week 1, MP's therapist decreased the ratio of actual movement to virtual movement from 100% to 70% which increased the amount of finger movement required to produce paddle movement. This allowed MP to control his paddle more accurately. Gain was increased (by 15%) to 85% on day 6 and back to 100% for the last week of the trial as MP's accuracy scores increased (Figure 2).

During his examination, MP had difficulty handling objects that were more than 60 cm from his body due to difficulty stabilizing his arm and hand with his shoulder elevated. We implemented the Hammer simulation to address this impairment (Figure 3, Left Panel). MP moved a virtual hammer over virtual pegs in a three-dimensional space and then hammered them using a repetitive finger extension-flexion movement. We used an algorithm that modified the area of the top of the target, to reinforce UE-stabilizing behavior. We increased target size, which decreases stability demands, when MP hammered targets efficiently and decreased the area, which increases the need to stabilize when he finished targets quickly. MP made steady improvements in this construct during the first two weeks of the trial and maintained them despite increases in the weight of his arm supported during this simulation (Figure 3, Right Panel). In addition to shaping proximal stabilization we also gradually increased the percentage of the weight of arm support that was provided during this activity. This percentage was increased when MP averaged <15 s to hammer pegs over the course of an entire training day (Figure 3, Right Panel).

MP demonstrated difficulty performing activities requiring pronation of his forearm. We utilized a modified version of the hammer simulation described above to train pronation in varying degrees of elbow extension and shoulder flexion, with the arm fixed in space during

a set. Fixing the arm decreased the load MP needed to stabilize with his shoulder musculature. We attempted to utilize an algorithm that modified the proportion of patient movement to avatar movement. The therapist decreased the amount of pronation required to swing the hammer in order to increase MP's success rate. This approach was successful during week 2 but the gains were not maintained during week 3, when the pronation to hammer movement ratio was returned to normal. A second attempt was made using this approach during week 3 with little success (Figure 4).

During his examination, MP had difficulty reaching and bending at the waist in a coordinated fashion. We utilized the Cup Reaching simulation to improve this ability (Figure 5, Left Panel). To perform this simulation, MP attached his hand to a virtual cup resting on a table near his body, reached forward and placed it in one of the nine spaces on a haptically rendered shelf. We set the height, width, and distance of the shelves based on MP's maximum reaching excursions. We calibrated the workspace reaching weekly, with MP's trunk moving freely and encouraged him to flex at the trunk to increase his forward reaching distance. We started each week of training in 65% of the maximum reaching space and increased the percentage if MP's time to place a set of nine cups decreased on a given day. The volume of the workspace and average time to place nine cups for each day is summarized in Figure 5, Right Panel.

We utilized a second simulation Reach-to-Touch to also address forward reaching impairments focusing on the shoulder and elbow through three-dimensional reaching movements. In this simulation, MP was encouraged to keep his trunk still during the reaching task and was cued to sit back if he bent at the waist to complete a movement. A similar schedule of workspace calibration was followed, calibrating every third day throughout the intervention using the same protocol used for the Cup Reaching simulation. MP's time to perform this simulation decreased steadily despite systematic increases in the size of the reaching movements he performed (Figure 6).

Results

MP did not make changes in UEFMA subsequent to the month of home PT/OT (pre-test 1 to pre-test 2) but demonstrated a 4-point improvement in the UEFMA subsequent to the 12 sessions of robotically facilitated VR training (pre-test to post-test). MP achieved an inconsequential, 5-s improvement in JTHF time following home therapy but demonstrated a 35-s improvement following the robot/VR intervention. MP performed 3 s slower on the WMFT following his period of home training but made a substantial 44-s improvement subsequent to robotic training. MP's NHPT time improved by 14 s following robotic training.

All 3 of the 24-h activity measurements collected before and after the VR/robotic training improved as well. Active vertical plane movement increased (26 min) which is comparable to changes demonstrated during an acute rehabilitation stay [14]. The time for performing pronation and supination increased by 13 min. The ratio of impaired arm movement to unimpaired arm movement increased from 41% to 51%. Subjects in a CIMT study of subjects poststroke made a similar 10-percentage point increase in UE ratio [20]. MP

demonstrated an improvement of seven points on the hand scale of the SIS, six points on the social participation scale, and eight points on the ADL scale. MP's caregivers also reported a dramatic increase in MP's ability to participate in pull-to-stand transfers with his impaired UE.

Conclusions

The clinical, kinematic, and 24-h real-world activity monitoring demonstrate the positive outcomes from this case study showing potential advantages in this personalized robotic/VR intervention. MP made substantial improvement in the JTHF and WMFT. Each of these tests contains several items that involve object manipulation and transport with accuracy demands beyond those of a gross grasp. In addition, MP made small improvements in ADL function and demonstrated improvements in all four measurements of impaired arm use as measured by activity monitor. Despite these changes, MP demonstrated no improvements in the wrist-hand portion of the UEFMA. A large majority of the robotic intervention studies for persons with stroke utilize the UEFMA as their primary outcome measure and a lack improvement in wrist-hand function is cited as a limitation of robotic UE interventions [2]. We feel that MP's pattern of improvement may suggest a lack of sensitivity in the UEFMA for determining changes in wrist-hand function.

Multiple authors espouse limiting trunk movement as a method for decreasing abnormal and inefficient compensatory trunk movement during reaching activities [21, 22]. Others cite evidence of coordination of trunk and arm movement in normal motor control [23]. Poorly coordinated trunk and UE movement were impairments that we targeted for MP's intervention by utilizing large excursion reaches and encouraging MP to use trunk movement to accomplish them. MP made substantial improvements in his ability to perform this movement during training and as measured during the Modified Functional Reach test. MP's caregivers also commented that he was better able to transfer because of improved forward weight shift and increased ability to reach forward for grab bars. We attempted to balance the development of maladaptive reaching strategies by presenting MP with two more reaching activities (Hammer simulation and Bubble Explosion simulation) that trained reaching without trunk movement.

Modifications in approach to training were made based on therapist observation in three of the six simulations (Piano Trainer, Space Pong, and Cup Reach), all of which resulted in substantial improvements in MP's performance of the simulations. The training protocols described in a large majority of the investigations of rehabilitation robotics involve set protocols that do not vary significantly based on subject response [2]. This may result in an underestimation of the potential benefits of this technology as the training programs utilized in these studies fail to leverage the flexibility of robotics and virtual environments as rehabilitation platforms.

The manipulation of the relationship between participant and avatar movement during virtually simulated rehabilitation activities has been examined by Bagec et al. [24]. In their study, conditions in which the avatar moved less than the participants' actual movement resulted in increased levels of cortical activation, and decreased levels of cortical activation

when avatar movement exceeded the actual amount of movement performed by the participant. Interestingly, MP demonstrated improved levels of motor performance during performance of Space Pong, which presented MP with very small avatar movement compared to his actual movements and no improvements in pronation during performance of the Hammer Task in which we presented large avatar movements compared to MP's actual movement. This technique has been used previously to transform tiny amounts of active movement into "meaningful" movements in an attempt to improve motor learning/neuroplasticity [25].

Two of the simulations utilized in this study incorporate adaptive algorithms that scaled task parameters based on MP's performance in real time as MP performed training tasks. The Hammer Task simulation gradually decreased the area of the target as MP improved his ability to stabilize his hand and the Piano Trainer simulation required progressively larger levels of individuated finger flexion to strike piano keys based on MP's performance of the previous 10 repetitions. Brief discussions of our approach to modifying task parameters in response to a participant's performance have been described elsewhere [1, 19] and a more in-depth discussion of this approach has been presented by Cameirão et al. [26]. It is important to note that this technique has the potential for making rehabilitation activities more effective because high levels of intensity are maintained, and more cost effective, and because it decreases the need for direct supervision of a therapist to make minor modifications of task parameters. With the feasibility of this approach well established, further investigations comparing the effectiveness of adaptively scaled activities to more traditionally presented activities are indicated.

This case report clearly demonstrates the flexibility of a robotic and VR rehabilitation system and its ability to personalize a program of robotically facilitated repetitive task practice. This individualized application of VR training has not been adequately evaluated by the standardized treatment protocols reported in the existing literature. Further evaluation of this approach will be critical for the translation of VR training from the laboratory to widespread clinical practice.

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Figure 1.
Left Panel: subject performing Virtual Piano Trainer simulation. Center: CyberGrasp™ worn over a CyberGlove™ (Immersion Technologies, USA) as used in this case. Right Panel: daily averages for fractionation score demonstrated by MP.

Figure 2.

Right Panel: daily averages for accuracy (blue boxes) and gain which is the ratio of finger movement to avatar movement. Left Panel: Screenshot of Space Pong (©Steve Taylor, 2003).

Figure 3. Left Panel: Screenshot of Hammer simulation. Right Panel: daily averages for time to hammer 10 targets (blue boxes) and arm fixation scores (red circles) lower numbers equal less extraneous movement. Note that assistive forces decrease every 3 days.

Figure 4. Description of daily averages in pronation active range of motion and gain which is the ratio of forearm movement to avatar movement.

Figure 5. Left Panel: subject performing Cup Reaching simulation. Right Panel: daily averages for reaching depth (open figures) and time to move 10 cups (closed figures). Workspace was calibrated every 3 days.

Figure 6.

Left Panel: subject performing the reach-touch simulation. Right Panel: daily averages for workspace volume (red circles), smoothness (blue boxes), and the average time to complete a set of 10 targets.